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The development of a practical heat stress assessment methodology for use in UK industry

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The development of a practical heat stress assessment methodology for use in UK industry

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A series of ten experiments were conducted at the Human Thermal Environments Laboratory at Loughborough University to compare the validity of ISO 7933 Required Sweat Rate (SW_{req}) and Predicted Heat Strain (PHS) index predictions with observed physiological data. Comparisons were made between the predicted and observed sweat rates and the time it took core temperature to reach 38°C (Duration Limit Exposures). The results showed that neither the SW_{req} nor the modified SW_{req} model were valid predictors of Duration Limit Exposures (DLE) and predicted sweat rate for people wearing protective clothing in warm humid environments. The PHS DLE predictions were more representative of the ISO predictions that the observed DLEs in all but one experiment. Although the PHS model predictions of sweat rate were an improvement on the ISO predictions. The model also significantly underestimated the observed sweat rates. Following the validity study, a heuristic evaluation of the usability of ISO 7933 was also performed. This found that the standard is unnecessarily scientific and may not encourage users to use it. The format and the information provided do not satisfy ergonomic guidelines of usability. The need for a more practical heat stress assessment methodology was identified. A framework was formulated for the design, development and evaluation of such a methodology. This framework consisted of three stages; an Exploratory Stage, a Design and Development Stage and an Evaluation Stage. This resulted in the development of a practical heat stress assessment methodology.

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- The workers who took part in the field experiments,
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Foreword

It has long been known that work in the heat can compromise health and safety and lead directly or indirectly to worker injury and death. This project, sponsored by the Health and Safety Executive in the United Kingdom, was conducted to ensure that developments in heat stress assessment were evaluated and where to advantage, included in assessment methods appropriate for use in British industry. The project was conducted by the Human Thermal Environments Laboratory at Loughborough University who are nationally and internationally active in the field and have been involved in heat stress research for over 20 years.

The project presented in this report is unique in that it addresses the issues of both validity and usability. It was conducted in parallel with a number of national and international initiatives into heat stress assessment. Professor Ken Parsons was particularly well placed to ensure that the project could act on up-to-date developments. As Chairman of ISO TC 159 SC5 'Ergonomics of the Physical Environment', Convenor of CEN TC 122 WG11 'Ergonomics of the thermal environment' and Chairman of BSI PH9/1 'Ergonomics of the thermal environment', he was involved in the revision of relevant standards. Professor Parsons and Damian Bethea were also involved in the production (through the Department of Trade and Industry and the Institute of Occupational Medicine, Edinburgh) of the standard BS 7963 (2000) *Ergonomics of the thermal environment – Guide to the assessment of heat strain in workers wearing personal protective equipment*'. BS 7963 improved the application of the method used in ISO 7933 (1989), based upon the calculation of required sweat rate, to take account of protective clothing and equipment. The revision of ISO 7933 is underway and the proposal is to replace the required sweat rate index (SWreq) with the Predicted Heat Strain index (PHS). We are fortunate to have had access to full documentation of this work as well as to the related heat stress assessment strategy proposed by Malchaie *et al*. (2000). This is because Loughborough were also participants in the European Union BIOMED II project which reviewed and extensively revised the method presented in ISO 7933 (1989).

The BIOMED II research team was co-ordinated by Professor Jacques Malchaire (Universitée Catholique de Louvain, Belgium) and involved the following researchers and laboratories: Alain Pettite (Université Catholique de Louvain), Professor Barbara Griefahn, Peter Menhert (IfaDo, Dortmund, Germany), Professor Ingvar Holmér, Hakan Nielsson (National Institute for Working Life, Stockholm, Sweden), Dr George Havenith (now at Loughborough), Emile Den Haag (TNO, Sousterburg, Netherlands), Professor Ken Parsons, Damian Bethea (HTEL, Loughborough, UK), Dr Bernhard Kampmann (German coal mines, Dortmund, Germany), Dr Hans Jurgen Gehardt (Wuppertaal, Germany) and Professor Gaetano Alfano (University of Naples, Italy).

The present project achieved its aim of investigating the validity and usability of existing (ISO 7933; 1989) and proposed (PHS and risk assessment strategy) methods. It also provided a proposal for a heat stress assessment strategy that could be effectively used by British Industry.

Ken Parsons and Damian Bethea
Loughborough, January, 2001.

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EXECUTIVE SUMMARY

Methods for the assessment of hot environments have been developed at national, European and international levels. It is generally recognised however, that they are limited in their application. BS EN ISO 27243 has been the accepted as a simple assessment method since 1984. It is based upon the wet-bulb globe temperature index (*WBGT*). ISO 7933 (BS EN 12515) presents an analytical approach to heat stress assessment called the Required Sweat Rate (SW_{req}) index. The SW_{req} index evolved from the Heat Stress Index (HSI – Belding and Hatch, 1955). A revision of the SW_{req} index has lead to the development of the Predicted Heat Strain (PHS) model.

Criticisms of existing methods for the assessment of heat stress are mainly in three areas:

- The **SCOPE** of the methods is often not sufficient to meet the varied realities of industrial heat stress. For example, methods do not account for the effects of protective clothing and equipment, yet workers in hot environments often wear this sort of clothing;
- The **VALIDITY** of methods has been questioned. Does the method really relate to the heat strain on the workers?
- In recent years the **USABILITY** of methods has been recognised as important. Methods may be valid and sufficient in scope but if they are too complex or not presented in a way that is complementary to the context, people and organisations who use them then they may not be used correctly, if at all.

A series of ten experiments were conducted at the Human Thermal Environments Laboratory at Loughborough University to compare the ISO 7933 Required Sweat Rate SW_{req} and PHS predictions with observed physiological data. The SW_{req} model was also modified to provide a modified skin temperature for conditions where subjects wore clothing with clothing insulation values of greater that 0.6 clo (as required in the standard). This was called the ISO_{mod} model. Comparisons were made between the predicted and observed sweat rates and the time it took core temperature to reach 38°C (Duration Limit Exposures). The results showed that neither the SW_{req} nor the modified SW_{req} model were valid predictors of Duration Limit Exposures (DLE) and predicted sweat rate for people wearing protective clothing in warm humid environments. The PHS DLE predictions were more representative of the ISO predictions that the observed DLEs in all but one experiment. Although the PHS model predictions of sweat rate were an improvement on the ISO predictions. The model also significantly underestimated the observed sweat rates.

One area of concern was that in industry users of the indices would probably predict the metabolic rate. As such, comparisons were made between the results when estimated metabolic rate and measured metabolic rate were inputted into the models. Insignificant differences in metabolic rate inputs ($p<0.42$) had a greater impact on the predicted DLEs in the ISO models, with little effect evident in the PHS predictions. These differences between observed and predicted DLE within each model were insignificant. However, the differences in metabolic rate inputs had a significant effect on the SW_p in the PHS model ($p<0.00$) and not on the ISO ($p<0.25$) and ISO_{mod} ($p<0.24$) SW_p predictions.

THE USABILITY OF ISO 7933

A heuristic evaluation of the usability of ISO 7933 was performed. Three main areas of the standard were investigated; the paper based standard, the computer program, and the practical use of the model to determine safe work times. The paper based standard had poor or inadequate usability in a number of areas; simplicity, structure, consistency, speaking the user's language, providing adequate information and minimising user memory load. The standard appears unnecessarily scientific and would not encourage users to use it. The format and the information provided do not satisfy ergonomic guidelines of usability. Users should not be expected to use the equations presented in the standard and to work through them manually. This standard can only be used as a computer program and, as such, much of the information provided in the body of the standard is superfluous to their requirements.

THE DESIGN, DEVELOPMENT AND EVALUATION OF A PRACTICAL HEAT STRESS ASSESSMENT METHODOLOGY

The following framework for the design, development and evaluation of a practical heat stress assessment methodology was formulated. The overall strategy of the system life cycle was adopted to establish and define the processes that would be employed in the design, development and evaluation of the methodology to meet the specific requirements of this research. The life cycle consisted of the three stages:

Exploratory Stage - Involved the background research into the subject area with a literature review of those topics that would be investigated during the research. Knowledge of ISO 7933 SW_{req} was gained through a series of validity studies and a heuristic analysis of the usability of the standard.

Design and Development Stage - During this stage a number of methods were used to establish a formal definition of who the users would be so that their requirements of a practical heat stress assessment methodology could be identified. A further requirement was to define what the functional specification of the methodology should be. This information, along with the findings of detailed literature survey would provide the basis for the development of the methodology.

Evaluation Stage - Production of Final Prototype will be followed by a formal comparative usability evaluation of the prototype methodology with the three stage model developed by the BIOMED project.

The structure of the system's lifecycle was dynamic and underwent a number of alterations due to the difficulties encountered as the project progressed. A number of ergonomic methodologies were used to elicit data to enable the development of user requirements and a functional specification of a practical methodology as well as its evaluation. The methods used included; hierarchical task analysis, informal interviews, questionnaires, structured discussion groups and user trials. The result was that a practical heat stress assessment methodology has been developed and is proposed for further detailed evaluation in UK industry.

CHAPTER 1
INTRODUCTION & LITERATURE SURVEY

1.1 SUMMARY

The aims of this chapter are to introduce the topic of heat stress risk assessment, and to identify the context and issues within which the development of a valid and usable heat stress assessment method can be carried out.

Chapter 1 includes Sections 1.2 (Introduction) and 1.3 (Literature Review) of the Report. In Section 1.3, the concept of a heat stress index and current British, European and International standards are introduced. Research objectives were identified in relation to the evaluation of heat stress based on the validity and usability of the existing SW_{req} model and the proposed predicted heat strain PHS model. The outcome of the project was to be the user-oriented design, development and evaluation of a practical heat stress assessment methodology for UK industry.

The aim of the literature review was to use past research and current knowledge and activity to provide direction for the research. It was concluded that there is growing evidence that the current international standard ISO 7933 (1989) has limited validity and is not usable. A BIOMED II European Union project has produced a Predicted Heat Strain (PHS) index. This index has only been validated by its developers and should be investigated further through independent evaluation.

1.2 INTRODUCTION

A heat stress index integrates the effects of relevant environmental and personal factors into a single number that varies in direct relation to the degree of heat strain on people.

The **validity** of an index is an indication of how well the index value relates to heat strain and the **usability** of the index relates to how easy it is to apply by users; for example, in an industrial context. There are a number of possible benefits to be obtained from a valid and usable index, for example;

- to indicate the degree of heat strain expected in workers,
- to monitor work to ensure that there is acceptable risk,
- to determine acceptable exposure times to work in the heat.
- to provide limits beyond which unacceptable heat strain would occur.

"*An optimal heat stress index should provide an accurate prediction of the worker's physiological state at any time of exposure, thus allowing the occupational hygienist to assess the permissible duration of exposure and the duration of rest breaks. This objective implies that the index value at a given time takes proper account of the characteristics of past exposure and the response-time constant of the physiological variable considered. This feature of the index variation can only be studied in well controlled conditions where both the input parameters (metabolic rate, climatic* *parameters) and the output variables (sweat rate, body temperature, heart rate) are measured with accuracy*," Mariaux and Malchaire, 1995.

Since the industrial revolution and the resultant proliferation and advancement of industrial technology, people have been at risk from exposure to occupational hazards that would have adverse effects on their health and well being. One such occupational hazard is heat. The thermal environment in industry is a direct result of the advances in the mechanisation of the production process and differs greatly from the ambient weather-dependent climatic conditions (Eissing, 1995). Since all humans are susceptible to the stresses of exposure to heat, knowledge of the magnitude of the environmental heat load would enable the consequences of the exposure to be predicted (Belding and Hatch, 1955). To estimate the magnitude of the heat load, the six human thermal environmental variables (parameters) - air temperature (t_a), radiant temperature (t_r), air velocity (Va), humidity (h), clothing properties and metabolic rate are critical.

1.2.1 Heat Stress Indices

A great deal of research has resulted in the development of practical methodologies for the design and evaluation of hot working environments. The integration of this knowledge has resulted in the concept of the heat stress index to specify safe working conditions for hot environments. Belding and Hatch expanded upon the six basic parameters and described 13 parameters which they divided into 2 subgroups:

- **Factors determining imposed heat**: Temperature of the air, of walls etc, of the skin, water vapour pressure, air velocity, metabolic heat production, body surface area exposed and postural attitude, and finally clothing.
- **Factors determining resulting strains:** Heat tolerance and the consequences of increased deep body temperature, exposure duration, skin wettedness and other consequences of sweating, vasodilatation of blood vessels at the skin and the consequences of this increased blood flow to the skin.

It is from these expanded parameters that the principles of rational heat stress indices have been based, as these parameters cannot be treated separately. The development of heat stress indices has also been aided by an improved understanding of the interaction of these parameters, along with technical advances and an increase in the use of computers. Computer models of thermoregulation and the development of international and national standards has created the mechanisms for thermal audits and education and the methodologies for their execution (Parsons, 1995). Standardisation of these methods has provided exposure limits for the worker who may be at risk from heat stress.

A number of influential bodies throughout the world that have been responsible for the development of these standardised methods. These bodies include the International Standards Organisation (ISO), British Standards Institute (BSI), American Conference of Governmental Industrial Hygienists (ACGIH), American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) and more. The most significant recent development has been the international co-operation that led to the development of ISO standards for the ergonomics assessment of human thermal environments. Many of these standards have also been adopted as European Standards by CEN (European Standards body) and nationally by the relevant bodies, such as the British Standards Institution (BSI). The European Coal and Steel Community (ECSC) has developed and used ergonomics methodologies and principles extensively, to the point where it now plays a major role in the occupational health and safety of both industries (Parsons, 1995). An important consideration in understanding the development of ergonomics within the ECSC framework is that much of the impetus of the programmes' development was 'action oriented' and industry based. The creation of wealth is not threatened by the improvements in the quality of working life and health and safety. The prevailing philosophy behind this development has been that action and research activities must be differentiated. Thus, the research aim should be to sustain the action by providing relevant data.

Many of the research activities of the ECSC led to the development of *ISO 7933. Hot Environments, Analytical determination and interpretation of the thermal stresses using calculation of required sweat rate* (*SWreq*). This standard is also a British standard (BS EN 12515), however as this is almost identical to ISO 7933, for the purpose of this report it will be referred to as ISO 7933. The SW_{req} index is a rational heat stress index, although it's validity has been questioned and consequently a European project called BIOMED HEAT was conducted. The objective of the BIOMED project was to co-ordinate the work of eight European laboratories specialising in human thermal environments to improve the assessment of hot working environments. Malchaire (1999) provides the following list of the specific objectives of the BIOMED project:

1. *"To design and validate a strategy for the assessment of the strain related to hot working conditions, strategy that can be used by practitioners in the field to determine maximum allowable exposure durations and to optimise the improvement of the working environment;*
2. *To extend the validity of the present modelling of the role of clothing;*
3. *To improve the validity of the present indices in cases of high radiation, high humidity or high air velocity;*
4. *To better define the criteria for the determination of the maximum allowable exposure duration and in particular the inter-individual differences in sweating rate, evaporation efficiency, water loss and increase in core temperature".*

This resulted in a new rational model of heat stress called the Predicted Heat Strain (PHS) index and a three-stage approach to the assessment of heat stress involving Observation, Analysis and Expert Stages.

According to Parsons, these heat stress standards can potentially contribute to a reduction in heat stress casualties, although their implementation has not had as large an impact as may have been hoped. To this end, this project is concerned with the development of practical guidelines for the use of the appropriate standards paying particular attention to the requirements of UK industry.

1.2.2 Research Objectives

There were four main objectives:

1.) To evaluate the Validity of the ISO 7933 Required Sweat rate (SW_{req}) and Predicted Heat Strain (PHS) models (**see Chapter 2**)
2.) To evaluate the Usability of ISO 7933 (**see Chapter 3**)
3.) To design, develop and evaluate a practical heat stress assessment methodology (**see Chapter 4**)
4.) To produce a practical heat stress assessment methodology (**see Chapter 5**)

1.3 LITERATURE SURVEY

1.3.1 Aims

The aim of the Literature Review is to provide an overview of past research and current knowledge of heat stress relevant to ISO 7933 and those other Standards and methods concerned with the assessment of hot working environments. The survey is extensive and provides a rationale for the approach taken to achieve the project's aim to develop a valid, usable and practical method for the assessment of heat stress in British industry.

1.3.2 Human Thermoregulation

Introduction

The temperature of the human body is an important indicator of the state or condition that it is in. Leitheid and Lind (1964) recalled work by Claude Bernard in 1878, who proposed the concept of the "*milieu interior*" where an effective thermoregulation mechanism helps maintain the mechanisms of the internal body organs. This thermoregulation occurs when receptors, sensitive to change, send messages via the Central Nervous System to the hypothalamus, from where it is believed the regulation of body temperature is controlled. The ultimate control and co-ordination of thermoregulation in humans is controlled by the autonomic system which is that neural system within the human body that controls those bodily functions which are not usually under voluntary control. When set point is exceeded, blood vessels widen (vasodilatation) and blood is pumped to the skin, thereby loosing heat from the blood to the skin. This in turn reduces the gradient between skin temperature and the air temperature, reducing the gain of heat through convection and conduction. Through this process of thermoregulation, humans maintain their deep body temperature at or about 37°C and any deviation of a degree or more (plus or minus) from 37°C can have serious consequences.

The concept of heat stress can be confusing with Leithead and Lind (1964) pointing out that "*the term heat stress expresses an easily recognised concept which has a practical value but which is difficult to define*". Belding (1955) also identified the possibility for confusion, but in terms of heat exhaustion and heat stroke. What is appreciated is that discomfort and fatigue are caused by low levels of heat stress, performance impairment by higher levels, while a heat that exceeds tolerance levels may be a health hazard (Rodahl and Guthe, 1988).

The Heat Balance Equation

For the internal body temperature to be maintained at around 37°C, there must be an equilibrium between the amount of heat generated within the body and the heat transferred to or from it. This equilibrium, or balance, is by no means constant, but is as dynamic as the conditions within which the body is working. The concept of the heat balance equation for the human body explains and provides an understanding of how 37°C internal body temperature is maintained. Parsons (1993) points out that all heat balance equations have the same underlying concept: heat generation within the body, heat transfer, heat storage. Equations **1** and **2** show the conceptual heat balance equation where metabolic rate (M) provides energy enabling the body to perform mechanical work (W). The remainder of the energy is given off as heat (M-W). There are a number of ways that heat transfer can be achieved: evaporation (E), radiation (R), convection (C) and conduction (K). The resultant heat production and loss provide the storage (S), where in heat balance, S = zero.

$$M - W = E + R + C + K + S \tag{1}$$

when S=0

$$M - W - E - R - C - K = 0 \tag{2}$$

Core Temperature Limits

Deep body temperature (core temperature) can rise to 39°C in controlled conditions (NIOSH 1986). It is not therefore a forgone conclusion that a worker will become a heat stress casualty when their core temperature reaches 38°C or even 39°C. According to NIOSH, 38°C provides a "*modest safety margin*" because as core temperature exceeds 38°C, so the risk of heat stress occurring increases. This is further complicated by the degree of accuracy with which the actual environmental and work rate loads are assessed may be suspect, with this safety margin allowing some degree of error in the assessment. If insufficient heat is lost, deep body temperature will continue to rise to between 38°C and 39°C (where collapse may occur) and 41°C (where heat stroke may occur).

The Importance of Metabolic Rate

Since heat is produced in proportion to the work rate, deep body temperature has been found to be more closely related to metabolic rate than to the rate at which body heat had to be eliminated (Nielsen, 1967). Therefore, metabolic rate is a major contributor to heat stress even when environmental conditions would suggest that worker is not at risk. Core temperature in a steady state is dependent upon work rate, while under severe environmental conditions this thermoregulation fails. Graveling and Morris (1994) stated that the criteria of many heat stress documents, e.g., ISO 7243 1989, ISO 7933 1989 and NIOSH 1986, operate on the principle that an increase in work rate should be compensated for by a reduction in the environmental heat load. It is here that the criteria for the setting of limits in an industrial setting are set. These "limit" conditions must be cooler than those that cause heat stress.

Effects on Cardiac Output

Work under heat stress conditions results in a competition for cardiac output because less blood is returned to the deep body due to vasodilatation of the blood vessels in the skin (NIOSH). The blood therefore is not only carrying oxygen to the muscles but it is also acting as a cooling fluid. As a result, heart rate increases to maintain the same cardiac output and at a sub-maximum work rate, thermoregulatory requirements override the working muscle's requirements for oxygen. Consequently, heart rate increases during heat stress compared to the same work rate in neutral conditions. This difference decreases as VO_2 nears maximum (Shepherd and Webb-Peploe (1970) cite work by Rowell *et al* (1966). The phenomenon of this heat-induced increase in heart rate is known as cardiac beats or thermal drift. This, when coupled with the demands placed upon the heart due to work rate, amplifies the problems even in healthy workers and can manifests itself in heat exhaustion or collapse, due to the inadequate cardiac output providing an insufficient blood supply to the brain (Rodahl and Guthe, 1988).

Due to its ease of use and its apparent wide use in industry, Vogt *et al* (1983) investigated whether the use of heart rate in the setting of industrial work-rest schedules in the heat was a possible solution. However, they found that even when rest schedules were observed, the heart rate at the end of the experiment was the same as that found when continuous work was observed. This suggested that the thermal component of the subject's heart rate did not decrease sufficiently during the rest schedules. They also found that the use of heart rate alone was not a valid determinant for the establishment of self regulated work-rest schedules even though heart rate may be closely linked to the reason the worker stopped working.

Therefore, although heart rate is an excellent indicator of the general stress imposed on the body, it is not an accurate measure of heat stress because the resultant heart rate will be affected by the thermal strain under which the person is working. Heart rate is only really useful in heat stress assessment if other influencing factors are controlled. Heart rate closely follows core temperature in a general way, but may parallel skin temperature, especially under high radiant temperatures (Rodahl and Guthe, 1988).

Sweating

The action of sweating itself does not contribute to the loss of heat. Rather, it is the evaporation of the sweat from the skin that drives cooling and in hot environments the evaporation of sweat is the dominant mechanism for maintaining a steady core temperature for a given metabolic rate. In humid environments the driving force encouraging sweat evaporation is diminished due to the resultant decrease in the difference between the partial vapour pressure at the skin and in the environment. As such, in humid environments the effectiveness of heat loss through sweating is reduced as the capacity for evaporation is reduced. This can lead to profuse sweating where dripping of sweat from the skin occurs resulting in insignificant loss of heat with a further reduction in body fluid. A decrease in sweating may occur as the deep body temperature continues to rise and the skin is completely wet. The situation is further complicated when a worker is wearing protective clothing. An example of the power of sweating is provided by NIOSH (1985) which states that each litre of evaporated sweat will provide a loss of 675W of energy. During sweating, salt is lost at about 4g per litre for unacclimatised workers and 1 g per litre in acclimatised workers. Rodahl and Guthe (1988) state that "*prolonged exposure to heat and/or prolonged exercise almost always causes hypohydration*". Additionally, rectal temperature which is used as an indication of core temperature is always significantly higher in dehydrated subjects. The increase in heart rate due to thermal stress is further exacerbated by the loss of water through sweating because large sweat losses reduce the body's water content (hypohydration) and therefore reduces the blood volume.

Acclimation

Sweating efficiency increases with acclimation because maximum sweat production is greatly increased and a sub-maximum sweat production level is achieved at a much lower t_{sk} and t_c. Another consideration is that the distribution of sweat is improved with an overall improvement with respect to the total surface area where sweat is being produced and the amount of sweat produced. Acclimation is achieved with repeatedly exposing an individual to a hot environment over a number of days.

1.3.3 Heat Stress in Industry

Leithead and Lind (1964) wrote that "*for the most part*", industrial work presents only low levels of heat stress although in many cases those environmental conditions found naturally are exceeded greatly. Meyer and Rapp (1995) stated that despite technological advances "*heat stress remains one of the most frequent complaints of French workers*". This contrasts with work they cite by Millican *et al* (1981) who stated that heat stress "*comes low on the list of hazards*" although a survey by the French Ministry of Social Affairs reported a daily or frequent occurrence of heat stress in 16.6% of workers. These results may show an overall decrease in complaints since a similar survey conducted in 1979 suggested 19.4% of workers suffered heat stress. Meyer and Rapp reported that these results would seem to be applicable to other western countries where one of the most frequently reported stress factors is working in the heat. (For a detailed review of heat stress in industry see the literature review by Rodahl and Guthe, 1988.)

One of the features associated with the assessment of heat stress in industry appears to be that the exposures are often infrequent and may be for short periods. This is important, because the assessors of the risks may be conducting heat stress assessments so infrequently that they find it difficult to transfer their knowledge from one assessment to the other. Meyer and Rapp (1995) provide three examples of what they call "*unusual field situations*".

1. Bin incinerator workers cleaning a furnace, where protective clothing is worn (including fresh air supply), high metabolic rates are observed, with exposures lasting between 4 and 10 minutes.
2. Maintenance of food sterilising conveyors where the work has to be carried out during normal operation. Workers may work in a confined area for time periods of between 10 to 30 minutes.
3. Workers checking the operation and maintenance in paper drying rooms with exposures lasting for between one and two minutes.

Here the definition of risk provided by Covello and Merkhofer (see Section **0**) suggests the need to consider "uncertainty" in the heat stress risk assessment procedure.

The following list of industries where workers may be at risk from heat stress has been compiled from literature reviews by Meyer and Rapp (1995), NIOSH (1986) and Rodhal and Guthe (1988) who also included a review of their own work:

- Glass products manufacturing plants;
- Drying operation in glass-wool manufacture;
- Potash Mines, Coal mines, gold mines, etc;
- Steam and compressed air tunnels;
- Conventional and Nuclear power plants – Sweeper tasks and maintenance tasks;
- Iron, steel, aluminium and other non-ferrous foundries and smelting operations;
- Brick-firing and ceramics operations;
- Plants producing rubber and rubber products;
- Electrical utilities (particularly boiler rooms);

- Bakeries, confectioneries and catering kitchens;
- Laundries and Ironing in dry cleaning shops;
- Food canneries.

1.3.4 Personal Protective Equipment (PPE)

Personal Protective Equipment is considered to be a "*last resort*" to protect workers from the hazards in the workplace (HSE, 1992). Wherever possible, engineering controls and safe systems of work should be provided. In practice though, Crockford (personal correspondence) found that PPE is often used as a first resort as it is cheaper than introducing engineering controls. This is mainly because the effects the environment has on worker performance are clearly less severe than they are on safety.

PPE and Heat Transfer

The very nature of PPE means that it interferes with the body's ability to lose heat from the skin to the environment because of the insulation provided by the clothing and the micro-climate within the garment (Kerslake, 1972; Goldman, 1988; Kenney *et al*, 1988; Parsons, 1993; Bethea and Parsons, 1998; Bernard and Metheen, 1999). The thermal insulation required to maintain a thermal balance for a human seated in a room at 21°C (air and radiant temperature), humidity less than 50% and air velocity equal to 0.1 $m.s^{-1}$ was defined as 1 clo by Gagge *et al* in 1941. One clo is equal to a clothing insulation of 0.155$°C.m^2.W^{-1}$ (the boundary layer of air around the human body is equal to 0.12 $°C.m^2.W^{-1}$).

Evaporation of heat for humans under warm or hot working environments provides a powerful cooling mechanism. "*Clothing both inhibits evaporation by producing a humid microclimate and diminishes the cooling effect of the evaporation that does take place*" (Nunnely, 1989). This means that heat stress in wearers of protective clothing occurs at lower environmental temperature and humidity values than for those of nude subjects.

The ability to transfer heat from the deep body tissue to the skin is achieved through the transfer of heat by blood to the skin and a key factor in heat stress amongst wearers of PPE is the convergence of skin temperature and core temperature. A skin temperature of 33°C and core temperature at about 37°C is usually observed when seated at rest. It is this 4°C difference between core temperature and skin temperature that enables heat to be transported to the skin. Therefore, as skin temperature increases so the amount of heat that can be transferred per unit of blood will reduce linearly (Goldman, 1988). As a result there is an insulation induced rise in skin temperature and the resultant limited ability to dissipate heat will causes a rise in deep body temperature.

According to NIOSH (1986), the skin temperature must be maintained at least 1°C below the core temperature if the blood is to be cooled before returning to the body core. Due to this convergence of t_{sk} and t_c, heart rate increases in an attempt to maintain cardiac output while the volume of blood pumped during each beat decreases. According to Goldman, "*if it does not occur beforehand, heat exhaustion collapse is almost certain to occur at or before the point where skin temperature reaches deep body temperature*". Here Goldman cites work by himself and Pandolf (1978) which showed that collapse may occur with core temperatures "*as low as 38.2°C with skin temperatures in the 37°C range*". The skin temperature though is affected by the insulative properties of clothing.

This inability to lose heat from the body when PPE is worn may even result in many workers either wearing the PPE incorrectly or not at all because it makes them feel hot (McCullough, 1983). Meyer and Rapp (1995) cite Millican *et al* (1981) and Badet *et al* (1983) who stated that protective clothing was seen more as a handicap than as protection. This is illustrated by Dukes-Dobos *et al* (1986) who reported that bin incinerator workers in the Aluminium plants that they studied seldom wore their protective clothing. Thus, these workers are exposing themselves to the hazards from which the PPE was supposed to be protecting them, thereby rendering their PPE ensembles redundant.

PPE and Metabolic Rate increase

Duggan (1988) suggested that when estimating metabolic rate for wearers of PPE, the extra metabolic heat production caused by the PPE needs to be considered and the practical implications of this concerns job design. Here, if a worker is to perform a particular task while wearing PPE, they will have a higher metabolic rate than when doing the same task with no PPE. Therefore, it is necessary (where possible) to redesign jobs so that the worker does not have to work at the same intensity as they would if they were not wearing the clothing. This is an important point because this resultant increase in metabolic heat production has two possible consequences:

1) The onset of fatigue will occur sooner than it would without PPE
2) Increased heat production increases the need for heat dissipation from the worker and the clothing ensemble.

Teitlebaum and Goldman (1972) reported that in a series of experiments, the PPE worn increased the work rate more than when the equivalent weight of the PPE was worn on a belt. They reported an increase of 18%, while they cite other authors as reporting varying increases in metabolic rate from 5 to 10% (During *et al*, 1966) and 11 to 13% (Consolazio *et al*, 1963).

More detailed estimates of the increases in metabolic rate associated with the wearing off PPE are provided in BS 7963 (2000). The table below is reproduced from Table 2 of BS 7963 (2000).

Table 1: Estimated Increases in Metabolic rate due to wearing PPE

	INCREASE IN METABOLIC RATE DUE TO WEARING RPE (W.M-2)				
	Resting	**Low metabolic rate**	**Moderate metabolic rate**	**High Metabolic rate**	**Very high metabolic rate**
Safety shoes/short boots	**0**	**5**	10	15	20
Safety boots (long)	**0**	**10**	20	30	40
Respirator (low/moderate performance e.g. P1, P2)	**5**	**10**	20	30	40
Respirator (high performance e.g. P3)	**5**	**20**	40	60	80
Self contained breathing apparatus	**10**	**30**	60	95	125
Light, water vapour permeable chemical coverall (e.g. Disposable)	**5**	**10**	20	30	40
Chemical protective water vapour impermeable ensemble [e.g. polyvinyl chloride (PVC)] with hood, gloves and boots	**10**	**25**	50	80	100
Highly insulating, water vapour semi-permeable ensemble (e.g. firefighter's gear consisting of helmet, tunic, over trousers, gloves and boots)	**15**	**36**	75	115	155

According to BS 7963: 2000, the following needs to be considered:

- Metabolic rate values have been rounded off to the nearest 5 W.m^{-2}.
- Respirator classification defined in BS EN 143 (1991).
- As can be seen from the estimated increases in metabolic rate, very high metabolic rate cannot be maintained when wearing some forms of PPE. Here job redesign would probably be necessary if engineering controls were not possible.
- Do not add footwear induced increased in metabolic rate for sedentary tasks.
- The table presents empirical data. If more accurate methods of obtaining metabolic rate values are required, refer to BS EN 28996.
- If metabolic rate is measured instead of estimated, corrections for the increased metabolic rate are not necessary.

1.3.5 Risk Assessment & Management Considerations

Introduction

The development of a practical heat stress assessment methodology requires that not only are the heat stress issues considered, but that the role such a methodology may play in the overall risk management and assessment process is understood. To this end, a detailed review was conducted on risk assessment and risk management literature and appropriate principles have been adapted to meet the very specific requirements of not only this project but heat stress assessment as a whole. Primarily though, this has been done from a user-oriented approach and not from an industry or risk specific perspective in order to better understand how health and safety professionals, occupational hygienists etc. may tackle a general risk assessment, what their expectations may be, and what their training tends to cover. This will provide a benchmark by which the current processes of heat stress risk assessment are compared to identify if there are any areas where current heat stress risk assessment strategies do not meet those of generic risk assessment procedures.

The Process of Risk Assessment

"*In many countries the requirement to provide a safe environment is a requirement by law*" (Osborne and Gruneberg, 1983). The UK is no different, where there is legal requirement for companies to identify hazards and to evaluate the risks that these hazards impose. The regulations for risk assessment are provided in the Management of Health and Safety at Work Regulations, 1992 consisting of the following documents:

- Manual Handling Operations Regulations 1992 (Manual Handling Regulations);
- Personal Protective Equipment at Work Regulations 1992 (PPE);
- Health and Safety (Display Screen Equipment) Regulations 1992 (Display Screen Regulations);
- Noise at Work Regulations 1989 (Noise Regulations);
- Control of Substances Hazardous to Health Regulations 1994 (COSHH);
- Control of Asbestos at Work Regulations 1987 (Asbestos Regulations); and
- Control of Lead at Work Regulations 1980 (Lead Regulations).

To comply with current health and safety legislation, employers and the self-employed are required by Regulation 3 of the Management of Health and Safety at Work Regulations 1992 to carry out a risk assessment to identify the measures they need to take.

Hazards and Risks

The most common definition for a **hazard** describes something that has "*the potential to cause harm*" while a **risk** is "*the likelihood of that the harm will be realised*". HSE (1991) provides the well-published equation for estimating risk where hazards are scored based on severity and probability,

$$\text{Risk} = \text{hazard severity} \times \text{likelihood of occurrence} \tag{3}$$

Everley (1994) added to this equation by multiplying risk by a number that represents the number of people who may be exposed to the risk. Recently though this definition has been considered to be somewhat restrictive and an alternative has been provided by Covello and Merkhofer (nd) where;

> "**Risk**. *A characteristic of a situation or action wherein two or more outcomes are possible, the particular outcome that will occur is unknown, and at least one of the possibilities is undesired.*"

Although this appears to be a somewhat cumbersome definition, it highlights an important principle. Risk is a two dimensional concept where one of two possible options may be found:

1. "*The possibility of an adverse outcome*
2. *Uncertainty over the occurrence, timing or magnitude of that adverse outcome.*"

A risk exists therefore, if there is uncertainty about the risk. Risk therefore is something that is both uncertain and undesired. The traditional definition of risk as the product of occurrence probability and consequence magnitude is relatively simple to define when one considers the cause-and-effect of single parameter hazards such as chemicals, noise etc. The risk of heat stress is extremely difficult to define due to the interaction of the six basic parameters. Added to this, the interpersonal differences in physiological responses further complicate the risk estimation.

ISO definition of heat stress

A formal definition of heat stress is defined by the standards as "*heat stress to which a person exposed to a hot environment is subjected, in particular, is dependent upon the production of heat inside the body as a result of physical activity and the characteristics of the environment governing heat transfer between the atmosphere and the body.*" Although this report refers to International Standards, where a standard has been ratified as a British Standard, the standard's reference number is provided in brackets.

Definition of Heat Stress Risk Assessment Methodology

From this definition the following definition for a Heat Stress Risk Assessment Methodology was developed:

> **Heat Stress Risk Assessment Methodology:** "*A self-contained, systematic procedure which in part, or full, achieves the goals of the specified heat stress risk assessment.*"

HSE Five Steps to Risk Assessment

The Health and Safety Executive (HSE) has produced a "Five Steps to Risk Assessment" procedure that provides an easy to use, practical approach to risk assessment. The five steps are:

STEP 1: Look for the hazards;
STEP 2: Decide who might be harmed and how;
STEP 3: Evaluate the risks and decide whether the existing precautions are adequate or whether more should be done;
STEP 4: Record your findings;
STEP 5: Review your assessment and revise it if necessary.

Therefore the methodology developed for this project must meet the overall strategy of the "five steps" approach.

Decision Making Sequence

According to Glendon (1987) there are three main areas in human error that may lead to a system failure (when health and safety is viewed as a system):

- **Cognition**: This includes areas such as the perception of hazard and of risk, the ability to label hazards and risks, the development and learning processes involved and ascribing responsibility, cause and blame;
- **Behaviour**: How people respond to hazards, cause accidents, make errors and correct their behaviour as a result of those errors. This author however would add "the macho factor" where the worker is not willing to admit that they may be experiencing discomfort or stress;
- **Environment**: Valid indicators of the risk associated to hazard exposure, the culture of safety, training and education and communication.

The training objectives for both the individual and the organisation should follow a specific decision making sequence according to Glendon (1995). This is an important consideration for this project as it may dictate how any practical methodology may be implemented. His approach has been adapted specifically for application in environments where workers may be at risk to heat stress, and is discussed in further detail in **Section 4.3.5** on **Page 163**

1.3.6 Health Surveillance in the UK – Specific to the Thermal Stress

Honey *et al* (1996) conducted an HSE sponsored research project to investigate health surveillance by employers in the United Kingdom. Their study consisted of a postal questionnaire of 5000 employers (35% response rate) and over 30 interviews. One of the areas that they considered was hot and cold working environments. Although there was no separation of this category into hot environments and cold environments, their results are discussed in the section as they provide some insight into the risk assessment and control of health surveillance for employees working in extreme thermal environments. It is recognised that many of the respondents may have been from companies with cold working environments, however since the philosophies for the assessment of both types of environment are similar, their findings may be relevant to both. All data reported were weighted according to the base percentages of responses that could have been given. If the responses were below the 50% base they were presented in brackets to indicate that the data should be treated with caution, and below 25% base response "(no data)" will be shown. Some findings of the survey by Honey *et al* are presented below:

- 13.7% of respondents identified hot and cold environments as a hazard from which their employees were at risk. The following are industry sectors that identified thermal hazards (the proportion of each is also presented): Agriculture (no data); Energy/Water 30.3%; Metals/Minerals 16.3%; Engineering 11.3%; Other manufacturing 8.7%; Construction 30.6%; Distribution/Hotels 1.5%; Transport/Comms 23.6%; Business Services (3.4%); Other Services 23.4%; All Establishments 13.7%. The sector with the highest percentages was construction, followed by Energy/Water;
- Of these, 5.9% of respondents classified thermal stress as being the most serious hazard in the workplace of which only (34.1%) conducted risk assessments specific to the thermal environment. (Note: the bracket shows that this was for less than 50% base of respondents who

reported thermal issues.) (65.4%) did not conduct thermal risk assessments and (0.6%) did not know if thermal assessments were conducted. The (34.1%) was the lowest percentage of risk assessment for any category, with all the other categories having risk assessments by at least two thirds of respondents;

- Another finding of concern was that only (13.7%) of respondents reported pre-employment assessments (such as medical examinations and self completion questionnaires) for workers working in environment where hot/cold conditions were found. The rest, (86.3%), conducted no pre-employment assessments. This is a concern because the health status of the worker is critical in hot working environments. Unfortunately, Honey et al also found that (81.1%) reported that health surveillance was not undertaken for hot and cold conditions. From the (18.9%) where it was conducted, insufficient data (i.e. less than 25% base of respondents) were available for different health surveillance strategies. The strategies they categorised were; "*inspection of readily detectable conditions, enquiries about symptoms, medical surveillance by a qualified doctor, biological effects monitoring, biological monitoring.*" One high-risk population is pregnant women. The study reported that (52.3%) of respondents did not make provisions for pregnant women, while (47.2%) stated that they were not at risk. Only (0.3%) did make provisions;
- Considering the importance of health status and other factors such as experience, skill etc. when working in thermal extremes, it was concerning to find that the lowest percentages for any of the hazards were reported in the areas of employee (37.9%) and management (47.2%) training in hot/cold environments. Record keeping was another area where hot and cold hazards were not being adequately addressed, with (93.1%) of respondents stating that no records were maintained.

Although no direct conclusions with regard to hot/cold environments were drawn from the postal survey, a number of thermal environment conclusions (for hot/cold) can be drawn:

1.) Of the respondents that listed hot/cold environments as a hazard, less than 50% answered many of the questions, as was evident by the percentages given in brackets. This may be for two reasons:
    i.) Thermal stress is not high on their list of high-risk hazards and as such is considered secondary to the other risks to which their workers may be exposed;
    ii.) Respondents may not have had sufficient knowledge of thermal stress risk assessment and/or the consequences of exposure to thermal hazards;
2.) Health surveillance, risk assessment and pre-employment screening of thermal stress were inadequately performed in those industries where heat stress was considered a risk;
3.) Record keeping needs to be improved so that the effectiveness of controls, health status of workers and the accuracy of thermal risk assessments can be monitored.

1.3.7 Heat Stress Indices

Introduction

Many attempts have been made over the years to develop an index which, through a single figure, is able to provide an indication of the risk of heat stress (Kerslake, 1972). However, a thermal index has yet to be developed which can accurately predict a person's physiological strain to all environments (NIOSH, 1986). Goldman (1988) and Morris (1994) say that there is a growing body of opinion that computer modelling provides the best solution to the prevention of heat stress.

Belding provides the following recommendations to anyone who is "*so bold as to improve on existing standards*":

- One of the major problems seems to be the establishment of criteria which are representative of physiological stress and strain;
- To accurately predict the level of strain in such a way as to provide a practical application;
- The "*ultimate index should provide a means for rating time-limited exposures*";
- The use of sweat rate is only really justified in terms of dehydration levels and salt depletion;
- Mean skin temperature is the result of the effects of environment and metabolic heat loads on the circulatory efficiency of the blood and the evaporative cooling effectiveness.

A heat stress index is a model of human thermoregulation. Models (and indices) are, by their very nature, limited in their functionality and as such the model (whether it be graphical or numeric representation, mathematical equations) will never be a perfect representation. Therefore, when investigating models, errors or deviations from the observed are expected but the performance criteria is not so much how accurate it is, but rather whether or not these inaccuracies are significant in terms of the application or situation to which it is intended to be applied. This is very much the case in Human Modelling because there is such a wide variation between individuals in their physiological responses. This is still further complicated by the fact that much of our knowledge of human responses to thermal environments is incomplete. This however, by no means negates the potential that human modelling has in the development of research methods and practical applications to address human responses to thermal environments.

Types of heat stress indices

There are generally three types of methods used for the assessment of hot environments:

- Empirical: Data from laboratory studies provided data that makes it possible to predict the likely effects an environment will have on a human, (i.e. Physiological responses);
- Direct: Standardised measuring instruments are used to measure environmental parameters such as globe temperature;
- Rational: Calculations of the heat exchanges between the human and the environment provide a method to predict the human responses.

These methods all have the same criteria in common, in that their purpose is to define or establish the physiological responses of humans to their environment. Figure 1 shows a simplification of the method of calculating climatic indices, which results in a simplified value or combined measure which can represent the large possible combinations of the parameters that make up the human thermal environment. According to Eissing (1995), this simple index-value allows for a simple comparison between environments, different working situations and different clothing ensembles to be made.

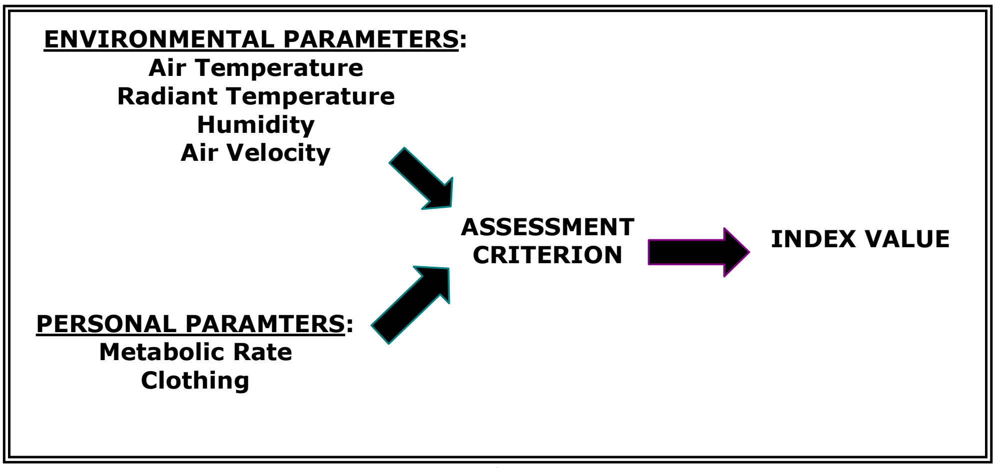


Figure 1: A diagrammatic representation of calculating climatic indices as described by Eissing (1995)

*Effective temperature (*ET*) and corrected effective temperature (*CET*)*

The Effective Temperature (*ET*) scales were originally devised by Hougton and Yaglogou in 1923 as comfort indices and, in 1927, Yaglou realised that it would be a good physiological index of stress (Leithead and Lind, 1964). *ET* takes wet bulb temperature, dry bulb temperature and air velocity into account but does not take into account radiant heat. Bedford in 1946 proposed the replacement of an air temperature measure with the use of globe temperature to provide a measure of radiant heat. This produced the Corrected Effective Temperature (*CET*). The *CET* has been used extensively within the coal mines in the UK.

The Heat Stress Index (HSI)

The Heat Stress Index (*HSI*), was developed by Belding and Hatch (1955) as an analytical index that provides an expression on a scale of 0 to 100 that represents heat stress and hence heat strain and thereby the amount of time a worker can be exposed to a hot environment. Table 2 provides the equations used in the calculation of *HSI* and the resultant Allowable Exposure Times (AET), while Table 3 provides an interpretation of the *HSI* values.

Table 2. Equations used in the calculation of the (*HSI*) and Allowable Exposure Times (*AET*), (from Parsons, 1993)

		CLOTHED	UNCLOTHED
Radiation Loss ($W.m^{-2}$)	$R = k_1 (35 - t_r)$	for $k_1 = 4.4$	7.3
Convection Loss ($W.m^{-2}$)	$C = k_2 v^{0.6} (35 - t_a)$	for $k_2 = 4.6$	7.6
E_{max} ($W.m^{-2}$)	$E_{max} = k_3 v^{0.6} (56 - P_a)$ (upper limit of 390 $W.m^{-2}$)	for $k_3 = 7.0$	11.7
E_{req} ($W.m^{-2}$)	$E_{req} = M-R-C$		
Heat Stress Index	$HSI = (E_{req} / E_{max}) \times 100$		
Allowable Exposure Time	$AET = 2440/(E_{req} - E_{max})$ mins		

Table 2 shows the equations for the Heat Stress Index, which is based on a comparison of E_{req} and E_{max}. Although it is derived independently, the *HSI* value is related to the required skin wettedness (w_{req}) value (which is derived from $E_{\mathrm{req}}/E_{\mathrm{max}}$). As such, it describes strain in terms of sweating, and because it multiplies the w_{req} value by a 100, it describes a prescriptive zone between 0 and 100 (see **Table 3**). When a value is obtained that is greater than 100, an AET is produced because it effectively means that a skin wettedness value greater than that capable of being produced (remember it is related to w_{req}) is required.

Table 3: Effects of environments at different HIS values to an eight hour exposure

HSI VALUE	EFFECT OF EIGHT HOUR EXPOSURE
-20	Mild cold strain (e.g. recovery from heat exposure)
0	No thermal strain
10-30	Mild to moderate heat strain – Little effect on physical work but possible effect on skill.
40-60	Severe heat strain, involving threat to health unless physically fit – Acclimation required
70-90	Very severe heat strain – Personnel should be selected by medical examination, adequate water and salt intake must be ensured.
100	Maximum strain tolerated daily by fit acclimatised young men.
OVER 100	Exposure time limited by rise in deep body temperature.

Table 3 describes the prescriptive zone as calculated by HSI. Note how as the HSI value increases so the strain imposed on the worker increases.

Due to it's reliance on E_{max}, HSI cannot be applied if temperature and humidity are high (BOHS, 1996).

The American Conference of Governmental Industrial Hygienists (ACGIH)

The ACGIH provide an annual book for practical use by trained industrial hygienists called "Threshold Limit Values and Biological Exposure Limits." These include Threshold Limits Values (TLVs) for heat stress. NIOSH state that "*these Threshold Limit Values (TLVs) refer to the levels of physical agents and represent conditions under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effect*." Further practical information and advice regarding working practices in hot environments supplement the TLVs. The TLVs however, provide a method of determining heat stress in terms of WBGT values that are based on physically fit, acclimatised workers wearing summer clothing. Recently the ACGIH TLVs have included corrective values based on different types of PPE which are subtracted from the reference value so as to take into account the effects the PPE may have on the wearer.

Recommended Exposure Limits (REL) and Recommended Alert Limits (RAL)

These are two methods developed by NIOSH (1986) to provide Recommended Exposure Limits (REL) and Recommended Alert Limits (RAL) for workers exposed to a combination of environmental heat (WBGT) and metabolic heat. They are represented by limiting curves of one hour, time weighted averages for both environment and metabolic heat. Both are based on a standard worker who is healthy, acclimatised, normally clothed and limited to a deep body temperature of 38°C. The REL is based on an acclimatised worker while the RAL is based on an unacclimatised worker. It is again evident that these methods are also based on normally clothed workers, and no account has been made for the "non-normal" nature of PPE.

1.3.8 British, European and International Standards: *Ergonomics of the thermal environment*

Introduction

As part of the standardisation of information produced by the International Standards Organisation (ISO), Ergonomics standards have been developed to provide information to people concerned with the design, development and assessment of products, systems, equipment and workplaces. According to Nachreiner (1991) the purpose of these Ergonomics standards is to promote health and safety, wellbeing and worker efficiency both in terms of the performance of the worker as well as the performance of the system as a whole. As part of the Ergonomics standards, a series of documents intended for the assessment, control and management of the risk in of hot working environments. These heat stress documents are part of a larger scope of documents developed for the assessment of human thermal environments as a whole.

Aims of the ISO Standards - Ergonomics of the thermal environment

Parsons (1995) stated that the combined experiences and knowledge of those people who are experts/experienced in human thermal environments (e.g. environmental ergonomists and engineers, occupational hygienists and medics, thermal physiologists etc.) enhance and enable the evolution and development of these standards. ISO Standards for Ergonomics of the Thermal Environment list a number of aims, which for this series of Standards in particular are (see Figure 2, for a diagrammatic representation of standards for thermal environments):

- To provide a definition of terms that are to be used in the measurement, testing and interpretation methodologies, taking into account existing standards and those which are being drafted;
- The "drafting of specifications relating to the method of the measurement for physical parameters characterising thermal environments";
- To provide the reader with a selection of methods of interpretation of the parameters;
- In instances where exposure to thermal environments in areas such as comfort and extreme environments, the standards establish recommended or maximum levels of exposure;
- The "drafting specifications relating to the method of the measurement of the efficiency of devices or procedures for individual or collective protection against heat and cold".

The purpose and methodologies of the Standards concerned with heat stress are briefly explained below.

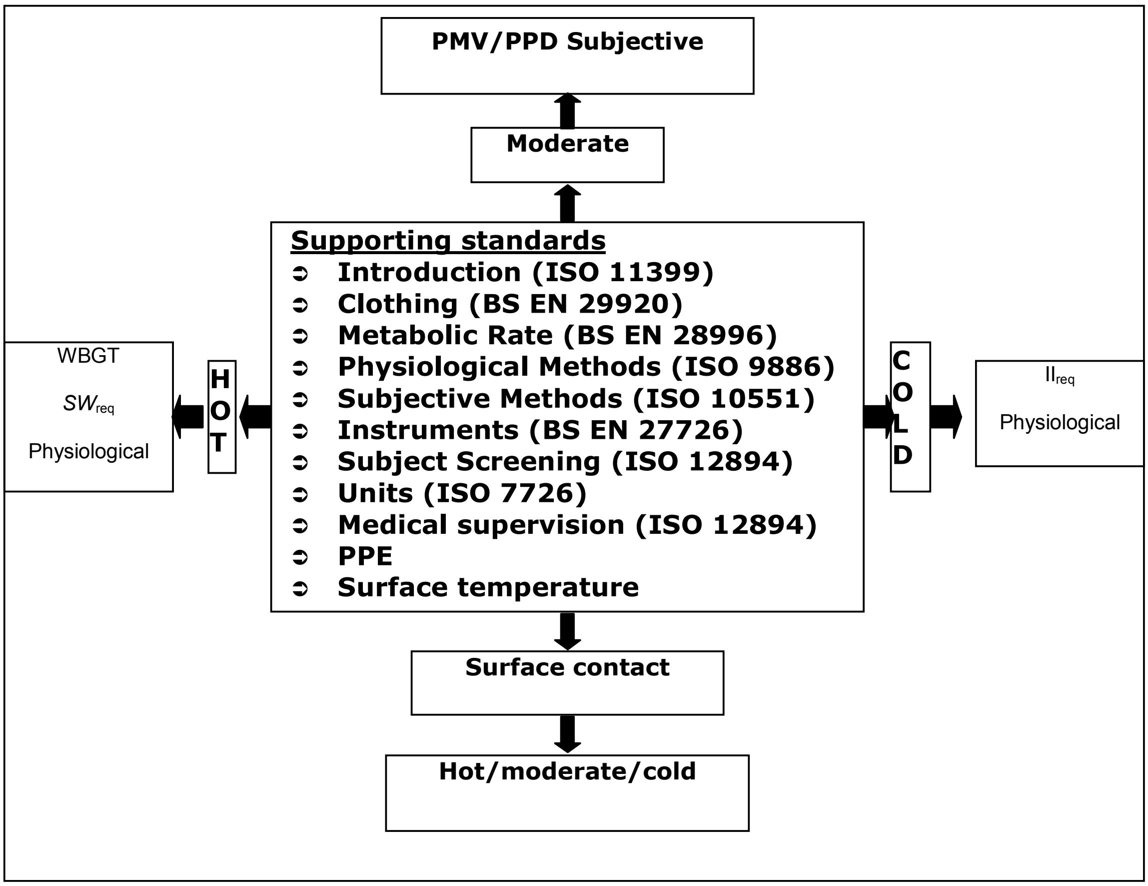


Figure 2: A diagrammatic representation of ISO standards concerned with human thermal environments (updated from Parsons 1993, p. 253)

1.3.9 Supporting standards

ISO 11399, Ergonomics of the thermal environment - Principles and application of relevant International Standards

This standard provides the user with information for the "*correct, effective and practical use of International Standards concerned with the ergonomics of the thermal environment*". This is achieved by describing the relevant standards and how they complement each other when assessing the thermal environment. Brief descriptions of the underlying principles of each standard and also the underlying principles of ergonomics of the thermal environment are provided. This, therefore, should allow the users to decide upon, and develop an appropriate strategy that would be suitable for the environment, the clothing the worker is wearing and nature of the work that they are to assess. This standard covers those standards that should be used when assessing hot, moderate and cold environments, human contact with solid surfaces, and those complimentary standards that include the measurement of physiological responses, the use of subjective responses, the estimation of the clothing insulation etc. Only those standards that are applicable to the assessment of heat stress will be discussed further in this document.

At the time of writing (December 2000), this standard has been recommended for revision to bring it up-to-date, as a number of the standards are currently under revision.

ISO 7726, Thermal environments - Instruments and methods for measuring physical quantities (BS EN 27726)

ISO 7726 specifies the minimum characteristics of instruments for the measurement of the physical quantities that characterise the human thermal environment. Its aim is to standardise the recording of information in order to ensure that these measurements follow recognised procedures, thereby enabling the user to use the other standards in the series to obtain an overall index of thermal comfort or strain. It is also meant as a source of reference for both the manufacturers and users of measuring equipment and instruments used in the measurement of the physical parameters of the environment. It applies to all human thermal environments, whether hot, comfortable or cold.

ISO 8996, Ergonomics of the thermal environment – Estimation of metabolic heat production (BS EN 28996)

This standard provides fundamental support to the other standards in this series, by providing information and data for estimating and calculating metabolic heat production. The standard describes three types of methods for obtaining values for metabolic heat production:

1. Tables for estimating metabolic rate – Different Tables are presented:
    - General description (Low, Medium, High);
    - Specific descriptions of occupations (bricklayer etc);
    - Summing components of tasks (basal metabolic rate + posture component + movement component).
2. Heart rate –Total heart rate is considered as the sum of several components. Heart rate (at greater than 120 beats per minute) is linearly related to metabolic rate;
3. Calculation of metabolic rate from oxygen consumption and carbon dioxide production during both activity and rest.

The estimation of metabolic heat production from activity is an influential part of heat stress assessment. It is difficult to provide an accurate estimate; however, a revision of the standard is underway.

ISO 9920, Estimation of the thermal characteristics of a clothing ensemble (BS EN 9920)

This standard provides a comprehensive database of clothing items and ensembles, materials, insulation values etc. It enables the user to choose a garment or clothing item, then to obtain a measure of the insulation based on the material of the clothing. The purpose of this is to provide the user with an estimate of Intrinsic Clothing Insulation (I_{cl}). One problem with the database however, is that it is actually quite difficult to use.

Recent studies have provided a more detailed understanding of the thermal properties of clothing. The use of thermal manikins, vapour resistance properties of clothing and the pumping or bellows effects of clothing are all topics to be included in a revision of the standard.

ISO 9886, Evaluation of thermal strain by physiological measurements

This standard describes methods for measuring and interpreting different physiological measures such as heart rate, core temperature, skin temperature and body mass loss. It covers a number of aspects to their application, such as technical complexity, accuracy and risks, applicability as heat stress measures, etc. Its main purpose is to provide a reference for the monitoring of physiological responses to extreme environments. This enables the user to make an informed decision on what measurements may be required, how to measure them and then to interpret them.

ISO 9886 has been revised to consider diary methods of assessments. It is at present under international voting and will eventually become a revised British, European and International Standard. The British Standards Institution committee PH9/1 'Ergonomics of the Thermal Environment' has sponsored the development of a draft standard through the Department of Trade and Industry (DTI) that is concerned with the specification of physiological measuring instruments. The work is being contracted by the Defence Evaluation Research Association (DERA) and a draft standard and report will be produced by Summer 2001.

1.3.10 ISO 7243. Hot Environments – Estimation of heat stress on a working man, based on the WBGT –Index (wet bulb globe temperature). (BS EN 27243)

The *WBGT* index is an empirical index which represents the heat stress to which an individual is exposed. It was developed during the 1950s by US military as part of a applied programme to reduce heat stress casualties in the US Marine Corps and was evaluated by Yaglou and Minard (1957) as a climatic index to replace the Corrective Effective Temperature (*CET*). The purpose of the *WBGT* was to provide a method that could be easily used in an industrial setting allowing a fast diagnosis. It is widely recognised that this has been done as a compromise between the need for an precise index and the need to be able to easily control measurements in an industrial setting (Parsons, 1994). This need for an easy to use method meant that the adoption of the WBGT as an International Standard was heavily influenced by the Threshold Limit Values (TLVs) set out by the ACGIH. A consequence of this compromise between ease of use and accuracy is that it applies to the evaluation of the mean effect of the heat during the period of the worker's activity. It does not however apply to those occasions when the worker may be exposed only for short periods, nor where the heat stress limits are close to the zone of comfort. It also makes no provisions for estimating the effect of PPE. Therefore, the *WBGT* index is to be used to estimate whether or not a problem exists, by identifying whether the reference values are exceeded. If this occurs, the more advanced Standard (ISO 7933) is to be used to provide a more accurate estimation of stress.

The *WBGT*-index combines the measurement of two derived parameters; natural wet-bulb temperature (t_{nw}) and globe temperature (t_g), and a direct parameter air temperature (t_a). These measures are applied using the Equations 4 and 5.

Inside buildings and outside buildings without solar load:

$$WBGT = 0.7t_{nw} - 0.3t_g \qquad (4)$$

Outside buildings with solar load:

$$WBGT = 0.7t_{nw} + 0.2t_g + 0.1t_a \qquad (5)$$

The measurements are inputted into the equations above to obtain a *WBGT* value. The *WBGT* value is then compared to the reference values provided in the standard for the appropriate metabolic rate and state of acclimation of the worker. These reference values are provided in Table 4 of the standard. They refer to conditions where 95% of the working population can be repeatedly exposed to heat stress with no adverse health effects (ACGIH, 1989; Dukes-Dobos and Henschel, 1973). It is important to note that these reference values correspond to a given situation where the worker is physically fit, and in good health. The workers are also "normally clothed, with adequate salt and water intake and, if conditions stay within limits, are able to work effectively without exceeding a body core temperature of 38°C" (WHO, 1969; ACGIH, 1989).

Table 4. Reference values of *WBGT* heat stress index from ISO 7243. The values given relate to a maximum rectal temperature of 38°C

METABOLIC Rate class	METABOLIC RATE, M		REFERENCE VALUE OF WBGT			
	Related to a unit skin surface area W/m^{-2}	Total (for a mean skin surface area of 1.8m^2) W	Person acclimatised to heat °C		Person not acclimatised to heat °C	
0 (RESTING)	$M \leq 65$	$M \leq 117$	33		32	
1	$65 < M \leq 130$	$117 < M \leq 234$	30		29	
2	$130 < M \leq 200$	$234 < M \leq 360$	28		26	
3	$200 < M \leq 260$	$360 < M \leq 468$	No sensible air movement	Sensible Air movement	No sensible air movement	Sensible air movement
			25	26	22	23
4	M>260	M>468	23	25	18	20

Griefahn (1994; 1997) reported finding that under conditions of thermally induced heat stress the *WBGT* provided a suitable predictor of heat stress. A number of limitations have been reported:

- The estimation of metabolic rate causes a high variability in reference values (Hill, 1985; Ramsey and Chai, 1983) which may be compounded by the difficulty of interpreting the results when small deviations in the reference values are observed;
- Pulket *et al* (1980) reported that under conditions of light work in humid environments, the *WBGT* correlates well with the skin temperature, but poorly with other physiological variables of heart rate, rectal temperature, and sweat loss;
- Another limitation is that the reference values are representative of the mean effect of heat, over a long period of work. It therefore does not provide a reference for those instances where workers are exposed to peak values of heat for very short periods of time (e.g. a few minutes). These exposures could be a result of either exposure to a very hot environment or a short period of intense physical activity. In these cases the reference values may not be exceeded even though the heat stress may exceed the permissible value. The highest metabolic rate value is used as the reference value, where there is uncertainty about the metabolic rate that is to be adopted;
- BS EN ISO 27423 does not provide corrections to *WBGT* values for different types of PPE, although the ACGIH TLVs (which are based on the *WBGT* index) do provide corrections for PPE.

ISO 7243 has been confirmed as a useful standard since 1984. Recently there has been a suggestion that it could be brought into line with the ACGIH developments. The limitations of the *WBGT* index are recognised where evaporation of sweat is restricted by impermeable clothing or high humidity. Here the rationale for the WBGT index (heavy weighting to t_{nw}) falls down.

I.3.10.1 ISO 7933, Hot Environments – Analytical determination and interpretation of thermal stress using calculation of Required Sweat Rate (SW_{req}) (BS EN 12515)

When *WBGT* values are exceeded, the user is directed to the required sweat rate model for a more detailed analysis of the work environment. As ISO 7933 is a major topic of this report, a detailed description is provided below.

Required Sweat Rate (SW_{req}) Explained

Required Sweat Rate (SW_{req}) is a rational/analytical index that is based on the heat balance equation. It was developed at laboratories in Strasbourg by Vogt *et al* (1981), evaluated by an ECSC project in industrial contexts and was finally published in 1989. For a full description of the methods (and computer program listing), the reader is referred to the Standard.

The parameters used to measure and define the thermal environment are air temperature, mean radiant temperature, humidity (in the form of partial vapour pressure) and air velocity. These are inputted into the model along with the clothing insulation value, metabolic rate and posture. The model then calculates the heat exchange between a standard person and the environment through convection and radiation, as well as respiratory heat loss. Other processes, such as sensible heat loss for cotton clothing, convection and radiation coefficients, are also modelled. Since the evaporation of sweat is the main driving force for heat loss, the model predicts the sweat rate required to facilitate the evaporation required to maintain zero heat storage. One of the main calculations therefore is the calculation of mean skin temperature. The model then interprets these calculations to provide a Duration Limited Exposure (DLE) in minutes. If the required sweat rate can be achieved, without unacceptable dehydration, heat storage or wettedness, then an eight hour exposure is acceptable. If not, then an acceptable work period (DLE) is calculated.

If heat balance is not maintained then core temperature will rise as a result of heat storage. If the required sweat rate can be achieved and does not exceed the maximum allowable water loss, then there will not be a time limit due to heat exposure in a working day. If the maximum allowable water loss value is exceeded, then a Duration Limited Exposure (DLE) is imposed, based either on the amount of water lost or the rise in core temperature. The index will then provide limiting values based on the maximum amount of allowable water loss without dehydration occurring, or the time for core temperature to reach 38°C (estimated from heat storage). These limiting values are known as Duration Limited Exposures (DLE). SW_{req} provides a method for identifying the relative importance of the different parameters that make up human thermal environments, thereby allowing for the assessment of control measures that may be employed (see Figure 3). However, the BOHS (1996) states that the standard is “complex and difficult to use, and does not lend itself to occasional or casual use.”

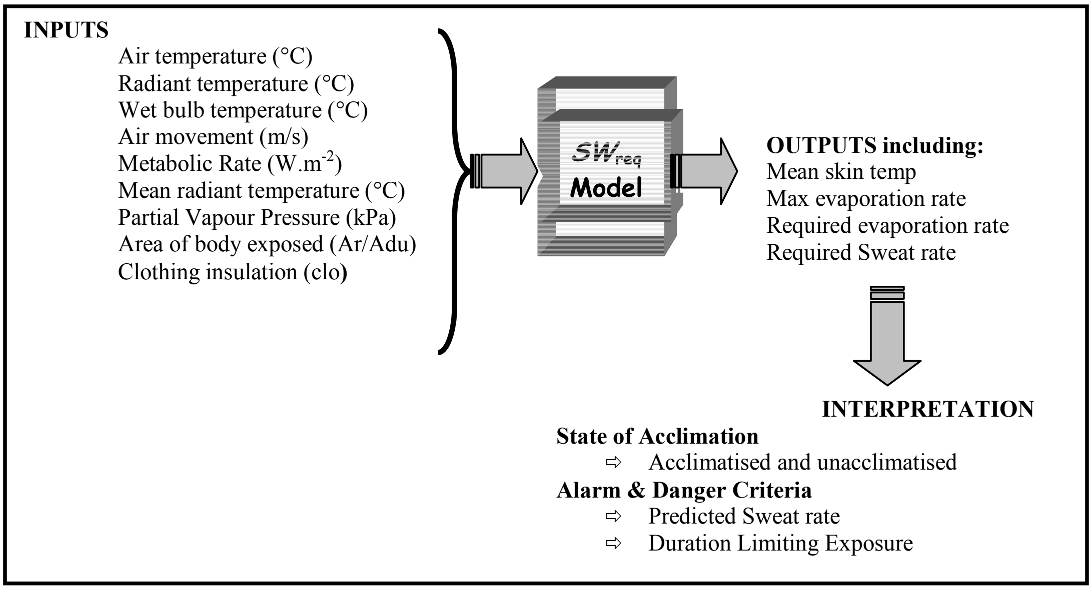


Figure 3: Diagrammatic representation of the inputs, outputs and interpretation of the SW_{req} model

ISO 7933 Equations

Required Evaporation (E_{req})

Therefore, with K=0, the general heat balance equation can be written as

$$E + S = M - W - C_{res} + E_{res} - C - R \qquad (6)$$

However if S = 0, then the $E = E_{req}$ and therefore the equation for the evaporative rate required to keep the body in thermal equilibrium is

$$\mathrm{E}_{req} = M - W - C_{res} - E_{res} - C - R \qquad (7)$$

Require skin Wettedness (w_{req})

The required skin wettedness (w_{req}, dimensionless) is defined as the ratio between the required evaporation rate, (E_{req}) and the maximum evaporative rate (E_{max}). E_{max} is the maximum evaporation that can be achieved under hypothetical conditions when the skin is completely wet.

$$w_{req} = E_{req} / E_{max} \qquad (8)$$

Required Sweat Rate (SW_{req})

$$SW_{req} = E_{req} / r_{req} \qquad (9)$$

Where:

r_{req} is evaporative efficiency of sweating (dimensionless), which corresponds to the required skin wettedness.

The SW_{req} equation, through the use of r_{req}, takes into account the dripping of sweat from skin which does not contribute to heat loss.

***NOTE**: The sweat rate in watts per square metre represents the equivalent in heat of the sweat rate expressed in grams of sweat per square metre of skin surface per hour. 1W/m^2 corresponds to a flow of 1.47 g/(m^2.h) [for standard subject (1.8 m^2 of body surface) a flow of 2.6 g/h].*

Interpretation of Required Sweat Rate

Two criteria of stress and two criteria of strain form the basis for the interpretation of the values calculated by the index. These interpretations are presented for acclimatised and non-acclimatised subjects, and according to the degree of protection which is desired (warning and danger levels).

Stress criteria:

a) max skin wettedness (w_{max});
b) max sweat rate (SW_{max}).

Strain criteria:

a) max heat storage (Q_{max}, in watts hours per square metre);
b) max water loss (D_{max}, in grams).

Abbreviated from standard:

SW_{req} cannot exceed SW_{max} ;
w_{req} cannot exceed w_{max}

SW_{max} and w_{max} are both functions of the acclimatisation of the subject.

When the model predicts non-equilibrium of thermal balance, any heat storage or water loss is limited by the maximum values for each.

Analysis of the work situation

Predicted values are determined for the analysis of the work situation where:

w_{p} - predicted skin wettedness
E_{p} - predicted evaporating rate
SW_{p} - predicted sweat rate

taking into account the required values ($_{\mathrm{req}}$) and the limit values ($_{\mathrm{max}}$).

If w_{max} exceeds w_{req} and SW_{max} exceeds SW_p , the body is in thermal equilibrium and the predicted values are.

$$w_p = w_{req} \quad (10)$$

$$E_p = E_{req} \quad (11)$$

$$SW_p = SW_{req} \quad (12)$$

The theory here is that since the predicted values do not exceed the maximum values that they are achievable and as such sufficient sweat can be evaporated to maintain thermal equilibrium. The following calculations are made when the required values exceed the maximum values and thermo-equilibrium is not possible:

$$w_p = w_{max} \quad (13)$$

and therefore:

$$E_p = w_p E_{max} \quad (14)$$

$$SW_p = E_p/r_p \quad (15)$$

where r_p is the evaporative efficiency of sweating corresponding to w_p.

When the SW_{req} or the SW_p at the preceding step exceeds the SW_{max}, it is necessary to determine the w_p and the evaporative efficiency (r_p) such that by substitution:

$$w_p E_{max} = SW_{max} r_p \quad (16)$$

taking into account the relationship between w_p and r_p

therefore;

$$E_p = w_p E_{max} \quad (17)$$

and

$$SW_p = SW_{max} \quad (18)$$

Determination of allowable exposure time (DLE, min)

The allowable exposure times is calculated as a function of the maximum values for body heat storage (Q_{max}) and water loss (D_{max}). No time limit is placed on an 8 hour working day if $E_p = E_{req}$ [i.e. E_{max} value not exceed and if $SW_p < D_{max}/8$ (SW_p is less than SW_{max} per hour over 8 hours)]. It is necessary to calculate allowable exposure times based on either heat storage or water loss if these conditions above are not met. Heat storage (Q_{max}) is calculated as the difference between E_{req} and E_p resulting in an increase in body temperature and the following expressions are used to predict the DLEs based on an increase in core temperature.

$$\mathrm{DLE}_1 = 60\, Q_{max} / (E_{req} - E_p) \quad (19)$$

When excessive water loss is predicted, the DLE calculation is

$$\mathrm{DLE}_2 = 60\, D_{max} / SW_p \quad (20)$$

The shortest DLE shall be used for limiting the duration of work.

Reference Values

Table 5: ISO reference values for the different criteria of thermal stress and strain.

Criteria	**NON ACCLIMATISED** **Warning**	 **Danger**	**ACCLIMATISED** **Warning**	 **Danger**
Max Skin Wettedness				
W_{max}	0.85	0.85	1	1
Max Sweat rate				
Rest:				
$M<65$ W/m^2 SW_{max} W/M^2	100	150	200	300
g/h	260	390	520	780
Work:				
$M>=65$ W/m^2 SW_{max} W/m^2	200	250	300	400
g/h	520	650	780	1040
Maximum Heat Storage				
Q_{max} h/m^2	50	60	50	60
Maximum Water Loss				
D_{max}.h/m^2	1000	1250	1500	2000
g	2600	3250	3900	5200

1.3.11 Literature review of the Validity of the ISO 7933 SW_{req} index

The complexity of intra- and inter-individual physiological responses means that it is very difficult to predict, with accuracy, an individual's responses. The SW_{req} aims to reduce this uncertainty by predicting for acclimatised and unacclimatised workers, by providing the alarm and danger criteria, and by limiting the exposure based on either sweat loss or core temperature increases. As such therefore, any evaluation of the SW_{req} index should aim to investigate as many of these criteria as possible.

Practical Applications of SW_{req}

For many years the importance of the body's ability to maintain heat balance has been understood, with Haines *et al* (1952) stating that "*body heat balance is a physiological requirement for comfort and health.*" Belding and Hatch (1955) first proposed an additive index (HSI) based on the calculation of energy balance where all the environmental and personal parameters are taken into consideration in this calculation.

The practical application of this theory is difficult since there is a conflict between the engineering application of a heat stress standard and its application by human physiologists. This conflict arises as a result of the precision of the relationships between the physical stress factors of the environment and the human's physiological responses to heat. As such they identified the need for a practical engineering application, where the assumption is that a worker who maintains thermal balance with the environment does not "*find the accompanying stress of serious consequence.*" The philosophy being that the index would provide a benchmark that allows the calculation of the required evaporative capacity over the maximal evaporative capacity, allowing the comparison of one heat exposure with another over a variety of conditions. This provides the capacity to express heat stress in terms of evaporative requirements as an engineering, design and control tool, whereby the proposed changes to the conditions can be assessed in relation to the predicted physiological responses. This is a fundamental point, and one which seems to have been lost over the proceeding years, where the identification of heat stress was the issue and not as much the evaluation of the proposed solutions as perhaps could have been. The use of algorithms to model human thermoregulation in terms of the heat balance equation requires that suitable coefficients (such as those for evaporation and convection) need to be considered so as to describe the environmental parameters. ISO 7933 is not valid for all thermal environments; for example, the standard describes the boundary limits of its performance envelope for predicting mean skin temperature (Table 6).

Table 6: The range and unit of measure for each parameter to determine mean skin temperature

Parameter	UNIT	RANGE
$\mathbf{t_a}$	°C	22.9 to 50.6
$\mathbf{t_r}$	°C	24.1 to 49.5
$\mathbf{P_a}$	kPa	0.8 to 4.8
$\mathbf{V_a}$	$m.s^{-1}$	0.2 to 0.9
M	$W.m^{-2}$	44.6 to 272
$\mathbf{I_{cl}}$	clo	0.1 to 0.6
$\mathbf{t_{sk}}$	°C	32.7 to 38.4

One of the major criticisms is that much of the data that led to the development of the equations were from laboratory studies that may only partly represent industrial situations. Kampmann and Pierkarski (1999) cite examples of the problems that they have identified:

- Skin temperature is described as a linear function rather than being calculated in a "*self-consistent manner*". Therefore, comparisons with other studies need to be made to ascertain whether the assumptions that are made are adequate;
- Two variables are suitable for such a comparison:
    1. The *SW*p can be compared with those values actually observed;
    2. Those core temp rises that are determined in experimentation (Δt_{re}) can be compared with the limit value .0.8°C (for Alarm Criteria) and 1°C (for Danger Criteria).
- Furthermore, they query whether the limit values are explained in such a way that they are meaningful to the reader (w_{max}, SW_{max}, Q_{max}, D_{max}.);
- There are errors in prediction of SW rate and predicting the rise in core temperature especially in humid or warm conditions.

These points provide some criteria whereby the validity of SW_{req} can be investigated.

Kähkönen *et al* (1992) in their study of the applicability of ISO 7933 in Tanzania, found that even when *WBGT* index did not limit the work (i.e. permitted continuous heat exposure), ISO 7933 provided DLE time limits. Peters (1991) also reported this, with some 90% of cases providing the same result. Kähkönen (1993) also stated that the use of indices as a predictive tool to estimate the effects of introducing controls in advance was a useful practical application in industry. It was decided therefore to use this principle as part of both the usability and validity study of ISO 7933.

One area where the usability could be a problem was provided by Kähkönen who stated that the model should provide information to the user when a parameter outside the operating envelope of the model is inputted. The relative advantage of using a heat balance equation index over the use of an index such as the effective temperature scale is that it combines the four environmental parameters and therefore does not obscure their respective contributions to the problem. It also allows the user to apply solution engineering and/or administrative controls to the situation and to assess what impact these individual or combined changes will have on the worker.

Cooke *et al* (1961) provide an important example of the necessity of being able to identify the effects of individual parameters when assessing the problems encountered in mines. They state that of the four environmental parameters, the two that can most easily be controlled by mine ventilation engineers are air velocity and air temperature. Air velocity is controlled either by the amount of air fed into the tunnels or the distribution of the air in the tunnels. Air temperature changes usually arise as a result of changes in air velocity, however they can also be changed independently. Mean radiant temperature in mines is dependent on the surface temperature of the rock, which in turn is a function of the virgin rock temperature, and the time the surface has been exposed to ventilating air. However, mean radiant temperature is not of much concern in mines because there is much evidence that the physiological responses at a mean radiant temperature of a couple of degrees above air temperature are relatively much less than those experienced when there is a 1°C increase in wet bulb temperature.

Kampmann *et al* (1995) who have also used coal mines as an area for applying ISO 7933 have identified what they call "*considerable*" problems in the practical application of the standard, when comparing those studies performed under climatic chamber conditions and those in the field. Specifically they mentioned practical difficulties with establishing limit values for those measures described by Belding as being essential:

- Maximal degree of skin wettedness - w_{max}
- Maximal sweat rate - SW_{max}
- Maximal permissible heat storage - Q_{max}
- Maximal permissible degree of dehydration – D_{max}
- and the evaluation of the thermal environment in situations where the worker was clothed was also a problem. This is especially the case where clothing is saturated with sweat.

Although they state that ISO 7933 (1989) was an improvement on the earlier 1985 version. Kampman *et al (*1995), identified two main areas that they felt needed to be addressed:

1. They questioned the results as being "misleading" when evaluating the combined exposure of climatic stress at a combination of climatic conditions. Specifically warm and humid environments.
2. They raise the issue that the "alarm" and "danger" limiting criteria have not been sufficiently defined.

Clothing

Since the model is based on the heat balance equation, its ability to predict the heat lost due to evaporation of sweat is critical and as such, so are the effects of clothing. Parsons (1995) states that the "*description and quantification of the effects of clothing, by the standard are overly-simplistic*". The effects of air velocity, the pumping effect, clothing insulation etc should be considered to provide a resultant insulation and evaporative resistance of the clothing rather than using the standard basic data. Another problem is that there is no consideration for evaporative heat loss when clothing is worn, such as the wicking effect where water is evaporated from the clothing surface. Also evident from the equation is the omission of quantifying the pumping effects of air movement within the garment when the wearer moves. Only the intrinsic clothing insulation of garments and ensembles worn are considered, with no consideration given for other material properties such as vapour impermeability (i_m). This is a recognised weakness and as such was to be addressed by the European research project BIOMED HEAT in the development of the new Predicted Heat Strain (PHS) model.

Skin Temperature

ISO 7933, estimates mean skin temperature as a function of the environment al and personal parameters (ISO 7933). An alternative for mean skin temperature is provided in the Annex C for I_{cl} values greater than 0.6 clo, whereby the program is altered to make an approximation of t_{sk} equal to 36°C. Parsons (1995) suggests that although this method is "crude", it may provide a sensible alternative. The validation stage of the present research project will investigate this.

In a series of studies conducted by Kähkönen *et al* (1992), the mean skin temperature was adapted in the model to equal 34.5°C when the environmental conditions exceeded those for which the SW_{req} model is applicable. However, the standard recommends adapting the mean skin temperature to 36°C. This was acknowledged in their work but provided a practical example of the modification of ISO 7933 mean skin temperature parameter in the assessment of field conditions. The use of this 36°C fixed skin temperature value was originally used in the SW_{req} model and was criticised by Mairiaux *et al* (1986) and by both Malchaire (1986) and Hettinger *et al* (1987) in the final report of the ECSC project. However, the acceptance of an appropriate equation was complicated when the different data sets of different authors were compared with respect to their proposed equations. Mairiaux and Malchaire discussed the differences between the following equations proposed by Mairiaux *et al* (1987) and Hettinger *et al* respectively (both references cited by Mairiaux and Malchaire and not referenced here).

$$t_{sk} = 30 + 0.138ta + 0.254Pa - 0.57Va + 0.00128M - 0.553I_{cl} \qquad (21)$$

$$t_{sk} = 30.67 + 0.10t_a + 0.46Pa - 0.0099M + 0.48I_{cl}. \qquad (22)$$

A main difference between these equations is the coefficient for the clothing insulation owing to the differences in clothing worn during the studies that developed the equations. For the first equation subjects were wearing light clothing (0.5 to 0.6 clo) and in the second they wore heavy clothing (0.7 to 1.0 clo). This shows the difficulty of modelling for skin temperature where one coefficient needs to be valid for all possible clothing ensembles. Work by Candas (1987) referred to by Mairiaux and Malchaire showed that when the t_{sk} predictions were compared to measured t_{sk} data that the equations underestimated by a mean of 1 and 2.4°C respectively. These differences were significant above 30°C air temperature. The equation provided in the SW_{req} model is an adapted version of Mairiaux's equation where the air temperature coefficient has been divided by three and reallocated into two coefficients, one for air and one for radiant temperature. This author questions whether the mathematical allocation of the coefficients by two thirds of 0.138 (=0.093) air temperature and one third (0.045) to radiant temperature is a valid process. No literature could be found to support this allocation, although a review of the coefficients presented in the *WBGT* index shows that two thirds are allocated to globe temperature and one third to air temperature. Although a direct comparison between the two models cannot be made, it provides for an interesting analysis and questions the science behind the SW_{req} skin temperature coefficients.

$$t_{sk} = 30.0 + 0.093t_a + 0.045t_r - 0.57Va + 0.254Pa + 0.00128M - 3.57I_{cl} \quad (23)$$

A knowledge of thermal physiology would indicate that a simple linear regression equation could not accurately predict skin temperature nor could such an equation be a causal model. An example of this is the term involving clothing insulation (I_{cl}). It can be seen that if clothing insulation increases, then skin temperature falls. This is contrary to what would be expected.

This point not withstanding, if air temperature equals radiant temperature, then the expected error would be between 1°C and 2.4°C (from Candas above). This error seems to be beyond what should ordinarily accepted considering the interdependence of the parameters in the SW_{req} model and the fact that small variations in skin temperature can actually severely restrict the worker's ability to cope with heat (Goldman, 1988). Underestimating mean skin temperature results in errors in other areas of the heat balance equation (Mairiaux and Malchaire, 1988). This is illustrated by Wadsworth and Parsons (1986) who reported observed mean skin temperatures of between 37 and 38°C, which, according to Goldman (1988), is within the range in which people are at risk to heat induced collapse.

Evaporation

Another area of concern is the validity and applicability of the relationship between the evaporative efficiency of sweating to skin wettedness. The original equation was developed from work by Candas *et al* (1979) on supine subjects at rest, however work by Alber-Wallerstom and Holmer (1985) showed that there was less evaporative efficiency for subjects who were exercising upright than those in Candas' work.

This evaporation will be dependent on the ambient humidity of the environment. The evaporative capacity (E_{max}) is higher in a dry environment than in an environment where the humidity is high. The ratio between E_{req} and E_{max} will determine how much evaporation is possible and is described as required wettedness (w_{req}), first proposed by Gagge (1937) and adopted independently into the Heat Stress Index (HSI) (Belding and Hatch, 1955).

Sweat Rate

In their assessment of the validity of predicted sweat rates compared to observed sweat rate, Mairiaux and Malchaire (date) reported strong correlations. This seems at odds with other research. Kampmann *et al* (1992), reported from studies in coal mines that the model underestimated the predicted sweat rate in experiments where low I_{cl} values were observed and significantly overestimated the predicted sweat rate with high I_{cl} values. Hanson and Graveling (1997), referring to the work by Voss *et al* (date, described above), reported that if the model were used to evaluate a warm humid environment, the observed sweat rates may be considerably higher than the maximal sweat rate (SW_{max}) limit of 1000 g/h. The limitation imposed by the low SW_{max} value will predict that less sweat is produced than is observed and as such the model will predict that less heat is lost than is observed. The result of this under prediction of heat loss will be that the predicted DLEs will be lower than the observed DLEs. This was illustrated by Alder-Wallerström and Holmér (date), who found sweat rates of 1152 ±462 g/h and 1206 ± 330g/h which were greater than the SW_{max} values described in Table C.2 of the Standard of 520 g/h (alarm) and 650 g/h (danger). This is further complicated by the assumed maximal degree of skin wetting (w_{max}), where w_{max} may not be exceeded (as described in Section 5.2 of the standard). This causes the SW_p to be reduced. This is not necessarily an issue under hot dry conditions where SW_{max} will limit the SW_{p}. However in warm humid environments where skin wettedness exceeds the w_{max} limit value for the criteria under which it is being applied, the limit value will result in a lower SW_{max} and as such a lower SW_{p}, which in turn will result in a lower predicted DLE.

Kampmann (date) referred to Voss *et al* (1991) stating that there were "considerable errors" when the observed data were compared to the predicted values, in both the prediction of sweat rate in humid and warm situations and the rise of core temperature. Kampmann and Pierkarski (1995) stated that a comparison between the predictive capacity of the standard with observed data from laboratory and field studies can be made by comparing the predicted sweat rate (SW_{p}) with the observed values for sweat loss. Mairiaux and Malchaire (date) questioned the use of a maximum skin wettedness (w_{max}) value of 0.85 for unacclimatised subjects. Candas (date) quotes work by Belding and Kamon (1973) which mirrored his own findings that, where skin wettedness is greater than 50%, unacclimatised workers exhibited a constant increase in core temperature and as such that exposure times should be limited or should restricted to acclimatised workers. A problem with the work reported by Mairiaux and Malchaire (*ibid*) is that although the slope values and corresponding correlation coefficients were presented, no analysis of the residuals were provided. This would show the magnitude of the error in the prediction of observed data. The practice of only providing correlation coefficients as a measure of validity is flawed as it only provides an indication that there is a relationship but not how accurate that relationship is. Their main finding was that an exponential model of sweat rate would improve the accuracy of the predictions. As a result of this, and work by Hettinger *et al* (date) the BIOMED HEAT project tried to develop such an equation.

A conservative approach is adopted by the standard to the problem of rehydration as it assumes that no fluid replacement to the tissues is available to replace that fluid lost as a result of sweating.

Core Temperature

Alder-Wallerström and Holmér (date) reported that their studies showed that ISO 7933 predicted a danger DLE at 29 minutes based on an excessive rise in body temperature (rise to 38°C), while an observed alarm category rise (to 37.8°C) in temperature was not observed within the experiment lasting 60 minutes. There has also been research that has shown that the index provides a conservative prediction of the physiological responses of workers due to an over prediction of the effects of the thermal environment (McNeill and Parsons 1999; Peters, 1995). Wadsworth and Parsons (1986) on the other hand, found that the SW_{req} model under-predicted the effects of the thermal environment when comparing the DLE with observed core temperature. One explanation may be that the model that Wadsworth and Parsons (1986) and Mairiaux and Malchaire (1986) studied was the original ISO DIS 7933 (1983) which had a fixed mean skin temperature of 36°C. Therefore any direct comparisons between this earlier work and later work investigating ISO 7933 (1989) would not be possible. Although Wadsworth and Parsons (1986) did alter the skin temperature by ±1°C and they reported that this did not have an effect on the predictive accuracy of the model. There were also other changes to the 1983 version (ISO DIS 7733). These included a significant change to the qualification of the vapour permeability properties of clothing.

Limit Values

Kampmann and Pierkarski (date) highlight the importance of the effects of the limiting values on the permissible exposure times. The fact that the ISO 7933 SW_{req} is based upon a rational model of human heat balance means that any limiting reference values that may be used to calculate the predicted values are not independent of each other and, as such, if they are incorrect they may influence predictions other than those which they are limiting. This they state, may "confuse" the results of the predictions. The interdependence of the limit values means that if the predicted values are not accurate, then inaccurate results may be achieved. However this is not a result of the interdependence of the limit values, but rather a result of the reference values such as the D_{max} being inaccurate. Kampmann *et al* (1995) cite as an example that, during chamber trials, the observed sweat rate was higher than the predicted SW_{max}. The result, due to the equation, is that the heat storage is unrealistically high, due to the dependence of the core temperature heat loss on the sweat rate. However, the problem is not with the interdependence of the limit values but rather with the accuracy and validity of the predictions. If an index is to provide limiting values which are representative of the input values of an equation, then there is no alternative for the values to be but dependent. Perhaps what should be questioned is the validity of the interdependence the index models (i.e. do small variations in metabolic rate have a representative effect on DLEs etc.).

Parsons (1995) quotes Kampmann *et al* (1992) to provide possible reasons for the poor performance of ISO 7933 under warm humid conditions:

a) The interdependence between core temperature and sweat rate in the model is not a valid representation of the thermo-physiological effects.
b) Both the predicted sweat rates and the maximum sweat rates on which they are based are exceeded by observed sweat rates in field and laboratory studies.
c) The previous point leads to a poor prediction of heat storage and therefore an over prediction of the core temperature increases, thereby under-predicting the DLE time limit.
d) The effects of drinking are not taken into account and they should be.
e) Effects of clothing on thermoregulation are not representative of observed effects.
f) Calculation of the mean skin temperature is over simplistic.
g) W_{max} should not be a limiting criteria under warm-humid conditions.

This poor performance of ISO 7933 and the resultant uncertainty is in itself a risk and therefore, it seems, has not been extensively used.

1.3.12 BIOMED HEAT and the Predicted Heat Strain (PHS) Model

Introduction to the BIOMED HEAT project

Eight European laboratories collaborated on a project concerned with the assessment of hot working environments and the improvement of the predictive capabilities of ISO 7933. The laboratories were located in Belgium (1), Germany (3), Italy (1), Netherlands (1), Sweden (1) and Loughborough in the UK. The projects were led by the following scientists: Malchaire (Co-ordinator), Griefahn, Gebhardt, Kampmann, Alfano, Havenith, Holmér and Parsons respectively. The three year programme (1996-99) involved two phases. Phase I was concerned with the development and collation of knowledge in areas required to improve the method described in ISO 7933. These included heat exchange through clothing, prediction of mean skin temperature, conditions with high humidity, the evaporative efficiency of sweating, criteria for estimating exposure times, and a measuring strategy. Phase II provided a validation stage and the development of a new model along with a philosophy of application. The results have been published in a series of eight papers (Malchaire *et al*, 1999 – 2000).

Malchaire (1999) provided the following list of the criticisms of ISO 7933:

1. Skin temperature prediction;
2. The effect of clothing on convection, radiation and evaporation;
3. The combined effects of clothing and movement (the pumping effect);
4. The link of metabolic rate and the increase in core temperature;
5. The accuracy of the prediction of sweat rate in very humid conditions;
6. The limiting criteria (i.e. the SW_{max}, E_{max}, Q_{max}, D_{max}), and specifically the Alarm and the Danger criteria level;
7. The maximum water loss allowed to predict dehydration levels.

As a result of the BIOMED HEAT collaboration and past research into the validity of ISO 7933, a number of changes were to be made to the predictive algorithms. Additionally a major shift in philosophy was observed, whereby the DLE would no longer predict for “alarm” and “danger” criteria but for the mean subject (Kampmann, Malchaire and Piette, 1999). Figure 4 uses the same process as used in Figure 3 (SW_{req}) to describe visually some of the aspects of the new PHS model.

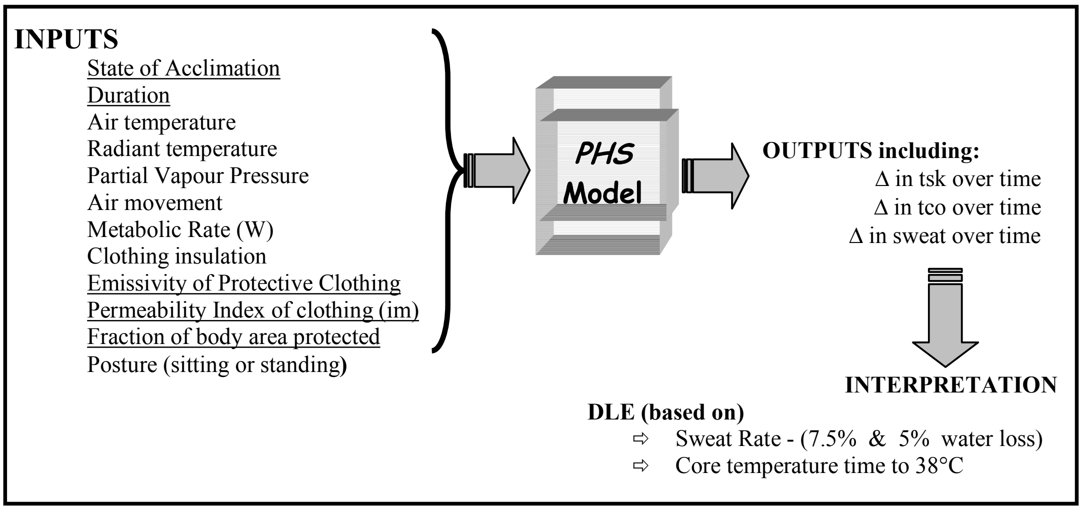


Figure 4: Diagrammatic representation of how the *PHS* model may be used to evaluate possible control options

(Note: The underlined input values are new to the PHS model and were not inputted into the ISO SW_{req} *model*

The Predicted Heat Strain (PHS) model

Through the collaboration of the eight partners, a database was generated of 1113 experiments (one subject per experiment) with minute by minute data of environmental conditions and physiological responses. It consisted of 747 laboratory and 366 field experiments. The laboratory experiments were divided into 2 subsets with 369 (subset 1) and 378 (subset 2) experiments. Subset 1 was used to generate the PHS model and subset 2 to validate it. Male subjects made up 1020 of the experiments and 452 of the subjects were acclimatised. More than 50% of the laboratory data consisted of experiments on nude or semi-nude subjects (clo<0.5) and 95% of the field experiments had clothed subjects. From the data used, the following ranges for each parameter were generated for which the model would be validated.

Table 7: Range of data for each input parameter for which the PHS model has been validated (from Piette and Malchaire, 1999)

RANGES OF VALIDITY OF THE PHS MODEL		
	Min	**Max**
t_a (°C)	15	50
Pa (kPa)	0	4.5
t_r-t_a (°C)	0	60
va ($m.s^{-1}$)	0	3
M (W)	100	450
I_{cl} (clo)	0.1	1

One of the major criticisms of the SW_{req} was that it was only validated for clo<0.6 and did not take PPE into account. This table shows that PHS will only be valid for clo<1, which again seems to not be valid for most of the PPE that may be worn. NIOSH (1986) stated that most PPE worn in industry had an insulation value of about 2 clo.

BIOMED HEAT Validation of PHS

Data considerations

The BIOMED HEAT project evaluated the validity of the PHS model when compared to observed data. Statistical weight was afforded to each experiment dependent on duration, thereby negating the effects that time may have had. The following criteria were used to produce the Table below:

1. Mean sweat rate over the whole experiment was used.
2. One rectal temperature per hour (randomly selected) was used.

Some of the results of the BIOMED HEAT analysis (from both the statistics and the scatter plots) are presented below.

Table 8: Regression between observed and predicted temperatures and sweat rates (Piette and Malchaire, 1999)

	LAB			**FIELD**
	1	**2**	**SUBSET 1&2**	
Sweat Rate (*g/h*)				
N	327	345	672	237
Observed (mean±sd)	415 ±159	432±183	424±172	317±187
Predicted (mean±sd)	448±151	454±157	451±154	344±132
Slope	0.768	0.900	0.848	1.056
Intersection	63	23	48	-46
r	0.7461	0.7730	0.7601	0.7448
Alpha	0.911	0.924	0.918	0.851
Alpha (CI95%)	0.537-1.506	0.543-1.539	0.540-1.523	0.328-1.936
Observed – Predicted (mean±sd)	-33.2±110.4	-22.1±117.4	-27.5±114.1	-26.7±125.1
Rectal Temperature				
N	938	999	1937	1028
Observed (mean±sd)	37.44±0.47	37.46–0.48	34.45±0.47	37.40±0.44
Predicted (mean±sd)	37.46±0.47	37.48–0.48	37.46±0.47	37.40±0.34
Slope	0.639	0.668	0.664	0.770
Intersection	13.49	12.43	12.57	8.6
r	0.644	0.6712	0.6585	0.5940
Alpha	1.000	1.000	1.000	1.000
Alpha (CI95%)	0.979±1.020	0.980-1.020	0.980-1.020	0.981-1.019
Observed – Predicted (mean±sd)	-0.01±0.40	-0.01±0.38	-0.01±0.38	-0.01±0.36

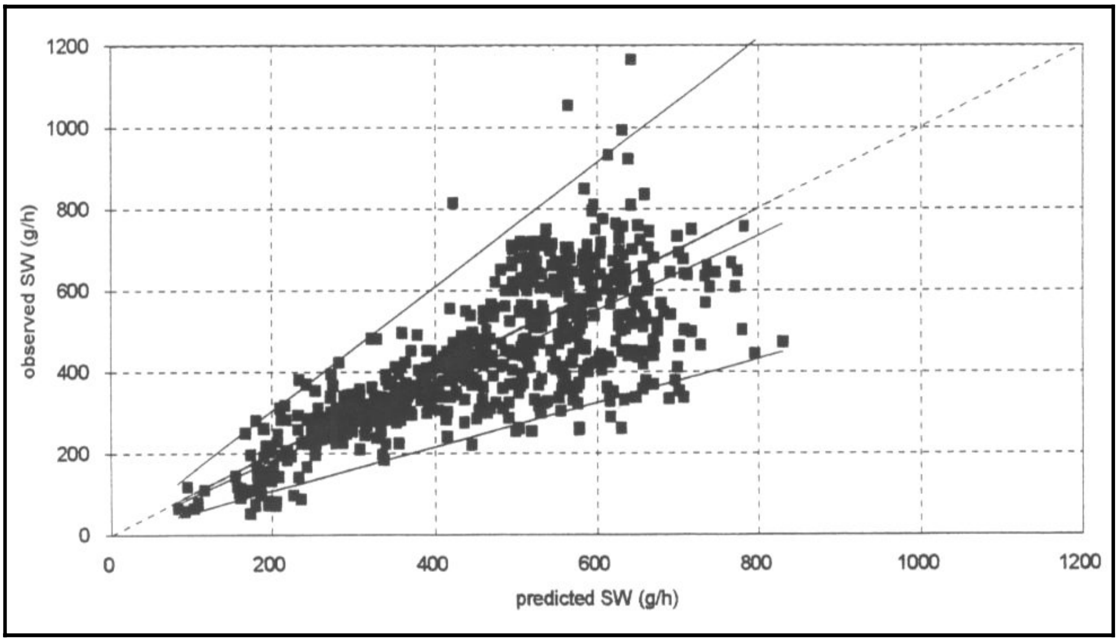


Figure 5: BIOMED HEAT – Observed and predicted sweat rates (with 95% CI limits) in the 672 laboratory experiments (taken from Piette and Malchaire, 1999)

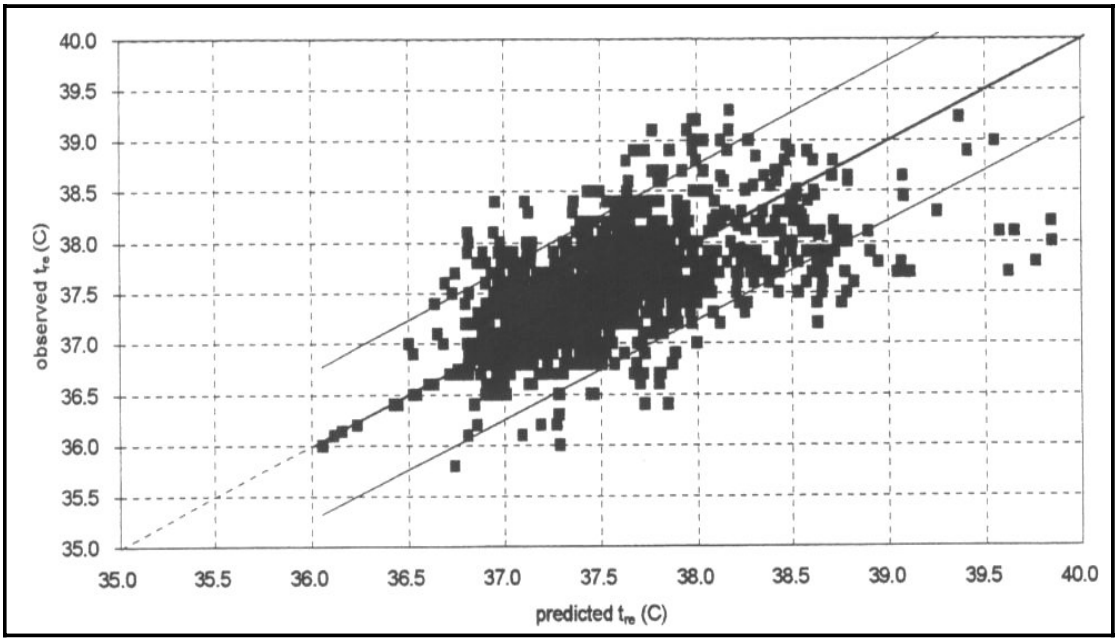


Figure 6: BIOMED HEAT – Observed and predicted rectal temperatures (with 95% CI limits) in the 672 laboratory experiments (taken from Piette and Malchaire, 1999)

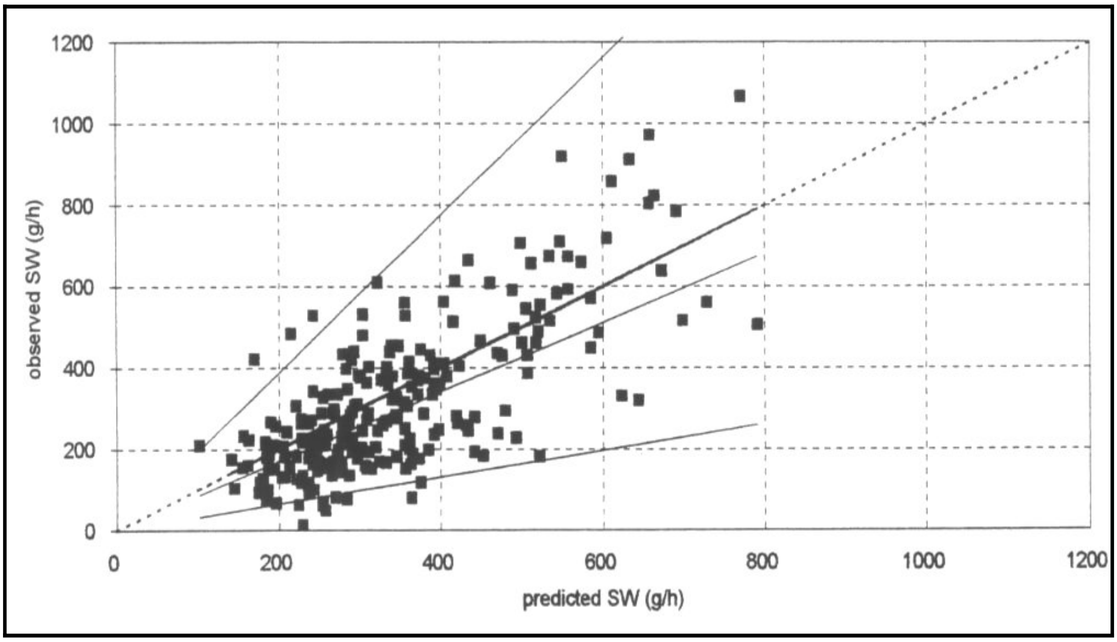


Figure 7: BIOMED HEAT – Observed and predicted sweat rates (with 95% CI limits) in the 237 field experiments (taken from Piette and Malchaire, 1999)

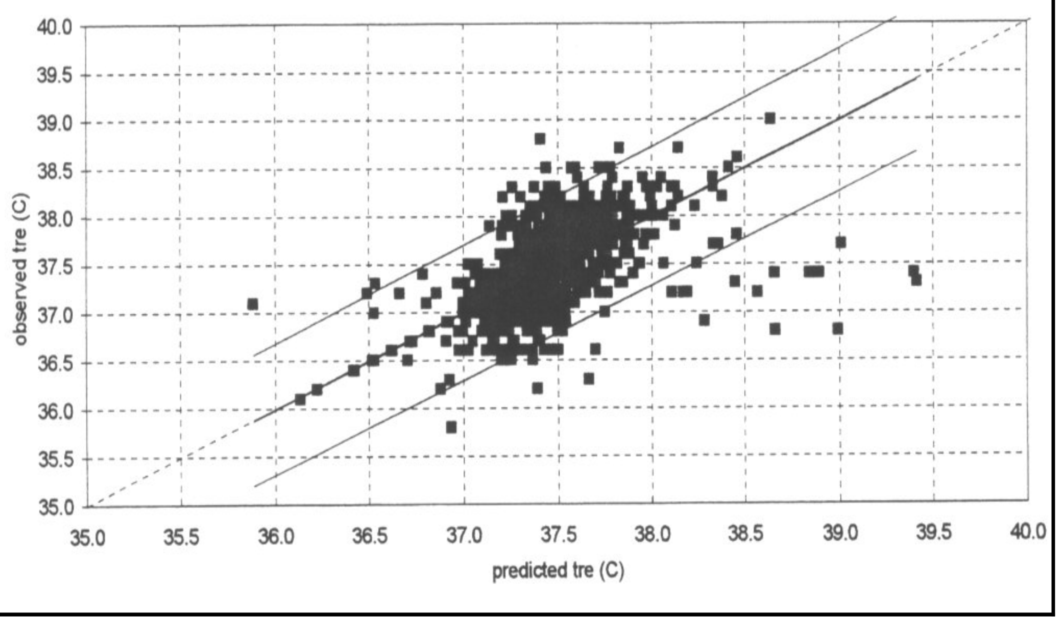


Figure 8: BIOMED HEAT – Observed and predicted rectal temperatures (with 95%CI limits) in the 237 field experiments (taken from Piette and Malchaire, 1999)

Piette and Malchaire (1999) attribute the difference in the appearance of the scatter plots between the laboratory and field trials to the "*precision of the climatic and physiological measurements*" being lower in the field resulting in their observation that "*the correlations between observed and predicted values are lower and the 95% confidence intervals are larger.*" However, if the statistics in Table 8 are viewed, this difference is actually quite small and could be attributed to the larger sample size in the laboratory set (subset 1 & 2). A further comparison of the **mean ± standard deviation** of the difference between the observed and predicted values shows that here too, the two data sets perform similarly.

The mean sweat rate over the whole experiment is a reasonable criterion to use as it allows for the estimation of sweat rate in grams per hour. The difference between the 95% CI for the sweat rates from both sets of data however is relatively small since the units are in grams per hour.

The validity study is based on the accuracy with which the PHS model can predict random rectal temperatures to within 95% CI that are considered safe. This equation was developed by extrapolating predictions from a selection of one rectal temperature per hour. This seems to be an inappropriate validation criterion as it raises a number of issues for which the validity of the model will not only be dependent but which users would judge its success; the model predicts safe exposure duration (min). The use of a random rectal temperature that is neither time-dependent nor limit criteria dependent (i.e. t_{re}=38°C) does not allow for the comparison of the most critical output from the user's point of view: TIME. How the t_{re} deviations around the regression line of the relationship between randomly, non-time-dependent selected data, will translate into deviations of time is not quantified.

Another inaccuracy may be that the validators have established 95% CI (see scatter plots), for individual data points and not the mean. Since the purpose of the PHS model is to predict the mean DLE and therefore the duration to a mean Δt_{re} to 38°C, any CI limits should be established for the scatter around the mean value and not around individual values? Although the data sets had been weighted to negate the effects of time, the actual time for Δt_{re} to 38°C should have been investigated and compared to predicted data.

The fact that the t_{re} slope does not have a time coefficient means that there is no way of establishing what this effect would be in terms of time when points at or near the CI limits are observed. Kampmann *et al* (1999) and Piette and Malchaire (1999) presented graphs showing how the DLEs for each model changed with different input values (two parameters while all the others are held constant), from which they concluded that the PHS model provided more "*realistic results*" than the ISO model. Yet no direct statistical comparison of the ISO and PHS DLEs was made. No statistical analysis was performed by BIOMED HEAT to compare the predicted and observed DLEs for the increase in core temperature. This, combined with the inappropriate use of the Δt_{re} and not the DLEs as the validation criterion, means that the validity of the PHS model to predict safe work times has not yet been established.

Conclusions

The following conclusions can be drawn from this literature review:

1. There has been extensive research into providing a valid heat stress index and a number of indices have been produced and are used;
2. There is a system of international standards that can contribute to the assessment of hot environments;
3. ISO 7933 (1989) provides a comprehensive heat stress index (SW_{req}) and method of assessment of hot environments. However, there is growing evidence that it has limited validity and is not usable;
4. A BIOMED European research project has updated the methods used in ISO 7933 and integrated the results into a new index – the Predicted Heat Strain (PHS);
5. The PHS index has been validated by those who developed it but further validation is required;
6. The validity and usability of both ISO 7933 (SW_{req}) and PHS models need to be established as part of a systematic approach to developing a heat stress assessment method for British industry.

CHAPTER 2
LABORATORY EVALUATIONS OF THE VALIDITY OF THE ISO 7933 AND PHS MODELS

2.1 SUMMARY

Chapter 2 is concerned with the validity of the existing and proposed standards for heat stress assessment (SWreq and PHS respectively) and contains Sections 2.2 to 2.12 of the report. The validity is determined by comparing the thermal strain of people exposed to a range of hot conditions in a climatic chamber with the thermal strain predicted by the standards.

Sections 2.2 to 2.6 describe the experimental design, rationale and aims of the studies. Sections 2.7 to 2.9 describe the three studies that were involved. They covered 10 experiments and 77 subject exposures. Study 1 (Experiments 1 to 6) involved subjects in boiler suits performing stepping tasks in hot conditions, Study 2 (Experiments 7 and 8) involved subjects wearing relatively impermeable clothing and performing stepping tasks. Study 3 was not designed directly for this project but allowed a validity assessment as full data were available and it was performed in the same laboratory as Studies 1 and 2. It was an investigation into simulated Indian tea picking for which subjects wore traditional ethnic dress. Over all 10 experiments, air temperatures ranged from 35 to 45 ^{o}C, radiant temperature was similar to air temperature, there was low air velocity and humidity ranged from 3.3 to 4.5 kPa ? To ? % rh). Exposure times ranged from 45 to 90 minutes.

During the experiments, internal body temperature (aural), skin temperatures, sweat rates and metabolic rates were measured. Section 2.10 describes the results. An important finding is that both models are highly sensitive to metabolic heat production. This was either measured (by indirect calorimetry) or estimated using a number of models. A comparison is made of measured and estimated values for the same conditions. Subsequent analysis of validity is conducted for both values of metabolic rate (estimated and measured). Comparisons were made between predicted and observed values for Duration Limited Exposures (allowable exposure times based upon physiological criteria) and sweat rates. Section 2.11 discusses the outcomes and consequences of the validity study. Section 2.12 concludes that neither the SW_{req} nor PHS models were valid predictors when protective clothing is worn. It was found that subjects generally produced more sweat than that predicted by the PHS and especially ISO models.

2.2 INTRODUCTION TO THE VALIDITY STUDY

To assess the validity of a measure it must be correlated against test criteria. If there is a strong correlation, the measure is valid, while if there is no relationship, it is not. Another type of validity is face validity where a model is tested to evaluate whether it does what it says it will do. This section describes ten laboratory experiments conducted as part of three separate studies to evaluate the validity of the ISO 7933 SW_{req} model and the proposed BIOMED PHS model. The studies were conducted in the thermal chamber at the Human Thermal Environments Laboratory (HTEL) in the James France Building at Loughborough University.

- **Study 1**: Experiments 1 to 6: by D. Bethea;
- **Study 2**: Experiments 7 and 8: by K. Davis and D. Bethea;
- **Study 3**: Experiments 9 and 10: by M. McNeill.

The validity of the models was evaluated by comparing the predictions of the models with the observed physiological responses of subjects in hot environments for the following parameters:

1. Sweat Rate;
2. Duration Limit Exposure (time for core temperature to reach 38°C).

The SW_{req} model will be referred to as ISO in this section to reduce the confusion between the sweat rate variables being investigated (SW_{o} and SW_{p}). Evaporation rate w be not be evaluated as no measures of dripping sweat was made. As previously discussed, ISO 7933 defines the Alarm and Danger criteria limits as being a result of an increase of 0.8°C and 1°C to the core temperature (37.8°C and 38°C) respectively, while the PHS model predicts a mean response time to 38°C core temperature. Therefore, in order to make a direct comparison between predicted DLEs only the Danger criterion has been evaluated.

2.3 AIMS OF STUDIES

The series of studies presented in this chapter compared the physiological responses of human subjects with predictions made by the ISO and PHS models. The studies involved a range of hot environments as determined by the environmental factors (air temperature, radiant temperature, humidity and air velocity) and personal factors (activity level, clothing). The aim of the studies was to establish the validity of the models on the assumption that the more accurate the predictions are, the more valid are the models. The studies therefore also allowed a comparison of models. The aims of the studies can be represented by the following specific aims and associated null (H_o) and alternative hypotheses:

1. To assess the validity of ISO 7933 predictions by comparison with the observed physiological responses of clothed subjects while exercising in a hot environment (one-tailed prediction based on literature survey).
   - $\mathbf{H_1}$: ISO 7933 is not a valid predictor of the physiological responses of clothed subjects in warm humid environments;
   - $\mathbf{H_{0(1)}}$: ISO 7933 is a valid predictor of the physiological responses of clothed subjects in warm humid environments.
2. To assess the validity of PHS predictions by comparison with the observed physiological responses of clothed subjects while exercising in a hot environment.
   - $\mathbf{H_2}$: PHS is not a valid predictor of the physiological responses of clothed subjects in warm humid environments;
   - $\mathbf{H_{0(2)}}$: PHS is a valid predictor of the physiological responses of clothed subjects in warm humid environments.
3. To compare the predictions of the ISO 7933 and the PHS models for clothed subjects while exercising in hot environments.
   - $\mathbf{H_3}$: PHS is a better predictor of the physiological responses of clothed subjects in warm humid environments than ISO 7933;
   - $\mathbf{H_{0(3)}}$: PHS is not a better predictor of the physiological responses of clothed subjects in warm humid environments than ISO 7933.

2.4 ISO SW_{REQ} AND PHS INDICES USED IN VALIDATION

2.4.1 ISO 7933 SW_{req} index

The SW_{req} computer program as described in Annex D.2 of ISO 7933, 1989 was used. The code was compared with that provided in the standard and the Outputs and Interpretations were validated against the two example scenarios provided in Tables D.1 and D.2 in the standard. For Studies 1 and 2, the expected environmental data, the clo values and the estimated metabolic rates were inputted into the model prior to any of the experiments so that estimated DLEs could be obtained. The results of these DLE predictions were used to design the experimental protocols for each study. These data were not used in the analysis. Upon completion of the experiments, the measured data and the appropriate metabolic rates (estimated and measured) were inputted, and it was the results of these inputs that the validity studies were based. The SW_{req} model will be referred to as ISO in this report.

2.4.2 ISO 7933 SW_{req} (modified) index

The standard recommends that for conditions where the clo value exceeds 0.6 clo, that the mean skin temperature algorithm is to provide a fixed value of 36°C. To this end, the program as described in the standard was altered to provide a mean skin temperature of 36°C. This modified model will be referred to as ISO(mod) in this report.

2.4.3 PHS index

A number of PHS programs were released by the BIOMED project team between January and July 2000. The final program called SIMULJUL.EXE was submitted as the final PHS model for the BIOMED HEAT project. A copy of this model was sent to D. Bethea by Jacques Malchaire who headed the BIOMED HEAT project and was used as the model for the validation study. No comparative code was provided to ensure validity of the code in the SIMULJUL.EXE program. An important point to note, was that although there was code in the model for corrections to clothing insulation and resultant air velocity based on air velocity, direction of worker movement and vapour permeability of the clothing, the model did not use this code and as such the validity study of the PHS model is based on the model without the clothing corrections developed by Parsons, Havenith and Holmér. Since this was the only model that was made available and that it was proposed as the BIOMED HEAT's final program, this program will be evaluated. The PHS index will be referred to as PHS in this report.

2.5 DATA CONSIDERATIONS

The same input values for each experiment were inputted into the three programs. Where alternative information was required (as in the case of the PHS model) this was inputted as required.

2.5.1 ISO and ISO(mod)

All ISO and ISO(mod) results were obtained using the BASIC version described in the standard. The data were then inputted into Microsoft Excel™ versions (created by D. Bethea) of each ISO index and the results validated by the author and an independent researcher to ensure that the Excel models provided the same results as the BASIC versions. The data from the Excel models were then used as these provided greater flexibility for the analysis.

2.5.2 PHS model

The PHS model was also in BASIC format with the results saved as ASCII file. Although the model provided a breakdown of the interpretation data, the ASCII file for each subject was saved as an Excel file and the data inspected to validate the predictions. This also allowed for obtaining other predictions such as mean skin temperature, changes in core temperature over time, etc.

2.6 ANALYSIS OF RESULTS

The table below explains how the observed and predicted measures were arrived at so that they could be compared. Predicted values were obtained for both estimated metabolic rate and measured metabolic rate.

Table 9: Description of how observed and predicted DLEs and sweat rates were obtained

	OBSERVED	PREDICTED	
		ISO 7933	**PHS**
SWEAT RATE	• Total sweat rate calculated from the difference between pre & post semi-nude weight -corrected for H_2O intake • Total sweat loss was divided by the total time in experiment to obtain a value for g/min. This was then multiplied by 60 to get Sweat Loss in g/h.	• Provided as an Interpretation by the ISO Model • Model predicts Sweat Rate in g/h and is not time dependent.	• Model predicts Total Sweat Loss (TSW) for each minute. • This was divided by the PHS predicted time for core temperature to reach 38°C. Thereby providing g/min, corrected to g/h.
DURATION LIMIT EXPOSURE	• Time for aural temperature to reach 38°C.	• Provided as an Interpretation by the ISO Model • Model predicts a Duration Limit Exposure (mins) based on heat storage or water loss (which ever occurs first). • Danger criteria DLEs for unacclimatised subjects were analysed.	• Model predicts the Duration Limit Exposure based on minute by minute increases in core temperature and minute by minute changes in sweat rate. • DLEs were based on increases in core temperature to 38°C (rounded to 3 decimal places).

2.6.1 Statistical Analysis to be used

Descriptive Statistics and Standard Deviation

Standard deviation (SD) is an average measure of the dispersion or deviation around the mean. 68% of cases fall within one SD of the mean in a normal distribution and 95% of cases fall within 2 SD. For example, if the mean age were 30, with a standard deviation of 5, 95% (2 SD) of the cases would be between 20 and 40 in a normal distribution. The standard deviation will provide a rough measure of the similarity within and between models and between the models and the observed data. This will be supplemented by a statistical evaluation of these relationships using correlations and paired sample *t* tests. Where data are missing, descriptive statistics will be provided for the whole data set, and then only for those paired data sets that both have data.

Correlations

Pearson correlations will be used to measure how the variables are related. Before calculating a correlation coefficient, data have to be screened for outliers that may cause misleading results and possibly lead to type one errors. Cases with missing values for one or both of a pair of variables for a correlation coefficient are excluded from the analysis. Since each coefficient is based on all cases that have valid data on that particular pair of variables, the maximum information available is used in every calculation. This will result in a set of coefficients based on a varying number of cases for each variable when one or more data sets are missing. Pearson's correlation coefficient is a measure of linear association; however, although it provides a measure of their relationship it does not provide information about how accurate this relationship is. To do this a pair sample t test will be performed. Scatter plots will be provided with regression lines to show whether the relationship is linear.

Paired-Samples t Test

A paired sample *t* test will be used as a test of the null hypothesis that two population means are equal. A number of assumptions should be made for the *t*-test:

1. Observations for each pair should be made under the same conditions.
2. The mean differences should be normally distributed.
3. Variances of each variable can be equal or unequal.

One of the benefits of this test is that it is robust and the data do not have to be normally distributed; because the data are interval in nature for paired samples the difference in the variance of the two samples is not an issue (Coolican, 1992). It was selected instead of ANOVA for this reason. Additional calculations for the correlation, average difference in means, t test, and 95% confidence interval (CI) for mean difference will be computed. Any missing data will be excluded from the pair-wise analysis. Therefore sample sizes may vary from test to test dependent on whether data were available for each variable pair.

2.7 STUDY 1 (EXPERIMENTS 1 TO 6): VALIDITY OF ISO AND PHS MODELS FOR PEOPLE WEARING BOILER SUITS IN A RANGE OF HOT CONDITIONS

2.7.1 Method – Study 1

Experimental Design

The experimental design was formalised following a pilot study. A number of decisions were made *a priori* that dictated the experimental procedure. Eight healthy male volunteers would take part in each experiment, with each experiment consisting of four sessions, each with two subjects. Two morning exposure sessions and two afternoon exposure sessions produced a balanced design. To ensure that consistency was maintained throughout the experiment, across all exposures a number of procedural methodologies were adopted before each session. The environmental conditions for each of the six experiments in Study One were selected using the following decision process, which then decided the conditions for the following experiments:

- The six experiments would be conducted as three pairs of conditions, where:
  - **Pair 1** = Experiments 1 and 2
  - **Pair 2** = Experiments 3 and 4
  - **Pair 3** = Experiments 5 and 6

- Each experiment would be analysed individually. Each of the pairs was separated by a minimum of seven days to eliminate any acclimation. This allowed for a between subject analysis of the data and for each experiment to be treated independently of the other;
- For Experiment 1, a number of combinations of environmental parameters were entered into ISO 7933 to gain a Duration Limited Exposure (DLE) for unacclimatised subjects of around 30 minutes for the Alarm Criteria and 45 minutes for the Danger criteria;
- To reduce the stress on the subjects in Experiment 2, their metabolic rate was reduced. This was kept the same for Experiment 3, but the environmental conditions were more severe;
- Metabolic rate was then reduced for Experiment 4, keeping the environment conditions the same as Experiment 3;
- Experiment 5, again increased the severity of the environmental conditions, while keeping the metabolic rate the same as Experiment 4;
- In Experiment 6, the process was repeated by keeping the environment conditions the same as Experiment 5, but reducing the metabolic rate.

This was done to provide a variety of environment and metabolic rate conditions and to meet the experimental requirements of the usability study (see Section **3.2.5**).

Withdrawal Criteria

Limiting criteria were established *a priori* to safeguard the subjects and to satisfy the requirements of Department of Human Sciences generic ethical protocol for the exposure of human subjects to the heat in the thermal environment chamber at HTEL. Subjects were withdrawn if:

- Core (aural) temperature reached 38.5°C (mean);
- Heart rate reached 200 minus Age;
- The subject was showing signs of reduced mental capacity, e.g. confusion, loss of co-ordination, verbal communication skills decrease, etc;
- Subject requested to be removed from the chamber;
- The time limit of 75 minutes was reached, even if none of the limiting criteria had been met.

Subjects

Eight health male volunteers took part in each experiment, with three different groups of subjects taking part in each pair of experiments. They represented a stratified sample as they had volunteered after responding to notices placed around Loughborough University Campus. Not all the subjects were students. Descriptive statistics are provided in **Table 10**.

Table 10: Descriptive statistics of subject age, height and weight for each experiment in Study 1

		N	MEAN	ST DEV	MIN	MAX
EXPERIMENTS 1 AND 2	**Age**	8	25.4	4.03	17	31
	Height (m)	8	1.7	0.05	1.69	1.86
	Semi-nude Weight (Kg)	8	71.3	3.97	64.20	77.45
EXPERIMENTS 3 AND 4	**Age**	8	25.4	1.60	23	28
	Height (m)	8	1.8	0.05	1.7	1.86
	Semi-nude Weight (Kg)	8	75.6	7.44	68.35	87.33
EXPERIMENTS 5 AND 6	**Age**	8	27.0	3.02	25	34
	Height (m)	8	1.8	0.03	1.72	1.82
	Semi-nude Weight (Kg)	8	76.7	7.94	67.89	89.62

Apparatus

Dry bulb air temperature, humidity, air velocity and globe temperature were recorded at chest height using two 12bit ELTEK 1000 series squirrel data loggers inside the chamber. VAISALA VH-G-Z3-0 capacitive humidity and temperature probes fitted with Vaisala HUMICAP™ sensor and a Grant U Type temperature sensor were used to measure shielded air temperature and humidity respectively (this air temperature was only to be used as backup). Air temperature was measured using Grant UU type thermistors encased in a steel cover, providing shielded air temperature. *WBGT* parameters were measured using a *WBGT* unit developed at HTEL in accordance with ISO 7226 and data were recorded on a Grant 8bit Squirrels™ data logger. Air temperature and humidity were also monitored externally on a 10bit Squirrel that was attached to the central control panel.

Aural temperature was measured with bead thermistors placed through a rubberised ear plug to allow about 4 mm of the thermistor to rest within the auditory canal once the ear plug was put in place. Aural thermistors were further insulated from the external environment with taped down cotton wool and a pair of ear defenders with a soft foam sponge lining. Skin temperature was measured using surface temperature sensors Type EU, with copper base, also made by Grant Instruments. All subject temperature data were recorded on Grant 8 bit Squirrels™ data loggers. Calibration of all squirrels and thermistors were evaluated using a Grant heated water bath prior to each session. Heart rate was measured using Polar Sport Tester® hear rate monitors. All data were recorded at one-minute intervals.

Reebok ® steps provided the step for the exercise activity. 1.8 cm thick wooden boards were also used to provide varied step height dependent on subject's weight. Douglas bags with 2-way valves were used to collect the subject's exhaled air while exercising. They were analysed using a Sybron Taylor Servomex O_2 Analyser, an ADC carbon dioxide analyser and a Harvard dry gas meter. The analysers were calibrated each morning of an experiment. Dynamic weight (mean of three measures) was measured using a Metler ID1 Multi-range scales, which were calibrated before each experiment.

Eight 100% cotton drill, one-piece boiler suits with front poppers, open sleeve and leg cuffs were worn. Subjects also wore their own underwear (cotton boxer shorts and cotton rich, short ankle socks), trainers and cotton T-shirts. The clothing insulation value of each ensemble was estimated as 0.8 clo using the Tables in ISO 9920. As a manual backup, manual recording data sheets were also used with readings taken at fixed intervals throughout each experiment.

2.7.2 Procedure

Pre Experiment.

The step height for each subject was calculated based on an equation by Wadsworth and Parsons (date) to provide a ratio of between each subject's weight and their required estimated metabolic rate. Once this step height had been obtained, it was inputted into the ACSM equation to obtain the estimated metabolic rate. This provided an adjusted step height in an attempt to equalise the metabolic rates by providing step height ratios based on subject weight.

$$VO_2\,(\mathrm{ml{\bullet}kg^{-1}{\bullet}min^{-1}}) = \left(\frac{\mathrm{steps}}{\mathrm{min}} \times 0.35\ \frac{\mathrm{ml{\bullet}kg^{-1}{\bullet}min^{-1}}}{\mathrm{steps.min^{-1}}} \right) + \left(\frac{\mathrm{m}}{\mathrm{steps}} \times \frac{\mathrm{steps}}{\mathrm{min}} \times 1.33 \times 1.8\ \frac{\mathrm{ml{\bullet}kg^{-1}{\bullet}min^{-1}}}{\mathrm{m.min^{-1}}} \right) \qquad 24)$$

Preparation

All the procedures followed had been passed by Loughborough University's Ethical Committee as HTEL's generic protocol for heat stress exposure in the thermal chamber.

After completion of a consent form, subjects drank a 250 ml glass of water before entering their preparation room, where they stripped to their underwear and were weighed semi-nude. An aural thermistor was placed in each ear canal and insulated with cotton wool and a pair of industrial ear defenders. The 5 skin thermistors were then placed on the subject using, 3M Transpore™ tape. The Ramanathan 4 point mean skin temperature sites were used (the chest, the upper arm, the thigh and the calf) along with an upper back site situated at the sub-clavicle. The heart rate monitor was attached and they dressed in a T-shirt, boiler suit, socks and trainers and sat in the preparation room for 20 minutes. Oral temperature was taken with a mercury glass thermometer to provide a reference value with the aural temperature and to identify when the environment within the auditory canal had stabilised. When both subjects had been prepared and were ready to enter the thermal chamber, they completed a subjective thermal comfort questionnaire. Data recordings on the squirrel data loggers and the polar sports tester heart rate monitors were started and objective measures were manually recorded on the data sheets by the experimenter.

The Experiment

A three minutes staggered start was observed, with subjects entering the chamber accompanied by an experimenter. Subjects were weighed clothed and started stepping in time to an audio metronome beating once every second, thereby providing for a total of 15 complete steps per minute. A complete step was where the subject stepped up onto the step and then back onto the floor with both feet. At 25 minutes subjects provided a VO_2 sample by breathing into a Douglas Bag which were then analysed immediately by the second experimenter. When a withdrawal criteria was met, all physiological measures and completion time were recorded manually, all physiological data recordings were stopped and the subject was weighed clothed and semi-nude before leaving the chamber. Water intake was calculated and weight loss was corrected for water intake. Subjects were removed from the chamber and were laid down on a string-mesh bed and cooled by fans. All subjects were monitored upon completion of the exposure and were not allowed to leave the laboratory until they had recovered from the exposure. Oral temperatures were taken after 30 minutes to ensure no post heat stress re-heating had occurred.

Inputs

Table 11: Data inputted into models

	INPUT VARIABLES	N	MEAN	ST DEV	MIN	MAX
EXP 1	**Air Temperature (°C)**	8	34.9	0.27	34.6	35.2
	Globe Temperature (°C)	8	35.0	0.20	34.7	35.2
	Air Velocity (m/s)	8	0.22	0.07	0.10	0.28
	Mean Radiant Temperature (°C)	8	35.1	0.14	34.9	35.2
	Partial Vapour Pressure (kPa)	8	3.4	0.13	3.3	3.6
	Estimated Metabolic Rate (W/m^2)	8	193	7	187	207
EXP 2	**Air Temperature (°C)**	8	35.0	0.07	34.9	35.1
	Globe Temperature (°C)	8	34.7	0.04	34.7	34.8
	Air Velocity (m/s)	8	0.28	0.04	0.20	0.32
	Mean Radiant Temperature (°C)	8	34.4	0.09	34.3	34.6
	Partial Vapour Pressure (kPa)	8	3.3	0.07	3.2	3.5
	Estimated Metabolic Rate (W/m^2))	8	177	6	166	187
	Measured Metabolic Rate (W/m^2)	8	158	18	126	186
EXP 3	**Air Temperature (°C)**	8	39.5	0.09	39.4	39.6
	Globe Temperature (°C)	8	39.3	0.12	39.1	39.4
	Air Velocity (m/s)	8	0.07	0.01	0.07	0.08
	Mean Radiant Temperature (°C)	8	39.2	0.16	39.0	39.3
	Partial Vapour Pressure (kPa)	8	4.5	0.24	4.3	4.8
	Estimated Metabolic Rate (W/m^2)	8	173	6	166	177
	Measured Metabolic Rate (W/m^2)	8	161	20	137	194
EXP 4	**Air Temperature (°C)**	8	39.7	0.11	39.6	39.9
	Globe Temperature (°C)	8	39.5	0.07	39.4	39.6
	Air Velocity (m/s)	8	0.08	0.01	0.06	0.11
	Mean Radiant Temperature (°C)	8	39.3	0.08	39.2	39.4
	Partial Vapour Pressure (kPa)	8	4.5	0.15	4.3	4.7
	Estimated Metabolic Rate (W/m^2)	8	153	5	145	155
	Measured Metabolic Rate (W/m^2)	8	142	17	122	169
EXP 5	**Air Temperature (°C)**	8	45.0	0.19	44.7	45.2
	Globe Temperature (°C)	8	45.0	0.11	44.9	45.1
	Air Velocity (m/s)	8	0.08	0.00	0.08	0.09
	Mean Radiant Temperature (°C)	8	44.9	0.17	44.7	45.1
	Partial Vapour Pressure (kPa)	8	3.8	0.04	3.8	3.9
	Estimated Metabolic Rate (W/m^2)	8	153	5	145	155
	Measured Metabolic Rate (W/m^2)	8	134	14	116	162
EXP 6	**Air Temperature (°C)**	7	44.7	0.04	44.7	44.8
	Globe Temperature (°C)	7	44.2	0.09	44.1	44.3
	Air Velocity (m/s)	7	0.09	0.00	0.09	0.09
	Mean Radiant Temperature (°C)	7	43.8	0.16	43.5	44.0
	Partial Vapour Pressure (kPa)	7	3.9	0.04	3.8	3.9
	Estimated Metabolic Rate (W/m^2)	7	87	0	87	87
	Measured Metabolic Rate (W/m^2)	6	101	7	93	111

2.8 STUDY 2 (EXPERIMENTS 7 AND 8): VALIDITY OF ISO AND PHS MODELS FOR PEOPLE WEARING CLOTHING WITH DIFFERENT VAPOUR PERMEABILITY PROPERTIES.

2.8.1 Method – Study 2

Experimental Design

K. Davis conducted this project as part fulfilment of her BSc (Hons) in Human Biology in the Department of Human Sciences, Loughborough University. D. Bethea supervised the project.

The purpose of this study was to follow on the experimental protocol established for Study 1, and to investigate the validity of ISO 7933 for conditions where subjects were wearing clothing ensembles of the same design but with different vapour permeabilities but similar clothing insulation values (clo). Four ensembles were selected from the clothing database at HTEL. All ensembles were of similar cut, fit, shape, etc. Following a biophysical study to determine the vapour permeability of the four ensembles, two were selected; the PU coated nylon ensembles and the cyclone coated nylon ensembles. The biophysical study showed that the Cyclone ensemble was more vapour permeable that the PU coated ensemble (for further information see Davis, 1998).

The experimental design was formalised following a pilot study.

The experiment consisted of two exposures separated by at least seven days to eliminate any acclimation. This allowed for a between subject analysis of the data and for the experiments to be treated independently of each other. A Latin Square design was adopted to the allocation of ensembles to randomise the order and to reduce any order effects of clothing worn. Subjects were not informed of the nature of the suits so as not to influence their subjective responses. Each experiment consisted of four sessions, with two subjects in each.

Withdrawal Criteria

Limiting criteria were established *a priori* to safe guard the subjects and to satisfy the requirements of Department of Human Sciences generic ethical protocol for the exposure of human subjects to the heat in the thermal environment chamber at HTEL. Subjects were withdrawn if:

- Core (aural) temperature reached 38.5°C (mean);
- Heart rate reached 200 minus Age;
- The subject was showing signs of reduced mental capacity e.g. confusion, loss of co-ordination, verbal communication skills decrease, etc;
- Subject requested to be removed from the chamber;
- The time limit of 60 minutes was reached, even if none of the limiting criteria had been met.

Subjects

Eight health male volunteers took part in each experiment. They represented a stratified sample as they had volunteered after responding to notices placed around Loughborough University Campus.

All subjects were undergraduate students at Loughborough University. Descriptive statistics are provided in Table 12.

Table 12: Descriptive statistics of subject age, height and weight for each experiment in Study 3

		N	MEAN	ST DEV	MIN	MAX
EXPERIMENTS 7 AND 8	**Age**	8	20.6	1.85	18	24
	Height (m)	8	1.8	0.04	1.75	1.86
	Semi-nude Weight (Kg)	8	76.7	8.04	65.93	91.05

Apparatus

The same apparatus to measure the environmental and physiological parameters were used as in Experiment 1. The same procedure for step height ratios to subject weight was not used. All subjects stepped at the same height.

The ensembles consisted of a jacket and trousers. ISO 9920 did not provide sufficient information for the estimation of clo values. As a result, the ensembles (all sizes) were sent to the Defence Evaluation Research Agency (DERA) in Farnborough, Hampshire, where Dr. W. R. Withey and Dr. P. Redman evaluated the suits on a thermal manikin. These tests provided the following clo values:

Table 13: Clo values obtained from thermal manikin trials held at DERA

ENSEMBLE TYPE	Size	CLO VALUE FROM MANIKIN TRIALS
PU	**Large**	0.761
	Medium	0.674
CYCLONE	**Large**	0.741
	Medium	0.716

Allocation of ensemble sizes was dependent on the subject's size and the appropriate clo value for each subject's ensemble was inputted into ISO, ISO(mod) and PHS models (corrected to include underwear, T-shirt and trainers).

2.8.2 Procedure

The experimental procedure was based on the protocol developed for Study 1.

Inputs

Table 14: Data inputted into models for Study 2

		N	MEAN	ST DEV	MIN	MAX
EXP 7	**Air Temperature (°C)**	8	40.10	0.32	39.70	40.50
	Globe Temperature (°C)	8	39.25	0.32	38.90	39.70
	Air Velocity (m/s)	8	0.15	0.00	0.15	0.15
	Mean Radiant Temperature (°C)	8	38.69	0.34	38.24	39.17
	Partial Vapour Pressure (kPa)	8	3.721	0.092	3.533	3.865
	Estimated Metabolic Rate (W/m^2)	8	177	0.00	177	177
	Measured Metabolic Rate (W/m^2)	8	190	17.83	166	218
	Intrinsic Clothing Insulation (Clo)	8	0.82	0.04	0.75	0.84
EXP 8	**Air Temperature (°C)**	8	40.04	0.27	39.70	40.50
	Globe Temperature (°C)	8	39.25	0.32	38.90	39.70
	Air Velocity (m/s)	8	0.15	0.00	0.15	0.15
	Mean Radiant Temperature (°C)	8	38.73	0.42	38.24	39.50
	Partial Vapour Pressure (kPa)	8	3.725	0.095	3.533	3.865
	Estimated Metabolic Rate (W/m^2)	8	177	0.00	177	177
	Measured Metabolic Rate (W/m^2)	8	190	8.44	176	199
	Intrinsic Clothing Insulation (Clo)	8	0.81	0.01	0.80	0.82

2.9 STUDY 3 (EXPERIMENTS 9 AND 10): VALIDITY OF ISO AND PHS MODELS FOR TEA LEAF PICKERS IN A SIMULATED HOT ENVIRONMENT

2.9.1 Introduction

Dr. M. McNeill conducted this project as part fulfilment of his PhD in Ergonomics in the Department of Human Sciences, Loughborough University. The purpose of this study was to evaluate the validity of ISO 7933 for assessing the thermal stress in industrially developing countries. Tea leaf picking was used as a representative agricultural task. (For a more detailed description see McNeill and Parsons, 1999.)

2.9.2 Method – Study 3

Experimental Design

The experimental design was formalised following a pilot study. Limiting criteria were established *a priori* to safe guard the subjects and to satisfy the requirements of Department of Human Sciences generic ethical protocol for the exposure of human subjects to the heat in the thermal environment chamber at HTEL. Subjects were withdrawn if:

- Core (aural) temperature reached 38.5°C (mean);
- Heart rate reached 200 minus Age;
- The subject was showing signs of reduced mental capacity e.g. confusion, loss of co-ordination, verbal communication skills decrease, etc;
- Subject requested to be removed from the chamber;
- The time limit of 60 minutes was reached, even if none of the limiting criteria had been met.

Subjects

Eight healthy male and eight healthy female volunteers took part in each experiment. They represented a stratified sample as they had volunteered after responding to notices placed around Loughborough University Campus. The males took part in Experiment 9, while the females were in Experiment 10. Subjects carried out the simulated agricultural task of tea picking while in the thermal environment chamber at HTEL. The environment, the tasks and the clothing worn were selected to simulate conditions described by Sen *et al* (1983) (as referenced by McNeill).

The experimental protocol was formalised following a pilot study.

Table 15: Descriptive statistics of subject age, height and weight for each experiment in Study 3

		N	MEAN	SD	MIN	MAX
EXPERIMENT 9 (MALES)	**Age**	8	21.5	1.93	19	25
	Height (m)	8	1.8	0.06	1.65	1.85
	Semi-nude Weight (Kg)	8	75.9	5.82	68.62	83.14
EXPERIMENT 10 (FEMALES)	**Age**	6	19.8	1.72	18	23
	Height (m)	6	1.7	0.04	1.66	1.78
	Semi-nude Weight (Kg)	6	66.5	7.74	58.57	77.26

Apparatus

The same apparatus to measure the environmental and physiological parameters were used as in Experiments 1 and 2.

Clothing

Subjects wore a clothing ensemble that was representative of that worn by Indian agricultural workers. The males wore a *punjabi* (a long sleeved, thing length shirt of 65% cotton and 35% polyester composition) and a *lungi* (a 100% cotton ankle length wrap-around). The females wore a *shalwar kamize* (65% cotton and 35% polyester long sleeved, thing length blouse and tight fitting pyjama style trousers). The clothing was supplied by HTEL but they wore their own cotton underwear. No footwear was worn. From ISO 9920, the male and female ensembles were estimated as 0.5 and 0.46 clo respectively.

Tea bushes

To simulate the conditions found in an Indian tea plantation, rhododendron bushes were placed on tables in aisles. These represented tea bushes, as tea bushes were not available.

Procedure

The Experiment

All the procedures followed had been passed by Loughborough University's Ethical Committee as HTEL's generic protocol for heat stress exposure in the thermal chamber. All subjects provided informed consent upon completion of the HTEL consent and medical questionnaire.

One male and one female subject participated in each session. Prior to entering the chamber, subjects were weighed and the average of two dynamic measures was used as their semi-nude weight. Their clothing ensembles were weighed separately. Subjects were then instrumented in the same way as in Experiments 1 and 2. Once instrumented, subjects remained in the neutral room for a further 10 minutes or until the aural thermistors reached equilibrium.

Upon entering the thermal chamber, subjects were instructed in how to carry the tea basket either over their head or shoulder. The subjects then walked around the thermal chamber randomly picking leaves from the "tea bushes", placing the leaves in their basket. To simulate the terrain in a tea plantation, steps were placed at intervals around the chamber. Metabolic rate was measured using Douglas Bags at 30, 60 and 90 minutes into the experiment. A controlled amount of water was provided upon request to ensure that subjects drank during each session.

Upon completion of the session, subjects were removed from the chamber and weighed semi-nude. Their clothing was again weighed separately.

Inputs

Table 16: Data inputted into models

		N	MEAN	ST DEV	MIN	MAX
EXP 9	**Air Temperature (°C)**	8	37.18	0.28	36.86	37.56
	Globe Temperature (°C)	8	36.86	0.30	36.48	37.30
	Air Velocity (m/s)	8	0.17	0.04	0.11	0.24
	Mean Radiant Temperature (°C)	8	36.63	0.39	35.92	37.14
	Partial Vapour Pressure (kPa)	8	4.447	0.179	4.107	4.604
	Measured Metabolic Rate (W/m^2)	8	138	15.36	116	161
	Intrinsic Clothing Insulation (W/m^2)	8	0.50	0.00	0.50	0.50
EXP 10	**Air Temperature (°C)**	6	37.19	0.31	36.86	37.56
	Globe Temperature (°C)	6	36.87	0.34	36.48	37.30
	Air Velocity (m/s)	6	0.17	0.05	0.11	0.24
	Mean Radiant Temperature (°C)	6	36.62	0.45	35.92	37.14
	Partial Vapour Pressure (kPa)	6	4.451	0.182	4.107	4.576
	Measured Metabolic Rate (W/m2)	6	115	17.20	91	134
	Intrinsic Clothing Insulation (Clo)	6	0.60	0.00	0.60	0.60

2.10 RESULTS OF THE 3 STUDIES - COMPARISON OF ISO 7933, ISO(MOD), PHS AND OBSERVED PHYSIOLOGICAL DATA

The results are presented in the following format:

1. Comparison of Estimated and Measured Metabolic Rates
2. Comparison of within model predictions between estimated and measured metabolic rate inputs
3. Comparison between ISO and PHS model predictions and Observed Data
4. Comparison of between ISO and PHS model predictions

2.10.1 Comparison of Estimated and Measured Metabolic Rates

The ISO and PHS models present heat stress indices and interpretation (in terms of allowable exposure, for example) that depend upon a rational interaction of inputs which include air temperature, radiant temperature, humidity, air velocity, clothing insulation and metabolic rate. The prediction of the models is therefore sensitive to all of the inputs and will be affected by the accuracy of measurement or estimation of their values. Of particular importance is the estimation or measurement of metabolic rate. For an active worker the sweat required to cool the body by evaporation is often closely related to the heat produced by activity and hence metabolic rate. It is important therefore, that consideration should be given to the estimation of metabolic rate. In the present studies, metabolic rate was estimated using Tables (ISO 8996), empirical equations specifically designed to predict metabolic rate from a stepping activity (Wadsworth, American College of Sports Medicine, date). Metabolic rate was 'measured' using the technique of indirect calorimetry (ISO 8996).

One of the problems with estimating metabolic rate is that there can be an error as great as 60% (NIOSH, date; Parsons and Hamley, 1989). It is clear that, since ISO 7933 is based on the heat balance equation, the heat gained through physical activity is a critical factor that will determine whether or not heat storage will occur. The accuracy therefore of the prediction will largely be dependent on the accuracy of the metabolic rate value entered into the equation. However when estimating metabolic rate from equations, the prediction will be dependent on the empirical data from which that equation has been derived. It is highly likely therefore that the validity of the method employed to estimate metabolic rate may be questioned. Therefore, under heat stress conditions, when physiological responses are stressed and alterations in the cardiovascular output are observed, it is necessary to compare the metabolic rates that were derived from estimation with those that were measured directly. Attempts were made therefore, by using the Wadsworth equation, to obtain a step height to body weight ratio for each subject. Estimated and measured metabolic rate inputs were only used in Studies 1 and 2, while only measured metabolic rate was used in Study 3. However, due to equipment failure no measured metabolic rate data is available for Experiment 1 (in Study 1).

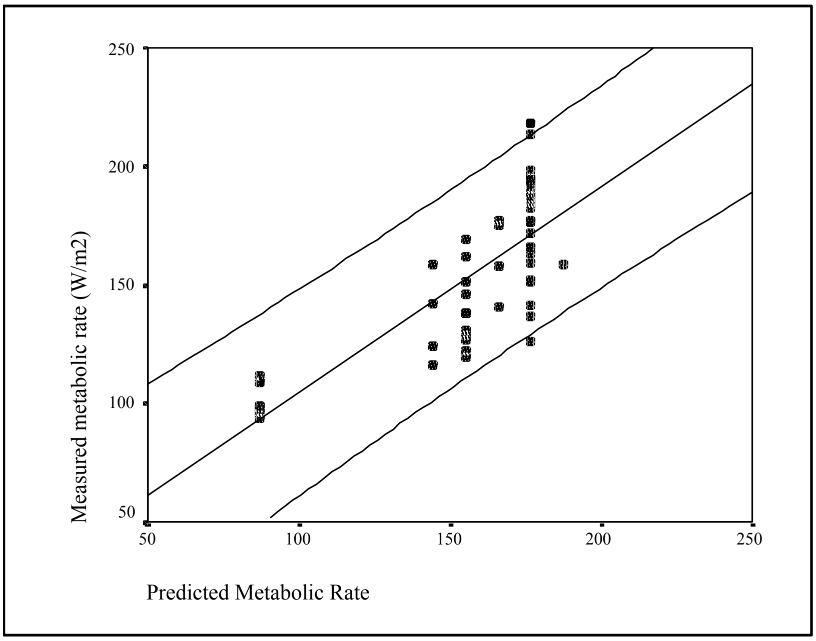


Figure 9: Scatter plot of estimated and measured metabolic rates for all experimental data, showing the regression line and the 95th percentile CI limits.

The scatter plots of metabolic inputs shows that although there was an expected narrow range in the estimated figures, that all but two of the data points were within the confidence intervals. The ISO and PHS predicted data obtained from these two outliers were removed from the data set and were not included in the validity analysis.

Table 17: Descriptive statistics of all Estimated and Measured Metabolic Rates for all experimental data.

	N	MEAN	SD
Estimated Metabolic Rate	63	162	29.9
Measured Metabolic Rate	68	150	31.6
Valid N (Listwise Cases)	54		

Table 18: Descriptive statistics of Estimated and Measured Metabolic Rates for all experimental data with outliers removed.

	N	MEAN	SD
Estimated Metabolic Rate	63	162	29.9
Measured Metabolic Rate	67	150	31.7
Valid N (Listwise Cases)	53		

Only 53 cases are valid (i.e. have both measured and estimated metabolic rate values) and as such any analyses of the relationship between the predicted and measured metabolic rate values will be carried out on these 53 cases. The descriptive statistics in Table 18 show that the mean values are similar with the estimated metabolic rate value less than 10% higher than the measured value. This is well below the possible overestimation of between 20 to 50% normally associated with estimating metabolic rate. This suggests therefore, that the use of the ACSM equation when data across all exposures are compared was successful in limiting the differences between the two inputs. The following table describes the pair-wise data (i.e. pairs where both estimated and measured data were available).

Table 19: Pair-wise descriptive statistics of Estimated and Measured Metabolic Rates for all experimental data with outliers removed

	N	MEAN	SD
Estimated Metabolic Rate	53	159	28.1
Measured Metabolic Rate	53	156	31.8
Valid N (Listwise Cases)	53		

Table 20: Results of Pearson Correlation and Paired Analysis Comparisons of Estimated and Measured Metabolic Rate (W.m^{-2}) for all experimental data

PAIRED SAMPLES CORRELATIONS				**PAIRED DIFFERENCES**					
Metabolic rate	**N**	**r^2**	**P**	**Mean**	**SD**	**SEM**	**95% CI of the Difference**		**Sig. (2-tailed)**
							Lower	**Upper**	
Estimated vs Measured	53	0.79	0.00	2.25	19.93	2.74	-3.25	7.74	0.42

Table 20 shows a significant correlation (r^2=0.79, p<0.001) between estimation and measured metabolic rates with no significant differences observed between the two (p<0.42). Although there was no significant difference between the two input variables, a comparison of the interpretations from both input variables is necessary as it has been shown that even small variations in metabolic rate inputs may have significant effects on the accuracy of the ISO model.

2.10.2 Comparison of within model predictions for estimated and measured metabolic rate inputs

For each set of results, all the data will be described. Then only the pair-wise data will be analysed. This was done because not all the experiments had data for both estimated and measured metabolic rate inputs. Additionally, any metabolic rate inputs identified as outliers were removed from the analysis.

Comparison of Sweat Rate predictions for estimated and measured metabolic rate inputs

The relationship between predicted sweat rates from the two metabolic input variables is investigated. All three models are included. Abbreviations have been used to indicate estimated metabolic input (Est Met) and measured metabolic (Meas Met) rate input data.

Table 21: Descriptive statistics of all SW_p data (gh^{-1}) for all three models and both metabolic inputs for all experimental data

	N	MEAN	SD
ISO SW_p (Est Met)	63	318.6	60.4
ISO SW_p (Meas Met)	66	299.4	59.0
ISO_{mod} SW_p (Est Met)	63	313.1	76.3
ISO_{mod} SW_p (Meas Met)	52	295.4	71.6
PHS SW_p (Est Met)	63	560.6	51.2
PHS SW_p (Meas Met)	64	560.9	39.9
Valid N (listwise)	52		

There was a large difference between the ISO models and the PHS model when all experiments were included. The lower N values for the ISO_{mod} condition are due to the ISO_{mod} not being used to evaluate Experiments 9 and 10 in Study 3 as the clothing worn did not exceed 0.6 clo. The table below provides the descriptive statistics for the pair-wise (i.e. where both input variables are available).

Table 22: Pair-wise descriptive statistics of SW_p (gh^{-1}) for all three models and both metabolic inputs for all experimental data

	N	MEAN	SD
ISO SW_p (Est Met)	52	308.4	60.7
ISO SW_p (Meas Met)	52	306.9	61.6
ISO_{mod} SW_p (Est Met)	52	296.6	71.3
ISO_{mod} SW_p (Meas Met)	52	295.4	71.6
PHS SW_p (Est Met)	50	543.2	37.8
PHS SW_p (Meas Met)	50	558.5	43.2

An interesting point to note from the standard deviation of the sweat rate from the PHS model is that it seems to be more susceptible to variations in metabolic rate input. Although the ISO_{mod} had the largest standard deviation (±71.6) for both metabolic rate input variables, it showed the smallest deviation between variables. This is probably due to the skin temperature remaining at 36°C.

Table 23: Pearson Correlation Coefficients and Paired Analysis Comparisons of Predicted Sweat Rates from both metabolic rate inputs for all experimental data

Paired Samples Correlations				**Paired Differences**					
Comparisons of SW_p	**N**	**r^2**	**P**	**Mean**	**SD**	**SEM**	**95% CI of the Difference**		**Sig. (2-tailed)**
							Lower	**Upper**	
ISO SW_p	52	0.99	0.00	1.45	9.07	1.26	-1.08	3.98	0.25
ISO_{mod} SW_p	52	0.99	0.00	1.22	7.39	1.02	-0.84	3.27	0.24
PHS SW_p	50	0.77	0.00	-15.3	28.23	3.99	-23.34	-7.29	0.00

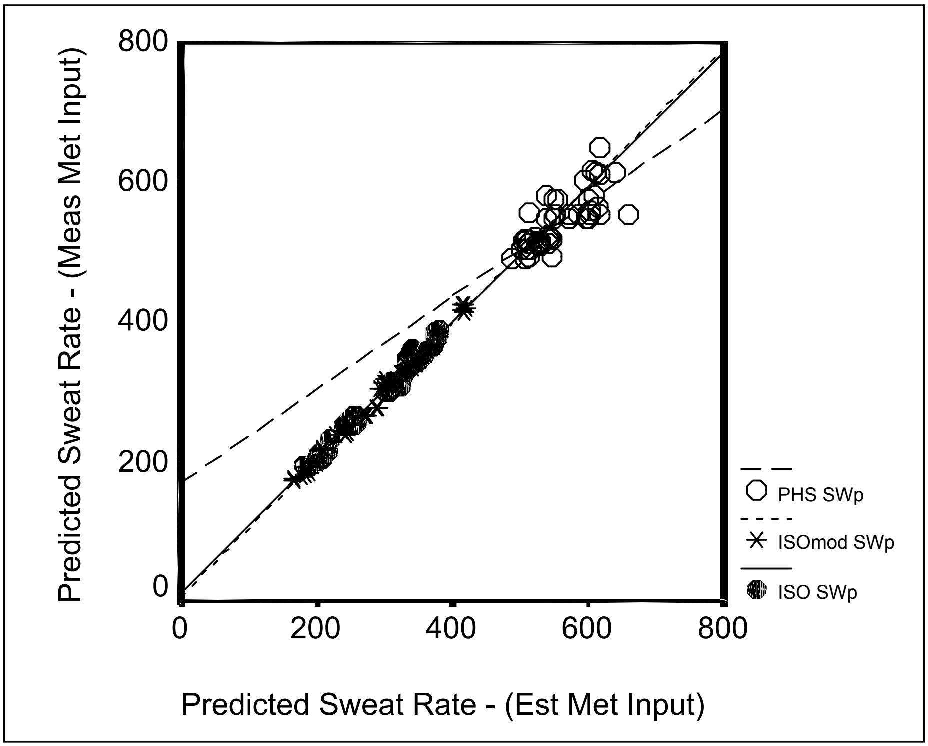


Figure 10: Scatter plot of Predicted Sweat Loss for Estimated and Measured Metabolic rate input values

There is a highly significant correlation ($p<0.001$) between each of the model's SW_p for both metabolic inputs with the ISO and ISO_{mod} producing r^2 values of 0.99. The PHS model shows a significant intra-SW_p difference between the two input results ($p<0.001$) and the mean difference is negative (-15.31) compared to that of the ISO models (1.45 and 1.22). This means that the PHS SW_p values from measured metabolic inputs are higher than those for estimated inputs. This is a shift from the ISO models where the estimated input produced higher SW_p values. Since the estimated metabolic rate inputs were greater than measured rates, this is an unexpected occurrence and suggests that the model is more sensitive to metabolic rate variations because the data is from paired experiments where the only difference in each pair was the metabolic rate input value. This can be seen in **Figure 10** where the PHS regression is not as steep as that for the ISO models, which have a regression equation that is almost on the line of origin. By observing the values of the differences, it can be seen that they are in tens of grams per hour, and although statistically significant, the actual differences are not important. Both input variable outputs however, will be compared with the observed data because both inputs were not available for all experiments.

Comparison of Duration Limited Exposure (DLE) predictions for estimated and measured metabolic rate inputs

The DLE predictions for both metabolic inputs for all three models are presented and evaluated. Only the Danger DLEs (t_{re}=38°C) are analysed. No comparisons between the PHS model and the ISO ALARM DLEs would be possible due to the PHS model only predicting for t_{re}=38°C, and the Alarm criteria (t_{re}=37.8°C) is not provided for.

Table 24: Descriptive statistics of predicted DLEs for both metabolic inputs for all experimental data

	N	MEAN	SD
ISO DLEs (Est Met)	63	40	13.7
ISO DLEs (Meas Met)	65	44	14.9
ISO_{mod} DLEs (Est Met)	63	40	12.8
ISO_{mod} DLEs (Meas Met)	51	39	14.5
PHS DLE (Est Met)	63	36	9.2
PHS DLE (Meas Met)	51	35	9.5
Valid N (listwise)	51		

Table 24 shows that the means within each model are very similar for both metabolic rate input variables. Interestingly, unlike in the analyses of the sweat rates, the PHS model appears to be less sensitive to variations both within each and between each metabolic rate input variable. The table shows all the data, and for an accurate comparison to be made, the paired data were analysed.

Table 25: Pair-wise descriptive statistics of SW_p for all three models and both metabolic inputs for all experimental data

	N	MEAN	SD
ISO DLEs (Est Met)	52	39	14.1
ISO DLEs (Meas Met)	52	40	13.1
ISO_{mod} DLEs (Est Met)	52	38	13.0
ISO_{mod} DLEs (Meas Met)	52	40	17.8
PHS DLE (Est Met)	51	35	8.8
PHS DLE (Meas Met)	51	35	9.5

The means for each model presented in **Table 25** are almost identical for both of the ISO models and are identical for the PHS models (rounded to the nearest unit). Here too the PHS DLEs are less sensitive to the variations in metabolic rate input variables, with SDs of 8.8 and 9.5 for estimated and measured inputs respectively. This was unexpected because the PHS SW_p were more susceptible to metabolic rate variation than the ISO models were. The ISO_{mod} DLEs however had a greater difference between the SDs for the two variables. This does not appear to be significant. The results were further analysed.

Table 26: Pearson Correlation Coefficients and Paired Analysis Comparisons of predicted DLEs for both metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r2	P	Mean	SD	SEM	95% CI of the Difference		Sig. (2-tailed)
							Lower	Upper	
ISO DLEs	52	0.77	0.00	-1.1	9.2	1.3	-3.6	1.5	0.41
ISO_{mod} DLEs	52	0.78	0.00	-2.2	11.1	1.5	-5.3	0.9	0.16
PHS DLE	51	0.89	0.00	-0.4	4.3	0.6	-1.6	0.8	0.52

Here too, as with sweat rate there is a correlation, although the r^2 values are slightly lower for the ISO models and higher for the PHS model. The mean differences are all low and negative with the 95% CI of the difference showing that the DLEs from the estimated input metabolic values tended to be higher than the measured metabolic input DLEs. The difference between the two ISO_{mod} DLEs also showed the greatest standard deviation, with the PHS showing the smallest deviation. The Paired Analysis shows that none of these differences is significant. This can be seen in the scatter plot in **Figure 11** which shows the smaller scatter of PHS predicted DLEs around their regression line than either of the ISO models.

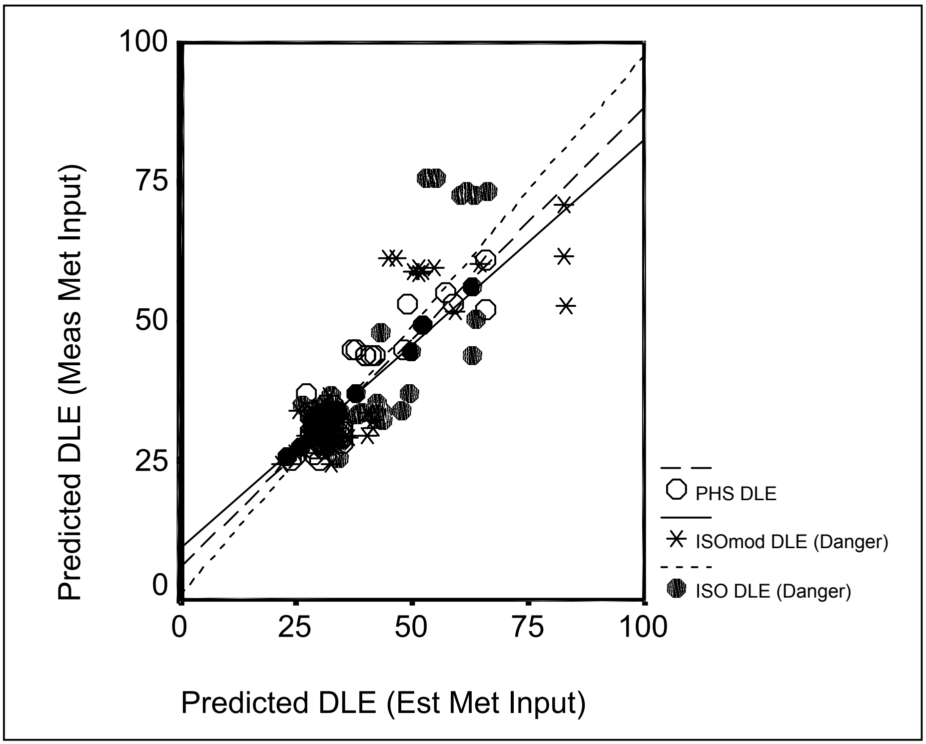


Figure 11: Scatter plot of Predicted DLEs for Estimated and Measured Metabolic rate input values

2.10.3 Comparison between ISO and PHS model sweat rate predictions and observed data

The results from each experiment and for all data combined, are presented in this section. Each experiment was analysed to identify if any of the experimental differences (such as clothing, work rate, partial vapour pressure, etc.) may have had a specific effect on the data. All the data were then combined for analysis so as to evaluate the validity of the models across a range of conditions.

The table cells shaded grey show those experiments where no data were available.

- **Experiment 1:** No measured metabolic rate data available.
- **Experiments 9 and 10**: No estimated metabolic rate data available. No ISO_{mod} data from either as the clo value was less than 0.6clo.

Sweat Rates – Descriptive Statistics for all experiments

Table 27: Table showing descriptive statistics of all predicted and observed sweat rates (gh^{-1}).

		Variable	ESTIMATED MET AS INPUT					MEASURED MET AS INPUT				
			N	Mean	SD	Min	Max	N	Mean	SD	Min	Max
Study 1	EXP1	ISO SWp	8	373	20.5	341	391	N/A	N/A	N/A	N/A	N/A
		ISOmod SWp	8	405	25.4	366	425	N/A	N/A	N/A	N/A	N/A
		PHS SWp	8	651	27.7	615	695	N/A	N/A	N/A	N/A	N/A
		Observed SW	8	832	136.7	626	1024	N/A	N/A	N/A	N/A	N/A
	EXP2	ISO SWp	8	377	11.8	351	388	7	370	12.9	346	380
		ISOmod SWp	8	414	13.8	382	426	7	408	14.7	378	418
		PHS SWp	8	617	13.6	602	649	6	614	14.7	596	640
		Observed SW	8	804	196.6	502	1110	7	802	212.3	502	1110
	EXP3	ISO SWp	8	229	34.4	191	265	8	225	34.4	181	259
		ISOmod SWp	8	213	36.9	174	251	8	210	36.6	166	247
		PHS SWp	8	507	22.0	489	555	8	516	16.5	488	546
		Observed SW	8	1133	539.6	542	*2265*	8	1133	539.6	542	*2265*
	EXP4	ISO SWp	8	225	19.6	197	251	8	221	19.5	194	257
		ISOmod SWp	8	210	21.6	179	238	8	206	21.1	177	243
		PHS SWp	8	512	7.6	503	522	8	520	18.1	502	542
		Observed SW	8	924	237.2	604	1280	8	924	237.2	604	1280
	EXP5	ISO SWp	8	355	4.8	348	362	8	344	10.0	333	364
		ISOmod SWp	8	311	4.6	305	318	8	303	8.1	293	319
		PHS SWp	8	516	4.6	509	521	8	529	11.5	511	545
		Observed SW	8	853	255.0	570	1315	8	853	255.0	570	1315
	EXP6	ISO SWp	7	302	5.1	298	308	6	311	9.9	303	325
		ISOmod SWp	7	270	5.6	266	278	6	278	9.2	270	290
		PHS SWp	7	578	1.8	576	580	5	570	31.8	538	609
		Observed SW	7	702	148.7	522	895	6	731	138.0	566	895
Study 2	EXP7	ISO SWp	8	343	18.0	314	365	7	343	22.0	310	372
		ISOmod SWp	8	337	17.9	310	359	7	337	19.9	306	364
		PHS SWp	8	554	6.2	547	566	7	590	37.2	539	659
		Observed SW	8	1116	220.0	897	1535	7	1123	236.8	897	1535
	EXP8	ISO SWp	8	343	13.6	320	366	8	348	15.0	326	372
		ISOmod SWp	8	338	14.8	315	365	8	342	16.0	320	371
		PHS SWp	8	552	6.0	547	566	8	592	26.3	550	618
		Observed SW	8	1081	333.6	694	1588	8	1081	333.6	694	1588
Study 3	EXP9	ISO SWp	N/A	N/A	N/A	N/A	N/A	8	289	32.8	256	357
		ISOmod SWp	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		PHS SWp	N/A	N/A	N/A	N/A	N/A	8	563	24.6	528	595
		Observed SW	N/A	N/A	N/A	N/A	N/A	8	578	137.8	427	790
	EXP10	ISO SWp	N/A	N/A	N/A	N/A	N/A	6	247	32.1	220	307
		ISOmod SWp	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		PHS SWp	N/A	N/A	N/A	N/A	N/A	6	577	23.8	546	603
		Observed SW	N/A	N/A	N/A	N/A	N/A	6	327	28.6	290	355

For details of experimental conditions, see **Table 28**.

Table 28: Mean experimental conditions for ten laboratory experiments

EXP	N	t_a °C	t_r °C	v ms^{-1}	Pa KPa	M Est Wm^{-2}	M Meas Wm^{-2}	Icl clo
1	8	34.9	35.1	0.22	3.40	193	-	0.8
2	8	35.0	34.4	0.28	3.30	177	158	0.8
3	8	39.5	39.2	0.07	4.50	173	161	0.8
4	8	39.7	39.3	0.08	4.50	153	142	0.8
5	8	45.0	44.9	0.08	3.80	153	134	0.8
6	7	44.7	43.8	0.09	3.90	87	101	0.8
7	8	40.1	38.7	0.15	3.72	177	190	0.82
8	8	40.0	38.7	0.15	3.73	177	190	0.81
9	8	37.2	36.6	0.17	4.45	-	138	0.5
10	6	37.2	36.6	0.17	4.45	-	115	0.6

Note: **Experiments 1 to 6** were a stepping task wearing a boiler suit.
Experiment 7 was a stepping task wearing a vapour impermeable suit.
Experiment 8 was a stepping task wearing a vapour impermeable suit.
Experiments 9 (males) and **10** (females) were a simulated tea leaf picking task.

The Sweat Rate descriptive statistics show that for each experiment, the ISO and ISO_{mod} predicted values were less than the PHS (SW_p) values, which in turn were less than the observed (SW_o) values.

From Experiment 3, the maximum SW_o value of 2265 g/h was identified as an outlier and will be removed from any further statistical analysis. The statistical analysis of data from each experiment and for both metabolic rate input variables is presented below. The experiments are coded into the 10 experiments (E1 to E10) and for both metabolic rates (-E and –M); for example, Experiment 1 with Est Met data is coded as E1-E.

Sweat Rates – Pearson Correlations and Paired Analysis Comparisons

Comparison of the predicted (SW$_p$) and observed (SW$_o$) sweat rates for the ISO model

Table 29: Pearson Correlation Coefficients and Paired Analysis Comparisons of ISO SW_p and SW_o for estimated metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r^2	p	Mean	SD	SEM	95% CI of the Difference Lower	Upper	Sig. (2-tailed)
E1-E	8	-0.48	0.22	-459.4	147.7	52.2	-582.9	-335.8	0.00
E2-E	8	0.10	0.82	-426.4	195.8	69.2	-590.1	-262.7	0.00
E3-E	7	0.51	0.24	-738.1	293.1	110.8	-1009.2	-467.1	0.00
E4-E	8	-0.69	0.06	-698.9	251.0	88.8	-908.7	-489.0	0.00
E5-E	8	-0.12	0.77	-498.0	255.6	90.4	-711.7	-284.3	0.00
E6-E	7	0.09	0.84	-399.5	148.3	56.1	-536.7	-262.3	0.00
E7-E	8	-0.26	0.53	-773.4	225.4	79.7	-961.9	-584.9	0.00
E8-E	8	-0.44	0.27	-737.9	339.8	120.1	-1022.0	-453.8	0.00
E9-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E10-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 30: Pearson Correlation Coefficients and Paired Analysis Comparisons of ISO SW_p and SW_o for measured metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r^2	p	Mean	SD	SEM	95% CI of the Difference Lower	Upper	Sig. (2-tailed)
E1-M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E2-M	7	0.33	0.48	-431.7	208.4	78.8	-624.5	-238.9	0.00
E3-M	7	0.55	0.20	-743.5	291.0	110.0	-1012.6	-474.3	0.00
E4-M	8	-0.44	0.28	-703.3	246.3	87.1	-909.2	-497.4	0.00
E5-M	8	0.18	0.67	-509.0	253.4	89.6	-720.9	-297.1	0.00
E6-M	6	0.63	0.18	-419.9	132.0	53.9	-558.4	-281.4	0.00
E7-M	7	-0.21	0.66	-779.3	242.3	91.6	-1003.4	-555.2	0.00
E8-M	8	-0.30	0.47	-732.8	338.4	119.6	-1015.7	-449.9	0.00
E9-M	8	-0.23	0.58	-288.3	148.8	52.6	-412.7	-163.9	0.00
E10-M	6	0.28	0.59	-79.9	36.6	15.0	-118.4	-41.5	0.00

No significant correlations are observed for either metabolic rate input. All paired comparisons show a significant difference between the predicted and observed values ($p<0.001$). All the mean differences are negative showing the observed data were greater than the predicted data. The observed mean values were all greater than the predicted mean values in every experiment except E9 and E10 (see **Table 27**)

Comparison of the predicted (SW$_p$) and observed (SW$_o$) sweat rates for the ISO$_{mod}$ model

Table 31: Pearson Correlation Coefficients and Paired Analysis Comparisons of ISO$_{mod}$ *SW*$_p$ and *SW*$_o$ for estimated metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r^2	p	Mean	SD	SEM	95% CI of the Difference Lower	Upper	Sig. (2-tailed)
E1-E	8	-0.48	0.23	-427.0	150.6	53.3	-552.9	-301.1	0.00
E2-E	8	0.15	0.73	-389.2	195.1	69.0	-552.3	-226.1	0.00
E3-E	7	0.51	0.24	-753.7	291.9	110.3	-1023.7	-483.8	0.00
E4-E	8	-0.69	0.06	-714.1	252.5	89.3	-925.2	-503.0	0.00
E5-E	8	-0.05	0.91	-541.4	255.3	90.2	-754.8	-328.0	0.00
E6-E	7	0.07	0.88	-431.2	148.4	56.1	-568.5	-294.0	0.00
E7-E	8	-0.21	0.62	-778.6	224.5	79.4	-966.2	-590.9	0.00
E8-E	8	-0.41	0.32	-743.0	339.9	120.2	-1027.1	-458.8	0.00
E9-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E10-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 32: Pearson Correlation Coefficients and Paired Analysis Comparisons of ISO$_{mod}$ *SW*$_p$ and *SW*$_o$ for measured metabolic inputs for all experimental data

				PAIRED DIFFERENCES					
	N	r^2	P	Mean	SD	SEM	95% CI of the Difference Lower	Upper	Sig. (2-tailed)
E1-M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E2-M	7	0.34	0.46	-394.4	207.8	78.5	-586.6	-202.2	0.00
E3-M	7	0.54	0.21	-757.9	290.5	109.8	-1026.6	-489.3	0.00
E4-M	8	-0.51	0.20	-717.7	248.6	87.9	-925.5	-509.8	0.00
E5-M	8	0.20	0.64	-550.1	253.5	89.6	-762.0	-338.1	0.00
E6-M	6	0.64	0.17	-453.7	132.3	54.0	-592.5	-314.8	0.00
E7-M	7	-0.17	0.72	-785.9	241.0	91.1	-1008.7	-563.1	0.00
E8-M	8	-0.31	0.46	-738.9	338.8	119.8	-1022.1	-455.6	0.00
E9-M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E10-M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Here too, no significant correlations are observed for either input metabolic rates and all paired comparisons show that a significant difference between the predicted and observed values was found ($p<0.001$). All the mean differences are negative showing the observed data were greater than the predicted data. The observed mean values were all greater than the predicted mean values in all experiments. The mean differences between *SW*$_p$ and *SW*$_o$ for all but the E8-E estimated metabolic rate input results are lower than the *SW*$_p$ results from measured metabolic rate inputs; thus reflecting the higher ISO *SW*$_p$ from higher metabolic rates.

Comparison of the predicted (SW_p) and observed (SW_o) sweat rates for the PHS model

Table 33: Pearson Correlation Coefficients and Paired Analysis Comparisons of PHS SW_p and SW_o for estimated metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r^2	P	Mean	SD	SEM	95% CI of the Difference		Sig. (2-tailed)
							Lower	Upper	
E1-E	8	-0.11	0.79	-181.6	142.5	50.4	-300.8	-62.4	0.01
E2-E	8	0.46	0.25	-186.5	190.7	67.4	-345.9	-27.0	0.03
E3-E	7	0.23	0.62	-461.4	304.9	115.2	-743.3	-179.4	0.01
E4-E	8	-0.60	0.11	-412.0	241.8	85.5	-614.2	-209.9	0.00
E5-E	8	0.48	0.23	-336.9	252.9	89.4	-548.3	-125.5	0.01
E6-E	7	0.16	0.74	-123.6	148.4	56.1	-260.9	13.6	0.07
E7-E	8	0.01	0.98	-562.1	220.0	77.8	-746.1	-378.2	0.00
E8-E	8	-0.27	0.52	-528.3	335.3	118.5	-808.6	-248.0	0.00
E9-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E10-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 34: Pearson Correlation Coefficients and Paired Analysis Comparisons of PHS SW_p and SW_o for measured metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r^2	P	Mean	SD	SEM	95% CI of the Difference		Sig. (2-tailed)
							Lower	Upper	
E1-M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E2-M	6	0.64	0.17	-212.2	212.3	86.7	-434.9	10.6	0.06
E3-M	7	0.26	0.57	-451.3	306.1	115.7	-734.4	-168.1	0.01
E4-M	8	-0.88	0.00	-403.7	253.2	89.5	-615.3	-192.0	0.00
E5-M	8	-0.04	0.93	-323.4	255.7	90.4	-537.2	-109.6	0.01
E6-M	5	0.77	0.13	-168.7	130.2	58.2	-330.4	-7.0	0.04
E7-M	7	-0.07	0.88	-532.7	242.4	91.6	-756.9	-308.5	0.00
E8-M	8	0.47	0.24	-488.8	322.1	113.9	-758.1	-219.5	0.00
E9-M	8	-0.13	0.75	-14.6	143.2	50.6	-134.3	105.1	0.78
E10-M	6	0.12	0.82	249.9	35.0	14.3	213.2	286.7	0.00

The PHS model mean sweat rate was closer to the mean of SW_o than the predictions of the other two models. Although as can be seen from the SD of the mean difference the scatter around the mean was comparable in magnitude to that of both the ISO models. However, the CIs are narrower due to the higher PHS SW_p values. Only one data set, E4-M provided a significant correlation ($p<0.001$) between SW_p and SW_o, but a significant difference between them ($p<0.001$) was found. This suggests that although the relationship was linear the scatter around the mean was too great for the correlation to be valid. In all but 3 experiments [E6-E ($p<0.07$), E2-M ($p<0.06$) and E9-M($p<0.78$)] the differences were significant. Added to this, the mean difference for E9-M (-14.6) was the lowest of any of the SW_p for any of the experiments, although the standard deviation of the difference was higher than that observed in E10-M, where the SD was only 35.

Comparison of the predicted (SW$_p$) and observed (SW$_o$) sweat rates over all experiments and for all models

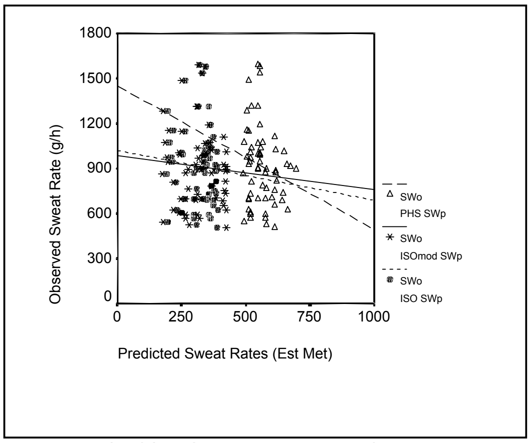
Table 35: Pearson Correlation Coefficients and Paired Analysis Comparisons of all *SW*$_p$ and *SW*$_o$ for both measured metabolic inputs

PAIRED SAMPLES CORRELATIONS				**PAIRED DIFFERENCES**					
Comparison of SW$_p$ vs SW$_o$	**N**	**r^2**	**P**	**Mean**	**SD**	**SEM**	**95% CI of the Difference Lower**	**Upper**	**Sig. (2-tailed)**
ISO (Est Met)	62	-0.07	0.56	-592.2	271.5	34.5	-661.1	-523.2	0.00
ISO$_{mod}$ (Est Met)	62	-0.06	0.62	-597.4	275.9	35.0	-667.5	-527.4	0.00
PHS (Est Met)	62	-0.19	0.15	-350.9	274.7	34.9	-420.6	-281.1	0.00
ISO (Meas Met)	65	0.20	0.11	-531.5	311.1	38.6	-608.6	-454.4	0.00
ISO$_{mod}$ (Meas Met)	51	0.03	0.85	-634.2	281.2	39.4	-713.3	-555.1	0.00
PHS (Meas Met)	63	0.02	0.90	-275.4	322.9	40.7	-356.7	-194.0	0.00

Any cross comparison between data sets of different sample sizes is difficult as the size of the data set may have a bearing on the results. However, where large differences are observed (such as the ISO$_{mod}$ *SW*$_p$ (Meas Met) and *SW*$_o$ (N=51)), possible explanations for the differences will be provided in the discussion section. The differences between data sets may be due to the type of data that were excluded.

No linear relationships, and therefore correlations, were found between any of the predicted sweat rates and the observed sweat rates. It is interesting to note that the estimated metabolic inputs provided negative relationships with the observed data, while the measured metabolic rate inputs resulted in a positive relationship. This can be seen in the scatter plots below (**Figure 12** and **Figure 13**). All sets of data had significant differences between *SW*$_p$ and *SW*$_o$ ($p<0.001$). The greater variability in measured metabolic input *SW*$_p$ suggests that the *SW*$_p$ in both models was sensitive to changes in metabolic rate. Another consideration is that the lower clothing insulation values in E9 and E10 coupled with the lowest sweat rates provided by the females in experiment 10 probably had an effect on the overall results, hence individual experiments were also analysed.

Neither model allowed for the difference in the vapour permeability between the ensembles in E7 and E8 to be considered.



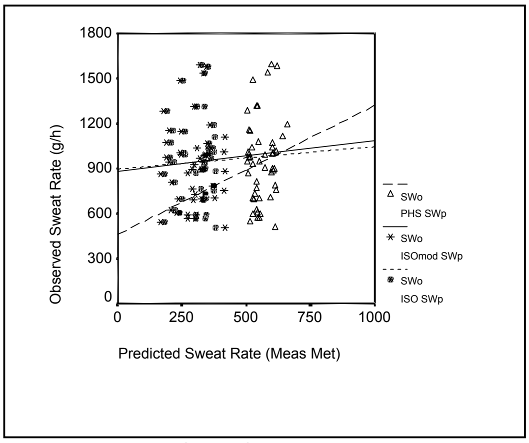


Figure 12 (left): Scatter plots of observed sweat rates with SW_p from estimated metabolic rate inputs

Figure 13 (right): Scatter plots of observed sweat rates with SW_p from measured metabolic rate inputs

2.10.4 Comparison between ISO and PHS model DLE predictions and observed data

The table cells shaded grey show those experiments where no data were available.

It is important to remember that the ISO models predict a Danger DLE to protect most of the workers, while the PHS predicts the mean response. Therefore, although statistical analysis (correlation and paired sample *t*-test) has been conducted on the means of data, this is not appropriate for a direct comparison between observed DLEs and the predicted DLEs from the two ISO models. However the analysis has been conducted on the means to obtain a statistical measure of their relationship because the relationship would be linear (although significantly different) between the parameters if the ISO models were providing valid predictions. A direct comparison between the predictions from the PHS model and the observed data is valid as the PHS is attempting to predict the mean time for core temperature (t_{co}) to reach 38°C.

DLE - Descriptive Statistics for all experiments

Table 36: Table showing descriptive statistics of all predicted and observed DLEs (mins). (Note: Experimental conditions for all experiments are shown in Table 25a.)

		Variable	**ESTIMATED MET AS INPUT**					**MEASURED MET AS INPUT**				
			N	**MEAN**	**SD**	**MIN**	**MAX**	**N**	**MEAN**	**SD**	**MIN**	**MAX**
Study 1	**EXP1**	**ISO DLE**	8	39	2	36	44	N/A	N/A	N/A	N/A	N/A
		ISO_{mod} DLE	8	45	4	41	52	N/A	N/A	N/A	N/A	N/A
		Observed DLE	2	57	14	47	67	N/A	N/A	N/A	N/A	N/A
		PHS DLE	8	43	4	37	48	N/A	N/A	N/A	N/A	N/A
	EXP2	**ISO DLE**	8	49	4	44	56	8	49	4	44	56
		ISO_{mod} DLE	8	59	6	52	71	8	59	6	52	71
		Observed DLE	1	73	.	73	73	1	73	.	73	73
		PHS DLE	8	54	5	45	61	8	54	5	45	61
	EXP3	**ISO DLE**	8	28	2	25	31	8	31	4	23	35
		ISO_{mod} DLE	8	27	2	24	29	8	29	4	22	34
		Observed DLE	8	39	9	29	56	8	39	9	29	56
		PHS DLE	8	28	4	25	37	8	28	3	24	31
	EXP4	**ISO DLE**	8	32	2	30	35	8	36	6	30	44
		ISO_{mod} DLE	8	31	2	28	34	8	34	6	28	42
		Observed DLE	7	43	9	36	60	7	43	9	36	60
		PHS DLE	8	29	1	28	31	8	32	3	28	35
	EXP5	**ISO DLE**	8	34	2	33	37	8	41	6	32	50
		ISO_{mod} DLE	8	30	1	29	32	8	35	4	28	42
		Observed DLE	8	42	14	25	68	8	42	14	25	68
		PHS DLE	8	29	1	28	30	8	32	2	28	35
	EXP6	**ISO DLE**	7	75	2	73	78	6	60	5	53	66
		ISO_{mod} DLE	7	60	2	59	63	6	50	4	45	55
		Observed DLE	6	51	15	31	75	5	46	10	31	59
		PHS DLE	7	44	1	44	45	6	39	2	37	42
Study 2	**EXP7**	**ISO DLE**	8	34	1	32	36	8	31	3	26	35
		ISO_{mod} DLE	8	33	1	32	36	8	30	3	25	35
		Observed DLE	8	29	6	23	38	8	29	6	23	38
		PHS DLE	8	33	1	32	35	8	31	2	28	33
	EXP8	**ISO DLE**	8	34	1	33	37	8	31	2	28	34
		ISO_{mod} DLE	8	33	1	32	36	8	30	2	28	34
		Observed DLE	8	36	8	28	51	8	36	8	28	51
		PHS DLE	8	33	1	32	35	8	31	2	29	33
Study 3	**EXP9**	**ISO DLE**	N/A	N/A	N/A	N/A	N/A	8	54	12	37	71
		ISO_{mod} DLE	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Observed DLE	N/A	N/A	N/A	N/A	N/A	6	88	21	48	106
		PHS DLE	N/A	N/A	N/A	N/A	N/A	8	41	6	32	49
	EXP10	**ISO DLE**	N/A	N/A	N/A	N/A	N/A	6	66	18	45	90
		ISO_{mod} DLE	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
		Observed DLE	N/A	N/A	N/A	N/A	N/A	2	85	15	74	95
		PHS DLE	N/A	N/A	N/A	N/A	N/A	6	45	8	36	54

In Experiments 1 and 2, only two and one (respectively) of the eight subjects reached a limiting criteria of t_{co} = 38°C, yet both models predicted DLEs less than the maximum experimental time of 75mins. In Experiments 3 and 5, where the partial vapour pressure was high, the difference between the predicted and observed DLEs decreased. The low metabolic rates (100 ± 7 $W.m^{-2}$) in

Experiment 6 reversed the predictive trend of the previous experiments (1 to 5) by over predicting the time for t_{co} to reach 38°C.

In E7 and E8, there is a polar shift from a mean observed DLE of 29 mins to 36 mins respectively. The reason for this is probably due to the greater vapour permeability of the Cyclone suits worn in Experiment 8. (Data not included in this report showed that the cyclone suit allowed about 25% more sweat to evaporate then the PU suit in Experiment 7.) This is supported by the lower mean and minimum SW_o values in E8 (See **Table 27**on **Page 65**) which suggests that the subjects in E8 were experiencing less thermal stress than the subjects in E7 due to the clothing even though the experimental conditions were almost identical.

In E9 and E10 the observed DLEs are again longer than predicted DLEs, with only two out of six subjects reaching withdrawal criteria in E10. Interestingly, the mean ISO DLEs are for longer than the PHS and are closer to the observed data than the PHS DLEs are. Another point to note is that the combination of a higher clo value (0.6clo) and the lower measured metabolic rate input values (115 $W.m^{-2}$) for the female subjects in E10 does not appear to result in as large a proportional change in the PHS model as in the ISO model when compared to the predictions for the males in E10. This is also reflected in the higher ISO mean SW_p for E9 and conversely the PHS mean SW_p is higher in E10. This confirms that the ISO SW_p is more sensitive to metabolic rate changes (Kähkönen, 1993) than is the PHS SW_p and that the PHS SW_p is more sensitive to clothing insulation changes. Neither model though allowed for the inter-gender differences between males and females in heat stress conditions.

It is here that the difference in philosophy between the two models requires that different statistical analysis be carried out on each. The ISO models' DANGER criteria, predict a level "*at which certain subjects, although physically suited to the activity under consideration and in good heath, could already be at risk.*" This definition is somewhat vague (Kampmann *et al.*, 1995) and the number or percentage of people that are protected by the DANGER criteria is not defined. Therefore, an estimated limit of 95% of people in a normal distribution has been placed on the accuracy of the ISO danger DLE predictions for the number of people that may be protected. This is based on the presumption that the ISO predicted mean DLE would protect those people who would fall within two observed standard deviations of the observed DLE. This will provide a measure of the face validity of the model (i.e. the model is doing what it says it does).

The PHS model has been included in this analysis, with the expected result showing that around 50% of the population would be protected if the PHS DLE prediction is valid. The analysis performed was a normal cumulative distribution for the specified observed mean and observed standard deviation to obtain the cumulative distribution function (Predicted %tile) of the predicted DLE. This provided the "Protected %tile" by subtracting it from 100%.

Percentile Analysis of ISO and PHS predicted DLEs and Observed DLEs.

Table 37: Validity of ISO and PHS predicted DLEs for population percentile protected, based on a comparison of means (Estimated metabolic rate inputs)

		VARIABLE	**ESTIMATED MET AS INPUT**				
			Predicted mean DLE	**Observed mean DLE**	**Observed SD**	**Predicted %tile**	**Protected %tile**
Study 1		**ISO DLE**	28	39	9	11.1	**88.9**
	EXP3	**ISO$_{mod}$ DLE**	27	39	9	9.1	**90.9**
		PHS DLE	28	39	9	11.1	**88.9**
		ISO DLE	32	43	9	11.1	**88.9**
	EXP4	**ISO$_{mod}$ DLE**	31	43	9	9.1	**90.9**
		PHS DLE	29	43	9	6.0	**94.0**
		ISO DLE	34	42	14	28.4	**71.6**
	EXP5	**ISO$_{mod}$ DLE**	30	42	14	19.6	**80.4**
		PHS DLE	29	42	14	17.7	**82.3**
		ISO DLE	75	51	15	94.5	**5.5**
	EXP6	**ISO$_{mod}$ DLE**	60	51	15	72.6	**27.4**
		PHS DLE	44	51	15	32.0	**68.0**
Study 2		**ISO DLE**	34	29	6	79.8	**20.2**
	EXP7	**ISO$_{mod}$ DLE**	33	29	6	74.8	**25.2**
		PHS DLE	33	29	6	74.8	**25.2**
		ISO DLE	34	36	8	40.1	**59.9**
	EXP8	**ISO$_{mod}$ DLE**	33	36	8	35.4	**64.6**
		PHS DLE	33	36	8	35.4	**64.6**

The analysis presented in **Table 37** shows that there is a wide variation in the population percentile protected by the ISO models' and the PHS model's predictions when estimated metabolic rate is the input. The target for the ISO models is 95%, while that for the PHS is 50%.

The results from Experiments 1 and 2 are not included because only two and one subject respectively reached a core temperature of 38°C. No estimated metabolic rate data were available for Experiments 9 and 10.

Neither of the ISO models reaches the 95% criteria, although the ISO$_{mod}$ provides a better percentile estimate than the ISO model across all experiments. The best results were achieved in E3 and E4 with the ISO$_{mod}$ predicting for an estimated 88.9%, for both inputs. In Experiment 6, the ISO DLEs would only have protected 5.5% of the population, while the ISO$_{mod}$ predicted for 27.4%.

The PHS model however, more closely followed the ISO and ISO$_{mod}$ percentiles than it did the 50% criteria in all experiments apart from E6. Again, this appears to support the theory, developed in the analysis of the sweat rate data, that the PHS model is more sensitive to metabolic rate variations when predicting *SW*p than DLE.

The measured metabolic rate input data was also analysed.

Table 38: Validity of ISO and PHS predicted DLEs for population percentile protected, based on a comparison of means (Measured metabolic rate inputs)

			MEASURED MET AS INPUT				
		VARIABLE	**Predicted mean DLE**	**Observed mean DLE**	**Observed SD**	**Predicted %tile**	**Protected %tile**
Study 1	**EXP3**	**ISO DLE**	31	39	9	18.7	**81.3**
		ISO_{mod} DLE	29	39	9	13.3	**86.7**
		PHS DLE	28	39	9	11.1	**88.9**
	EXP4	**ISO DLE**	36	43	9	21.8	**78.2**
		ISO_{mod} DLE	34	43	9	15.9	**84.1**
		PHS DLE	32	43	9	11.1	**88.9**
	EXP5	**ISO DLE**	41	42	14	47.2	**52.8**
		ISO_{mod} DLE	35	42	14	30.9	**69.1**
		PHS DLE	32	42	14	23.8	**76.2**
	EXP6	**ISO DLE**	60	46	10	91.9	**8.1**
		ISO_{mod} DLE	50	46	10	65.5	**34.5**
		PHS DLE	39	46	10	24.2	**75.8**
Study 2	**EXP7**	**ISO DLE**	31	29	6	63.1	**36.9**
		ISO_{mod} DLE	30	29	6	56.6	**43.4**
		PHS DLE	31	29	6	63.1	**36.9**
	EXP8	**ISO DLE**	31	36	8	26.6	**73.4**
		ISO_{mod} DLE	30	36	8	22.7	**77.3**
		PHS DLE	31	36	8	26.6	**73.4**
Study3	**EXP9**	**ISO DLE**	54	88	21	5.3	**94.7***
		ISO_{mod} DLE	N/A	N/A	N/A	N/A	**N/A**
		PHS DLE	41	88	21	1.3	**98.7***

***only 6 subjects reached tco=38°C in E9. Data must be treated with caution.**

Table 35 presents the data for predicted values when measured metabolic rate was the input. Again, the data for E1 and E2 are not presented. Data for E9 have been included, although these findings must be treated with caution as two subjects reached t_{co}=36°C. The findings of **Table 37** are similar, with the ISO_{mod} protecting the greater population percentile than the ISO model. In all experiments, ISO_{mod} again provided the best percentile protection when compared to the ISO model. Here too the PHS model would have protected more than 50% of the population and provided predictions closer to the ISO models than the 50% target in all experiments, except E6.

DLE - Pearson correlations and Paired Analysis Comparisons

The analysis of the percentile protected by the ISO, ISO_{mod} , and PHS models showed that they were not meeting the requirement of "face validity"; they were not doing what they said they could do. The next stage of analysis was concerned with evaluating the relationship between the observed and predicted values. This analysis is specifically for the PHS model because it is supposed to be predicting the mean t_{co}=38°C and therefore the mean DLE. The ISO models have been included in this analysis to allow for their relationship with observed DLEs to be further investigated. The analysis for each model is presented in turn.

ISO DLEs and Observed DLEs

Table 39: Pearson Correlation Coefficients and Paired Analysis Comparisons of ISO DLEs and observed DLEs for estimated metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r^2	p	Mean	SD	SEM	95% CI of the Difference Lower	Upper	Sig. (2-tailed)
E1-E	2	-	-	-	-	-	-	-	-
E2-E	1	-	-	-	-	-	-	-	-
E3-E	8	-0.14	0.75	-12	9.8	3.5	-19.8	-3.4	0.01
E4-E	7	-0.32	0.48	-11	9.5	3.6	-20.1	-2.5	0.02
E5-E	8	0.51	0.19	-7	13.4	4.8	-18.4	4.0	0.17
E6-E	6	0.70	0.12	24	13.4	5.5	10.0	38.2	0.01
E7-E	8	0.25	0.55	5	5.7	2.0	0.3	9.8	0.04
E8-E	8	0.47	0.24	-1	7.1	2.5	-7.4	4.5	0.58
E9-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E10-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 40: Pearson Correlation Coefficients and Paired Analysis Comparisons of ISO DLEs and observed DLEs for measured metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r^2	p	Mean	SD	SEM	95% CI of the Difference Lower	Upper	SIG. (2-TAILED)
E1-M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E2-M	1	-	-	-	-	-	-	-	-
E3-M	8	0.44	0.28	-9	8.5	3.0	-15.8	-1.6	0.02
E4-M	7	0.60	0.16	-8	7.1	2.7	-14.7	-1.5	0.02
E5-M	8	0.59	0.12	-1	11.8	4.2	-10.5	9.3	0.89
E6-M	5	0.02	0.98	13	10.8	4.8	-0.5	26.4	0.06
E7-M	7	0.01	0.99	3	6.5	2.5	-2.8	9.2	0.24
E8-M	8	0.63	0.09	-5	6.5	2.3	-10.2	0.7	0.08
E9-M	6	0.28	0.59	-39	20.3	8.3	-60.1	-17.5	0.01
E10-M	2	-	-	-	-	-	-	-	-

No linear relationships were observed between the means of the data with significant differences between the means being observed for all but five conditions; E5-E and E5-M, E6-M, E7-M, E8-E and E8-M.

ISO$_{mod}$ DLE: Observed DLE

Table 41: Pearson Correlation Coefficients and Paired Analysis Comparisons of ISO$_{mod}$ DLEs and observed DLEs for estimated metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r^2	p	Mean	SD	SEM	95% CI of the Difference		SIG. (2-TAILED)
							Lower	Upper	
E1-E	2	-	-	-	-	-	-	-	-
E2-E	1	-	-	-	-	-	-	-	-
E3-E	8	-0.14	0.75	-12	9.8	3.5	-19.8	-3.4	0.01
E4-E	7	-0.30	0.51	-13	9.5	3.6	-21.5	-4.0	0.01
E5-E	8	0.51	0.19	-12	13.6	4.8	-23.0	-0.2	0.05
E6-E	6	0.73	0.10	10	13.7	5.6	-4.5	24.2	0.14
E7-E	8	0.38	0.35	4	5.5	1.9	-0.1	9.0	0.05
E8-E	8	0.53	0.17	-2	7.0	2.5	-7.8	3.8	0.44
E9-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E10-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 42: Pearson Correlation Coefficients and Paired Analysis Comparisons of ISO$_{mod}$ DLEs and observed DLEs for measured metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r^2	p	Mean	SD	SEM	95% CI of the Difference		SIG. (2-TAILED)
							Lower	Upper	
E1-M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E2-M	1	-	-	-	-	-	-	-	-
E3-M	8	0.43	0.29	-10	8.5	3.0	-17.1	-2.9	0.01
E4-M	7	0.58	0.17	-10	7.2	2.7	-16.4	-3.1	0.01
E5-M	8	0.58	0.13	-6	12.2	4.3	-16.6	3.8	0.18
E6-M	5	0.04	0.95	3	10.3	4.6	-9.6	16.1	0.52
E7-M	7	0.05	0.91	3	6.4	2.4	-3.4	8.6	0.33
E8-M	8	0.68	0.07	-5	6.4	2.3	-10.6	0.0	0.05
E9-M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E10-M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

The ISO$_{mod}$ results were similar to the ISO results with no linear relationships observed between the means of the data. Significant differences between the observed mean and ISO$_{mod}$ means were observed in fewer conditions. This is not important to these findings as the ISO$_{mod}$ and the ISO are predicting mean values.

PHS DLE Observed DLE

Table 43: Pearson Correlation Coefficients and Paired Analysis Comparisons of PHS SWp and SWo for measured metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				**PAIRED DIFFERENCES**					
	N	**r^2**	**p**	**Mean**	**SD**	**SEM**	**95% CI of the Difference Lower**	**Upper**	**Sig. (2-tailed)**
E1-E	2	-	-	-	-	-	-	-	-
E2-E	1	-	-	-	-	-	-	-	-
E3-E	8	-0.33	0.42	-12	11.3	4.0	-21.3	-2.4	0.02
E4-E	7	-0.30	0.51	-14	9.2	3.5	-22.6	-5.6	0.01
E5-E	8	0.62	0.10	-13	13.8	4.9	-24.1	-1.1	0.04
E6-E	6	0.42	0.41	-6	14.7	6.0	-21.6	9.2	0.35
E7-E	8	0.46	0.26	4	5.5	1.9	-0.6	8.6	0.08
E8-E	8	0.58	0.13	-3	7.1	2.5	-8.7	3.2	0.31
E9-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E10-E	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 44: Pearson Correlation Coefficients and Paired Analysis Comparisons of PHS SWp and SWo for measured metabolic inputs for all experimental data

PAIRED SAMPLES CORRELATIONS				**PAIRED DIFFERENCES**					
	N	**r^2**	**p**	**Mean**	**SD**	**SEM**	**95% CI of the Difference Lower**	**Upper**	**Sig. (2-tailed)**
E1-M	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
E2-M	1	-	-	-	-	-	-	-	-
E3-M	8	0.36	0.38	-11	8.8	3.1	-18.5	-3.8	0.01
E4-M	7	0.23	0.62	-12	8.7	3.3	-19.8	-3.7	0.01
E5-M	8	0.55	0.16	-10	13.1	4.6	-20.8	1.0	0.07
E6-M	5	-0.10	0.87	-7	10.3	4.6	-19.3	6.1	0.22
E7-M	7	0.12	0.81	3	6.0	2.3	-3.0	8.1	0.30
E8-M	8	0.66	0.08	-5	6.7	2.4	-10.1	1.1	0.10
E9-M	6	0.38	0.46	-50	19.6	8.0	-70.4	-29.3	0.00
E10-M	2	-	-	-	-	-	-	-	-

No significant correlations were found between the PHS predicted DLEs and the observed DLEs in any of the experiments for both metabolic rate input values. Negative linear relationships were reported in E3-E, E4-E and E6-M.

All predicted DLEs and observed DLEs data combined

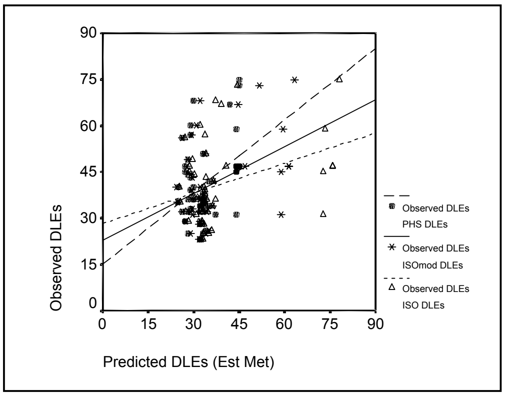
All data were combined and analysed using Pearson correlation and the paired sample *t*-test on pairwise data.

Table 45: Pearson Correlation Coefficients and Paired Analysis Comparisons of all predicted DLEs and observed DLEs for both measured metabolic inputs

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	**r^2**	**P**	**Mean**	**SD**	**SEM**	**95% CI of the Difference**		**Sig. (2-tailed)**
							Lower	**Upper**	
ISO DLEs (Est Met) & Observed DLEs	48	0.36	0.01	-2.5	15.6	2.2	-7.0	2.0	0.3
ISOmod DLEs (Est Met) & Observed DLEs	48	0.42	0.00	-5.2	13.0	1.9	-9.0	-1.4	0.0
PHS DLE (Est Met) & Observed DLEs	48	0.36	0.01	-7.9	12.2	1.8	-11.4	-4.3	0.0
ISO DLEs (Meas Met) & Observed DLEs	52	0.57	0.00	-7.9	17.8	2.5	-12.9	-3.0	0.0
ISOmod DLEs (Meas Met) & Observed DLEs)	44	0.58	0.00	-5.0	9.7	1.5	-8.0	-2.1	0.0
PHS DLE (Meas Met) & Observed DLEs	52	0.61	0.00	-13.8	19.0	2.6	-19.1	-8.5	0.0

Table 45 shows that when all data were combined, that the Pearson correlation provided a significant correlation for all combinations of predicted data with the observed data. The correlations for the predicted data obtained from measured metabolic rate inputs were stronger than those from the estimated metabolic rate inputs. Since the data from the individual experiments showed no correlations, this result is probably due to the power of the sample size (as seen by the low correlation coefficients). All the comparisons also provided significant differences between the means. Due to the larger SD in the measured metabolic rate predictions (due to the larger SD in measured metabolic rates) there is a greater mean difference between measured metabolic input predictions than those from estimated metabolic inputs for the ISO and the PHS models. This is not reflected in the ISO_{mod} results, which provides for a similar mean difference between the input variables.

The nature of these linear relationships can be seen in the scatter plots in **Figure 14** and **Figure 15** below.



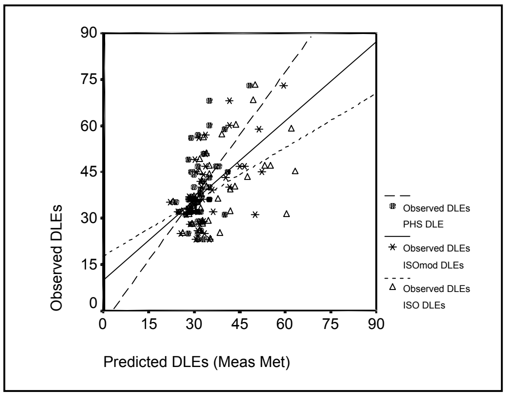


Figure 14 (left): Scatter plots of observed DLEs with predicted DLEs from estimated metabolic rate inputs

Figure 15 (right): Scatter plots of observed DLEs with predicted DLEs from measured metabolic rate inputs

2.10.5 Comparison between models

Since the predictions from the models have been shown to be similar, a comparison of model predictions was made. Although they are essentially predicting different percentile criteria, it was decided to compare the means of both the *SW*p and the DLEs.

Results of Sweat Rates – Predicted vs Predicted

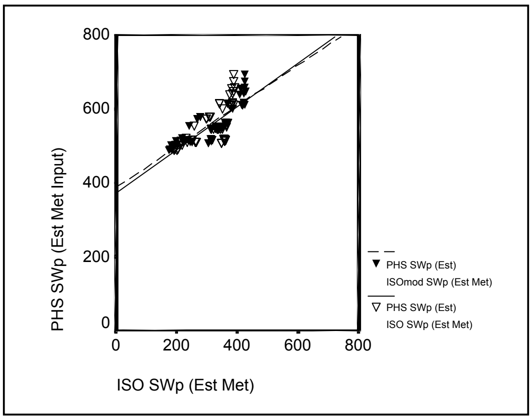
Pearson Correlations and Paired Analysis Comparisons

ISO SW*p and PHS* SW*p*

Table 46: Pearson Correlation Coefficients and Paired Analysis Comparisons of all predicted *SW*p for both measured metabolic inputs

Paired Samples Correlations				**Paired Differences**					
	N	**r^2**	**P**	**Mean**	**SD**	**SEM**	**95% CI of the Difference Lower**	**Upper**	**Sig. (2-tailed)**
ISO *SW*p (E) & PHS *SW*p (E)	63	0.69	0.00	-242.1	44.6	5.6	-253.3	-230.8	0.00
ISO$_{mod}$ *SW*p (E) & PHS *SW*p (E)	63	0.82	0.00	-247.5	44.9	5.7	-258.8	-236.2	0.00
ISO *SW*p (M) & PHS *SW*p (M)	64	0.61	0.00	-262.5	47.0	5.9	-274.3	-250.8	0.00
ISO$_{mod}$ *SW*p (M) & PHS *SW*p (M)	50	0.80	0.00	-264.7	45.2	6.4	-277.6	-251.9	0.00

The ISO_{mod} *SW*p had a stronger linear relationship with the PHS model than the ISO *SW*p did, although both ISO models showed significant correlations ($p < 0.001$) for both metabolic rate inputs. Interestingly, all paired differences were significant, although the mean differences were almost identical. This difference between the ISO and ISO_{mod} when compared to the PHS *SW*p, is a matter of grams and therefore it can be argued that there was no significant difference between the predictions of the ISO and ISO_{mod} models. The PHS *SW*p values were always higher than the corresponding ISO and ISO_{mod} *SW*p. **Figure 16** and **Figure 17** show the scatter plots of these relationships.



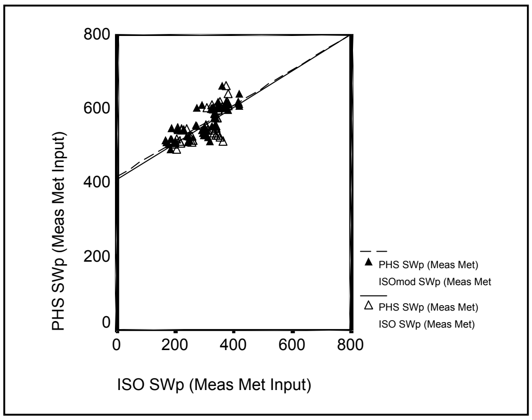


Figure 16 (left): Scatter plots of observed sweat rates with predicted sweat rates from estimated met inputs

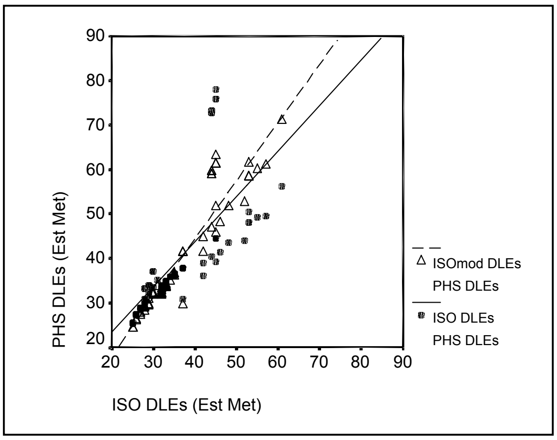
Figure 17 (right): Scatter plots of observed sweat rates with predicted sweat rates from measured met inputs

ISO DLE and PHS DLE

Table 47: Pearson Correlation Coefficients and Paired Analysis Comparisons of all predicted DLEs for both measured metabolic inputs

PAIRED SAMPLES CORRELATIONS				PAIRED DIFFERENCES					
	N	r2	P	Mean	SD	SEM	95% CI of the Difference		Sig. (2-tailed)
							Lower	Upper	
ISO DLE (E) & PHS DLE (E)	63	0.68	0.00	3.7	10.0	1.3	1.2	6.2	0.00
ISO_{mod} DLE (E)& PHS DLE (E)	63	0.94	0.00	3.2	5.1	0.6	1.9	4.5	0.00
ISO DLE (M)& PHS DLE (M)	65	0.83	0.00	7.2	8.9	1.1	5.0	9.4	0.00
ISO_{mod} DLE (M) & PHS DLE (M)	51	0.97	0.00	3.7	5.7	0.8	2.1	5.3	0.00

Here too both ISO models provide significant correlations with the PHS model, with the ISO_{mod} DLE providing the strongest linear relationship. All pairs however are significantly different, with the SD of the difference being greater than the mean of the difference. This shows a large scatter around the mean difference, which is not surprising considering that data from a number of environment conditions, metabolic rate rates and clothing ensembles were investigated. Again, considering the difference in philosophy of the two models, the mean difference would be expected to be larger than it is. This is illustrated in the scatter plots in **Figure 18**and **Figure 19** below.



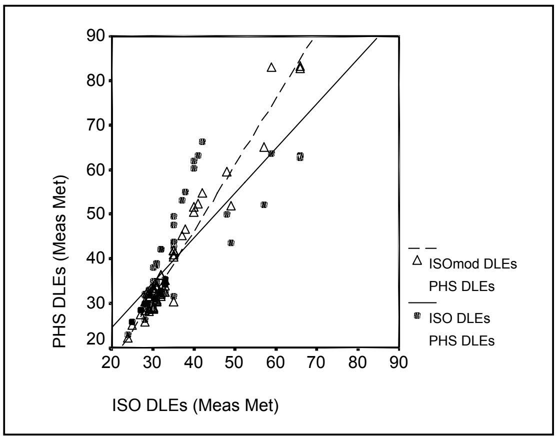


Figure 18 (left): Scatter plots of ISO DLEs with PHS DLEs from estimated metabolic rate inputs

Figure 19 (right): Scatter plots of ISO DLEs with PHS DLEs from measured metabolic rate inputs

2.11 DISCUSSION

As described in the literature survey, concern has been expressed that ISO 7933 in its current state is not a valid heat stress index for predicting human responses in warm, humid environments or when clothing is worn. The purpose of this experiment was to investigate these claims by validating two of the interpretations made by the model in ISO 7933: Duration Limit Exposures (DLEs) and the predicted sweat rate (SW_p). The findings showed that there was little or no correlation between the predicted measured *something?* (irrespective of whether the metabolic rate input was estimated or predicted).

The following hypotheses are rejected:

ISO and ISO$_{\mathbf{mod}}$

- **H$_{0(1)}$**: ISO 7933 is a valid predictor of the physiological responses of clothed subjects in warm humid environments.

PHS

- **H$_{0\ (2)}$**: PHS is a valid predictor of the physiological responses of clothed subjects in warm humid environments.

PHS and ISO models

- **SWEAT RATE** We can reject the null hypothesis **H$_{0(3)}$**: PHS is not a better predictor of the physiological responses of clothed subjects in warm humid environments than ISO 7933.
- **DLES –** We cannot reject the above null hypothesis. PHS is not a better predictor of DLEs when compared to the ISO models.

The SW_{req} index's calculations are based on the assumption that the whole population may be exposed to the environment, and as such it is claimed that it protects the person who is most heat intolerant. Therefore, a weakness of any study may be that subjects are not representative of the overall worker population. However, since only subjects that reached the limiting criteria were included in the statistical analysis of the DLEs, it could be argued that they were more susceptible to heat than those that did not reach the limiting criteria and as such would meet the assumptions of the model. The basis for this argument is taken from Piette and Malchaire (1999) who used the same criteria in their validation study of the PHS model.

It would seem from these results, that Kampmann's (1999) original criticism of ISO 7933 being developed from laboratory data and the resultant incorporation of field data to the development of the PHS model has not improved its validity.

These findings will now be discussed in further detail.

Sweat rates

From

, the average volume of sweat loss in each pair of experiments was similar. The only variations found were in E9 and E10, where the females in E10 showed a lower sweat rate (probably due to their smaller body surface area). This suggests that when clothing is worn, in hot humid environments that there is little change in the observed sweat rate when metabolic rate is decreased by less than 20%. This would need to be investigated further using clothing of different vapour and air permeability. However, of more importance is that the mean values are higher than all the maximum sweat rate values presented in Table C of Annex C in the ISO standard except for the Danger criteria of acclimatised subjects. This would suggest therefore that the reference values for the maximum sweat loss as presented in the ISO standard are not suitable for situations where clothing is worn. The observed sweat rates were also higher than the PHS *SW*p, although improvements to the model's prediction mean that the PHS *SW*p was higher than the ISO and $\mathrm{ISO}_{\mathrm{mod}}$ *SW*p's in all experiments.

Both the ISO and the PHS models provide a value for the predicted sweat rate in $\mathrm{W/m^2}$, which is converted to grams per hour. This assumes that all people of all sizes sweat in equal amounts and the conversion to grams per hour is based on an "average" body surface area. An example of how body size and weight should be taken into account in any calculation of sweat loss is provided in E9 and E10. In E9 the males lost a mean sweat rate of 578 g/h, while the females in E10 lost a mean of 327 g/h. Although the female metabolic rate was measured as lower than the males, the variation was less than 20% and if the observations above were correct, then there should have been little difference between the male and female sweat rates. Perhaps sweat loss should be calculated as a ratio of sweat loss to body weight, from which a volume sweat loss could be extrapolated to provide a sweat loss specific to that person.

Significant differences may be attributable to the differences in the metabolic rate input values, although these differences are relatively small when the sweat rates are compared visually between the measured and estimated predicted values than the differences of the observed sweat rate. Therefore, the fact that the method of obtaining a metabolic rate value may result in significant differences between the resultant values, it seemed to have little effect on the SW_p by the ISO models while the differences were much greater in the PHS model.

What effect the clothing had on this SW_p is unknown, and perhaps had subjects been subjected to the same conditions and work rates while semi-nude this effect would have been quantifiable. One interesting finding was that in E10 where light cotton clothing was worn, the mean SW_p were almost identical to the observed sweat rate (E9: PHS SW_p = 563 g/h, SWo = 578 g/h.)

DLEs and Observed Time

DLE is probably that factor which the end users would most likely use as a reference value for their estimations of work schedules. This value when combined with the SW_p would be of great importance to the practitioner, since it would provide them with not only a measure of time but a "control" measure whereby they could estimate the amount of fluid intake necessary to minimise dehydration. Unlike the SW_p, the differences between the estimated and predicted metabolic rates had a significant impact on the DLE predicted by the ISO models yet not by the DLEs predicted by the PHS model. **Table 45** shows that there is a higher correlation between the observed time and the DLE obtained from the measured metabolic rate inputs than with the estimated metabolic rate input. This suggests therefore that errors obtained when estimating metabolic rate and using those values as inputs does not have as great an influence on SW as they do on the DLEs from all three models.

The sudden reversal of the prediction, from where the model was making a significant under prediction of DLE on moderate metabolic rates to where it over predicted the DLE for the lowest metabolic rate seems to suggest that perhaps the ISO model is over sensitive to changes in metabolic rate when predicting DLE. Again this sort of shift was not evident in the SW_p values.

This is an interesting observation, since one would expect that the effect on the SW_p value would be similar to the effect on the DLE, due to the interdependence of the two. It would seem therefore that the SW_p values are being constrained, not by the work rate but by the maximum sweat rate values when using the ISO models.

In terms of Face Validity, neither model performed as it was supposed to.

Based on the data from this set of experiments, neither model provides a valid prediction of the time to reach a core temperature of 38°C.

2.11.1 General Discussion

No literature could be found that quantified the onset of sweat related problems such as hydromeosis and sweat gland fever. Are these a result of gross sweat rate over time, or volume of sweat rate in units such as an hour? Another question would be, "Even with replacing electrolytes, what is the maximum amount of water loss that can be replaced per hour?" Perhaps future limiting-values for the maximum sweat rate could be developed addressing some of these issues too.

Experiments 1 to 6 were not successful in ensuring that the metabolic rates were sufficiently different within pairs so as to exaggerate the effect of decreasing the work load by increasing the time of the predicted DLE significantly. It was important however that where possible, subjects showed physiological responses of heat stress (such as core temperature increase to 38°C) to provide data for the validation of the PHS model. At the time of the experimentation it was not know if the PHS criteria limit would be 38°C or 38.5°C.

Finally, an important aspect of the predictor capacity of the ISO model is that it does not take into account the thermal properties of the clothing sufficiently. For example, the cotton overalls were vapour and air permeable and, as such, would have allowed a greater rate of evaporation and convection than perhaps a different ensemble of the same clo value would. Further cooling of the skin may also have been caused due to the clothing being saturated with sweat which would have had a wicking effect, thereby increasing convection of heat away from the skin surface area. This was addressed by the BIOMED HEAT project team but the clothing corrections were not included on the model that was sent out as the final BIOMED model. The project team had to select a version of the PHS model to validate and it was decided that the final BIOMED HEAT PHS would be used and not any subsequent versions initiated into the CEN or ISO program. Therefore, subsequent inclusion of these clothing corrections factors cannot be accounted for or evaluated, as they were not available at the time.

2.12 CONCLUSIONS

1.) The results showed that the neither the ISO 7933 SW_{req} nor the modified ISO SW_{req} models were valid predictors of Duration Limit Exposures and predicted sweat rate for people wearing protective clothing in warm humid environments.

2.) The PHS model was also not a valid predictor of either DLEs or SW_{p} when PPE was worn. The PHS model did not predict the mean DLEs for any of the experiments. Although for E9 where light cotton clothing was worn, the mean SW_{p} was almost identical to the observed sweat rate.

3.) The PHS model predictions were more representative of the ISO predictions that the observed DLEs in all but one experiment.

4.) Furthermore, the limit values for the maximum sweat rates in the ISO models seem to be significantly under estimated, which in turn would have an effect on the DLE prediction. It also may result in a false positive decision being made by the user who will design an exposure time according to what they think is a DLE1 prediction, when in fact the worker may lose excess water before this occurs.

5.) The PHS model predictions of sweat rate were an improvement on the ISO predictions but the model also significantly underestimated the observed sweat rates.

6.) The influence of metabolic rate on the all the models is understandably critical. However, the effects of small changes in metabolic rate input seem to have a greater impact on the predicted DLEs in the ISO models and the SW_{p} in the PHS model.

7.) Metabolic rate variations have little effect on the ISO SW_{p} values and on the PHS values.

CHAPTER 3
USABILITY OF ISO 7933

3.1 SUMMARY

Chapter 3 is concerned with the usability of ISO 7933 and uses heuristic (expert) analysis based upon the usability literature. It includes Section 8 of the report. The 'paper' version of the standard and its computer program were evaluated against usability criteria. In addition, a form of usability testing was conducted involving pairs of laboratory experiments (previously described in Chapter 2). The standard/computer program was used to design conditions (identify modified work rate) for which subjects would be able to work without unacceptable thermal strain where previously they had experienced it. The standard was therefore tested for its usability as a design tool and method of providing controls.

The results are presented in tabular form and identify why usability criteria (e.g. language, structure etc.) are not met and suggestions for improvement. It was concluded that ISO 7933 did not meet usability criteria. Problems included that it did not speak the users' language, it was not consistent and the computer program did not afford the user sufficient control.

3.2 HEURISTIC EVALUATION OF ISO 7933

3.2.1 Introduction

The prerequisite of system or product design is to ensure that they suit the jobs to which they are intended. One way of achieving this is by the implementation of a user-centred approach in the design process. User-centred design is a process in which the tools and methods employed are selected and applied in such a way as to appreciate the diversity within a potential user group and is generally known as "usability". Criteria that are used to assess the usability of a product, and therefore the success or otherwise of the user-centred design process, include the product's ability to perform its intended function:

- Effectively;
- Efficiently;
- Safely;
- Comfortably.

Jefferies *et al* (1991) compared the effectiveness of a number of usability testing methods: empirical testing, heuristic (expert) evaluations, cognitive walk-throughs and guidelines. According to a number of authors, (including Jefferies *et al.*, 1991; Nielsen and Molich, 1990; Nielsen, 1992 and Smilowitz *et al*, 1994) heuristic evaluation identified more of the serious problems and was the most cost effective. A criticism of heuristic evaluations is that results tend to uncover a large number of low priority problems. Nielsen and Molich (1990) stated that heuristic evaluations tend to be used instead of empirical tests due to a lack of resources, knowledge, time or suitable representative users. Nielsen and Mack (1994) state that when both empirical and heuristic approaches are optimised, they can be equally effective in improving design.

3.2.2 Heuristic Analysis

Expert evaluation according to Jordan (1998) is an excellent method for providing diagnostic and prescriptive analysis based on any "faults" that are identified within the system. Thus the improvements that can be made to the system are based on the expert's knowledge. A disadvantage of the heuristic evaluation is that no direct empirical evidence is obtained from the users that any of the usability issues will actually affect the use of the system or product. According to Rengger (1990), McClelland (1995), Noyes and Baber (1999) the first requirement is to decide which heuristics to use and whether to base them on the characteristics of the product or on the knowledge of the discipline of the expert. The former was selected as the purpose of the evaluation since the expert's knowledge of ISO 7933 would have no bearing on how the users found the standard. The author qualified for conducting the evaluation both as a researcher in human thermal environments and a graduate in ergonomics. A number of authors, including Nielsen (1992), Lewis (1990) and Noyes and Baber (1999) suggested using a "walk-through" of the product to evaluate how users may use it and this strategy was used here.

The heuristic evaluation of the usability of ISO 7933 was concerned with three areas (codes are provided in brackets):

1.) The usability of the ISO 7933 standard as it appears in the standard (ISO Usability Paper)
2.) The usability of the ISO 7933 program (ISO Usability Program)
3.) The usability of the program for practically evaluating controls (ISO Usability – Practical example).

Data considerations

Two possible approaches can be adopted establishing the type of data that are needed.

1.) If usability performance criteria are established *a priori*, then quantitative data are required to ensure these criteria are met. It also provides a measure of performance.
2.) Qualitative data on the other hand can be used as an indication of what the quantitative data would be and to provide descriptive data for the identification of usability faults and prescribed solutions (Jordan, 1998).

Qualitative data would be used to report the results of the heuristic evaluation of the ISO 7933.

Usability Criteria

The following heuristic usability-criteria taken from Noyes and Baber (1999), Nielsen (1992, 1993) have been adapted from the assessment of interface design:

Simplicity To reduce, and where possible avoid, confusion the interface (paper or computer) or process (risk assessment) should be as simple and as intuitive as possible;
Structure To reduce complexity, aid in decision making and information extraction, the interface/process should follow a logical structure and where possible conform to the user's expectations;
Compatibility The interface/process should meet with the user's expectations, their experience of other heat stress indices and their knowledge of heat stress and its assessment. They should be able to easily apply the standard within the framework of standards in which it has been written. An additional consideration is that any heat stress assessment methodology will be used within the wider context of occupational risk assessment;
Control Here the level of control that the user has over the interface/process is important as humans do not like to lose their locus of control;
Adaptation The interface/model/process should be adaptable to meet the requirements of users (i.e. can it be easily reprogrammed etc.) in the different work environments in which it may be used;
Consistency This is vital to help reduce errors and cognitive load. The structure and the content should be consistent.
Speak User's Language – Language should be of a type that the user understands;
Adequate information – Adequate information should be provided to enable the user to use the standard without having to refer to other sources or other standards.

3.2.3 ISO Usability -Paper

Results of ISO Usability –Paper

This section describes the results of the heuristic evaluation of ISO 7933 Paper. The results are derived from an expert's (the author) assessment of ISO 7933 according to the above usability criteria.

Table 48: Description of Results of Heuristic Evaluation of ISO Usability – Paper

FEATURE OF PAPER BASED STANDARD	HEURISTIC CRITERIA	WHY CRITERIA ARE NOT MET (✗) AND RECOMMENDED SOLUTIONS (✓)
The Introduction states "the method for analytical estimation and interpretation of thermal stress allows the prediction of the physiological effects of work in the heat and the rational determination…"	• **Simplicity** • **Speak users' language**	✗ Language is complicated. Users would probably not know what "analytical estimation" and "rational" mean. ✓ Simple language should be used
Clause 3 ("*Principles of the method of evaluation*") briefly describes the format of the standard.	• **Structure** • **Simplicity**	✗ The description is wordy and novice users may find it difficult to follow ✗ Paragraph (a) does not include wet bulb temperature ✓ A flow diagram showing the structure of the standard should be provided ✓ All input variables should be listed and described
Clause 4 details the. Equations in the heat balance equation	• **Simplicity** • **Minimise user memory load**	✗ The users will be using the computer program and not the equations, the only interest they would have for the equations would be academic ✗ It is pointless to provide the equations in anything other than a reference annex because the users would probably not refer to them. More importantly, this provides an overcomplicated "first view" of the standard and may intimidate first time users into thinking that they need to understand the equations in order to accurately use the standard ✓ If equations are to be provided, they should be in an Annex

Description of Results of Heuristic Evaluation of ISO Usability – Paper (Cont)

FEATURE OF PAPER BASED STANDARD	**HEURISTIC CRITERIA**	**WHY CRITERIA ARE NOT MET (✗) AND RECOMMENDED SOLUTIONS (✓)**
Throughout Clause 4 (heat balance equation) each of the parameters equations are provided, however coefficients used in the equations are presented in Annex A (informative). Although this is explained in Clause 3, paragraph 5, this is not mentioned again in Clause 4.	• **Minimise user memory load** • **Structure** • **Simplicity**	✗ Assuming the users are able to understand the equations and want to refer to them, the separation of the equations from the coefficients makes it more difficult ✗ Users may not remember that the coefficients are provided in the Annex ✓ Provide equations in their entirety.
The provision of the equations in Clause 4.	• **Simplicity** • **Speak user's language**	✗ Code for computer program is provided in Annex and as such it is unlikely that the users will need to refer to equations. Providing equations in the body of the standard is unnecessary ✓ Put all equations in an Informative Annex ✓ Body of standard should concentrate more on explaining how to apply the index than on the science behind it
Cres and Eres equations in clause 4 (equations 2 and 3) differ from equations provided in Annex A (equations A.1 and A.2 respectively)	• **Consistency** • **Structure** •	✗ The Cres and Eres equations in the Annex are provided as alternative equations to those in Clause 4 and this is not explained explicitly ✓ Reasons for different equations need to be better explained
$P_{s,sk}$ – saturated vapour pressure at the skin temperature	• **Minimise user memory load** • **Provide adequate information**	✗ No definition or equation are given for Ps,sk. ✓ If explanations for some equations are given they should be given for all
In Annex A, heat transfer coefficients are provided in A.3 for natural and forced convection.	• **Provide adequate information**	✗ No definitions are provided for forced and natural convection for determining the convection coefficient ✓ Provide definitions for forced and natural convection

Description of Results of Heuristic Evaluation of ISO Usability – Paper (Cont)

FEATURE OF PAPER BASED STANDARD	**HEURISTIC CRITERIA**	**WHY CRITERIA ARE NOT MET (✗) AND RECOMMENDED SOLUTIONS (✓)**
Equation 10 in Clause 4 describes the required skin wettedness as the ratio between E_{req} and E_{max}.	• **Consistency** • **Provide adequate information**	✗ Insufficient information of skin wettedness is provided ✓ Provide information about the concept of skin wettedness.
In Annex A.4. the radiative heat transfer coefficient refers to the mean skin temperature *"as defined in equation (4)"*	• **Consistency**	✗ This is a referencing error as the equation for tsk is not equation 4 but is presented in Annex C.1. Although it is doubtful that the ordinary user will look for the equations, this error may lead to confusion if they did ✓ Ensure cross referencing is accurate
At the end of Clause 4, the following "Note" appears; *"The sweat rate in watts per square metre represents the equivalent heat of the sweat rate expressed in grams of sweat per square metre of skin surface per hour"*	• **Speak user's language** • **Simplicity**	✗ Again complicated language is used to explain something the user probably would not be interested in anyway ✓ Users would probably only be interested in quantifying sweat loss in terms of volume and not on heat transfer ✓ Provide sweat loss as grams per hour only
Clause 5 – Interpretation of required sweat rate	• **Speak user's language** • **Simplicity**	✗ Overcomplicated and wordy explanation of the interpretation criteria means that users may not be able to understand the principles behind the interpretation ✓ Simple language should be used
5.1 provides the basis of the method of interpretation. Criteria are provided in Annex C	• **Speak user's language** • **Provide adequate information** • **Structure**	✗ Complicated language and insufficient data about the process is provided ✗ Data for interpretation is provided in Annex C and not with descriptions in 5.1 ✓ Use simple language ✓ Provide data in the same section as the method of interpretation so that the user does not move between sections

Description of Results of Heuristic Evaluation of ISO Usability – Paper (Cont)

FEATURE OF PAPER BASED STANDARD	HEURISTIC CRITERIA	WHY CRITERIA ARE NOT MET (×) AND RECOMMENDED SOLUTIONS (✓)
New parameters of w_{max}, SW_{max}, Q_{max} and D_{max} are introduced in 5.1	• **Speak user's language** • **Minimise user's memory load** •	✗ Annex C, where the values for these parameters are defined is only referred to at the end of the section. This may lead to confusion ✓ Either provide a reference for Table C.1 at the start of the section or include it in the section.
Section 5.2 describes the "*Analysis of the work situation*" and introduces w_p, E_p and SW_p. Here the use of the formulae are dependent whether w_{req} exceeds w_{max}.	• **Speak user's language** • **Minimise user's memory load** •	✗ The language used is complicated and users may find it difficult to follow. Although a flow chart describing this section is provided in Annex D.3, it is not referred to in this section. ✓ Provide D.3 flow chart in this section and use simpler language
Clause 5.3 describes the maximum heat storage (Q_{max}) and maximum water loss (D_{max}) values. These are described here and provided in Table C.2, Annex C.	• **Provide adequate information** • **Minimise user's memory load**	✗ The user is required to move between 5.2 and Table C.2 to see what the Qmax and Dmax values are ✗ No information is provided to direct the user to Table C.2 ✓ All information should be supplied together and not separated into different sections
In 5.3 the equations for DLE$_1$ and DLE$_2$ are described.	• **Provide adequate information**	✗ Insufficient information is provided about the importance of the DLEs since this is the one interpretation that the user would most likely be interested in ✓ Provide additional information about the DLEs and how they could be used.
Clause 5.4 describes the "*Organisation of work in the heat*"	• **Speak user' language** • **Provide adequate information**	✗ The explanation of the organisation of the work is wordy and not well written ✓ Explanation should be written in language the user may understand ✓ A scenario or description of multiple shifts should be used help the user understand the concepts

Description of Results of Heuristic Evaluation of ISO Usability – Paper (Cont)

FEATURE OF PAPER BASED STANDARD	HEURISTIC CRITERIA	WHY CRITERIA ARE NOT MET (×) AND RECOMMENDED SOLUTIONS (✓)
Refers to the computer program in Annex D	• **Structure** • **Provide adequate information** • **Simplicity**	✗ This is the first time that the computer program is referred to. It appears in the final paragraph of the body of the standard ✓ The computer program should be referred to in the beginning of the standard in the "Scope" Section ✓ A description of it and the system requirements should be provided in its own section at the front of the standard
Annex B provides Tables B.1 and B.2 which describe the clothing insulation values of combined garments (B.1) and individual clothing items (B.2)	• **Provide adequate information** • **Consistency** • **Compatability**	✗ These tables are taken from BS EN ISO 29920 and yet no reference here or in the "Normative References" section (Clause 2) are provided ✗ The description of the estimation of clothing insulation is wordy and complicated ✓ A reference to BS EN ISO 29920 should be made in both Clause 2 and in Annex B ✓ The description of using the tables should be easier to understand and examples of clothing ensembles with items not described in Table B.1 should be provided
.Annex C.1 and Table C.1 defines the input value validity range based on the skin temperature equation	• **Structure** • **Provide adequate information** • **Simplicity**	✗ Important from a practical perspective as it tells the user whether the index is valid for their environment ✗ Annex C is not crossed referenced in Clause 1 "Scope" which states that "this method of assessment is not applicable to cases where special protective clothing is worn, nigh radiant temperature, high air velocity and saturated clothing" ✗ The need to alter the equation for skin temperature to a constant value of 36°C is not adequately highlighted. The user may not read the one sentence in which it appears ✓ This section should be cross referenced in Clause 1 "Scope" ✓ Table C.1 should appear in the front of the standard and not as an annex ✓ The need to assume an average of 36°C skin temperature must be more obvious.

Description of Results of Heuristic Evaluation of ISO Usability – Paper (Cont)

FEATURE OF PAPER BASED STANDARD	HEURISTIC CRITERIA	WHY CRITERIA ARE NOT MET (✗) AND RECOMMENDED SOLUTIONS (✓)
Annex C.2 describes the variations between individuals	• **Consistency** • **Provide adequate information** • **Speak user's language**	✗ C.2 defines "warning level" while in the program it is called Alarm Level ✗ No definitive value for those "certain subjects" that would not be protected by the standard ✓ The definitions need to be more specific and in language the users would understand ✓ Additionally consistency should be ensure
Table C.2 provides the reference values for $\mathrm{w}_{\mathrm{max}}$, SW_{max}, Q_{max} and D_{max}	• **Speak user's language**	✗ Units used (W/m2 and h/m2) are unlikely to mean anything to the users ✓ Only Use appropriate language (e.g. g/h and %body weight
Descriptions of program's Interpretation and DLE is provided in D.1.4	• **Provide adequate information** • **Consistency**	✗ Refers to Flow Chart yet no cross reference is given ✓ Where references are made, accurate cross references must be provided ✓ It may be easier to understand if the explanation is provided along side the flow chart
Annex D.4 describes the "*analysis of a situation comprising two work sequences*"	• **Structure** • **Simplicity** • **Minimise user memory load**	✗ This section would be of more use to the user if it were supplied in the body of the standard ✓ Provide this in the body of the standard

Conclusions ISO Usability -Paper

25 main usability problems were identified through the heuristic evaluation process. For nearly all of the problems more than one usability criterion was not met and a breakdown is provided below:

- **Simplicity**: 10 times
- **Structure**: 7 times
- **Compatibility**: Once
- **Control**: None
- **Adaptation**: None
- **Consistency**: 6 times
- **Speak User's Language**: 9 times
- **Provide adequate information**: 12 times
- **Minimise user memory load**: 7 times

Most of the problems are concerned with simplicity, structure, consistency, speaking the user's language, providing adequate information and minimising user memory load.

Throughout the standard, the user is required to move from one section to the other. The standard appears to be unnecessarily scientific and would not encourage users to use it. Users should not be expected to use the equations presented in the standard and to work through them manually. This standard can only be used as a computer program and as such, much of the information provided in the body of the standard is superfluous to their requirements.

The format and the information provided does not satisfy the requirements of ergonomics standards as set out by Branton (1985) who stated that they are developed for the end user.

Although this format may be useful for understanding the underlying principles on which the model is based, the standard and the users would be better served if the mathematics of the index were provided as an annex at the rear of the standard.

The flow diagram D.3 should be simplified and presented at the front of the standard to explain to the users what their decision process should be. This decision process should then be explained in simple language in a sequential format that follows the required decision process, along with detailed explanations where needed. A checklist that also served as a method of record keeping would aid this.

Scenarios should also present the results of the scenario when using the $WBGT$ index so that users can see where the SW_{req} could follow on from the $WBGT$ index and how information used in the $WBGT$ may be used in SW_{req} (e.g. clothing insulation, metabolic rate estimations, wet bulb temperature etc.)

No scenarios are provided to enable the users to validate the model if they have changed the mean skin temperature to 36°C.

3.2.4 ISO Usability -Program

Results of ISO Usability –Program

This section describes the results of the heuristic evaluation of ISO 7933 program. The programme listing provided in BASIC was implemented into a computer. The results of this heuristic evaluation are derived from an expert's (the author) assessment of ISO 7933 according to the above usability criteria.

Table 49: Description of Results of Heuristic Evaluation of ISO Usability – Program

FEATURE OF PROGRAM IN STANDARD	HEURISTIC CRITERIA	WHY CRITERIA ARE NOT MET (✗)AND RECOMMENDED SOLUTIONS (✓)
Computer program is in BASIC format which must be inputted into the computer by the user	• **Consistency** • **Control** • **Adaptability** • **Simplicity**	✗ The computer program is in basic format which when compared to current object-oriented software indicates that the interface is somewhat dated ✗ By producing the program in written format for the users to input the code into their computer, introduces a number of potential problems: **1.** The assumption is that the users would have the know-how to input the code **2.** Errors in the code input are possible, and this places an implicit requirement on the user to check the code to validate the input codes **3.** Another problem may be that the users will not use the standard because of the time it may take to perform these two tasks ✓ Provide a computer disk with the standard in an object oriented format that allows for the data to be saved into a spreadsheet format ✓ Alternatively the software could be downloaded from the BSI website
For situations where the the clo value exceeds 0.6 clo, the user is required to change the code for estimating mean skin temperature to a constant value of 36°C. (Lines 780 and 790)	• **Adaptability** • **Control** • **Simplicity**	✗ Again the assumption is that the users know how to do this ✓ An alternative program should be provided where skin temperature equals 36°C ✓ Alternatively the program should provide a logic argument to automatically allocate either the equation for mean skin temperature or the constant value of 36°C based on the input variables

Description of Results of Heuristic Evaluation of ISO Usability – Program (cont)

FEATURE OF PROGRAM IN STANDARD	**HEURISTIC CRITERIA**	**WHY CRITERIA ARE NOT MET (✗)AND RECOMMENDED SOLUTIONS (✓)**
No help facilities are provided in the program Users cannot navigate through the program	• **Adaptability** • **Control** • **Simplicity**	✗ Users may need easy to use help facilities as they may not be able to understand the standard. It is unlikely the users would have read the standard before using it ✗ Users have little control over the program and must rerun the program if they make an error while inputting data. This is compounded if sequences are being inputted ✓ Again, an object oriented program with help facilities or navigation aids may help this ✓ Alternatively, if a BASIC version is to be provided, it should provide help and navigation aids
The program computes the partial vapour pressure from wet bulb and air temperature if the user does not enter a partial vapour pressure value. (line 750) The program computes mean radiant temperature from air temperature, radiant temperature and air velocity (Lines 710 to 760)	• **Adaptability** • **Control** • **Simplicity** • **Provide adequate information**	✗ This is not indicated in the program to the user, and unless they understood BASIC programming language they would not know this ✓ This is mentioned in Annex D.1.2, but needs to be made clearer ✓ Users should be notified that these computations take place ✓ An input for humidity should also be provided
The user is required to input the wet bulb temperature	• **Provide adequate information** • **Consistency**	✗ Wet bulb temperature is a derived parameter which is used in *WBGT*. Although SW_{req} is supposed to be used if the *WBGT* reference values are exceeded, it is not appropriate to assume that the user will have done so. Users will be confused between aspirated wet bulb temperature and natural wet bulb temperature. It is aspirated wet bulb temperature that is required here ✗ Although mentioned in D.1.2, insufficient information is provided ✓ These calculations should be hidden and only provided if the users request it

Description of Results of Heuristic Evaluation of ISO Usability – Program (Cont)

FEATURE OF PROGRAM IN STANDARD	**HEURISTIC CRITERIA**	**WHY CRITERIA ARE NOT MET (×)AND RECOMMENDED SOLUTIONS (✓)**
User is required to enter the body area fraction exposed (A_R/A_{Du}): Seated = 0.7 & Standing = 0.77	• **Provide adequate information** • **Consistency**	✗ A_R/A_{Du} is only referred to in the standard in equation A.7 of Annex A ✓ The program should prompt the user to aid A_R/A_{Du} input or ask if the person is sitting or standing
The standard describes the ranges of input values for which the model is valid	• **Control** • **Adaptability** • **Simplicity** • **Provide adequate information** • **Minimise user memory load**	✗ The program does not tell the user if the values they have inputted are outside the range of validity and as such unless the user refers back to the standard they will not know the standard is not valid for their inputs ✓ The program should "flag" inputs that are outside of the program's validity
The calculations from the inputs are provided once the user has inputted all the data	• **Structure** • **Simplicity**	✗ This information is not required by users and therefore is unnecessary ✓ These calculations should be hidden and only provided if the users request them
The interpretations for alarm and danger criteria for both acclimatised and unacclimatised workers are provided from the calculations	• **Structure** • **Simplicity**	✗ The format of the screen that shows the interpretations is cluttered and difficult to interpret ✓ The structure and layout of the screen should be easy to read
The standard suggests using the model to identify how control measures are used	• **Consistency** • **Control** • **Adaptability** • **Simplicity** • **Provide adequate information** • **Minimise memory load**	✗ The program does not allow this to be performed easily. The user is required to run the program a number of times and to record the interpretations and to then make the comparisons themselves ✓ The program should allow for inputs to changed and to simultaneously (or through forward navigation) to see how the interpretations have changed ✓ Program should allow the user to compare runs

Description of Results of Heuristic Evaluation of ISO Usability – Program (Cont)

FEATURE OF PROGRAM IN STANDARD	HEURISTIC CRITERIA	WHY CRITERIA ARE NOT MET (✗)AND RECOMMENDED SOLUTIONS (✓)
The program outputs and interpretations are shown on the screen. This is not saved to a retrievable data file	• **Control** • **Adaptability** • **Minimise user memory load**	✗ This means that the user is required to make manual recordings of the results. This may introduce errors when transferring the results to another medium such as spreadsheets ✗ The data cannot be saved and the only record is either from PRINT SCREEN or from manual records. This is also time consuming ✓ The program should save results to a data file which could be viewed through other programs such as spreadsheets
Layout and Presentation of the interface	• **Simplicity** • **Provide adequate information** • **Speak the user's language**	✗ The layout of the interpretation is cluttered and has poor spatial structure. This makes the results difficult to interpret ✓ Results should be tabulated and saved to an text based format file (such as ASCII) to enable simple retrieval and storage of results

Conclusions ISO Usability –Program

- Eleven main usability problems were identified through the heuristic evaluation of the program. For nearly all of the problems, more than one usability criteria were not met. A breakdown is provided below:
  - **Simplicity**: 8 times
  - **Structure**: Twice
  - **Compatibility**: None
  - **Control**: 7 times
  - **Adaptability**: 7 times
  - **Consistency**: 4 times
  - **Speak User's Language**: None
  - **Provide adequate information**: 5 times
  - **Minimise user memory load**: 3 times

From this breakdown it can be seen that most of the problems are concerned with simplicity, consistency, providing adequate information, adaptability, control and minimising user memory load.

It is imperative that any risk assessment method, whether it be for the assessment of heats stress or any other risk, should be designed and developed with the assumption that the users may have little or no training and knowledge in both the area that they are assessing and the methods used to assess these risks. As such therefore, it would be inconceivable that users of ISO 7933 would be able to apply the methodology with the amount of information provided unless they had training and/or experience of conducting heat stress assessments.

This is further complicated by the need for users to input the program themselves and, for situations where clothing insulation is greater than 0.6clo, to alter mean skin temperature to a constant 36°C. This, added to the validity problems associated with the model in warm-humid environments, may explain the apparent lack of usage of the standard in industry. This is echoed by Meyer and Rapp (1995) who feel that the development of an easy to use methodology is a "*major duty*" for those people involved in the development of heat stress assessment methods. They also feel that the users of such a methodology need much more information.

3.2.5 ISO Usability – Practical Example

Method of ISO Usability – Practical Example

Parallel to the protocol for the validity study in Study 1, the usability of the index as a reverse engineering tool to help users evaluate and introduce control measures was investigated. The experimental protocol of Study 1 (Chapter 2) was dependent on the requirements of the validity study while also meeting the requirements for evaluating the usability of the standard.

The process by which this usability study protocol was established is described below:

- The usability experiments were evaluated in pairs, where the environmental and clothing conditions remained the same but in the second of each pair the subject's work rate was reduced to provide a DLE that was longer than the DLE of the first. The pairs were:

  Pair A Experiments 1 and 2;
  Pair B Experiments 3 and 4;
  Pair C Experiments 5 and 6 (See Table below).

Table 50: Data means inputted into ISO and PHS models

Exp	N	t_a °C	t_r °C	V ms^{-1}	Pa kPa	M (Est) Wm^{-2}	M (Meas) Wm^{-2}	Icl clo
1	8	34.9	35.1	0.22	3.40	193	-	0.8
2	8	35.0	34.4	0.28	3.30	177	158	0.8
3	8	39.5	39.2	0.07	4.50	173	161	0.8
4	8	39.7	39.3	0.08	4.50	153	142	0.8
5	8	45.0	44.9	0.08	3.80	153	134	0.8
6	7	44.7	43.8	0.09	3.90	87	101	0.8

Note: **Experiments 1 to 6 were a stepping task wearing a boiler suit.**

- This provided the following scenario for each pair of experiments:
- The environment in the chamber represents a working environment with the worker wearing coveralls and working at a particular work rate.
- A potential user needs to investigate how much longer the worker can remain in that environment if they work at a slower rate (lower metabolic rate) while all other parameters are kept constant.
- The user therefore reduces the work rate input (this was selected *a priori* arbitrarily) and obtains a new DLE for that work rate input.
- Therefore the second experiment in each pair investigates not only whether the new DLE is valid, but also provides for the evaluation of the usability of using the ISO model for implementing controls.

Results – ISO Practical Example

- A computer is needed to use the SW_{req} index which may limit its use.
- The model does not allow for the comparison of data from different input sequences. The results need to be recorded manually in order for a comparison to be made. This supports the findings of Hanson and Graveling (1997) who state that this may limit its use in evaluating control measures.
- The user needs to estimate metabolic rate which for users with little or no training in heat stress may be a difficult task to perform.
- Using the danger criteria, it was not possible to estimate the number of subjects who would not be protected by the index. This also supports the findings of Kampmann and Pierkarski (1995) who also questioned the meaningfulness of the alarm and danger criteria to users.
- In all conditions the clothing insulation values exceeded 0.6 clo and the mean skin temperature had to be changed to 36°C. It is unlikely that most users would have been able to do this unless they had a basic knowledge of BASIC programming.

3.2.6 Conclusions of Heuristic Evaluation of ISO 7933

ISO 7933 does not meet the usability criteria described in this evaluation. The following problems were identified:

1. The standard does not **speak the users' language** and is not **simple to use**.
   - The standard should use words, phrases, and concepts familiar to the user.
   - Scientific “jargon” should be in the Appendices and not in the body of the standard.

2. The standard is not **consistent**.
   - It should present information in a natural and logical order and should indicate similar concepts through identical terminology and graphics.
   - Ergonomic conventions for layout, formatting, structure etc. should be adhered to.

3. The standard does not **minimize the users' memory load.**
   - Efforts should be taken to maximise recognition rather than recall.
   - Users should not be required to remember key information across the different sections of the standard.

4. The computer program does not afford the user sufficient **control.**
   - Flexibility and efficient navigation and help systems should be maximised to accommodate a range of user ability, knowledge and diverse user goals.
   - Navigation aids would also make it easy for the user to return to different stages of the calculation (such as inputs or interpretations). Instructions should be provided where useful.
   - The interface layout should be arranged so that spatial differences and presentation enable rapid and frequently accessed information to be easily found and interpreted.
   - Information (such as the calculations) which is irrelevant and distracting and should be eliminated.

5. **Adaptability** and **compatibility** would be improved if data could be saved to a format such as ASCII files which users could access using different types of spreadsheet software.

6. **Flexibility** and **adaptability** of the program would be enhanced by additional code to be automatically used when clo > 0.6 for t_{sk} = 36°C.

7. The **ease of use** of the standard would also be improved by providing all the relevant data in the standard so that users are not required to access multiple standards to complete a single assessment.

CHAPTER 4
DESIGN, DEVELOPMENT AND EVALUATION OF A PRACTICAL HEAT STRESS ASSESSMENT METHODOLOGY

4.1 SUMMARY

The results of the validity study and heuristic evaluation led to the need to produce a practical heat stress assessment methodology. This was produced in three stages: an exploratory stage (Stage 1, Section 4.2); a design and development stage (Stage 2, Section 4.3); and an evaluation stage (Stage 3, Section 4.4). The exploratory stage identified requirements and methods for achieving those requirements. A literature review identified ergonomics techniques for data collection and user centred design and usability testing. The importance of identifying the users and users' characteristics was stressed. Methods adopted included informal interviews and questionnaires with participants at Occupational Hygiene conferences, Hierarchical Task Analysis (HTA) of the heat stress standards and heat stress assessment in a paper mill. A poster presentation at the BOHS annual conference attracted 38 participants who were subsequently interviewed. It was found that most participants were aware of the HSI and WBGT indices but few knew of ISO 7933. There was interest in information concerning heat stress assessment and all interviewees found the process complicated.

An HTA identified areas where the current standards do not support tasks that would ordinarily be performed in heat stress assessment. This led to a process diagram showing the stages of assessment and the relationships between them. Finally, a field trial was conducted in a paper mill, where assessment methods were used to assess a worker in a hot area. It was concluded that present methods are complex and inconsistent. Current heat stress assessment methodologies and standards do not follow established risk assessment formats. For example, there is no hazard identification stage in current strategies and it is suggested that this should be included.

Section 4.3 presents the design and development (Stage 2) of the practical methodology. The use of rating and ranking methods and checklists for risk assessment are reviewed. Group discussions were used to obtain information that could be used to design a generic heat stress strategy. Six experts from industry and academia were involved in structured group discussions. The discussions were recorded and transcripts made.

Expert opinion was also provided on a heat stress risk assessment strategy developed from the BIOMED II research project by Malchaire and others. To complement the experts' discussion group, user discussion groups were conducted among BOHS conference and special interest group members. A ten point generic assessment strategy was developed from the results of the expert discussion group. This was evaluated by the user group.

An outcome from both the experts and the user groups was the emphasis placed upon the role of health and safety managers. Expert opinion was obtained on the definition and characteristics of users, heat stress standards, user perception and information required.

To enhance information collected from the group discussions and questionnaires (for which there was a poor response after the discussion groups) a postal questionnaire was conducted. Questionnaires were sent to 270 health and safety departments of companies selected from the

Kompass Company Directory. Fifty-six were returned, 29 not completed but explaining that heat stress was not an issue. The 27 completed questionnaires were analysed in detail. An important finding was the low level of assessment and use of international and British standards. Conclusions of Stage 2 included the adoption of a ten point strategy for Management, Assessment and Control (MA&C) of heat stress. This is shown in a flow diagram.

Section 4.4 presents Stage 3 – the evaluation stage. This concentrated on the 'observation' part of the MA&C. User trials were conducted in field trials. One was conducted in a paper mill and another in a steel mill. (Seven health and safety personnel in each setting conducted the assessments.) The aim of the user trials was to compare the 'observation' assessment methods described in this project with that proposed as an ISO standard method by Malchaire and others from the BIOMED II project. A blind balanced order repeated measures design involved using the methods to assess industrial workplaces. After the assessments, a discussion group was held to discuss the results. The results showed that the proposed ISO method was easier to use. However, the ISO method was considered too simplistic, with little information of practical use. The method developed in the present project was preferred. The discussion groups provided advice on how the method could be improved.

4.2 STAGE 1 – EXPLORATORY STAGE

4.2.1 Aims

The main aim of the Exploratory Stage was to provide the background knowledge for the development of the practical heat stress assessment methodology. To this end the following specific aims were established:

1.) To establish the rationale for user input and to identify the research methodologies that will be used;
2.) To promote the project amongst potential users to obtain their possible participation in later stages;
3.) To investigate and describe the task of assessing the risk of heat stress using the current heat stress standards;
4.) To provide a practical example of a heat stress assessment in industry.

The Exploratory Stage was concerned with all aspects of heat stress assessment and not with any particular aspect (such as ISO 7933) to ensure that the practical heat stress assessment methodology would be based on the user's requirements within the framework of heat stress risk assessment.

4.2.2 Methods

Corresponding to the aims above, the following methods were used:

1.) Literature Review;
2.) Informal interviews and questionnaires with participants at occupational hygiene conferences;
3.) Hierarchical Task Analysis of the relevant heat stress standards;
4.) Heat Stress Assessment in a Paper Mill.

4.2.3 Ergonomics techniques for data collection

Matching Methodology to Theory

Breakwell (1995) suggests that research projects may often require a number of research tools to achieve their goals. The success of using multiple research tools, argues Breakwell, is simply the result of the conclusions yielded by each method being compatible with the theory being tested. This point is particularly relevant to this project because a number of ergonomic methods were required to gather information.

The users of any practical risk assessment methodology may be those people who are responsible for the health and safety of the work force in a company and those people who are expected to enforce the health and safety legislation. The participation of these people would be sought for this project. As with all applied ergonomic research, when the input of people from industry is required, there is a general concern that to engage potential users in the research process may impose additional time and commitment burdens upon them, on top of their work commitments. A consequence may be that user participation may be lacking, not due to the user's unwillingness to take part but that they do not have the time to do so. Therefore, different methods of investigation were reviewed to obtain a justifiable balance between "what was ideal" in terms of scientific research requirements and "what was possible" within the real-world time and expected sample participation constraints.

It was recognised early on that for formal one to one interviews, participants would be expected to travel to, or receive a visit from the researchers. This would be time consuming and could be overcome by gaining access to participants when they were attending conferences, one-day-workshops etc. These were then targeted for access to participants. BOHS conferences, one day Special Interest Group (SIG) meetings of BOHS members and one day meetings held at Loughborough and elsewhere were used as data collection and "networking" opportunities. It was hoped that the "networking" would encourage participants to take part in other aspects of the research such as the usability trials, field trips etc. The nature of conferences and one-day meetings meant that data collection methods such as formal interviews or questionnaires would yield few results, but informal interviews and groups discussions run as workshops would provide the best methods for data collection. The following ergonomic techniques for data collection were identified.

Table 51: Ergonomic techniques in the system life cycle.

EXPLORATORY STAGE	DESIGN & DEVELOPMENT	EVALUATION
Literature Review	Literature Review	User Trials (in the Field)
HTA	Group Discussions	Group Discussions
Interviews	Questionnaires	

Ergonomic methods for informal interviews, task analysis and questionnaire design are well published and therefore will not be discussed here, although a literature survey was conducted on these areas. Instead, usability testing and the use of structured discussion groups will be discussed as neither has been used previously in the development of heat stress assessment methods.

User Centred Design and Usability Testing

User Centred Design

The process requires the designer and/or engineer to establish who the users will be and to ensure that the product meets their requirements. This puts the user at the centre of the design process. According to Poulson *et al* (1996), three basic factors need to be established in analysing the user.

1. Identifying the stakeholders who will use the product;
2. Identifying the characteristics of these individuals or groups;
3. Identifying the requirements that these stakeholders have.

Importance of the User

The need to "know the user" according to Nielsen (1993) is the basic requirement of all usability guidelines. Suttcliffe (1988) and Hockos (1994) provided descriptions of users based upon criteria that categorised them in terms of their experience of technology. These categories have been adapted for this project to provide the following:

Table 52: Table showing categories and descriptions of potential users

USER CATEGORY	DESCRIPTION IN TERMS OF HEAT STRESS RISK ASSESSMENT
• **Novice**	Beginners to risk assessment, who do not have knowledge specific to heat stress risk assessment.
• **Occasional**	People who occasionally conduct risk assessments and who may or may not have a limited knowledge of heat stress risk assessment methods.
• **Transfer**	People who have extensive knowledge of risk assessments, but who may be new to heat stress risk assessments.
• **Skilled**	People who are both experienced and knowledgeable in risk assessments and heat stress risk assessments.
• **Expert**	People who have a detailed knowledge of heat stress, but who may not have a detailed knowledge of other risk assessment procedures. These people may be academics or health and safety or occupational hygiene professionals who have been involved in the development of British, European and /or International Standards.

Individual User Characteristics

It is necessary to define the user population so that their knowledge, work experience, education etc of the users can be understood. This enables the anticipation of what their performance expectations when using the product are, and what difficulties they may have so that appropriate limits of the complexity of the product can be set (Nielsen, 1993). Although this information may be available in some form in the literature, Nielsen recommends that direct communications and observations of the users be conducted to gain new insights that may be specific to the product being developed.

It is recognised that the boundaries between the categories listed may be somewhat blurred, with distinctions between categories being difficult to allocate. It is appropriate however, to assume that users should have at least a modicum of training and as such, it would probably be best to aim the methodology at the "Occasional" user than the Novice. The logic for this is supported by the literature review that showed that heat stress risk assessments are occasional rather than frequent occurrences. Another example is provided by The Health and Safety Executive's regulations that provide a formal definition of users for display screen equipment (DSE) where users are defined in terms of their usage of display screens. This does not provide a definition based on competence or knowledge but on frequency of use and while this has come about due to the risk being proportional to the usage for DSE, it none the less provides a comparative example. Here, the ability to actually perform a risk assessment is inversely proportional to the frequency with which the user conducts risk assessments and as such the risk of error increases the less frequent the assessment is done. Although it may be argued that any methodology should be designed for the "lowest common denominator", in this case beginners, the complexity of heat stress assessment means that it is reasonable to assume that people at least have some training in the area. The ACGIH TLVs, for example, are explicitly aimed at "*trained individuals*". However, it is recognised that training levels (competence) are varied and as such by making the lowest common denominator the "Occasional" user it is hoped that most users would be catered for. As with design decisions this is a compromise between the ideal and the reasonable. This description of competence, or knowledge, was at this stage of the project theoretical and as user input is obtained, it may be revised.

Usability Methods

Nielsen (1993) stated that each project may require a different combination of usability methods dependent upon the needs of the research and the time and financial constraints within which it is being conducted. The table below indicates that the methods used may often be reliant on the availability of representative users to be participants.

Table 53: Breakdown of the disadvantages and advantages of different usability assessment methods

USABILITY METHOD	NUMBER OF PARTICIPANTS	MAIN ADVANTAGES	MAIN DISADVANTAGES
Heuristic Evaluation	None	• Finds individual usability. • Can address expert user issues.	• Does not use real users. • May not find "surprises" relating to their needs.
Performance Measures	10	• Hard numbers. • Results easy to compare.	• Does not find individual usability problems.
Observation	3 or more	• Ecological Validity. • Reveals users real tasks. • Suggests functions and features.	• Appointments hard to set up. • No experimental control.
Interviews	5	• Flexible and in-depth probing.	• Time consuming. • Difficult to analyse and compare data.
Discussion Groups	6 to 12 per group	• Spontaneous reactions and group dynamics.	• Difficult and time consuming to analyse.
Questionnaires	At least 30	• Find subjective user preferences. • Easy to repeat.	• Pilot work needed (to prevent misunderstandings).

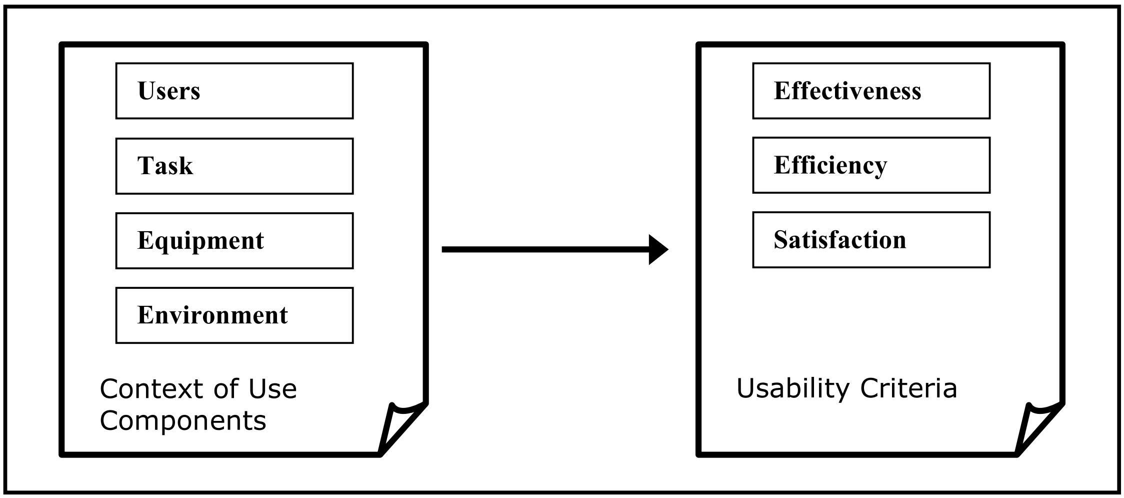


Figure 20: Diagrammatic representation of usability factors (from Bevan and Macleod, 1994)

The above diagram illustrates that the context within which the methodology will be used needs to be considered. Potential users will have as one part of their job the assessment of heat stress and the methodology should therefore be as easy to use while still providing the information that they need. Therefore the usability assessment of the methodology should be carried out in real world situations so that the "context of use components" are met.

Comparative Analysis.

Comparing prototypes with other competing products often provides for the sort of results that provide for the best improvements to the prototype. This enables the assessor to compare user preference and product performance. Nielsen (1993) recommends the use of heuristic evaluations based on established usability guidelines and then to conduct usability trials with the prototypes.

Setting of Evaluation Criteria

Since usability is not one-dimensional, it is may be possible to identify and describe those criteria by which it is to be evaluated before any evaluation process takes place (Chapanis and Budurka, 1990). This ensures that all criteria are not given the same weighting and that the criteria are based upon what is important to the users and their tasks. However, this is somewhat more difficult to achieve than it sounds, and therefore the primary requirement may be to establish which criteria the product is required to out perform the comparative product (Nielsen, 1992).

Task Analysis.

Poulson *et al* (1996) suggests the use of task analysis (TA) techniques to establish the user's requirements both for and from a product. It provides a breakdown of the tasks from high and low level activities enabling the organisation of the information into a structured sequence. This is supported by Nielsen, who quotes work from a number of authors (including Diaper, 1989; Fath and Bias, 1992; Garber and Grunes, 1992) who states that TA is extremely important for early input into the design process. TA provides a basis from which to explain processes to users and to identify those processes where users are not achieving the required goals. It is these weaknesses, in both the high and low level activities which themselves point to the required improvements.

Discussions Groups (DGs)

Groups of six to twelve people discuss topics of common interest in detail, with the view of developing solutions using the individual and common experiences of the group (Krueger, 1997). This is done through structured discussion, or brainstorming (Morgan, 1988) and this important interaction is dependent on the moderation of the researcher around the topic that he or she has introduced into the discussion (Stewart and Shandansani, 1990). It is this interaction that differentiates discussion groups from other interview strategies and that provides it with what Millward (1995) calls a "*controversial flavour*". The data produced is usually in the form of transcripts of the group discussions and is qualitative.

The literature on the use of discussion groups in research concentrates on their application as a primary research tool in Applied Psychology and Social Sciences. Secondary research, such the decision-making intervention and, specifically for this project, identifying user requirements, are not covered. Therefore, the applications of discussion groups in Psychology were investigated and, where appropriate, adapted to the application of the applied ergonomic requirements of this project.

As with the other research stages in any project the first stage is to define a goal based upon the problem. According to Morgan (1995) and Krueger (1995), DGs are extremely useful for the gathering of data, the identification of problems and the setting of goals as the participants will conduct their conversations in an open ended manner thus enabling research teams (even if they have a limited knowledge of the subject area) to establish what their priorities are. DGs are not only a powerful technique for enhancing the researchers ability to answer questions, but they also enable the researcher to generate questions from "new angles and perspectives" (Millward, 1995). As such, planning is fundamental to the success of the DGs. Random sampling of the population to obtain participants is not necessary because their purpose is not to obtain "*generalisable*" data (Krueger). What can be done to make a practical methodology that will improve their ability to assess and control heat stress problems within their workplace.

Table 54: Four areas of research and the stages and methods that support each (Morgan, 1995)

	FOUR BASIC AREAS OF RESEARCH			
	ACADEMIC RESEARCH	**PRODUCT PLANNING**	**EVALUATION RESEARCH**	**QUALITY IMPROVEMENT**
Problem Identification	Generating Research Questions	Generating New Product Ideas	Needs Assessment	Identifying Opportunities
Planning	Research Designs	Developing New Products	Program Development	Planning Intervention
Implementation	Data Collection	Monitoring Customer Response	Process Evaluation	Implementing Interventions
Assessment	Data Analysis	Refining Product or Marketing	Outcome Evaluation	Assessment Redesign

One of the main aspects that define DGs is that formal hypothesis testing is not the aim (Millward 1995, Stewart and Shandasani, 1990). Rather, DGs are used as a self-contained method of collecting data and/or as a supplement to other methods. It is important to note that the application of DGs as a supplementary research tools is as dependent on the validity of it's application as it is to the place it is given in the overall research design. It is here that the application of the DG within the research project needs to be carefully planned so that the results yielded by the other data collection methods can be compatible with the theories being tested or the goals being sought. This is an important point because, as Stewart and Shandasani point out, since DGs are an exercise in group dynamics, both the interaction of participants and the interpretation of the results must be understood within the context of the group's interaction. This definition therefore provides for the need to understand that a DGs consist of two interrelated parameters:

1. **The Group Process** – The interaction and communication between the members of the group;
2. **The content of the discussion** – The focal stimuli and issues arising from it.

This means that the group can be analysed on 2 levels:

1. **Interpersonal** – Thoughts and attitudes to the topics being discussed;
2. **Intragroup** – How people communicate within the group.

It is anticipated that the Interpersonal Level will be the level analysed as the purpose of the DGs will be the development of the User Requirements and the Usability of the prototypes. How people communicate within the group will not provide additional information. This is the advantage of the DG over individual interviews (Millward, 1995) because they provide additional information as opinions are formed through the structured discussion process. The outcome of DG is that issues may be raised that may otherwise not have been considered during the design of the DG.

According to Jordan (1998), there may be instances where the setting of *a priori* usability criteria may not be either possible or practical and as such it may be beneficial to enquire from the users what criteria they would accept.

Advantages of Discussion Groups

DG's can be used at any time of the design process. According to Jordan they are not particularly good methods for obtaining quantitative data. Therefore it was decided that where possible, and without affecting the groups dynamics, additional methods of data collection would be used to obtain quantitative data that may be of interest to the study (e.g. Questionnaire, role play etc).

Although DG's are excellent for establishing user requirements, they may not necessarily involve the users in a hand's on way (Jordan, 1998). Therefore, the use of workshops was investigated. Workshops provide a direct method for enabling user participation. Jordan seems to distinguish the two methods from each other it was felt that for this project an amalgamation of practical investigation methods within the framework of a structured group discussion could be used. To this end, although the overall philosophy of discussion groups and workshops were adopted, the format of the structured discussion groups was decided by;

a.) The participants;
b.) The Life cycle stage;
c.) The information requirements;
d.) The need to involve the participants and not allow them to get bored;
e.) To obtain as much information as possible from the participants in one session/sitting/group.

The final point was extremely important because due to the lack of user responses to the questionnaires, the discussion groups would need to cover more areas than may be covered in a typical discussion group session. An example of this was that three of the discussion groups sessions lasted for between four and six hours, whereas DGs usually only last for 1 to 1½ hours.

When preparing for the DGs there are several considerations, including who will participate, what questions will be asked, where will the discussions be held, and who will conduct the sessions? Once this has been established it was necessary to develop a discussion guide. The discussion guide should contain the questions that will be asked to participants during the discussion sessions and approximately 10 to 15 questions should be used. There were two elements to be considered when drafting the guide (Krueger, 1995). Firstly, identifying who to obtain information from and secondly, what type of information was to be obtained. The information is normally derived from transcripts of the discussions held during each session. However this will be complemented for this research with questionnaires, record sheets and user trials of the methodology prototype.

It is generally recognised that when developing the questions that all discussion groups should follow the same discussion guide. A question such as "Who benefits the most from the methodology?" could receive different responses depending on whether the participants are users, or non-users. By using a general format for each question, it allows the analyst to make comparisons between the responses of the various groups. However, in this study the information requirements from each participant category may be different and as a result the structure and questions for each group category may vary. The structure therefore, of each discussion group category may need to undergo iterative changes following the previous DG. It is envisaged that the DGs will provide a suitable research method for the Design and Development Stages of the Life Cycle.

Table 55: Adaptation of Research Methods and Areas from Morgan (1998)

STAGE OF DISCUSSION GROUP RESEARCH	LIFECYCLE STAGE	ADAPTED DISCUSSION GROUP METHODS
Problem Identification	**2**	• Generating Research Questions • Needs Assessment of users • Generating ideas for assessment method
	3	• Identify changes that need to be made to methodology
Planning	**2**	• Research Designs • Developing new methodology • Develop Usability Matrices
Implementation	**2**	• Data Collection of subject's requirements and functional specification • Data collection about process requirements
	3	• Data Collection • Implementing methodology • Monitoring User Responses
Assessment	**2**	• Analysis of Requirement's Data • Analysis of Usability Data
	3	• Methodology assessment Usability and Performance • Analysis of User recommendations

During this study, a series of DGs will be conducted to obtain information regarding:

- The characteristics of those representative users that would apply a heat stress methodology as part of their risk assessment strategy,
- The problems they may currently face when assessing heat stress.

4.2.4 Informal exploratory interviews.

A poster presentation entitled "**Heat Stress in British Industry: A usable and practical assessment methodology**" was presented at the BOHS Annual Conference 1998, at the Institute of Education, Russell Square, London. The author conducted informal interviews with attendees of the conference who stopped to read the poster. 38 attendees stopped to view the poster presentation. The following is a breakdown of the brief notes that the author made following talking to attendees (interviewee).

Results - Informal Interviews

Heat Stress Risk Assessment and Indices

- 18 people reported previous or recent experience of heat stress in their workplace. Not all the interviewees were from the United Kingdom, (four from Australia, one from Iran, two from the Gulf, one from Japan)
- They were all aware of Bedlings and Hatch's Heat Stress Index (HSI).
- All had experience of the *WBGT* index or the ACGIH TLVs.
- Only 4 knew about the $SW_{req}$and only 1 of the 4 had used the SW_{req} index, with the other three not using it as they felt it was too complicated.
- All 4 however, knew that SW_{req} should be applied if *WBGT* values are exceeded.
- Confidence in the *WBGT* standard was expressed by all the interviewees although the limitations of the *WBGT* index were acknowledged.

SW_{req} as a control tool of heat stress conditions.

- None of the 4 interviewees who knew of the SW_{req} index knew that it could be applied to investigate if changes to the environmental, clothing and/or working parameters as part of their control strategy could be suitable.
- All the interviewees expressed an interest in an index that could be used in such a manner.
- None had used the WBGT in this way either.

Heat stress experiences.

- The interviewees did not feel that there was a high incidence of heat stress in industry, although they did qualify this by stating that this was based upon their own individual experiences.
- Some of the interviewees who had assessed hot working environments had had some difficulties assessing the risk of heat stress.
- All interviewees said that additional information was needed.
- From their descriptions of anecdotal stories of their experiences assessing heat stress, the following points have been established:

Measurement of body temperature

- Eleven of the interviewees expressed confusion over the use of 38°C as a limiting criteria for core temperature. They had experienced aural temperatures in excess of 38°C (with 3 interviewees obtaining measures above 45°C) with workers showing signs of thermal discomfort, but not thermal strain or stress. After a brief conversation about the techniques they had employed the author identified that they had been measuring body temperature incorrectly.
    - **Aural Temperature**: Four of the interviewees had not insulated the auditory canal from the external environment and as such the environment had contaminated their measure. The method that they had adopted had been as a result of following the instructions from the manufacturers of aural temperature measuring devices. None had read ISO 9886 (1992) *Evaluation of thermal strain by physiological measurements*.
    - **Tympanic Temperature**: Six of the interviewees had used commercially bought infrared thermistors to measure tympanic temperature without identifying its environmental operating range.
    - **Oral Temperature**: Six of the interviewees had used mercury in glass oral thermometers to measure oral temperature during and post exposure. None were aware of the limitations associated with the use of this as a technique in warm or hot environments, or where workers have been breathing through their mouths. All of the interviewees had taken the standard 4 minute measure of oral temperature and had not allowed for a longer stabilisation time of oral temperature when the mouth is closed as recommended by Candas.
    - **Rectal and Oesophageal**: None of the interviewees had used either rectal or oesophageal temperature as they felt it was too invasive. A couple of the interviewees said that in certain cultures the use of rectal temperature would not be acceptable.
- None of the interviewees had used radio pills to obtain body temperature.

Measurement of skin temperature

- Only 2 of the interviewees had measured skin temperature. Here it was generally felt that the equipment needed would be too complicated to use and they were unfamiliar with how to interpret the information they would receive. Those interviewees that had measured body temperature had done so because they felt it was more important than skin temperature because it gave them a measure of they could associate with risk.

Measurement of metabolic rate

- None of the interviewees had ever measured metabolic rate as part of a risk assessment;
- One interviewee had, on occasion, called in an expert to measure the metabolic rate of the workers. The results, the interviewee said, were discarded because there was a large variation in the measures, both between measurements of different workers doing the same work and between different measures of the same worker.

Estimation of metabolic rate

- Only 12 of the interviewees questioned had estimated metabolic rate. They had all used the table presented in the *WBGT* or ACGIH TLVs.
- All the interviewees also expressed a view that they had found the process very difficult and that they did not have confidence in the figures that they had arrived at.

Discussion - Informal Interviews

Very few of the interviewees have experience or knowledge of the SW_{req} index, yet they all were aware of the HSI index. This would suggest that the training of occupational hygienists does not incorporate the SW_{req} index as an accepted approach to the assessment of heat stress in industry. This may be due to the fact that the standard is relatively new (published in 1989), compared with the *WBGT* or ACGIH TLVs which are well established. There is obviously a need for an index that can be used to investigate possible control approaches to aid occupational hygienists in the task of control strategy identification and implementation. It would seem therefore that if the validity of the standard can be improved and the envelope of its application clearly established to improve the confidence in its predictive capabilities in those people of influence within the BOHS, it may be more widely used and accepted as a heat stress index.

The benefit of using an index in this way would obviously provide the occupational hygienists with a valuable tool which not only tells them whether or not they have a problem, but how different solutions may help control the risk of heat stress if it is identified. There is a poor level of understanding of how to correctly and accurately measure and interpret the physiological responses of workers in hot environments. This is clearly indicated in the magnitude of errors that were made when measuring body temperature. Furthermore it brings into question the setting of limits that have been established scientifically when those people who are meant to interpret these limits do not query their techniques when these limits are exceeded by such high levels as those recorded (e.g. 45 °C).

Conclusions - Informal Interviews

- Few of the interviewees had experience of ISO 7933 and those that had found it difficult to use.
- All the interviewees were aware of the *HSI* and *WBGT* indices.
- There is both a need and an interest in a methodology that allows for control options to be identified, evaluated and implemented.
- There is also a need to either better promote the standard (such as ISO 9886) or to provide a guidance document which includes all the relevant information.
- All interviewees said that additional information was needed as they found the heat stress assessment process complicated.

4.2.5 Hierarchical Task Analysis (HTA) of Heat Stress Standards.

The HTA was conducted to identify if there were any areas where the current heat stress standards do not support the tasks that would ordinarily be performed as part of a heat stress risk assessment. This would also provide for a comparison of how the process differs from the 5 Step Risk Assessment strategy prescribed by the HSE. A detailed HTA of all processes described in each standard was conducted. The HTA has been simplified for this report to provide the following process diagram of how the standards may be applied and is presented in Figure 9.2.

HTA Findings

The format and sequence of the standards is such that the user is required to go directly into the measurement of the physical environment. None of the standards require of the user to conduct the first stage of requirement of all other risk assessments: **Identifying the Hazard**. This introduces a number of problems in that it does not follow the sequence or “steps” that users are familiar with from using other established risk assessment approaches. Thus, the risk assessment process as described in the standards does not conform to user expectation, user knowledge of risk assessment, transfer of knowledge from one risk assessment to another, and probably most importantly to the tried and tested sequence of appropriate risk assessment strategies. Furthermore, the standards appear somewhat complicated and where flow diagrams are used, they explain a theoretical process and not the actual practical process that the user is expected to follow. The underlying structure however is there, with the umbrella document (ISO 11399) providing a overview of the different thermal standards.

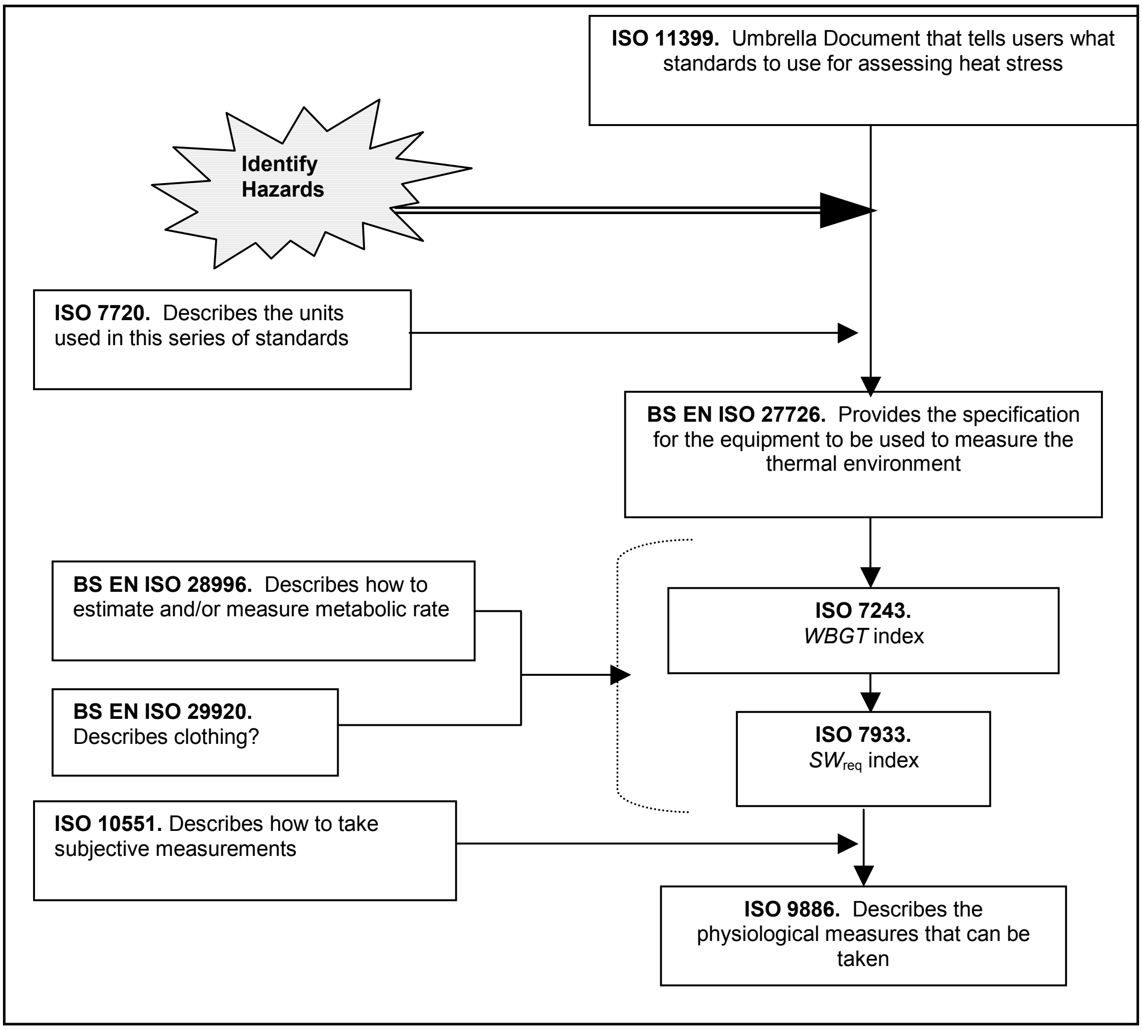


Figure 21: A simplified process diagram of using current heat stress standards to conduct a heat stress risk assessment. The “burst” shape shows where an observation method to identify the hazards may be introduced

4.2.6 Field Trials – Heat Stress Assessment in a Paper Mill

This section describes an example of how the WBGT and the SW_{req} index may be used in an industrial setting. The results of the assessment are provided following a description of the experimental protocol and results of physiological measures.

Introduction

The Health and Safety Executive (HSE) approached the Human Thermal Environments Laboratory (HTEL) to conduct a heat stress risk assessment in a Paper Mill. The study team was Professor K. Parsons and D. Bethea. The Paper Federation and the HSE Paper mill National Interest Group endorsed the assessment. The study was conducted in response to complaints of thermal discomfort while working in the basement of Paper Machine number 3 (PM3) and not as a result of any incidents in the mill relating to reported heat stress illness or accidents.

Method

Subject

One male volunteer took part in the study. He was an experienced paper mill worker, having worked at the plant for 21 years. He was 59 years old and he estimated his weight as being 70 Kgs and his height as being 167 cm. The subject was notified that he could withdraw from the study at any time, and following a description of the experiment and the measures to be taken, he provided informed consent and completed a medical questionnaire.

Apparatus

Environmental Measurements

Wet bulb globe temperature (*WBGT*), air velocity and humidity were measured on equipment conforming to the specifications as described in ISO 7726 and ISO 7243. All data was measured and stored on an Eltek 1000 Series Squirrel Data Meter/Logger at one minute interval.

Physiological Measurements

To record the subject's responses to the thermal environment a number of physiological measurements were taken at one-minute intervals. All measures conformed to the requirements stipulated in ISO 9886. The measures taken were aural and skin temperature and heart rate.

Calibration of measuring equipment

All equipment was calibrated pre and post study in the facilities at HTEL.

Procedure

The purpose of the study and the methods involved were explained to the line manager, the Union representative and the volunteer. All parties agreed to the procedures and once the subject had provided informed consent he was instrumented for taking physiological measures. Environmental measurements were taken at abdomen height within 2 metres of the area where the worker conducted most of his tasks within the basement. No measures were taken on the forklift truck or the area outside of the basement area of PM3. The physiological measures were taken for the duration of the study and recorded at 1-minute intervals throughout the assessment. Additional recordings were taken of the time it took the worker to conduct his tasks, along with any incidents that occurred, such as paper breaks etc. Visual recordings of the workplace and the nature of the work were made using a digital camera and video camera. The study team did not involve themselves in any way with the work the subject was performing and the worker did not perform any tasks other than those expected as part of his every day duties. The physiological measures continued during the subject's lunch break. The study was terminated at the subject's request.

Results

The results of the environmental and the physiological measurements are presented. The assessment of the basement is then presented using the *WBGT* index.

Environmental Measures

WBGT Measures

All data presented is for the periods once the black globe thermometer had reach equilibrium (after 30 minutes).

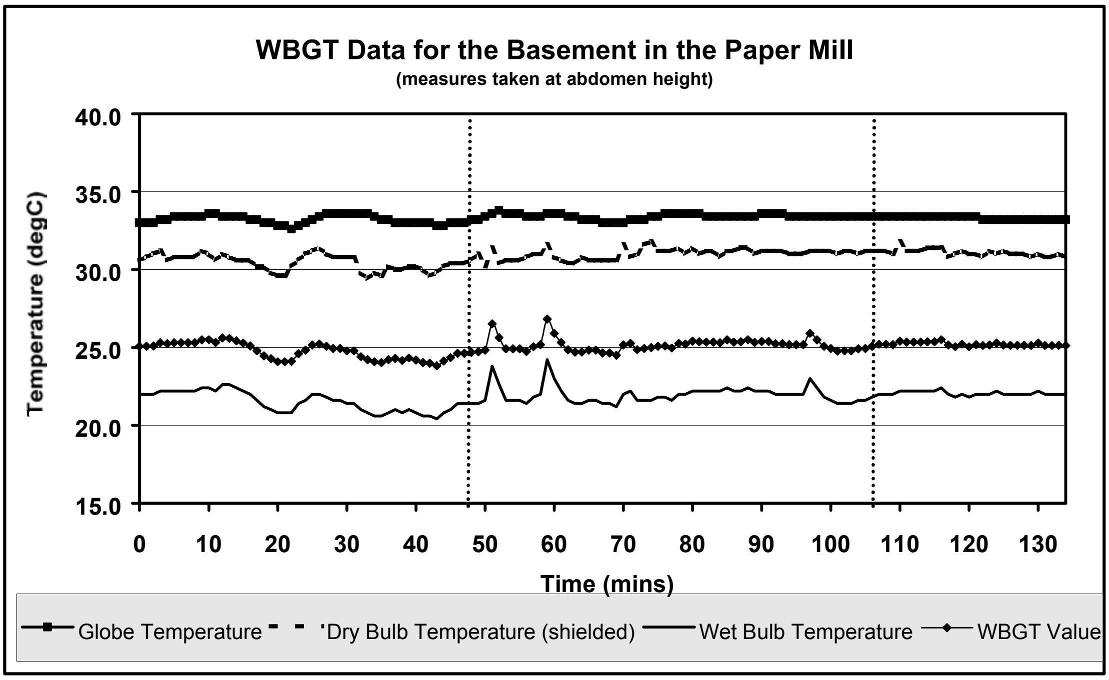


Figure 22. Line graph showing the WBGT values measured at abdomen height in the basement at the Paper Mill. The dotted lines show the hour that provided the highest WGBT value for the duration of the measurements.

Table 56: The descriptive statistics for the *WBGT* values measured at abdomen height in the basement at the Paper Mill.

	GLOBE TEMPERATURE	DRY BULB TEMPERATURE (SHIELDED)	WET BULB TEMPERATURE	WBGT VALUE
	°C	°C	°C	°C
Mean	33.3	30.8	21.8	25.0
SD	0.23	0.48	0.58	0.47
Minimum Value	32.6	29.4	20.4	23.8
Maximum Value	33.8	31.8	24.2	26.8

Figure 22shows the *WBGT* measures in the basement at abdomen height. The three small peaks observed in the wet bulb temperature and the resultant peaks in the *WBGT* value correspond with moments when large amounts of hot wet paper fell into the basement as a result of significant paper breaks. The descriptive statistics described in Table 1, show that the mean *WBGT* value at abdomen height in the basement as being 25°C. However the mean value for the period between the dotted lines in Figure 2 is 25.2 °C. According to the *WBGT* methodology it is this figure that should be used when assessing an environment.

Physiological Measurements

Heart rate, aural temperature and skin temperature were measured. From the temperature measures, the mean of each was calculated.

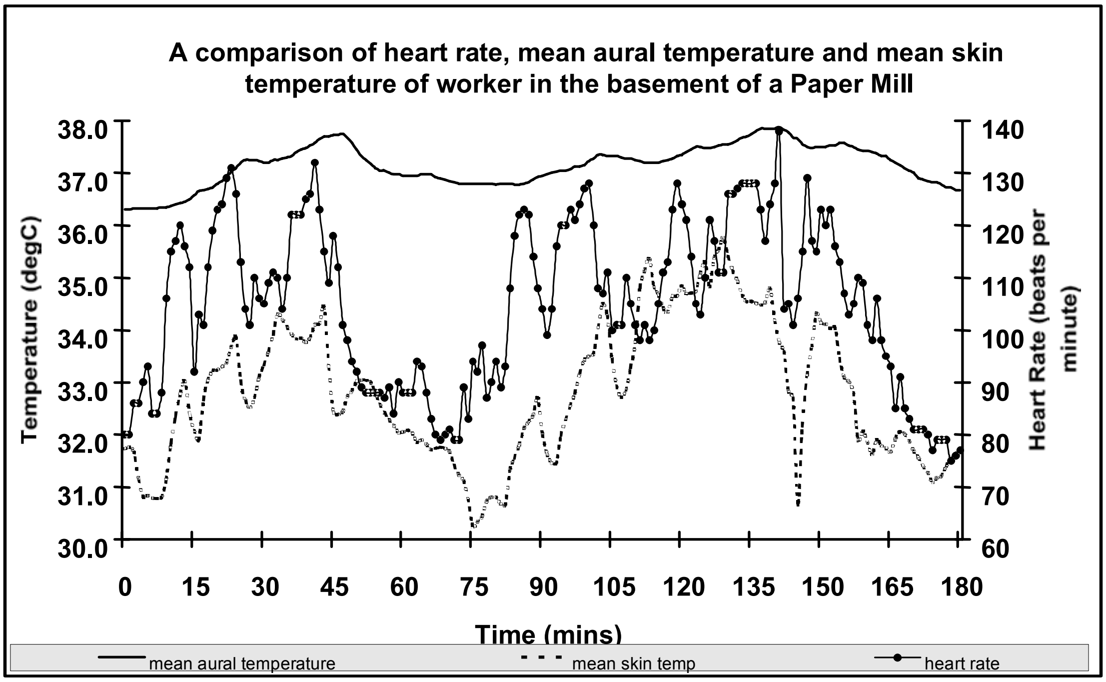


Figure 23. Line graph showing the relationship between mean aural temperature, mean skin temperature and heart rate over time.

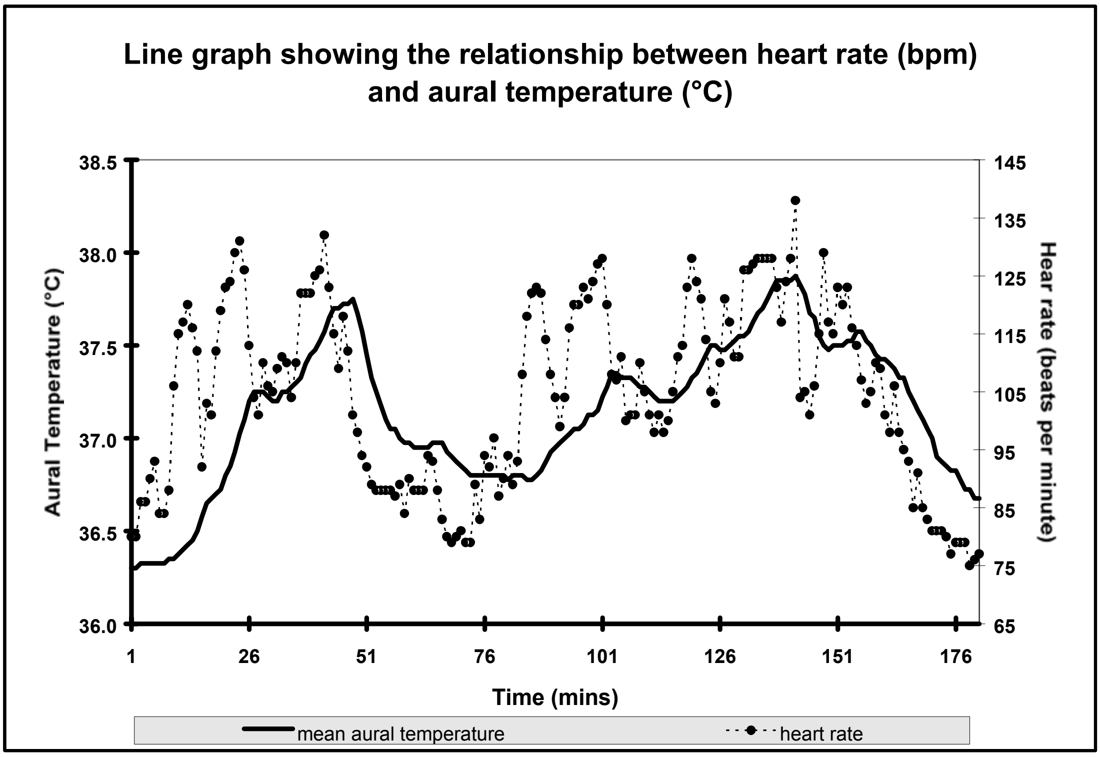


Figure 24. Line graph showing the relationship between mean aural temperature and heart rate over time.

From **Figure 23**, it can be seen that under the conditions studied, heart rate closely mirrored the changes in both mean skin temperature and mean aural temperature. In **Figure 24**the relationship between mean aural and heart rate over time can be seen more clearly. The peaks in both heart rate and the mean skin temperature profiles are at the same times as the two observed peaks in mean aural temperature. Mean skin temperature is also approaching 36°C at around 130 minutes.

Estimating the work rate by observing the worker.

From the heart rate profile above and from timings taken during the study the following graph has been produced. The work rate was separated into 2 main categories:

- L = Loading the skip with paper in the basement.
- U = Unloading the skip.

(For further information, see the Table presented in the Annex that describes the timings and the breakdown of tasks that make up the categories.)

The categories are presented in the graph below as blocks. The blocks show breaks that the subject took during the study. The first was a lunch break, while the second was at the end of the study.

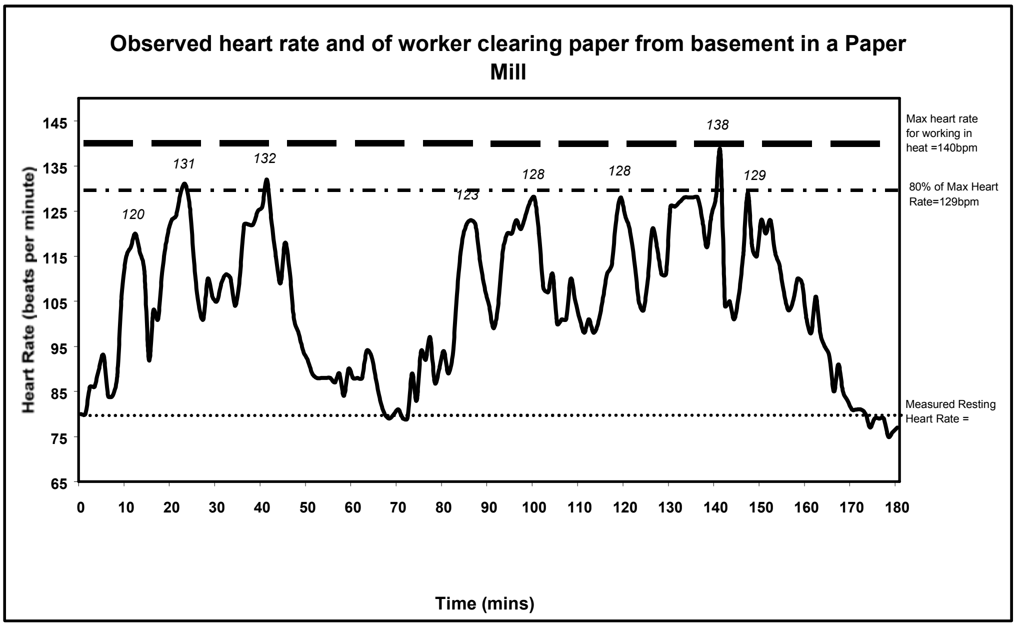


Figure 25. Line graph of heart rate measures taken overlaid by observed work sequences (L=Loading, U=Unloading.)

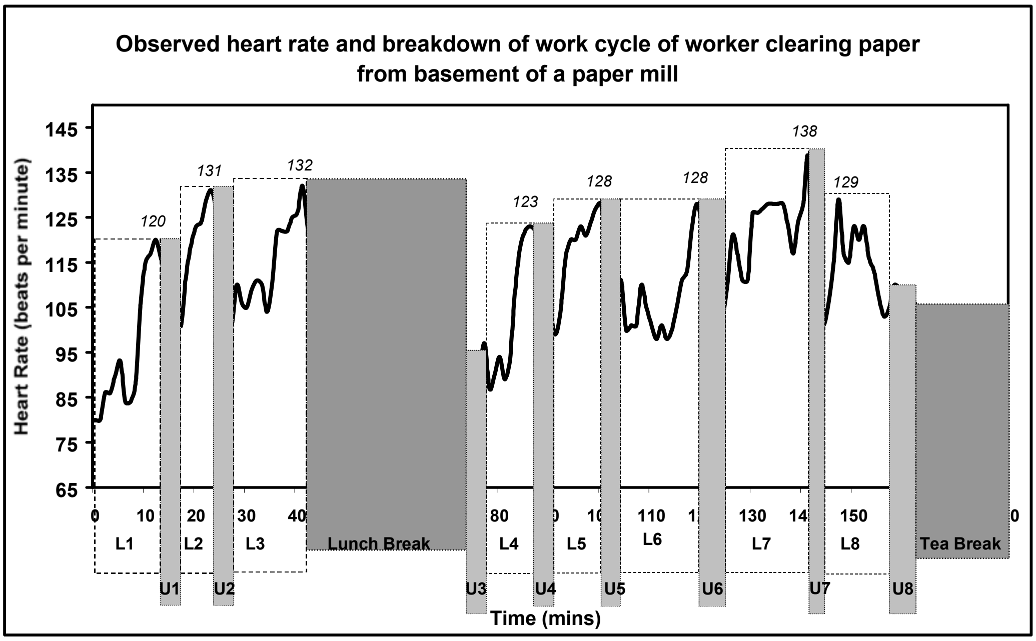


Figure 26. Line graph of heart rate measures

Reference lines for resting heart rate, 80% of the workers maximum heart rate under normal exercise conditions (80% of MAX = 129bpm, where MAX = 220-AGE) and the recommended maximum of 140 beats per minute for workers over 35 years old working in the heat.

A mean metabolic rate was estimated using ISO 8996 (1994). By breaking the work into the following components, an overall estimate of metabolic rate was achieved. (For further information see workings described in the standard.)

Table 57: Breakdown of the calculation of mean metabolic rate by calculating metabolic rate for the different component tasks (as described in ISO 8996)

ESTIMATION OF METABOLIC RATE DURING LOADING OF SKIP

From observations: Mean time spent LOADING skip: 11.5mins

DESCRIPTION OF ACTIVITY	DURATION (sec)	METABOLIC RATE W.m^{-2}	TOTAL ENERGY J.m^{-2}
Walking in the factory interior at about 2km/k	120	110	13200
Bending to pick up paper	180	160	28800
Carrying paper	210	235	49350
Lifting paper into skip	180	235	42300
Total	690		133650
Average metabolic rate		194	

ESTIMATION OF METABOLIC RATE DURING UNLOADING OF SKIP

From observations: Mean time spent LOADING skip 5.5mins

DESCRIPTION OF ACTIVITY	DURATION (sec)	METABOLIC RATE W.m-2	TOTAL ENERGY J.m-2
Dragging the skip to the door	30	260	7800
Driving the forklift truck	240	120	28800
Walking in factory at about 2km/h	30	110	3300
Pushing skip back into the basement	30	195	5850
Total	330		45750
Average metabolic rate		139	

OVERALL ESTIMATION OF METABOLIC RATE DUIRING THE WHOLE WORK CYCLE

From observations: Mean time spent during each L and U cycle: 17 mins

DESCRIPTION OF ACTIVITY	DURATION (sec)	METABOLIC RATE W.m-2	TOTAL ENERGY J.m-2
Loading Skip	690	194	133650
Unloading Skip	330	139	45750
Total	1020		179400
Average metabolic rate		176	

- Mean Metabolic Rate = 179 W.m^{-2}

Intrinsic insulation of clothing values (Icl).

ISO 9920 was used to estimate the intrinsic clothing insulation values of the clothing worn by the worker. The result was a clo value of 0.56 clo which was rounded up to provide a value of 0.6 clo.

WBGT index

From the *WBGT* reference table (see Table 4) the reference values for a metabolic rate of 179 W.m^{-2} are:

- Acclimatised worker = 28°C
- Unacclimatised worker = 26°C

The mean of the measured *WBGT* value was 25°C, however as discussed above the mean of the hour that gives the highest value should be used. Therefore the value to be used should be 25.2°C.

Required Sweat Rate index

The following data was entered into the SW_{req} program which is described at the back of the standard.

Air temperature (°C)	= 30.8
Globe temperature (°C)	= 33.1
Wet Bulb temperature (°C)	= 21.8
Air velocity ($m.s^{-1}$)	= 0.4
Metabolic rate ($W.m^{-2}$)	= 179
External Work ($W.m^{-2}$) =	= 0
Body fraction area exposed	= 0.77
Clothing insulation (clo)	= 0.6

Program calculated the following environmental parameters:

Mean radiant temperature	= 36.4
Partial vapour pressure	= 2.011

From this input data, the program predicted the following DLEs and predicted sweat rates (SWp).

Table 58: ISO 7933 SW_{req} predictions of DLE and SWp for the basement area in the paper mill

		DLE (MINS)	SWP (G/H)	REASON FOR DLE
UNACCLIMATISED	**Alarm**	300	520	Excessive water loss
	Danger	339	575	Excessive water loss
ACCLIMATISED	**Alarm**	406	575	Excessive water loss
	Danger	No limit	575	None

Discussion

The results as presented in the previous section are discussed in detail below.

Environmental Measures

The basement, under the environmental and personal conditions that were measured and estimated during this study does not exceed the recommended *WBGT* reference values.

Physiological Measurements

It is evident from the graphs of the physiological data that there was an accumulation of stress on the subject during the periods before and after lunch. At the lunch-break the worker commented that he was feeling hot and therefore was stopping for work, which was mirrored in his heart rate and aural temperature at that time. This is a typical behaviour that may be observed in experienced workers who adapt their work to subjective self-monitoring. Inexperienced workers may not have developed these patterns. A further point to consider is that if a worker is under pressure due to “down-time”, he may not be able to behave in this self-regulatory way. It is therefore important that workers are made aware of the need for frequent breaks from hot environments.

When increases in temperature in the body are observed, blood flow to the skin increases through the dilation of the blood vessels beneath the skin. This encourages the movement of heat from the blood, through the skin to the environment, thereby reducing the temperature of the blood returning to the heart, lungs muscles etc., where it is re-heated and the process continued in order to maintain core temperature. As skin temperature increases so the amount of heat that can be transferred per unit of blood will reduce linearly. As a result of this, heart rate increases in an attempt to maintain cardiac output while the volume of blood pumped during each beat decreases.

The worker's heart rate was close to, or over, what would ordinarily be considered his aerobic threshold value and at the end of the final session that he was approaching the maximum of 140 bpm for working in the heat. Under these conditions and at these heart rates, a conflict between the thermoregulatory system and the cardiovascular system may arise. This complication associated with the increase in heart rate arises because the capacity for exercise (or work rate in an occupational setting) decreases as the thermorgulatory response overrides any cardiovascular need to provide blood and oxygen to the muscles for exercise at sub maximal work rates. This is exacerbated by the loss of water through sweating because large sweat losses reduce the body's water content (hypohydration).

Again, during hotter months, the worker may well exceed these values and it may be necessary to introduce regular rest breaks. Additionally, the employment of lifting aids, correct lifting techniques and the introduction of a buddy system may help to further reduce the worker's metabolic heat production. Reducing the worker's metabolic rate would decrease their metabolic heat production that in turn would provide a lower deep body temperature.

Estimating the work rate by observing the worker

The method used to estimate the metabolic rate of about 15% could be expected. This error would still keep the worker in a work class that would be considered "**moderate**".

Intrinsic insulation of clothing values (Icl).

The clo value of 0.6 clo estimated as worn by the worker does not exceed the clo values that lead to the development of the *WBGT*. Therefore no reductions to the *WBGT* reference value are required.

Heat Stress Indices

WBGT Index

The basement, under those environmental and personal conditions that were measured and estimated during this study, does not exceed the recommended *WBGT* values. The observed mean value for the hottest hour was 25.2°C. The *WBGT* method requires the user to make a distinction between acclimatised and unacclimatised workers. However, best practice in industry suggests that it is safest to assume that all workers are unacclimatised. Therefore, it is recommended that the *WBGT* value be adopted as 26°C. Since the observed mean value and the limit value suggested by the standard are with 1°C of each other, it may be necessary for further measurements to be taken during hotter months when it is anticipated that this value will be exceeded.

SW_{req} index

Although the *WBGT* reference values were not exceeded they were sufficiently close to the observed values that it was decided to use the SW_{req} index to evaluate the risk of the worker suffering from heat stress. The interpretation of the input values gave DLEs greater than 300mins which is less time than time between breaks observed on the day even though the WBGT reference values were not exceeded. This supports the findings of Kähkönen *et al* (1992) and Peters (1991). One problem though with the SW_{req} model is that it is very sensitive to the metabolic rate input value and the DLE may vary greatly depending on the value obtained for the estimation of metabolic rate. However, an important point here was the fact that excessive water loss was the limiting factor and not an excessive increase in deep body temperature. This suggests that workers must be encouraged to drink water regularly throughout their shift with a minimum suggested amount of 500 ml (about a pint) per hour during the shift. Care should also be taken to make the workers aware of the dangers of diuretics such as caffeine based products (tea and coffee) and alcohol when working in an environment that may cause excessive water loss through sweating. The DLEs and SW_p should only be used as guidelines and common sense should prevail. (If a worker is feeling hot, they should be able to rest.)

Other observations

The worker was sweating profusely during the observation period. Although drinking facilities are provided on the main factory floor, the worker did not take a drink break during either work period. Dehydration may be a problem under these conditions and the worker should be encouraged to take regular breaks during his shift. Introducing water stations at or near the basement area could facilitate this.

Conclusions

- The mean *WBGT* value measured at the front of the basement for the hottest hour was 25.2°C.
- The intrinsic clothing insulation of the clothing was estimated as 0.6clo.
- The estimated metabolic rate for a worker clearing paper from the basement was 179W.m^{-2}
- The *WBGT* references value for a metabolic rate for unacclimatised worker working at a work rate of 179W.m^{-2} as described in the standard ISO 7243 is 26°C. This reference value was not exceeded under the conditions studied. However the study was conducted during October and therefore during hotter summer months this reference value will almost certainly be exceeded. Therefore a more detailed assessment using the Required Sweat Rate index is recommended.
- The SW_{req} index suggested that the workers might be prone to excessive fluid loss. Fluid replacement strategies are therefore recommended that encourage the worker to drink a minimum of a pint of water pre hour spent in the basement area.
- The worker was working at or above their normal anaerobic threshold heart rate and just below the absolute maximum for working in the heat. This would provide unnecessary additional stress and the worker should be monitored. Two possible solutions are recommended: 1) Heart rate should not exceed 120bpm, thus allowing for a possible 20bpm variation between individuals at the 140bpm threshold. 2) Further monitoring of the worker performing the task in a neutral environment would enable the establishment of how much the thermal strain is causing heart rate to increase (usually an increase of 1°C = a 30bpm increase). The threshold could therefore be set at heart rate at neutral plus 30bpm (if this is lower than 120bpm).

- It is recommended that a buddy system or improved lifting techniques and the use of lifting aids should be introduced to reduce the overall stress experienced by the worker.

The overall findings are that although the worker was not showing any direct signs of heat stress, that the interpretation of the combined physiological responses suggests that he was on the threshold of suffering from mild heat stress.

4.2.7 CONCLUSIONS OF STAGE 1 – Exploratory Stage

The exploratory stage provided the necessary background and practical knowledge of the process of conducting heat stress risk assessments based on the information and structure provided by the relevant international standards.

1.) The process of conducting a heat stress risk assessment is complicated because of the need to consider the 6 basic parameters. Discrepancies may occur between the *WBGT* and the SW_{req} predictions.
2.) The complexity of current standards (specifically ISO 7933) seems to negate its use in industry. This was shown by the interest of the interviewees in an index that aided the investigation, evaluation and implementation of controls, which ISO 7933 allows through the entering of input different environmental and personal values.
3.) Current heat stress risk assessment methodologies and standards do not follow the well established format of risk assessment. No HAZARD Identification stage is provided in the standards. There appears to be a need for such a method so as to be consistent with other hazard risk assessments.

4.3 STAGE 2: DESIGN AND DEVELOPMENT STAGE

4.3.1 Introduction

It has already been shown that there are a number of appropriate heat stress indices and standards which, theoretically, have established a mechanism for best working practises in the assessment of heat stress in industry. Occupational Hygienists are expected to use these methods to assess hot working environments and then to implement the appropriate control strategies to reduce the risk of heat stress to the worker. An overall strategy for the assessment of heat stress has been developed from these standards and from the existing requirements for generic risk assessment procedures. This section will discuss the design and development of a practical heat stress assessment methodology.

4.3.2 Rating and Ranking Methods for Risk Assessment

> "*Determining the relative importance of risks is an important element in risk assessment that identifies high risk areas which will demand a greater proportion of resources, both in the level of maintenance and control measures. Rating or ranking risks in relative importance can contribute to establishing risk control priorities*" (HSE, 1991)

Traditional methods of estimating risk, using exposure, consequence etc may not be possible due to the interaction of the thermal environment parameters. Added to the need for a visual methodology so that hazard identification and qualitative risk assessment can be done, a literature review of subjective rating and ranking methods in risk assessment was conducted. The aim of the review was to investigate what types of subjective assessment methodologies were currently being used elsewhere in risk assessment and whether any precedents had been set. This would provide the rationale behind any design decisions that may be made.

Risk assessment methods differ significantly dependent on whether quantitative or qualitative criteria have been set. It is this choice of perspective (quantitative vs. qualitative) that determines both the meaning of the probability/scores values and the interpretation of them. Therefore the establishment of qualitative values needed to be justified to ensure that where possible they accurately reflected the probability of risk. These ratings or ranks also needed to be in a format that the users would be able to understand and interpret.

Since it is the interaction of the six basic parameters, as well as our health status and state of acclimation, that determine our physiological responses to our environment, it would be extremely difficult to develop a qualitative methodology that would be both robust across any number of possible occupational situations while providing a valid indication without the use of objective data.

When estimating risk based on exposure-response analyses, epidemiologists use "*cut-points*" (statistical criteria such as quartiles, means etc) to categorise exposure-response analyses. This usually relies on an exponential relationship between the cause and the consequence, which according to Sullivan *et al* (1996) is an incorrect assumption to make. They cite work by various authors to explain the use of "*categorical exposure indices*", which have the advantage of assuming there is no specific or quantifiable relationship between the exposure and the response. Although this categorical strategy is statistical, it provides a possible philosophy whereby each of the thermal parameters are categorised and rated according to how differing levels/values of each may contribute to heat stress without providing a quantitative "*cut-point*" for this.

By describing the environment, the clothing, the work rate, the worker's state of acclimation and their health status as sequential categories with increasing magnitude of effect on heat stress, the user may be able to provide a risk-based measure. An example of an observation based risk assessment technique is found in the nuclear industry. "*Inservice Inspection*" (ISI) strategies which rely on visual inspections and condition monitoring to obtain a risk-based estimation of equipment failure enable the user to identify failure risks in terms of failure probabilities and rates (Balkey *et al*, 1998). A fundamental requirement of this strategy is that the user is required to make judgements of probabilities of failure occurring on plant equipment through the observation of component parts such as welds, pipes etc. Here too, the ISI strategy employed is not directly transferable to the assessment of heat stress, but there are processes that, if adapted, may provide foundations for the heat stress observation-checklist. It may be possible to provide an overall score for the risk of heat stress based on the contribution that each parameter may provide through the rating score it is given. It may also allow the user to identify where reductions in the risk can be made. This may be done for each individual parameter and thus for the overall risk score. Additionally, a conceptual decision, such as that described by Balkey *et al* may also be adapted to aid the user's decision making process. Three issues are raised by this:

1. How can the user's decision-making process be aided?
2. What scores are applied to each category and each parameter and how are they arrived at?
3. Will the scores be representative of the contribution to the risk that each parameter, and the combination of all parameters, may provide?

The decision-making processes and the scores attributed to each category are not independent of each other. Any score obtained will be directly dependent on the decisions the user has made and conversely the decisions made by the user may be influenced by the scores. Analysis of the decision making process shows that it involves the user evaluating the "*evidence*" (the thermal environment) and then determining what the successful way of achieving the set objective is (to identify if there is a risk of heat stress) (Chicken and Hayns, 1989). The success of this though is reliant on sufficient and valid information being presented to the user. Additionally, it is important that as much information as possible is provided to limit the possibility that even when subjective views are required that the same or similar results are achieved. (This argument can also be supported mathematically, although the probabilities (ratings) are based on expert opinion and not on empirical heat stress data as the probability data are not available.)

A number of authors, including Pate (1983), Spencer *et al* (1985) and Covello (1994), describe the need to consider the mathematical foundations of subjective scores. The theory described is called *Bayesian* or *judgmental view*, which states that when using subjective views, the probability (of risk) is no longer purely a function of the situation but also of the state of the information. This is understandable, since judgements can only be made based on the information provided. Since the information provided is independent of the user, it should be presented in such a way as to ensure that two people with the same background knowledge would assign the same probabilities (ratings). Insufficient information may not allow for sufficient choice, while too much information may only serve to confuse the user. Interestingly though, the literature also shows that most rating scores are allocated arbitrarily based on expert opinions. The Bayesian theory also seems to allow for this, as the theory is based on health and safety experts being ideally suited to providing subjective opinions. This can be done without the need to consider what Covello calls the "*classical" theories of probabilities*." This point is particularly important because no data are available about the risk probabilities that may exist under different combinations of thermal environment parameters. Therefore, any ranks or rating score, would be based on the opinion of an expert.

The ranking (rating) of hazards also allows the user to identify areas of concern where possible control options may be implemented as well as presenting the user with an order of the level of concern they may represent. HSE (1991) reported that in addition to the establishment of risk control priorities, systems that assess relative risk could also aid in:

- Deciding Health & Safety Objectives and Goals;
- Prioritising and improving levels of competence and training;
- Identifying high risk areas that require more detailed monitoring;
- Identifying areas that may require immediate control intervention;
- Deciding what levels of controls are required, the extent of resources etc;
- The review of control and intervention strategies.

However, this process is usually done using the risk estimation equation.

Types of Rating and Ranking methods in the literature

Everley (1994) reported that St John Holt and Andrews (no date) (Table 10.1) and the Croner Health and Safety at Work Bulletin Issue (Table 10.2) provided simplified scoring systems. The system by St. John and Andrews was based on rankings awarded according to severity and probability, while that by Croner, multiplied the ratings for frequencies and severity to obtain a risk rating. The risk ratings with the highest score indicated the highest risk rating.

Table 59: Hazard Ranking as cited by Everley (1994) (after St John Holt and Andrews, nd)

SCORE	SEVERITY	SCORE	PROBABILITY
1	Catastrophic	**1**	Probable
2	Critical	**2**	Reasonably probable
3	Marginal	**3**	Remote
4	Negligible	**4**	Extremely remote

Table 60: Risk rating as cited by Everley (1994) (after Croner Health and Safety at Work Bulletin Issue 3)

SCORE	FREQUENCY	SCORE	SEVERITY
1	Improbable	**1**	Trivial
2	Possible	**2**	Minor
3	Occasional	**3**	Major injury to one
4	Frequent	**4**	Major injury to plus one
5	Regular	**5**	Death of one
6	Common	**6**	Death of plus one

The resulting score ranges between 1 and 36 and there are a number of potential problems with the Croner method, as highlighted by Everley, including:

1.) It becomes difficult to distinguish between high frequency low consequence events and low frequency high consequence events (i.e. different combinations give the same result e.g. 1 *x* 6 and 6 *x* 1);
2.) There is no distinguishing between short term and long term risks;
3.) Most assessments may fall in the middle of the range of resulting scores.

The problem with considering these sorts of criteria for a qualitative heat stress assessment methodology is that there may not necessarily be the same classification of consequences in the heat as there are for other hazards such as chemicals, noise etc.

- **Severity**: One area where data are available is in the area of the pathological effects of thermal radiation exposure doses. One such data set are the cause and consequence tables of the effects of thermal radiation on humans (Hymes *et al.*, 1996) which provides probabilities of lethality based on thermal radiation exposure doses and time. However, these are quantifiable because of the pathological nature of the consequences. This is not the case with exposure to non skin-burning levels of radiation, or the other parameters. Severity does not appear to be applicable to the qualitative assessment of heat;
- **Consequence***:* Here too the consequences are not as clear-cut as "*minor*", "*major injury to one*" etc. Added to this is the lack of evidence that there are long term health effects from working in the heat. Therefore if consequence is to be used, it may be better to consider it in terms of how likely is heat stress to occur and/or what magnitude the different parameters may have relative to other parameters in it's category (e.g. clothing). Again this is difficult due to interpersonal differences between people. Harm (strain and stress) from heat is not an easily quantifiable consequence.

This interaction between what Chicken and Hayns (1989) call "technical factors" is not unusual, with these interactions often being "*non-linear*" and "*multi-directional*". The development of the judgements about each interaction or series of interactions often need to be refined during the development stage of the risk assessment process. To do this, justification has to be provided to explain the rationale behind the development of the rational arguments. Where rankings are provided for the different categories and parameters of heat stress, each ranking will reflect the judgement of the author as to the role and place that that category or parameter has in the interaction of the 6 basic parameters. For these rankings to have meaning, an overall philosophy needs to be adopted to describe the magnitude of the individual ranks both as stand alone criteria and when compared to other ranks. To this end, Chicken and Hayns provided an acceptability criterion for technical risks. Their criteria have been adopted for this project: (***Note****: the probability of death criteria heat stress not been included for heat stress*).

Table 61: Technical risk acceptability criteria for Heat Stress (adapted from Chicken and Hayns, 1989)

RISK RANK SCORE	ACCEPTABILITY	COMMENTS
3+	• Unacceptable level of risk from heat stress	• The risk would have to be significantly reduced for it to become acceptable
2-3	• Only acceptable under certain circumstances	• High risk of heat stress. • The risk would have to be reduced to make it acceptable • Further assessment using WBGT and/or SW_{req} required. • Physiological monitoring may also be required.
1-2	• Would require detailed evaluation to justify acceptability	• Moderate risk of heat stress • Further assessment using WBGT and/or SW_{req} required.
0-1	• May require additional evaluation to justify acceptability	• Worker may be experiencing thermal discomfort. • There may also be little risk of heat stress. • Further assessment using WBGT and/or SW_{req} required.
LESS THAN 0	• Little or no risk of heat stress. Acceptable without restriction	• No risk of heat stress therefore no further assessment required.

These ranks are the same as those in the ASHRAE thermal comfort scales and the PMV Scales (although they are polar around a neutral score of zero.)

4.3.3 Structured Group Discussions

There were two main aims of this part of the research.

1.) To provide the information for the specification of a proposed generic heat stress strategy.
2.) To provide the information necessary for the design and the development a practical heat stress assessment methodology which would be part of the proposed generic strategy.

(NOTE: A generic heat stress strategy is not being developed as part of this project. Rather, it will be described as a process which, following further development, would meet current user requirements.)

Two categories of participants were involved in the discussion groups:

1.) Representative users: The representative users were current or past occupational hygienists, occupational medics, health and safety professionals etc.
2.) Experts: These participants were those that are considered to be experts in the field of human thermal environments and consisted of 2 areas of expertise:
    - Academia / Research (***A/R***)
    - Industry (***I***)

All of the experts had experience in the development of heat stress standards.

All discussions would be moderated by D. Bethea.

Expert group discussion

Participants

- Mr. Geoff Crockford GC Occupational Hygiene Consultants (***I***)
- Dr. George Havenith Loughborough University (***A/R***)
- Mr. Robin Howie – Occupational Hygiene Consultant (***I***)
- Professor Rainer Goldsmith, Retired ex Loughborough University (***A/R***)
- Mr. Len Morris HSE, Bootle (***I***)
- Professor Ken Parsons Loughborough University (***A/R***)

Format and Procedure

Each member of the group was telephoned prior to the meeting and a brief telephone questionnaire was conducted to aid in the assigning participants to sub group and to ascertain arrival times etc nearer the date. A week before the session each participant received a Participant's Pack which contained a description of Discussion Groups. This was provided in order to aid the participants to prepare for the Discussion Group and to ensure that their points of view were well formulated. To provide an interesting and varied forum within which the members would interact, certain aspects of each session required the participants to break-up into smaller groups (or subgroups) to discuss specific areas of each topic. (Tables are presented below that show the topics where this occurred.)

The following topics were discussed at the discussion group.

- Current Heat Stress Standards.
- The information levels required
- User Requirements and the Functional Requirements
- Proposed strategy by Malchaire: 3 STEPS
    1.) Observation
    2.) Analysis
    3.) Expertise

Discussion Topics

Current Heat Stress Standards and their effectiveness in industry

The first Topic to be discussed was the role of three current heat stress standards and whether they are effective in assessing, monitoring and controlling heat stress in the industry:

- ISO 7933 (1989), Hot environments Analytical determination and interpretation of thermal stress using calculation of required sweat rate (SWreq).
- ISO 7342 (1989), Hot environments Estimation of the heat stress on working man, based on the WBGT-index (wet bulb globe temperature)
- ISO 8996 (1990), Ergonomics of the thermal environment: Estimation of metabolic heat production.

Each participant was given record sheets upon which they recorded their own views. In addition to these individual sheets, a subgroup sheet was provided upon which the person chosen to be the speaker of each subgroup recorded the subgroup's views and this sheet was used to present the subgroup's views to the rest of the participants. All record sheets were collected at the end of each session and new record sheets for the following session were provided.

Levels of Information Required

This session was specifically interested in the levels of information that the users may require to conduct a heat stress assessment. The participants were asked to decided whether a parameter was of primary importance (absolute requirement), secondary (not an absolute requirement but may prove useful for a more detailed analysis) or Not Required (of no use) for the assessment of heat stress. Upon completion of this part of the discussion, subgroups were again asked to report back to the rest of the group. This time the subgroups were allocated according to their area of employment, with Group A being from Industry, while Group B from the Academic/Research background.
Added to this, participants were asked whether they thought the **user** would have the knowledge to obtain the measures, whether an **expert system** would be able to guide them through the process or whether they needed to call in an **expert**. This would decide what sort of information would be required.

Three Step Strategy for Risk Assessment

This part of the session discussed a strategy proposed by Professor Jacques Malchaire as part of the European funded BIOMED HEAT project to rewrite the ISO 7933 SW_{req} model. The strategy as described by Malchaire consists of the 3 categories:

1. **Observation**: "To be performed by people who may not necessarily have a training in thermal physiology but who have a knowledge of the working conditions being assessed."
2. **Analysis** "To be performed, when necessary, by the same people as above, but with the assistance of people more able to make environmental and physiological measurements and to use these data to compute thermal indices."
3. **Expertise** "To be performed, in exceptional conditions, by the same people with the additional assistance of experts".

This discussion was conducted without breaking the group into subgroups. Participants were asked to provide their views on this strategy and to provide any alternative or complementary strategies that they felt would benefit the user.

Results

Current Heat Stress Standards and their effectiveness in industry

The following comments have been copied from the transcripts of the discussions of both the sub-group and the main group.

ISO 7243

- Generally considered by the experts to be the most widely used and understood of the standards, although this was attributed in part to the widespread use of the ACGIH TLVs.
- Introduce diagrams to explain the thermal environment and the relationships between the person and the environment. This would provide the **basic knowledge required** to then go into the document.
- Place all the technical information, such as equations etc in an Annex.
- Provide a "*Glossary of Terms*" at the front of the document.
- It needs to be emphasised that the document is also intended for management as well as those who may be doing the assessment.
- Then going back to the main part of the document, we would go through the Scope, emphasising that it is intended for management level as well as other levels and that it

is going to cover the measurement, assessment, control and applicability. After that we moved onto the actual measurement and assessment and we thought that that was probably what people wanted to read in it.
- Language must be as non-scientific as possible as it was felt that if a user was "lost" at the start of the document, they would "*not read any further.*"

ISO 7933

- Here too the structure of the document was criticised, with the participants feeling that the structure needed to be changed so that the Table of Contents was in more user friendly language. They recommended the avoidance of terms such as "*principles of the method*", which they replaced that with "*how does the method work and what is it based on*". Another example was that "*Scope*" could be replaced with "*Who should use it and when should it apply*",
- They also recommended the placing of the Normative References to an Annex and called it "Further Information".
- They thought there should be much more explanation throughout the standard of what actually happened at the different stages in the flow of the calculation. One of the areas where they identified the need for more information was how to interpret the index value and how to use it in drawing up schemes of control. They stated that the standard talks mainly about work organisation with DLEs and that it needed to lead into other types of control. One way in which that might be facilitated was by looking at the avenues of heat exchange in more detail and they recommending that this would enable the users to consider each parameter individually. This may guide them into the considerations they would need for the implementation of controls.
- Flow diagram and checklists would also need to be provided to further improve the usability of the standard.

ISO 8996

- The main finding here was that the provision of a decision tree may aid the usage of the index. Again the language used was simple, with the recommendation being to use something along the lines of answering the question: "*here is somebody at work, now what am I going to do about it*", and the decision tree then aids them in their decision making.

Levels of Information Required and Knowledge Requirements

Environmental Parameters

- One area where the two groups of experts would agree was expected to be in the area of environmental measurement. This was not necessarily the case, with the Industrial sub-group considering only plane radiant temperature and relative humidity as secondary information levels, while the academic group also considered MRT, Va and the *WBGT* value as secondary.
- It became apparent from the ensuing discussion that the Industrial experts were observing the "*whole process from start to finish*", while the Academics were only considering the process in terms of the *WBGT* and SW_{req} model, which only has input values for t_a, t_{wb}, t_g, Va. This, argued the Industrial experts, ignored the need for data that was of importance. The A/R group said that since *WBGT* used t_a, t_{wb} and t_g, the allocation of fewer environmental parameters as primary information levels would meet both the SW_{req} and the *WBGT* index requirements.
- Both groups agreed that RH was not used in any index and that RH meters were difficult to calibrate meant it only warranted a secondary information level allocation even though users could probably better identify with RH than partial vapour pressure.

- The sub-group had also discussed the knowledge requirements, and when these were reported back, there was again disagreement. This disagreement centred around the meaning of the phrase "Expert System". It was decided that for this project an Expert System meant any index or measurement-specific information (such as equations etc) that the user would need to perform a risk assessment. The following table shows the agreed Information Levels and the Knowledge Requirements from which any Expert System would be developed.

Table 62: Final allocations of information levels and knowledge requirements for environment parameters

	POST-DISCUSSION ALLOCATIONS **Information Level**	 **Knowledge Requirement**
Air Temperature	Primary	**User**
Wet bulb temperature (natural)	Primary	**User**
Radiant Temperature (globe).	Primary	**User**
Radiant Temperature (MRT).	Secondary	**Expert System** – How to obtain mean radiant temperature from t_g
Plane Radiant Temperature	Secondary	**Expert** – Difficult to measure and interpret.
Air Velocity	Primary	**User**
Relative Humidity	Secondary	**Expert System** – How to obtain relative humidity from partial vapour pressure
Partial Vapour Pressure	Primary	**Expert System** – How to obtain partial vapour pressure from t_{wb} and t_a
WBGT Value	Primary	**Expert System** – How to obtain WBGT from t_a, t_g and t_{wb}

Clothing parameters.

Here too the different types of information that may be importance provided some disagreement between the two groups. The A/R group considered the parameters in terms of input values, while the industrial group considered the parameters in terms of how they would be used by the users to obtain clo values. After further discussion, the allocations presented below were agreed.

Table 63: Final allocations of information levels and knowledge requirements for clothing parameters

	POST-DISCUSSION ALLOCATIONS	
	Information Level	**Knowledge Requirement**
Clothing insulation (clo)	Primary	**Expert System** – How to calculate clo values
Moisture permeability (im)	Primary	**Expert System** – How to obtain i_m values
Purpose of clothing (PPE)	Secondary	**Expert System** – ACGIH and now WBGT provide correction values for different types of clothing. Users need to know what they are to obtain new correction values.
Body parts covered by PPE	Secondary	**Expert System** –New PHS index will require body part covered to be entered into model
Air Permeability	Primary	**Expert System** – Importance of air permeability

Levels of Physiological Information Required.

Again there were differences, and again they were based on the process by which the users would get to the Estimated metabolic rate. The industrial group viewed description of work as a primary requirement because it would provide the information that the users would need to perform a task analysis of the work as the basis for estimating metabolic rate. Following discussions, it was decided that this would be a primary information requirement. Both groups agreed that the measurement of metabolic rate and physiological monitoring were both secondary requirements requiring expert input. The following allocations were agreed upon.

Table 64: Final allocations of information levels and knowledge requirements for physiological parameters

	POST-DISCUSSION ALLOCATIONS	
	INFORMATION LEVEL	**KNOWLEDGE REQUIREMENT**
Metabolic rate (measured)	Secondary	**Expert** is required to measure metabolic rate. User cannot be expected to have skills for metabolic rate measurement
Metabolic rate (estimated)	Primary	**Expert System**- Tabular Data and worked examples as in ACGIH TLVs and (AC) Estimate from description of work
Description of work	Primary	**Expert System** Task Analysis needed to estimate Metabolic Rate. Observations will build up background data which will Assist Control. Only needed for estimated metabolic rate estimation
Physiological monitoring (during exposure)	Secondary	**Expert** – Physiological monitoring may be required when environmental and clothing parameters are outside the envelopes of application of *WBGT* & SW_{req}
Physiological monitoring (after exposure)	Secondary	**Expert** – As above. May be needed in extreme environments.

Levels of Personal Information Required.

Here both groups agreed on most allocations apart from dehydration/rehydration levels of workers. The only differences were whether knowledge requirements were allocated to expert system and/or experts. The following was agreed.

Table 65: Final allocations of information levels and knowledge requirements for personal parameters

	POST-DISCUSSION ALLOCATIONS	
	INFORMATION LEVEL	**KNOWLEDGE REQUIREMENT**
Worker's state of acclimation	Primary	**Expert System** – Importance of state of acclimation should be explained.
Worker's experience	Primary	**Expert system** – Importance of worker experience and skill required t
Duration of exposure	Primary	**User**
Number of exposures per day	Primary	**User**
Dehydration/re-hydration levels of workers	Primary	**Expert system** – To provide guidance on fluid intake requirements to reduce risk of dehydration. Provide percentage body weight loss guidance so that risk of dehydration can be identified. **Expert** – Medical surveillance may also provide additional information
Subjective responses of workers	Secondary	**Expert System** – How to take subjective measures and to interpret them.
Age	Secondary	Groups were concerned that it may introduce age bias. Decided health status of worker was adequate to identify physiological issues (such as fitness etc) that due to ageing may reduce worker's ability to work in the heat
Gender	Primary	**Expert** – As part of Health Status e.g. pregnancy
Health Status (MEASURED BY A MEDIC).	Primary	**Expert** – Fundamental requirement to assess health status of workers prior to working in the heat.

Malchaire's Three Step Strategy for Risk Assessment

The three-step strategy as described by Malchaire was discussed in detail. Below are a number of relevant quotes taken from the transcript. Main points are highlighted in bold, and some resultant points are listed below that. If a question asked by the moderator is quoted below, (**DB**) appears after it. This is to indicate that the questions asked by the moderator did not bias the discussion.

Coming back to the Malchaire method of Observation, Analysis and Expertise. The method divides the world up into those three apparently progressive systems. Are we sure that is correct? Would an expert be involved in observation or would you need an expert to do observation or would you need the expert to do the observation?

- The need for an expert may actually be replaced by an expert system that tells you what you need to do and why.
- You would need expertise, but you do it with an Expert System to help you. Calling in an expert may not be possible or viable.
- Now in a way we have already been through some of the issues by deciding on whether the task would be completed by the User, the User and an Expert System, because if it was a user and an Expert System it could be the Analysis Stage and they therefore may not need more help from someone else assuming that the Expert System provided the viable assistance.
- There are very few experts around in this field and so what you have got to do is transfer the expertise as far as possible into Expert Systems.

What does Malchaire mean about Observation

- That would be the Analysis (**DB**).
- Analysis or Expertise?
- I think that there is a hierarchy of Expert System. I think you start off as a checklist, that is an Expert System on a very simple level and you know that could be terribly useful. If only people occasionally used checklists for all sorts of things there would be far fewer mistakes.
- One thing that we could do is enable people to follow the rules and come up with some sort of risk assessment. And when that is done, the next level up is a sort of case work type of role where you are using a much higher level of professional expertise, looking at new situations and applying the knowledge in more flexible ways. One thing I wondered is that perhaps one thing that we need to do is find the competence levels for the tasks to be done rather than say who should be doing the task. JM is fairly close to it here.
    - ⇒ I agree with that. You need a bit more in this than that.

Is there a need for an earlier step or stage, before the Observation Stage, where it is decided that the work needs to be carried out so that a management decision is made (DB).

- Yes, we need to provide some information to management.
- There are 5 steps to risk assessment. To me observation goes a little bit beyond that because there is knowledge of the working conditions there. SO that they have a level of judgement.
- Observation doesn't even include measurement of the environment. It's an observation/checklist.

The next stage should be "Measurement" or "Investigation" as opposed to "Analysis" because the word "Analysis" seems to imply that the next stage would be getting to an answer, when it is not.

- I think the term "Analysis" here means measurement doesn't it?
- Quoting from the document is says "*to make environmental and physiological measurements and to use this data to compute thermal indices*".
- Actually it is a "Technical Assessment" where someone competent in implementing the method would interpret them without being an expert in the sense that they could not design a job or understand the unusual, but they could routinely go through and run the measurements.

There appears to be more steps required than the number of steps described in the Malchaire method (DB).

- We seem to have five point system now don't we? Hazard Observation, Measurement, Analysis and Expert; we haven't explained what the expert would do but he would probably picks it all up in the end; job design and all that.
- I think that after the Observation, at that level, they could make simple control measures and indeed should. Then after the Analysis stage they could implement more detailed controls based on the measurements they have taken.
- Yes, I think that in between each of the nodes if you like, in between Observation and Technical Assessment there should be "if there is a Problem can you Control it?" from the Check List.
- Simple Controls.
- That is in all legislation, but I agree with Malchaire's definition of the Expertise level, because where you really need your experts is where there are quite unusual situations. The kind of things that come through to my office are the out of the ordinary situations where the indices don't seem to apply in a straight forward sense where people are

maybe wearing special PPC, such as to clean out ovens where the *WBGT* temperatures are well above the threshold values. You need that higher level of judgement.
- I think that as soon as you go over to, what you might call, the heat balance equation you need to go over to experts

Do you agree with the use of a checklist or are there other methods you think would be better from a user's perspective (DB)?

- Check Lists seem to work quite well in other areas.
- They are quite powerful. They just look quite simple.
- If you just give them a sort of a steer it helps them and as they go through the process of filling in the Check List, ideas form in their mind as how to control the problem or situation. That's what we want.

Discussion

Many of the allocations for levels of information and knowledge requirements made by the experts were based on the fact that workers are supposed to obtain training for working in hot environments. Yet Honey *et al.* (1996) (see **Section 2.3.3**) found that only 37.9% of less than 50% base rate of respondents with thermal hazard reported that employees underwent training specific to the environment in which they worked. This raises the issue of introducing a "*training*" stage into the methodology and further increasing the number of steps in the risk assessment strategy. For this to be successful, it was decided that a top-down approach that focused on the management, assessment and control of heat stress.

The experts agreed that the Malchaire approach was too narrow in its definition of it's application. Furthermore, they agreed that any strategy for the assessment of heat stress would probably contain more stages than those described in the 3 Stage Strategy. The reason for this is that when stages are presented and need to be followed, each stage should be autonomous from the previous following stages. Therefore, the "Analysis" stage (as defined) contains two decision nodal points:

1.) Take measurements
2.) Compute thermal indices.

Furthermore, the limited consideration in the Malchaire method regarding Experts does not take into account the use of "expert systems" or job aids. The expert discussion group felt that where possible, and in unusual situations, experts should only be called upon. Wherever possible therefore expert systems or job aids should be sufficiently comprehensive to enable the users to be as self-sufficient as possible. There are two main reasons for this they said:

1.) There are not many experts in the area of heat stress available,
2.) Some companies may be reluctant to bring experts in.

These findings were discussed with representative users in the User Discussion Groups.

User Discussion Groups

Introduction

Two focus group sessions were run with representative users. Due to difficulties in obtaining user participation, potential participants were targeted through British Occupational Hygiene Society (BOHS) conferences and Special Interest Groups (SIG). Although it is recognised that this provided a narrow base from which participants would be obtained, the users were nonetheless representative of potential users of this methodology. Another consideration is that the number of potential users with thermal risks in the UK may be as few 6% (Bunt, 1993). The first discussion group was held as a work shop at a BOHS PPE SIG meeting held in London in February 1999. The second was held also as a participatory workshop at the BOHS annual conference in London in April 1999. D. Bethea was the moderator in both.

Format and Procedure

An abstract was prepared and presented in the proceedings of each conference in order to provide information to the users about the purpose of the discussion group session and the format that it would take. Twelve (PPE SIG) and eleven (BOHS Conference) participants with an interest in heat stress took part in the discussion. They volunteered to take part in the workshop based on the information provided in the abstract. Following a brief introduction, the participants were informed that the discussion would be taped and transcripts of the tapes made. They were then given the opportunity to withdraw from the group if they wished. The discussion group was scheduled to last one hour for the PPE SIG and two hours for the BOHS conference workshop.

Discussion Topics

Participant information and their heat stress experiences

Users were asked to discuss their experiences, knowledge and any problems they experienced of heat stress risk assessment.

Management of Heat Stress?

Discussion of the top down approach management, assessment and control of heat stress as recommended by the expert discussion group focused on the inclusion of managers in the process and what the implication this may have for Small and Medium sized Enterprises (SMEs).

10 Point Approach

A flow diagram of a 10-point generic strategy for the Management, Assessment and Control of Heat Stress was developed following the expert discussion group. This was shown to the users and their opinions sought.

1. Managing Health and Safety of Workers
2. Training and Education of Workers
3. Hazard Identification
4. Observation
5. Simple Controls
6. Measurement/Evaluation
7. Analysis and Interpretation of Results
8. More detailed Analysis and Interpretation
9. Implementation of Controls
10. Obtain Expert Help

A Basic Assessment Observation

The concept of an Observation methodology as part of a generic strategy was discussed. Two examples, the one by Malchaire and a prototype developed following the expert group were shown to the users. The main questions were:

1.) How practical would this be
2.) Will managers accept Control recommendations if a simplistic approach has been used?
3.) What can be done to facilitate this to aid the Occupational Hygienist?

What Expert Systems are required for a generic strategy?

The following parameters were discussed:

- WBGT
- SW_{req} index
- Clothing Insulation (Clo)
- How to Estimate Metabolic Rate
- Physiological Monitoring.

Presentation of Information

Users were asked which of the following methods of presenting information they thought best suited their needs:

- Record sheets
- Checklists of measures to be taken
- Checklists of estimates to be obtained
- Incident Reports.

Results and Discussion

Participant information and their heat stress experiences

One participant was from company that manufactures PPE. The other eleven were responsible for, or involved in, occupational health and safety. Four of the participants had no formal training in occupational hygiene and had been promoted into their jobs from other areas such as factory floor, engineering etc. They had however been short courses. Only seven of the participants had experience of heat stress. All had used the *WBGT* as described in the ACGIH TLVs (none had used ISO 7243) and none had used ISO 7933. Another two had recently started working in industries that had heat stress problems and therefore expected to be involved in heat stress risk assessment. All the participants were aware of heat stress and unanimously agreed that the assessment of heat stress was something they were not adequately trained in.

All of the participants complained of a lack of information and that what information that is available tends to be too technical. The need to conduct heat stress risk assessments was infrequent for all the participants. The general consensus was that heat stress situations often occur sporadically, for example during the hotter summer months. Heat stress associated with PPE was a concern for all the participants but they were not aware of how different types of PPE could affect thermoregulation (i.e. none were aware of the PPE correction values by the ACGIH for their TLVs (*WBGT*) reference values). All of the participants agreed that manufacturers of PPE do not provide adequate information about the thermal properties of PPE. They all felt that more information should be provided by the manufacturers.

Management of Heat Stress?

All the participants thought that any method that included information for management would be beneficial. Management aids such as record sheets and information on heat stress and productivity, heat stress control options etc. were all considered necessary. The users seemed to think that the management needed more information that the experts had. This would be of particular benefit to SMEs, where resources were often low and/or line managers, product managers etc. were responsible for heat stress. Information though should not be technical in nature.

10 Point Approach

The 10 point plan was very well received. A structured approach where all the necessary information was provided was needed as they currently need to look for information from a number of sources which can be time consuming. A number of participants said they knew there was information "out there" but they didn't know where to find it. Since the 10 Point approach was an expansion of the current HSE 5 Step approach, they felt that it would fairly easy for someone with little experience of risk assessment to follow. One of the main points was that it would standardise the way heat stress was managed, assessed and controlled.. This would enable companies to standardise their heat stress strategies, where currently (in large companies) different sites within the same company may have different procedures in place. It may also provide them with a benchmark from which they could evaluate their own training programs and intervention successes. The only criticisms were in the use of the phrase "Thermal Audit". They recommended that this be changed to Quantitative Assessment as this was standard wording for describing the process of taking objective measurements. It was recommended that the Observation method, include Qualitative Assessment in its title.

A Basic Assessment – Observation

Only the observation technique developed by D. Bethea was shown as Malchaire's Observation checklist had yet to be ratified by the BIOMED HEAT project. All the participants regarded the concept of a qualitative assessment as being an improvement on the current requirement of needing to take quantitative measures as the first process.

What Expert Systems that are required for a generic strategy

WBGT

- All the participants knew of the *WBGT* index, although most of them had used the ACGIH TLVs and not BS EN 27243.
- They tended to know that the *WBGT* index was limited but had used it because it was a relatively easy method to use.

SW_{req} index

- None of the participants had used ISO 7933.
- 5 participants knew the standard and three had considered using it. None had used it because they felt it was too complicated and scientific.

Clothing Insulation (Clo) and other clothing information

- One of the participants knew what the i_m (vapour permeability) of an ensemble is, but they were not sure how to find out what it is.
- All of the participants knew what the clo value was but only four knew of BS EN 9920.

How to Estimate Metabolic Rate

- Nine participants knew that metabolic rate was required for a heat stress assessment. Three had used BS EN 28996 and the other used the ACGIH or NIOSH tables.

Physiological Monitoring
Nearly all of the participants were interested in taking physiological measurements.

Presentation of Information

- All the participants agreed that a practical, easy to use methodology was required. One of the participants stated "*what we need is an idiot's guide to heat stress*". Another said "*I need something that takes me by the hand and tells me exactly what I need to do and why.*"

Conclusions from Expert and User Discussion Groups

DEFINITION OF USERS

Formal definition of the users included a wider range of users than expected;

- Person who is responsible for Health & Safety of workers
- Occupational hygiene specialists, health and safety professionals
- Also non-specialists such as those in SME's where one person "wears many hats"
- Managers (both middle and higher) as they may ultimately be responsible for health and safety policy.

CHARACTERISTICS OF USERS

- Not all users may have formal training of heat stress
- Not all users will have formal training in health and safety and/or risk assessment
- There will be a diverse perception of the risk of heat stress
- Poor level of knowledge in Standards/methods.

HEAT STRESS STANDARDS

- There is currently a low level of use of current heat stress standards, specifically ISO 7933.which is probably attributable to its poor usability. Nine of the SIG user group and eight of the BOHS user group considered current standards too be complicated and difficult to use.
    - ⇨ There is an overemphasis on scientific content in ISO 7933 and to a lesser extent in the other standards.
    - ⇨ Poor level of understanding is due to complicated procedures and complicated language in the standards.
- Participants knew how to estimate metabolic rate but not where to find the information in the heat stress standard.
- A minority of attendees knew how to estimate clo value but not where to find the information.

USER PERCEPTION

- Unless there is a complaint, risk of heat stress is not considered or assessed and in many cases it is an infrequent occurrence to assess heat stress. Heat stress may be influenced greatly by the seasons, by the task or be a consequence of wearing PPE.
- Heat stress is a secondary concern as it is not considered to be a life-threatening condition.
- PPE and heat stress may always be a problem because workers can "*never have too much protection*".

INFORMATION REQUIRED

- More information is required including information on:
  - ⇨ Effects of heat on humans
  - ⇨ Effects of PPE on human thermoregulation
  - ⇨ Estimating metabolic rate, clothing insulation etc
  - ⇨ Interpreting result and control strategies
  - ⇨ Management and cost benefits
- Methods of presenting information that would be useful would include:
  - ⇨ Flow diagrams, diagrams, computer programs
- "Idiot's guide to heat stress"
- Problem is self perpetuating too complicated.

The methodology should **not** be developed as a purely "technical document", rather as a methodology for the overall **management of heat stress**. It should therefore, aid not only the assessment and control of heat stress but the decision process associated with conducting a risk assessment. This would seem to benefit both large companies, as well as small and medium sized ones where the occupational hygiene infrastructure may not be so well developed. **Heat stress is not only associated with hot environments**. A major area of concern is that of where **PPE** or **PPC** is worn, as such more information should be supplied to aid the user to better understand, evaluate and interpret the risk of heat stress associated with PPE and PPC. "**Expert Systems**" should be provided to enable the user to make a more detailed analysis of the environment and to better interpret and understand their results. More information about the possible **control strategies** should be provided. Information about the **Health Status** of workers should be included to help the user identify those people who may be at particular risk from heat stress.

4.3.4 Postal Questionnaire Survey

Aims and Objectives

There were five main aims of the questionnaire survey:

1. **General Information**: To identify and receive information about the responders and the companies in industry sectors that conducted heat stress risk assessments
2. **International Standards**: To establish user knowledge and use of current heat stress standards
3. **Heat Stress Indices**: To establish which heat stress industries potential users of the practical methodology may have used or are currently using
4. **Assessment** of **Hot Working Environments**: To identify which measurement methods and instruments users may use to conduct heat stress assessment
5. **Other Issues**: To identify if there are any particular reasons why heat stress controls may or may not be implemented.

Introduction

Due to the poor return of questionnaires from the informal interviews and the discussion groups it was decided to obtain information about practical issues that may currently be found in UK industry. It was hoped that the questionnaire would provide a large amount information at relatively low cost and relatively quickly. This may also enable the research team to obtain input from potential users who may not have attended the BOHS conferences.

Method

According to Sinclair (1995), one of the most important aspects of developing the questionnaire is the establishment of formal objectives and to decide early on what the format of the questionnaire will be. Therefore, the design of the questionnaire was approached with the specific research objective of obtaining information both complementary to and in addition to the findings of the structured discussion groups.

Sampling of Respondents

A prerequisite of conducting HSE sponsored research is that if the questionnaire is to be sent to more than 24 companies, that Survey Control Clearance from the HSE and the UK government is required. The basis of obtaining this clearance is that the burden placed on the companies by participating in the study would not be excessive. Clearance was obtained for a maximum of 300 questionnaires. Since the extent of occupational heat stress in the UK is not currently known and that a limit of 300 questionnaires was placed on the survey it was not possible to establish the number of responses required to meet a power calculation. Ordinarily though a response rate of 30% is expected for postal questionnaires, but it is recognised that the low level of control associated with postal questionnaires may well result in a much lower response rate. Therefore additional measures such as reminder letters would be used in an attempt to maximise the response rate.

Rationale for Questionnaire Design

The rationale used for each of the aims is described below.

General Information

As described in **Section 2.2.8** there are a number of industries that traditionally have heat stress environments. Added to the information about the industry sector each respondent was in, additional information would be sought, such as:

- The job title of the responder and their time in health and safety
- The number of people employed by the company
- How they rate their own competence as a health and safety professional, their knowledge of heat stress, PPE and heat stress and their ability to perform a heat stress assessment.

The purpose of obtaining this information was twofold:

1.) To provide a non-heat stress specific introduction to the questionnaire.
2.) Background information on company sizes, industry sectors and the responder's experience and knowledge would provide a basis for evaluating the sample response to the questionnaires.

International Standards

Current heat stress standard are considered by some authors to be widely used in the assessment of heat stress in industry, however the informal interviews and discussion groups suggested this was not the case. Therefore, information about international standard in the assessment of heat stress was needed from a wider sample base to investigate whether standards are used or not, and if they are used, to what extent they are applied.

Heat Stress Indices

As discussed in **Section 2.4** there are a number of heat stress indices, standards and supporting documents, however no information is available about which of these indices are used, and to what extent.

Assessment of Hot Working Environments

The standards and other guidance documentation such as the BOHS Guidance (1996) all provide descriptions of equipment that could be used in the assessment of the hot working environments. This section would investigate which of the instruments and methods are used and their ease of use.

Other Issues

From the Risk Assessment literature survey (**Section 2.3)** a number of possible issues for the effective management and control of risks were identified. This section was designed to provide data that may identify areas where particular attention may need to be paid by the practical methodology so as to meet the needs of the users within the framework of their current risk assessment strategies and policies.

Questionnaire Design

The questionnaire was designed to take about 20 minutes to complete. It consisted of a number of fixed questions with a fixed range of alternative answers, which were complemented by open-ended questions (Gray, 1975). Detailed instructions were also provided. Simple rating scales (as described by Sinclair, 1995) were used to obtain ratings from subjects. Each scale was 100mm long with anchor points and labels at each end. No interval points or labels were provided. General recommendations were followed.

Procedure

As it could not be sent to industrial respondents until survey control clearance had been received, the questionnaire and its instructions was piloted with three postgraduate researchers at HTEL. Additional input was received from Mr. Len Morris and Mr. Chris Quarrie from Health Division, HSE in Bootle. Over a three-month period, 270 companies were selected randomly as having possible heat stress conditions from the Kompass Company Directory. The questionnaires, with self-addressed envelopes enclosed, were sent to these companies, addressed to the "Health and Safety Department" of each. Two reminder letters were sent to all the recipients at two and four weeks after the questionnaires had been sent.

Results

Returns

A total of 56 questionnaires were returned, but only 27 of these were completed. The rest (29) were returned with letters explaining that heat stress was not an issue for the recipient company.

Analyses

This section will describe the results of the analysis of the 27 completed questionnaires. The completed questionnaires constituted a return of only 10%, which is below the 30% required for statistical analysis. Therefore, although statistical analysis was not possible it was hoped that an analysis of the questionnaires would provide sufficient information for identifying issues and trends using descriptive statistics and, for subjective rating scales, medians. The rating scales were converted to numerical values by measuring to the nearest centimetre.

All data was inputted in a spreadsheet, and was then analysed using Microsoft Excel 97© and SPSS© Version 9 for Windows. Ratings are presented as box-plots; the plot is based on the median, quartiles, and extreme values. The box represents the interquartile range (25th to 75th percentiles) which contains 50% of values. A line across the box indicates the median for the plotted data. Whiskers are lines that extend from the box to the highest and lowest values, excluding outliers and extreme values. The outliers (indicated by circles) are those values that are values between 1.5 and 3 box lengths from the upper or lower edge of the box. Extremes (shown by the stars) are those values more than 3 box lengths from the upper or lower edge of the box. The question to which the results refer are provided in brackets e.g. (**Q1**).

General Information

*Job title and time involved in Health and Safety. (**Q1** and **Q2**)*

Table 56 shows that a wide range health and safety professionals with a mean time in job of 11 years replied to the questionnaire. One point to note however, is that from the discussion groups it was ascertained that many of the people responsible for health and safety in industry are promoted from within and are not necessarily trained hygienists etc. but line managers, product managers etc. None of these sorts of job descriptions were amongst the responders.

Table 66: A breakdown of each respondent's job description and number of years in health and safety.

RESPONDENT	JOB TITLE	YEARS IN HEALTH & SAFETY
R1	Health and Safety Officer	5
R2	Principle Safety and Environmental Advisor Integrated management system co-ordinator	7
R3	Senior Occupational Hygienist	23
R4	Group Safety Manager	15
R5	Health and Safety Advisor	11
R6	Industrial Hygiene Advisor	15
R7	Head of Nursing	21
R8	Occupational Hygienist	7
R9	Health and Safety Manager	18
R10	Industrial Hygienist	4
R11	Health and Safety Co-ordinator	7
R12	Corporate Health and Safety Manager	24
R13	Senior Hygienist	12
R14	Occupational Hygiene Advisor	2
R15	Occupational Medic	22
R16	Hygienist	5
R17	Health and Safety Officer	10
R18	Factory Health and Safety Officer	3
R19	Production Manager	3
R20	Site Safety Manager	15
R21	Senior Occupational Hygienist	12
R22	Health and Safety Supervisor	8
R23	Site Health and Safety Advisor	4
R24	Health and Safety Officer	2
R25	Environmental Safety Manager	21
R26	Union Safety Representative	11
R27	Hygienist	17
	MEAN	11
	SD	7
	MIN	2
	MAX	24

Industry Sector (Q3 and Q4)

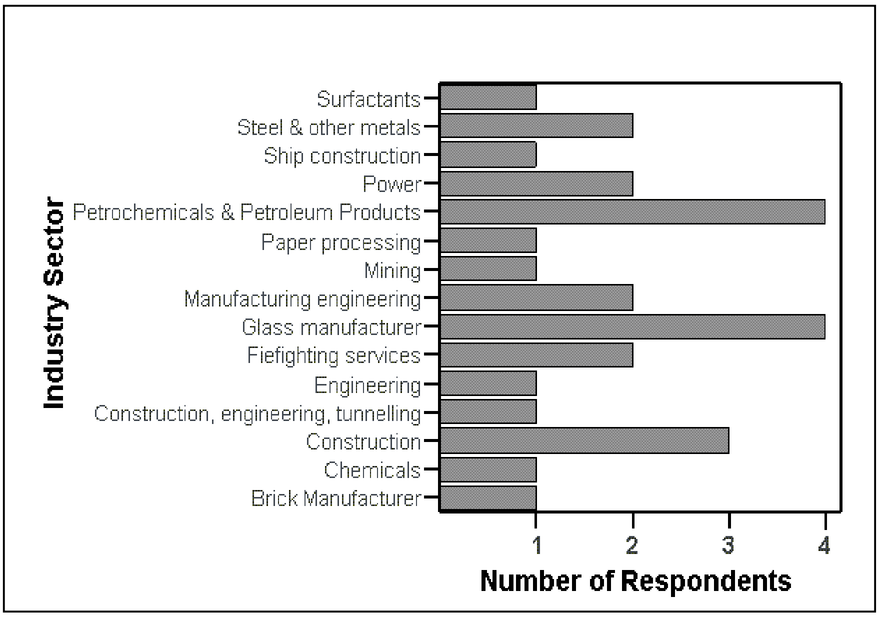


Figure 27: Bar chart showing the number of respondents per industry sector.

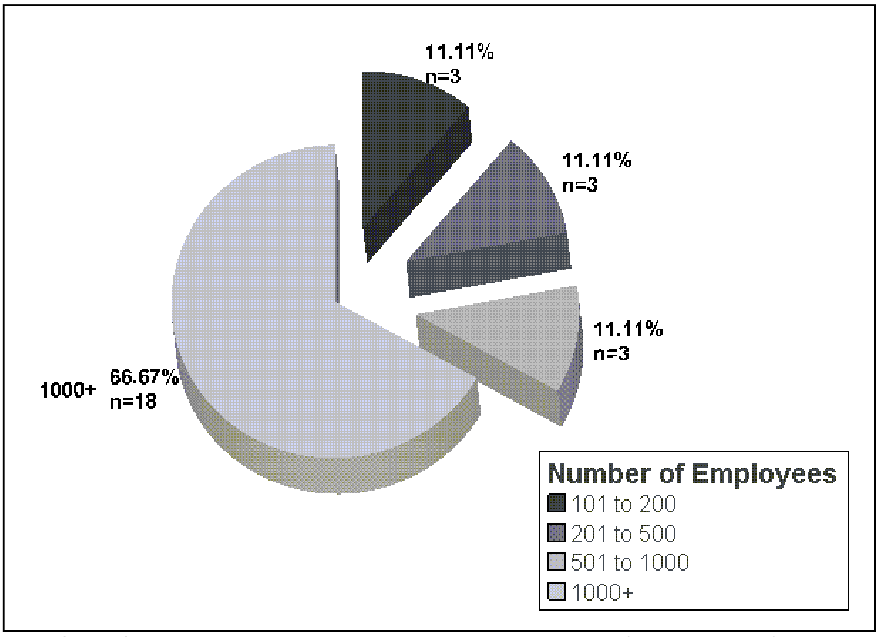


Figure 28 (right) A pie chart showing the breakdown of Number of Employees from respondent companies.

Figure 27 shows that the most responses were obtained from the Petrochemical and Petroleum Products (four) and Glass manufacturing industries (four). **Figure 28** shows that the majority of responses were from companies with more than one thousand employees (66.7%), while 11.11% of respondents were from companies employing in the ranges between 101 to 1000 employees. The ranges, 0 to 15, 16 to 50 and 51 to 100 had no respondents.

Ratings of competence and knowledge (Q 6 to 10)

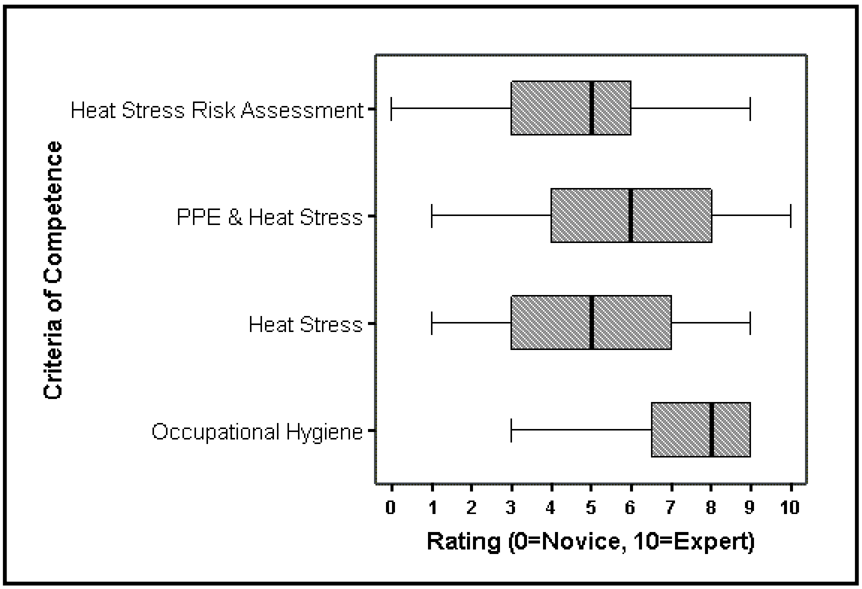


Figure 29: Box-plots of responder ratings of the competence and knowledge of occupational hygiene and heat stress issues (Medians are shown as thicker black vertical bars in each box)

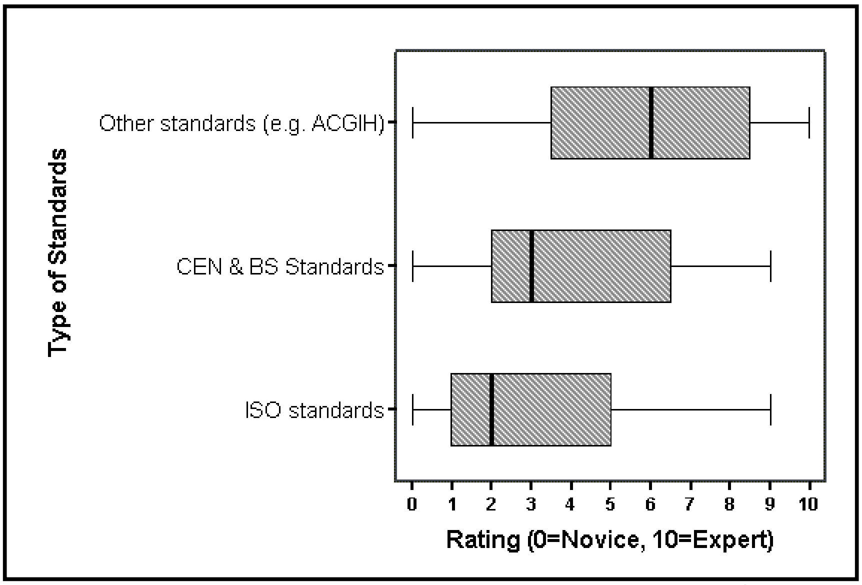


Figure 30: Box-plots with medians showing responder ratings of the level of knowledge of heat stress standards

Figure 29 shows that the median score was higher for competence rating of occupational hygiene than the areas of heat stress. Interesting though the median for “PPE and heat stress” is higher than for general “heat stress” issues. The ranges for all the heat stress issues were similar, although the median for occupational hygiene was higher than all the inter-percentile ranges for each of the other criteria. **Figure 30** shows that respondents gave a higher rating for other standards (specifically ACGIH) than they did for CEN or BS or ISO standards. ISO standards obtained the lowest ratings of level of knowledge although the ranges for all three types of standards were similar. Fifty percent of the ratings provided for other standards were higher than the medians for both CEN and BS and ISO standards.

Heat Stress Standards

Use and knowledge of current heat stress standards.
Four standards were identified as being critical to the assessment of heat stress, namely:

1. ISO 7432 (1989), Hot environments Estimation of the heat stress on working man, based on *WBGT*-index (wet bulb globe temperature)
2. ISO 7933 (1989), Hot environments Analytical determination and interpretation of thermal using calculations of required sweat rate (SWreq)
3. ISO 8996 (1990), Ergonomics of the thermal environment: Estimation of metabolic heat production.
4. ISO 9886 (1992), Evaluation of thermal strain by physiological measurements.

ISO 7243 and 7933 are the two indices for heat stress assessment. ISO 8996 is required for the estimation of metabolic rate (small variations in estimated metabolic rate may have significant results on the predictions of ISO 7933). ISO 9886 is recommended for the assessment of physiological responses when ISO 7933 limits are exceeded.

*Respondent knowledge of and confidence in the standards (**Q11** and **Q12**)*

Figure 31 provides a breakdown of the four standards showing the number of respondents who knew of each standard and the number that had used them. ISO 7243 (WBGT) has both the highest number of respondents who know and who use the standard (96.3% and 81.48% respectively). ISO 7933 on the other hand has the lowest scores for both the number who know and the number that have used the standard (48.15% and 14.81%). Both ISO 9886 and ISO 8996 have similar results.

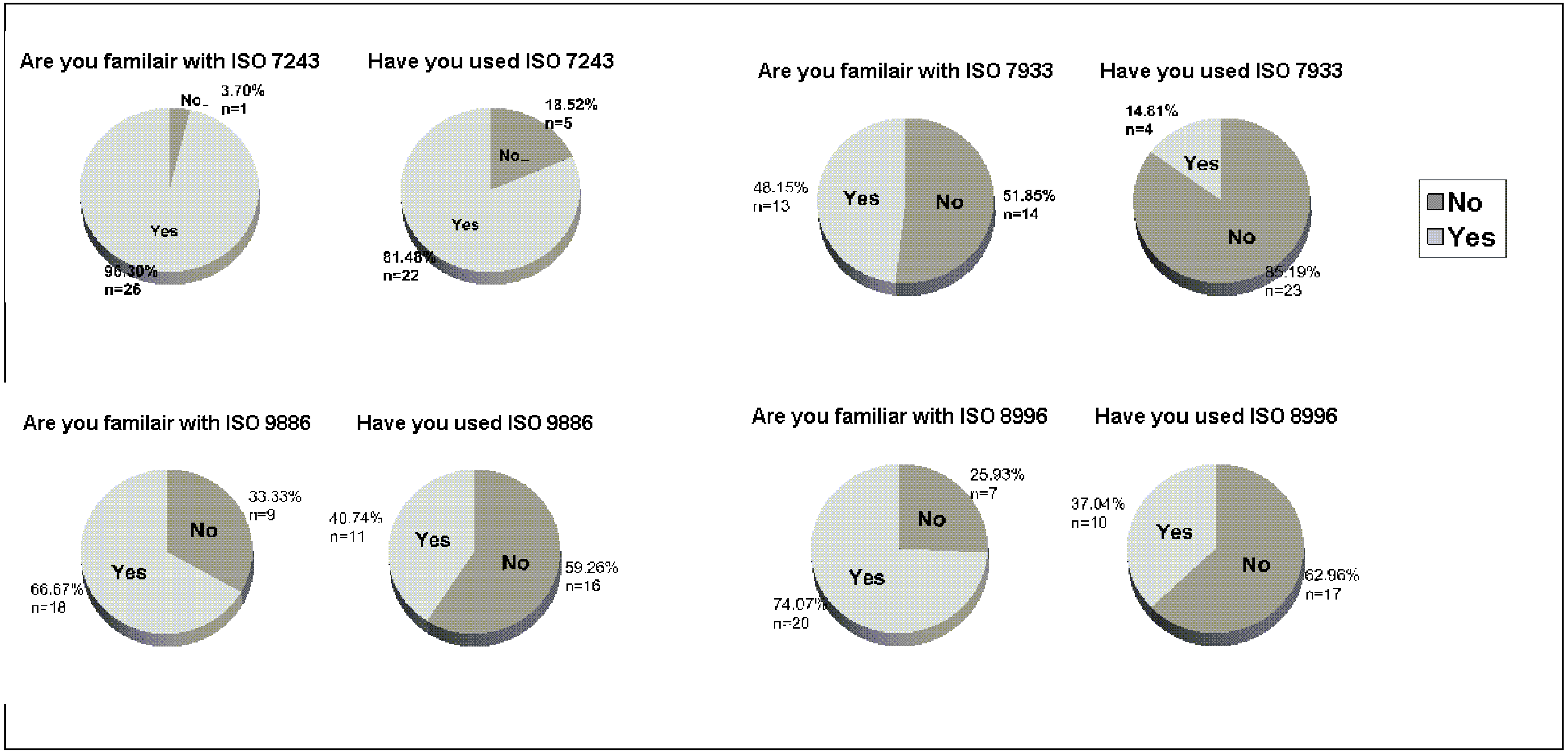


Figure 31: Pie charts showing the number of respondents who knew of the heat stress standards and that had used them

*Rating of knowledge of and confidence in the standards. (**Q11** and **Q12**)*

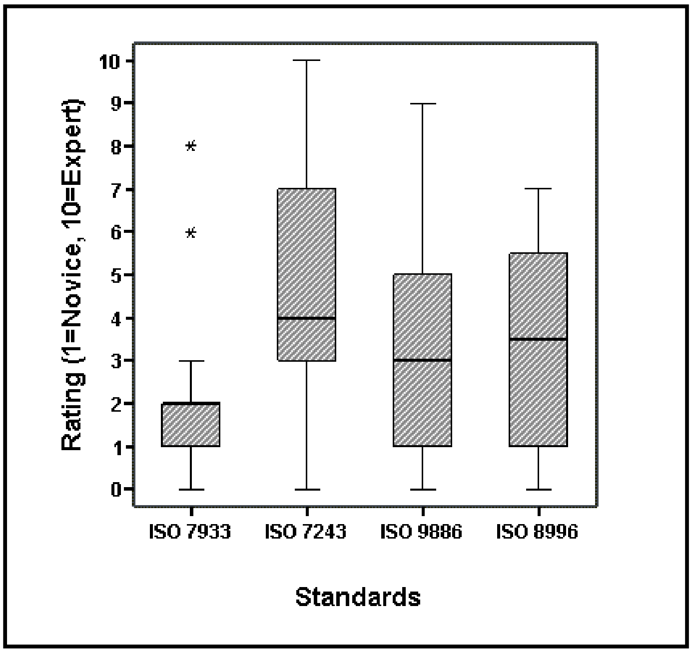


Figure 32: Box-plots showing the respondent ratings of the knowledge of current international heat stress standards

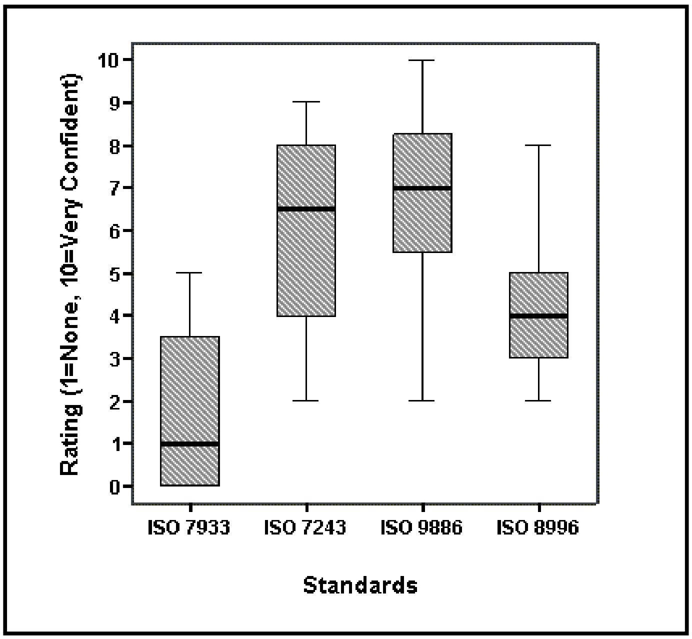


Figure 33: Box-plots showing the respondent ratings of their confidence in current international heat stress standards

Figure 32 shows that those respondents who knew of ISO 7933 rated their knowledge of it as worse than those who know the other standards. The inter-percentile range and the whiskers show that all but two respondents (extremes shown) rated their knowledge as less than a rating equal to 3. ISO 7243 had a median rating higher than the other standards. It also showed the greatest range of ratings. Here too ISO 9886 and 8996 provided similar median values. **Figure 33** shows those users who had used ISO 7933 had the lowest confidence rating in it than the ratings given to the other standards. The standard with the highest median rating was ISO 9886. Although ISO 9886's median was similar to that for ISO 7243, its inter-quartile range was narrower.

Heat Stress Indices (Q20)

Respondents were presented with a number of heat stress indices and standards and were asked which of these they had Never Used, had Previously Used, or were Currently Using.

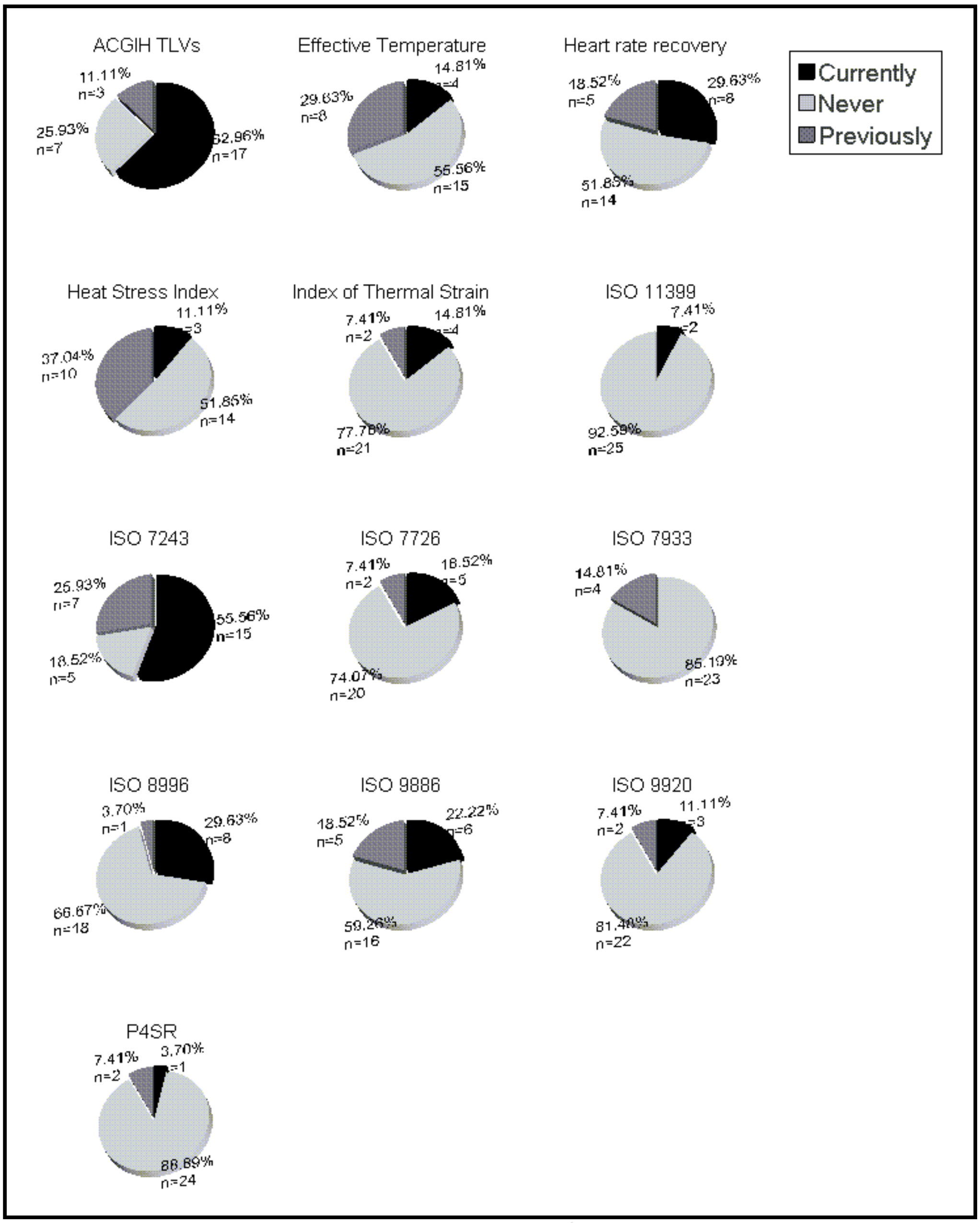


Figure 34: Pie charts showing the number of respondents who either currently, previously or never used heat stress indices and standards.

Figure 34, shows that of all the indices and standards listed ISO 7933 is the only standard that is not currently being used although 14.81% of the respondents have used it in the past. The only other standards with two categories obtaining responses was ISO 11399 with 7.41% Currently using it and 92.59% having never used it. At the other end of spectrum, ISO 7243 (55.56%) and the ACGIH TLVs (62.96%) had the second highest and highest Currently Used responses respectively. The Heat Stress Index (HSI) has the highest number of Previously Used responses (37.04%). ISO 8996 and Heart Rate recovery responses both recorded 29.63% for Currently Used as the third most used indices/standards after the TLVs and WBGT.

Assessment of hot working environments

Respondents were asked to indicate which of the follow methods they either currently, previously or never used and to provide Ease of Use ratings for those they had used. The ratings were based on the following asymmetrical scale: 1=Impossible, 2=Very Difficult, 3=Difficult, 4=Easy, 5=Very Easy.

Physical Measures of the Environment

Table 67: Methods used and Ease of Use Ratings for measuring the physical environment

		WHEN USED			**EASE OF USE RATING**
		Currently	**Previously**	**Never**	**Median**
Air Temp	**Mercury in glass**	21	2	4	**5**
	Thermocouple	10	3	14	**5**
	Thermistor	4	1	22	**5**
	Platinum resistance thermometer	3	2	22	**5**
	Semiconductor junction	None	None	27	**-**
Radiant Temp	**Two sphere radiometer**	1	1	25	**3**
	Black globe thermometer Large (150mm)	1	5	21	**5**
	Black globe thermometer Small (±40mm)	16	6	5	**4**
	Plane Radiant Temperature.	4	4	19	**2**
Humidity	**Whirling Hygrometer**	7	7	13	**4**
	Electronic Hygrometer	4	5	18	**4**
	Dew point technique	1	2	24	**3**
	Hygrograph	1	3	23	**3**
	Humidity Probes (resistance or capacitance)	6	3	18	**4**
	Psychrometer (eg Assman) – natural	None	4	23	**2**
	Psychrometer (eg Assman) –forced	None	4	23	**2**
	Lithium Chloride Cell	None	2	25	**2**
Air Velocity	**Hot Sphere**	1	2	24	**3**
	Hot wire anemometer	20	1	6	**5**
	Kata-thermometer	2	8	17	**3**

Most of the respondents (21) currently used the mercury in glass thermometer for measuring air temperature, followed by the hot wire anemometer (20) for air velocity, and the 40mm black globe thermometer (16) for radiant temperature. There was no clear preference for measuring humidity, with the whirling hygrometer and the humidity probes currently used by 7 and 6 respondents respectively. Medians for these methods showed that four highest currently used methods were either 5 (for mercury in glass and hot wire anemometer) or 4 (small black globe and whirling hygrometer).

Table 68: Methods used and Ease of Use Ratings for derived measures of the physical environment

	WHEN USED			EASE OF USE RATING
	Currently	Previously	Never	Median
Indoor climate analyser	3	2	22	**5**
Wet Bulb Globe Temperature (WBGT) Meter	14	10	3	**4**

The dedicated *WBGT* meters are commonly used; with 14 respondents currently using them, and 10 respondents having used them in the past. It obtained a median of 4, which corresponds to Easy on the scale.

Personal Measures of the Environment

Table 69: Methods used and Ease of Use Ratings for estimating the effects of clothing on thermoregulation

		WHEN USED			EASE OF USE RATING
		Currently	Previously	Never	Median
CLOTH-ING	**Thermal Insulation (clo)**	9	2	16	**3**
	Weight of clothing (e.g. light, medium, etc.)	6	None	21	**3**
	Body part covered	9	None	18	**3**
	Emissivity	4	1	22	**3**
	Air Permeability	5	1	21	**2**
	Vapour Permeability	4	1	22	**2**
WORK RATE	**Estimation (e.g. light, medium, etc.)**	**18**	4	5	**3**
	Measurement (Physiological testing)	**3**	6	18	**2**

The two most commonly used methods for estimating the effects of clothing on thermoregulation are estimating the clo value and body part covered (9 respondents each). The body part criteria corresponded with comments made by the respondents with respect specifically to the use of PPE such as helmets, breathing apparatus etc. Estimation of metabolic rate was currently used by 18 of the participants. All the criteria scored a median score of either difficult or very difficult.

Table 70: Methods used and Ease of Use Ratings for measuring physiological responses to hot environments

		WHEN USED			**EASE OF USE RATING**
		Currently	**Previously**	**Never**	**Median**
PHYSIOLOGICAL	**Pulse rate**	11	7	9	**4**
	Sweat loss	4	2	19	**4**
	Fluid intake	None	2	25	**4**
	Dehydration measures	None	2	25	**1**
	Hydration state of worker before work	None	2	25	**2**
	Body Temperature measures: Aural (inner ear)	7	4	16	**4**
	Body Temperature measures: Oral	2	8	17	**5**
	Body Temperature measures: Rectal	1	4	22	**2**
	Body Temperature measures: Other	None	2	25	**2**
WEIGHT		3	None	24	**5**
HEIGHT		3	None	24	**5**

Heart rate is currently used by 11 of the respondents with an Ease of Use rating of 4. The second most used physiological measure was aural temperature with 7 respondents currently using it. Only respondents had tried previously used measures of hydration, fluid intake and dehydration.

Table 71: Methods used and Ease of Use Ratings for identifying workers at risk from heat stress.

	WHEN USED			**EASE OF USE RATING**
	Currently	**Previously**	**Never**	**Median**
State of acclimation	2	16	8	**3**
Age	1	9	16	**5**
Gender	12	None	14	**5**
Health Status of the Worker	16	None	10	**4**
Subjective Scales such as Thermal comfort scales (e.g. Bedford)	1	8	17	**3**

The most commonly method currently used to identify workers at risk was Health Status of the Worker with 16 respondents, with no previous responses. It also had a rating of Easy. State of acclimation only had two respondents currently using it, while 16 had previously used it. It had a median score of 3, corresponding to difficult.

Other Issues

Why heat stress controls ***MAY NOT*** *be implemented*

In order to identify areas where users may require additional information to aid communication of the risks and their risk assessment findings with management a number of questions were asked concerning the following topics:

- Perception of Risk of Heat Stress;
- Competence;
- Working procedures;
- Cost of Controls and Resources available;
- Communication;
- Employee involvement in process;
- Management taking initiative.

The results are presented in the box plots below.

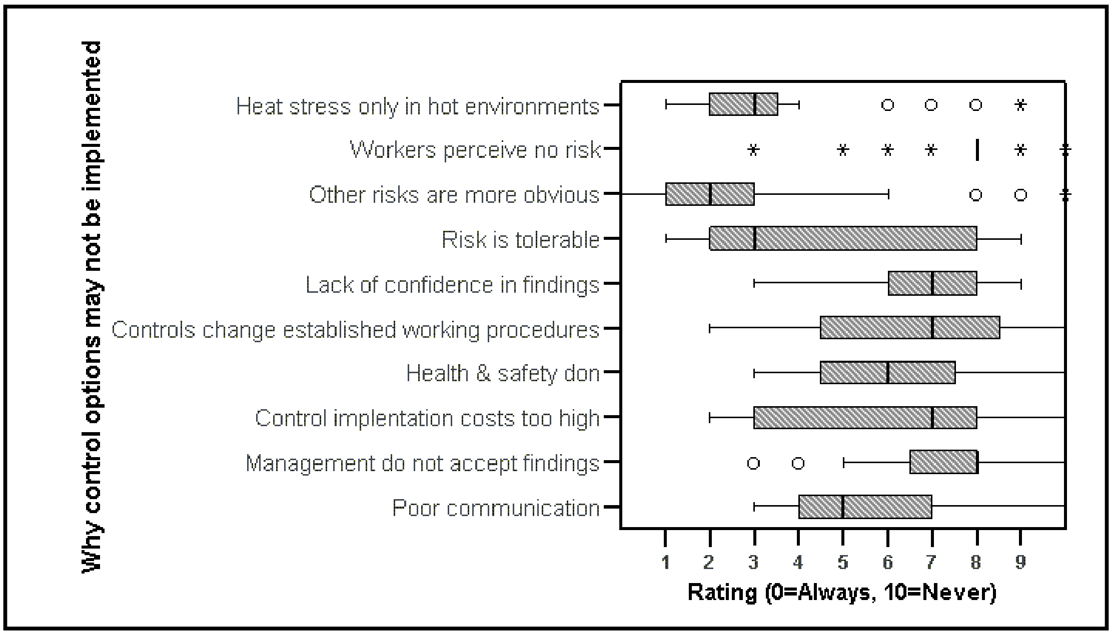


Figure 35: Box-plots of respondent ratings why heat stress controls may not be implemented.

*Why heat stress controls **MAY** be implemented*

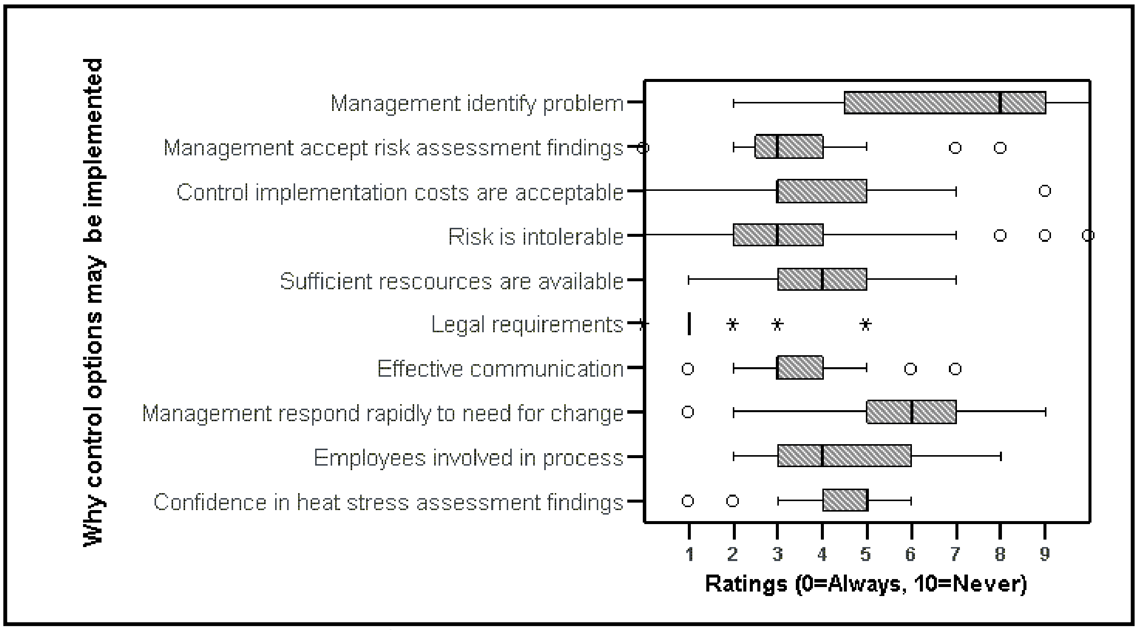


Figure 36: Box-plots of respondent ratings why heat stress controls may be implemented.

There doesn't appear to be any noticeable trends. One area of encouragement is that the boxplot shows that overall management accept the findings of heat stress risk assessments. This is mirrored in the responses to "management do not accept findings of risk assessment" and "management accept risk assessment findings". The legal requirement, as expected, was one of the main reasons why control options are implemented, with a median score of 1. The narrowness of the box shows that all but three respondents gave this a rating of 1. Interestingly, effective communication was also cited as a positive reason for the implementation of controls.

The literature breaks risks into two categories, tolerable and intolerable. Although the intolerable risk is generally considered as being a reason for the implementation of controls, the perception of "intolerable risk" does not appear to negate the implementation of controls. This was not expected, and perhaps shows that what the distinction between tolerable and intolerable heat stress risk is an issue when implementing controls.

However that said, management do not appear to play a part in the identifying heat stress problems. This suggests that further information is required, such as reviewing accident reports, productivity levels etc. so that management also plays a proactive role in the Management, Assessment and Control of heat stress. After all management are legally obliged to ensure that health and safety policies are observed.

Discussion

Parsons (1995) identified the need for better integration of methods of assessing heat stress, including those described in the standards, by combining them with sensible working practices of accounting for individual characteristics of both the worker and the workplace. The results from this questionnaire would seem to suggest that this has yet to be done in practice.

The low response rate means that insufficient data were obtained for a statistical analysis. The respondents were all from companies with more than 100 employees, although all the sectors targeted obtained a response. These findings therefore can only show possible trends and may highlight a number of issues that are specific to larger companies. Since no responses were obtained from smaller companies (<100 employees), two possible explanations can be provided:

1.) The sample techniques of obtaining company information from the Kompass Company Directory were unsuccessful, as it may not have allowed sufficient small companies to be targeted. However, since the samples were randomly selected it would be a safe assumption to make that the reasons for the lack of responses from these small companies may be due to the next reason.
2.) The larger companies may be better equipped, both in terms of resources and in terms of personnel, of ensuring that adequate heat stress risk assessments are performed. This latter reason may be more relevant if one considers the responses that claimed they did not have a need for heat stress risk assessments. All these responses were identified as companies that had process that would create heat. It seems unlikely therefore, that heat stress was not an issue. Rather, it would seem that heat stress was not an issue because it had not been identified as one (this may be a problem if companies rely on RIDDOR reporting as an accident only qualifies as a heat stress accident if the intervention of a third party is required).

Whatever the reason, the weaknesses of the study are recognised, but they may also be an indication of the confusion and/or lack of understanding of heat stress in industry, and specifically in smaller companies.

The respondents that were received had a mean time in health and safety of 11 years from a broad range of health and safety related occupations. An interesting finding was that ISO and BS standards were rated as worse than other guidance (such as ACGIH TLVs). If this is a reflection of what might be found in the general population it would suggest that the expert and user group assertions that current standards are not user friendly may be having an effect on their usage and application in industry. This is something that the standard writers should consider when it is time to redraft the standards. Another reason for the greater knowledge of the ACGIH TLVs may be due to the TLV booklet containing information on a range of hazards (chemicals, noise etc) and as such users have a readily accessible source of information that does not require the assessor to move between information sources as and when the need to conduct risk assessments arise. Although 90% (26) respondents were aware of ISO 7243, with 81.48% having used it. This was supported by the findings that respondents gave significantly different ratings for the knowledge and for their confidence in ISO 7243 when compared to ISO 7933 and ISO 7933 was the only index listed that was not currently being used. The ACGIH and ISO 7243 were the indices being used the most (63 and 52% respectively). The Heat Stress Index (the predecessor to ISO 7933 was still being used by three respondents (11%).

The following table has been drafted to compare the methods that the respondents currently use in their assessment of risk stress and the allocation of “Information Level” as decided by the expert discussion group. To allow for the large variation of the rated levels of knowledge of heat stress observed in **Figure 29**, a criteria limit of 75% (>20) has been placed on meeting the Primary Level recommendation and a limit of 50% (>14%) for Secondary Level. It is appreciated that these percentages are low, but have been set to obtain a measure representative of current usage and not what would be expected. It is also restricted by the small number of respondents. The resultant comparison shows that users are only performing six of the possible seventeen tasks investigated. This suggests that users need to be made aware of the importance of those methods that they are currently not employing.

Table 72: Comparison between what methods users report using and the allocated Information Levels from Expert Discussion Group.

DESCRIPTION OF MOST COMMON METHOD	CURRENTLY USE	PREVIOUSLY USED	TOTAL	EXPERT DISCUSSION GROUP - LEVEL OF INFORMATION ALLOCATION	DOES IT MEET EXPERT KNOWLEDGE ALLOCATION?
Air temperature **mercury in glass thermometer**	21	2	23	**PRIMARY**	✓
Radiant temperature **black globe thermometer (±40mm)**	16	6	22	**PRIMARY**	✓
Humidity – whirling hygrometer	7	7	14	**SECONDARY**	✓
Air velocity- hot wire anemometer	20	1	21	**PRIMARY**	✓
Wbgt – wbgt meter	14	10	24	**PRIMARY**	✓
Clothing insulation – clo value	9	2	11	**PRIMARY**	✗
Moisture permeability	4	1	5	**PRIMARY**	✗
Body parts covered	9	None	9	**SECONDARY**	✗
Air permeability	5	1	6	**PRIMARY**	✗
Metabolic rate (measured)	3	6	9	**SECONDARY (BY EXPERT)**	✗
Metabolic rate (estimated)	18	4	22	**PRIMARY**	✓
Worker's state of acclimation	2	16	18	**PRIMARY**	✗
Dehydration/re-hydration	None	2	2	**PRIMARY**	✗
Subjective responses of workers	1	8	9	**PRIMARY**	✗
Age	1	9	10	**SECONDARY**	✗
Gender	12	None	12	**PRIMARY**	✗
Health status (measured by medic)	16	None	16	**PRIMARY**	✗

4.3.5 CONCLUSIONS OF STAGE 2 – DESIGN Stage

Proposed Generic Strategy for the Management, Assessment and Control (MA&C) of Heat Stress

The Risk Analysis Approach

Glendon's model of the decision flow training objectives for an individual and an organisation was introduced. From data gathered in the Exploratory Stage and in the Literature Survey thus far, Glendon's model has been adapted to meet the requirements of an overall approach to the Management, Assessment and Control of Heat Stress (MA&C) in industry. It is from this generic requirement and the need for a holistic risk analysis approach that the process flow diagram has been developed. Both the model and the process diagram have been developed with the following functional specification in mind.

10 Point Approach MA&C of Heat Stress

The following 10 point strategy is recommended as the approach for the MA&C of heat stress. A process diagram to show the decision making sequence that should be taken is provided as Figure 10.10**.**

1. Managing Health and Safety of Workers
2. Training and Education of Workers
3. Hazard Identification
4. Observation
5. Simple Controls
6. Measurement/Evaluation
7. Analysis & Interpretation of Results
8. More detailed Analysis and Interpretation
9. Implementation of Controls
10. Obtain Expert Help.

Functional Specification of a MA&C of Heat Stress Strategy

The main function of the MA&C of Heat Stress Strategy will be to provide the necessary information, tools and user job aids to aid in the systematic identification, evaluation and prevention or control of heat stress in industry. A number of sub-functions will combine to meet this requirement, they include:

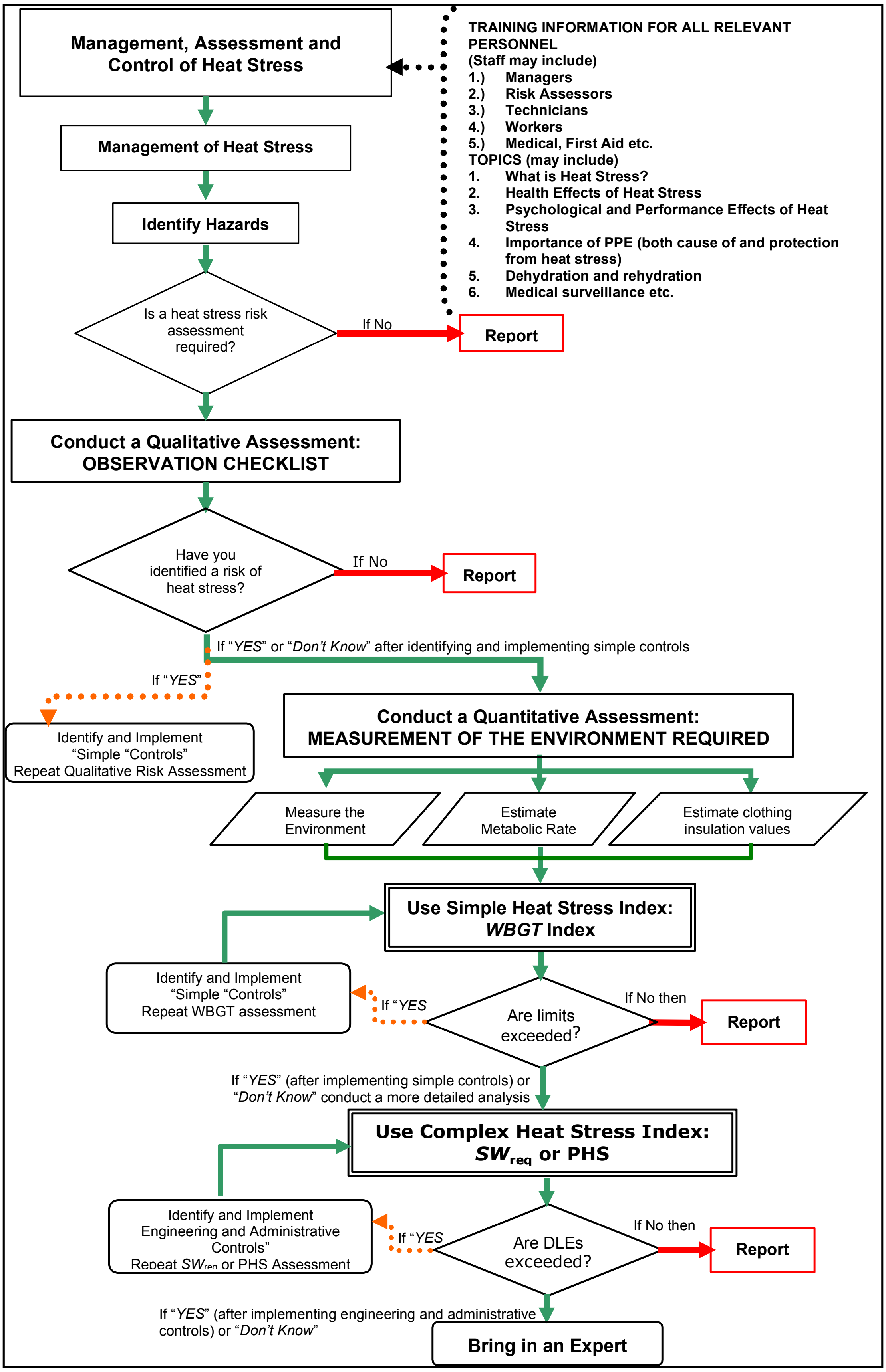
- Provide an effective and usable method for the management of heat stress
- Provide an effective and usable method for the assessment of heat stress
- Provide an effective and usable method for the control of heat stress
- Provide an effective and usable method for the communication of heat stress between all levels of a company.
- Provide a systematic approach to all aspects of the MA&C of heat stress
- Provide information that could help assign responsibility to managers, supervisors, and employees
- Provide information for the training of all employees
    1.) Training guidelines for workers working in the heat (e.g. emergency withdrawal procedures, rehydration requirements etc.)
    2.) Training guidelines for those responsible with the assessment and control of heat stress

- Provide guidelines based on current heat stress standards, best practice and published information.
- Provide clear statements on the recommended physiological limits for working in the heat
- Provide mechanisms whereby recording keeping can be ensured (e.g. record sheets etc)
- Provide information on control procedures for the different hazards that are associated with heat stress including, high radiation, high humidity, high metabolic rate, health status etc. Controls would include engineering, administrative and others.

Table 73: Adapted model of Glendon's decision making requirements for risk assessments

IDENTIFY HAZARDS	• Visual inspection of the work place to spot hazards that could pose a risk of heat stress. • This is done through visual observation (e.g. looking for a heat source) or physical measurements of the environment. • Reporting of accidents attributed to heat stress (e.g. fainting) and analysis of reports into accident. (Use of RIDDOR) • Management can also play a part, by investigating material other than accidents reports. The material could include: • Productivity reports to identify any possible reduction in productivity, • Human Resource Department – absentee rate, worker complaints, Medical Records Illness reported • Worker Representatives (Unions) worker complaints.
EVALUATE RISKS	• Formal heat stress risk assessment policy must be introduced into risk assessment procedures. • Development of technical skills and knowledge of both health and safety personnel and other employees may be required. • Ensure that whoever is to measure the environmental parameters knows how to do so. • Ensure whoever is to interpret the heat stress index used, knows how to use the index and what the results mean. • Ensure that whoever is to estimate metabolic rate and clothing insulation knows how to do so. • Ensure who ever is responsible for PPE policy knows how PPE may interfere with thermoregulation. • Specific legislation and relevant standards will dictate methods and indices to be used. Standards and methods may include: • WBGT, TLVs, Required Sweat Rate Model – ISO 7933 • Risk perception of those responsible for health and safety policy, employees and employers. • **Here an observation technique could be used. Such techniques are used elsewhere but not in heat stress risk assessments.**
DEVELOP AND IMPLEMENT CONTROLS	• Development of technical skills and knowledge of both health and safety personnel and other employees. (as above). • Development of procedural skills and ensure that other procedures are catered for • Formalise and rehearse drills and procedures for the evacuation of worker suffering from heat stress. • Ensure adequate fluid is available to prevent/reduce dehydration and aid rehydration of worker suffering from dehydration. • Formalise resuscitation and other first aid procedures etc. • Individual skills • Worker, manager and hygienist's attitudes towards heat stress are critical. • Additional information such as the affects of PPC and Work Rate on the worker must also be understood. • Behaviour and Motivation • Workers must be aware of the some causes and consequences of heat induced illnesses such as dehydration (e.g. the consumption of a large amount of alcohol the night before may pose a risk to dehydration.) • Worker's motivation to perform in hot environments will decrease as the strain increases. Moral should also be monitored. • Organisational skills (e.g. learning from mistakes (near misses), accidents and incidents) will help reduce the risk of heat stress.
MONITORING AND FEEDBACK	• Development and implementation of adequate risk assessment procedure to reduce heat stress. • Development and implementation of valid performance measures whereby workers can be monitored by those responsible for health and safety policy as well as by themselves to identify possible heat stress induced performance decrements. • Implementation of an organisation wide policy of training and education that encourages safety culture that is aware of the risks of heat stress.

Figure 37: Process flow diagram of the Management, Assessment and Control of Heat Stress in Industry



4.3.6 The proposed Observation Checklist for the Assessment of Heat Stress

Based on the findings of the research thus far, it was decided to concentrate the remainder of this project on the Observation Checklist as the practical heat stress assessment tool. The MA&C guidance will not be developed further, but have provided the basis for the role that the Observation Checklist will play in the overall strategy of heat stress risk assessment. The following tables show the design decisions that have been made for the Observation Checklist:

General Format of Observation Checklist

FEATURE	DESIGN AND DEVELOPMENT STAGE	
	DESIGN DECISION	RATIONALE
Basic Parameters	• Separate the parameters into Environmental, Clothing and Work rate categories. Each becoming a Parameter Group. • Provide a parameter group for Health Status of the worker	• Follows the method of conducting a quantitative heat stress assessment where the user would need to measure the environment, estimate the clothing insulation and estimate the metabolic rate (making corrections for any PPE). • Health status of the worker is crucial.
Instructions	• To provide simple, easy to read instructions based on standard ergonomic guidelines.	• Inaccurate or difficult to understand instructions would render the observation method useless.
Example Scenario	• Provide an example scenario with worked example of checklist.	• This would show the user how the checklist may be used, and how the information may be interpreted.
Layout	• To provide a logical and easy to follow layout with colour coded sections to aid navigation. • Keep instruction to one page. • Keep checklist to 3 to 4pages to minimise user memory load. • To provide a Scenario (with completed sample answer) to illustrate how checklist may be completed	• The layout was designed to enable the users to easily navigate their way through the process and to minimise their memory load. • Additional information such as the Instructions, Scenario etc will add to the method's length. Therefore the method needs to be as concise as possible.
Decision Process	• To provide a step by step process for observing the work place environment and the worker • To provide decision aids as and when needed to aid in the use of the checklist	• To further simplify the task each parameter would be observed in turn following a similar approach to that that might be followed when conducting other quantitative risk assessments.
Additional Information'	• To provide detailed breakdowns of the different aspects of the parameters.	• It was hoped that by providing a detailed breakdown of the different parameters users would become aware of how the different parameters interact and what aspects of the different parameters needed to be considered.

Ranking of Risks and Resultant Scores

FEATURE	**DESIGN AND DEVELOPMENT STAGE**	
	DESIGN DECISION	**RATIONALE**
Scoring	• Provide a scoring system for each parameter of each group. • Provide a mechanism for the comparison of scores between parameters to identify possible heat stress causal factors • Provide visual feedback about potential levels of risk of each parameter.	• No literature could be found to provide a mathematical basis for the ranking of thermal environment risks, therefore other risk ranking techniques were investigated. Most seemed to use an arbitrary raking system based on expert knowledge. • It was decided to use a polarised scoring ranking system of –2 to +3, with 0 being the neutral point. This was based on the ranking technique employed in the ASHRAE thermal comfort scale and the PMV index. • It was then discovered that Malchaire had used a similar ranking system.

Score as a measure of Overall Risk	• To provide an easy to understand overall estimation of the risk of heat stress.
	• To provide this as a SINGLE NUMBER representing a position on a qualitative scale of risk of heat stress.
		• Potential users had expressed the desire for a single estimate of risk for the overall working situation.
		• To weight categories according to possible impact, with the following weightings;
		  • Environmental Score X One
		  • Work Rate Score X Two
		  • Clothing Score X Three
		• The Estimate of Risk scores for each parameters were summed and then divided by six (sum of weightings; 1+2+3) to equalise the effects that each of the parameters may have had.
		• The resultant figure was an overall estimate of risk with the following criteria ranges:
		  • Less that 0 -= NO RISK
		  • 0 to 1 = Low Risk
		  • 1 to 2 = Moderate Risk
		  • 2 to 3 = High Risk
		  • 3+ = Unacceptable Risk

Environmental Parameters

FEATURE	DESIGN AND DEVELOPMENT STAGE	
	DESIGN DECISION	RATIONALE
Air Temperature	• To use descriptions or categories of air temperature instead of ranges based on measurements.	• The idea of a qualitative method must be that users are not required to take any measures but to simply "observe" their environment and the worker.
Thermal Radiation	• To adapt the radiation descriptions as used by Malchaire.	• No subjective descriptions of thermal radiation could be found in the literature. • A point that was raised during the preliminary discussion group sessions was that bare skin may not be exposed to the radiation. Therefore phrase “if skin were exposed” was used.
Humidity	• To adapt the radiation descriptions as used by Malchaire.	• No subjective descriptions of thermal radiation could be found in the literature.
Air Movement	• To adapt the radiation descriptions as used by Malchaire.	• No subjective descriptions of air movement could be found in the literature. Malchaire's descriptions were adapted to include temperature of air moving as hot air may increase heat transfer into the human through convection.

Work Rate Parameters

FEATURE	DESIGN AND DEVELOPMENT STAGE DESIGN DECISION	 RATIONALE
Type of Movement	• To describe the work rate as components tasks that make up the overall task.	• It was felt that to describe the work rate as types of work (e.g. driving, digging etc.) would be too detailed. • Therefore, the components as described in ISO 9886 (1994) were used. • Since each task may be made up of different tasks the user would have the capability of ticking more than one box and as such obtain an overall score for work rate based on the sum of the components. • A ratio was obtained by dividing the sum of scores by the number of ticks.

Clothing Parameters

FEATURE	DESIGN AND DEVELOPMENT STAGE DESIGN DECISION	 RATIONALE
Materials	• Provide different descriptions of clothing based on the vapour and air permeabilities.	• The permeability of the material of an ensemble may have a great impact on it's suitability in warm, hot environments. Users need to be aware of this. • Additionally, new indices (such as proposed PHS index) require users to input permeability index (i_m).
Hazard Protection	• Describe clothing based on the severity of the hazard from which it is protecting the worker (i.e. exposure could be fatal).	• If workers are working in areas of high risk from hazards such as chemicals, nuclear etc the nature of the clothing will interfere with thermoregulation.
Movement	• Describe clothing in terms of any restrictions it may have on the workers ability to perform tasks.	• Heavy and bulky clothing may inhibit movement thereby increasing the metabolic rate
Weight	• Describe clothing in terms of its weight (i.e. lightweight, heavy etc).	• As above
Reflective qualities of clothing material surface	• Describe reflective properties of clothing (i.e. black/dark clothing with no reflective properties).	• Recommendation from user discussion groups. • If high reflective clothing is worn in high radiation environments, the risk from the radiation may be reduced.

An overall design decision based on the above findings was that the clothing described in BS ISO 9920 (1995) and the references provided needed to be categorised so that the different ensembles could be ranking according their insulative properties.

The first prototype of the observation checklist is in the Appendix (section 17). The prototype (which will be called the Bethea and Parsons method) was then evaluated and compared with the method developed by Malchaire.

4.4 STAGE 3 – EVALUATION STAGE

4.4.1 User Trials

Smilowitz *et al* (1994) reported the successful use of what they call "*beta tests*" late in a product's development. Although this was used to assess software with "*real world users*" in "*real world situations*" it was decided that a similar evaluation process was needed for the Observation Technique. An empirical test, conducted in a thermal chamber in a laboratory using simulated situations (such as that used in the heuristic evaluation) would not be suitable as it did not reflect "real world" heat stress problems. As such, it may be too constrained by the controlled environment and limitations of the laboratory. Additionally, following the difficulty in obtaining user input into other parts of the study, it was recognised that it would be very difficult and time consuming to obtain representative users from industry to participate in laboratory trials. Since structured group discussions had been successful in obtaining representative user input it was decided to use them again for usability testing of the Observation Methodology.

4.4.2 Introduction

It was necessary to evaluate the observation checklist method developed for this project using representative users. Two groups of participants from two different industries volunteered to take part in the experiment. One group was from a large multinational steel company and the other group was from a number of companies in the Paper Industry. Two observation methods were evaluated in situ at a representative plant of each group. The two methods to be evaluated were:

1. Malchaire
2. Bethea and Parsons.

A direct comparison between the methods was to be made using the discussion groups to obtain qualitative data. From the results, iterative changes would be made to that method that the users preferred to provide the recommended observation checklist for this project.

4.4.3 Aims

The aim of the evaluation stage was to compare the usability of the two observation methods with representative users in real-life situations.

4.4.4 Method

Experimental Design Decisions

- The usability trial was to be run as a controlled experiment and as such a number of experimental design decisions were made *a priori*.
- Users would be required to use the two observation techniques to evaluate the risk of heat stress in an occupational setting.
- The users were not to be made aware of which methodology was which, in other words it was a "blind trial". This was done so as not to influence them in anyway. The only

information they had been given was that the two methods had been developed by different research teams.
- The users were asked not to discuss the methodologies, their observations or their opinions during the trail.
- No comparison of observations during the trial would be permitted.
- Other than the procedural information about the user trial, no information about how to use the methodologies would be provided. The users would be required to follow the provided instructions.

Subjects

Paper Mill Participants

Seven health and safety personnel took part in the study. They were responsible for the health and safety in their factory. Only two of the participants had any experience of heat stress risk assessment. The rest of the participants were relatively inexperienced in heat stress risk assessment. As such this was be representative of **OCCASIONAL** users.

Steel Mill Participants

Seven health and safety personnel took part in the study, and as in the Paper Mill group were responsible for the health and safety in their factory. All of the participants had experience of heat stress assessments using a number of methods including HSI, P4SR, *WBGT* and physiological monitoring. These participants were representative of the **SKILLED** users

Apparatus

- As mentioned above, the two methodologies were given to each member. The methodology by Malchaire was called **Method A**, and the other **Method B**.
- Each methodology had its own instructions specific to each.
- Detailed usability questionnaires were developed for users to complete upon completion of the trials (these were not used on the day because the researcher felt that it would unnecessarily interfere with the way the discussion group was going – i.e. sufficient information was being provided through the discussions).

Descriptions of Sites Evaluated

Paper Mill

Two sites were evaluated:

1.) The basement area beneath a Paper Machine. The environment was warm and humid. The tasks performed were the same as those described in Chapter 4**.**

2.) Behind the screen area in front of the rollers above the basement area. This environment was hot with high thermal radiation from the rollers. This environment is usually covered by a protective screen which is raised when paper breaks occur. Workers work in this area in close proximity to the rollers while removing paper jams. Occasionally they may be required to crawl between the rollers to remove and replace the felt-belts on which the paper moves. The *WBGT* value in this area is about 44°C, with a mean globe temperature of 51°C.

Steel Mill

Only one site was observed: a blast furnace was undergoing maintenance.
The end walls had been removed and maintenance crews were working to remove slagg from the floor of the furnace. The dry bulb air temperature was 45°C and the radiant temperature was about 80°C at the place of work. The work/rest schedules were 10 min on and 20 min off during which time they left the furnace. Their work rate was very high with them using pitchforks to loosen the slagg and then shovelling it into wheelbarrows. When full, the wheel-barrows where wheeled to the edge of the furnace and the contents tipped into a basement area below. Workers wore fire retardant coveralls, t-shirts, boots with wooden blocks strapped to the underside of the boot, fire retardant gloves, facemasks and safety goggles.

4.4.5 Procedure

Pre Experiment

- The discussion group sessions and the venue for the observation to be performed were on the same site. The site for each group was volunteered by one member of that group and was not subject to any restrictions from the research team other than it should be a warm or hot environment in which the participants felt heat stress may be an issue.
- Contact with each participant was made via email and the telephone a couple of weeks before the discussion group sessions.
- Each of the participants was sent a postal pack containing information one-week prior the session that included information about the discussion groups, an itinerary, and an explanation of the project's aims.
- The methodologies were not sent to the participants as their opinions may have been influenced prior to the session. Additionally the research team did not want the participants to talk amongst themselves about the methods so as to prevent any of the participants influencing the others.

Experiment

- All the participants arrived at the location and an introductory presentation about the procedures and aims of the experiment was given by the experimenter. Any queries regarding the format of the discussion group were dealt with prior to the experiment starting.
- Each participant was given the two methodologies along with the associated instructions. Each methodology had been coded to identify the participant and the order of application. This also enabled the experimenter to ensure all methodologies had been returned.
- Participants were given time to read through both the instructions and each method. They were asked not to discuss it amongst themselves.
- When they were all ready the participants and the experimenter went to the site of the observation assessment. Half the participants were asked to use Method A first and then use Method B and visa versa. This provided a balanced design and ensured that there was no order effect. Therefore, both methods were used at each site.
    - In the Paper Mill, where two sites were observed, the participants were given new methodologies and required to reverse the order that they had used for the previous site.

    - To meet the health and safety requirements at the steel mill the participants and the experimenter were only allowed to remain in the furnace for a maximum of 10 minutes. Therefore the participants were asked by the experimenter to consider the categories in each methodology and to complete the methodologies upon exit from the furnace.
- All completed methodologies were collected prior to the discussion groups commencing.

Post Experiment – The Discussion Group

The experimenter acted as the moderator. Usability criteria questions were asked, and the users discussed the merits of each methodology based on these criteria. They were also required to make direct comparisons between the two, based not only on the usability criteria but also on the practicalities of using them, interpreting them and the likelihood that they would be able to introduce controls as a result of each method.

4.4.6 Results

All data was to be transcribed and coded according to usability themes, preferences etc.

It is recognised that the sample size was relatively small and that the representative users only came from two industries. It is recommended that the proposed method is tested throughout a number of industries and with a much larger sample size to ensure it meets all their user and functional requirements.

As a result of the discussion groups the following points were identified:
1. Both discussion groups preferred the Bethea and Parsons method to the Malchaire method.
2. Malchaire's method was considered the easiest to use, but all the participants considered it too simplistic and with too little information to be of practical use. They also felt that it would be the least likely method to get results accepted by management.
3. The Bethea and Parsons method was considered more difficult to use, but this was soon overcome after using the scenario and the first assessment. All the participants preferred this method, however a number of issues were raised:
    - The components of work rate were difficult to interpret. Users would prefer descriptions of the types of work.
    - Participants wanted descriptions of the different parameters in language that they might understand. "What is humidity and how do you know if it is humid?" was one example given. This was a criticism of both methods.
    - The descriptions of the clothing based on material, movement etc was at times confusing. The participants recommended using descriptions of clothing instead.
    - All the participants thought the inclusion of worker health status in the Bethea and Parsons method was important.
    - Scenarios, such as that provided in the Bethea and Parsons method should be included. In the final version, they would like more than one example scenario.
    - The longer time taken to complete the assessment using the Bethea and Parsons method was not considered problematic. This was considered acceptable as it provided more information than the Malchaire method.
4. The scores for each workplace were very similar for each method, but between workstations the Bethea and Parsons method's OVERALL ESTIMATE OF RISK was not sensitive

enough to show the increases in actual risk. The process of obtaining a single risk figure requires more development.

5. The Bethea and Parsons method was considered to more closely resemble qualitative risk assessment than the Malchaire method.
6. The Bethea and Parsons method was considered to be the better of the two for communicating the parameters to be considered to the users.
7. The layout and spatial orientation of the Bethea and Parsons method was preferred, although a couple of the participants found the landscape orientation a little difficult to follow after the Portrait orientation of the instructions
8. The Bethea and Parsons method was considered to be more flexible to the user requirements.
9. All the participants expressed more confidence in the Bethea and Parsons method.

Added to this more specific data was obtained. This is detailed in the following tables, which show the original design decision, and the new design decisions along with the rationale which was provided by these user trials.

General Format of Observation Checklist

FEATURE	DESIGN AND DEVELOPMENT STAGE	POST EVALUATION STAGE	
	ORIGINAL DESIGN DECISION	NEW DESIGN DECISION	RATIONALE
Basic Parameters	• Separate the parameters into Environmental, Clothing & Work rate categories., each becoming a Group. • Provide a parameter group for Health Status of the worker	Not to make any changes to these basic parameters or their order.	• Users stated that by separating the parameters into the categories, it enabled them to identify what the issues were and what measures needed to be considered.
Instructions	• To provide simple, easy to read instructions based on standard ergonomic guidelines.	To provide general descriptions of the parameters as a glossary. Need to be in "non scientific" language and based on scenarios that users may be able to understand.	• Users said that they felt it was difficult to comprehend some of the concepts being described (e.g. radiant heat).
Example Scenario	• Provide an example scenario with worked example of checklist.	To keep scenario and worked example of checklist. When used in general guidance, include worked examples of heat stress indices such as $WBGT$ and SW_{req}.	• Although the scenario took time to work through, the users felt that it improved their understanding of the method. • Users wanted the provision of a number of example scenarios with detailed workings of the quantitative methods to be used. Use of scenarios should be continued.
Layout	• To provide a logical and easy to follow layout with colour coded sections to aid navigation. • Keep instruction to one page. • Keep checklist to 4 to 5 pages to minimise user memory load. • To provide a Scenario (with completed sample answer) to illustrate how checklist may be completed	No changes were made to the overall layout, although attempts would be made to keep all the pages in portrait orientation. When added to overall guidance, keep the worked examples and the actual checklist separate so that worked examples appear with indices examples	• The users all expressed their satisfaction with the layout, although some did state that moving from Portrait to Landscape layouts was a little confusing at first. • Users all said that a worked example section in final guidance would be used as a reference section.

FEATURE	DESIGN AND DEVELOPMENT STAGE	POST EVALUATION STAGE	
	ORIGINAL DESIGN DECISION	NEW DESIGN DECISION	RATIONALE
Decision Process	• To provide a step by step process for observing the work place environment and the worker • To provide decision aids as and when needed to aid in the use of the checklist	To keep the step by step approach and to keep the order in which the different parameter groups were presented. To introduce a glossary of all the parameters.	• The users felt that the decision process more closely followed other methods they had used (e.g. for manual handling, noise etc) than Malchaire's method.
Additional Information'	• To provide detailed breakdowns of the different aspects of the parameters.	To simplify the parameters and to reduce the number of possible answers. To include an uncertainty option (based on the definition provided by Covello and Merkhoffer).	• The users felt that there were too many parameters in the Work Rate and Clothing and that this confused them. • The simplicity of Malchaire's method was liked but was considered too simplistic. They all agreed that the simplicity of Malchaire's method would not provide them sufficient information for management to agree to the introduction of controls.

Work Rate Parameters

FEATURE	DESIGN AND DEVELOPMENT STAGE	POST EVALUATION STAGE	
	ORIGINAL DESIGN DECISION	NEW DESIGN DECISION	RATIONALE
Type of Movement	• To describe the work rate as To components tasks that make up the overall task.	To describe work rate by tasks and jobs and not in component information.	• User preference was different to that expressed by the experts in the discussion groups. Therefore, a combination of the descriptions in ISO 8996 and Ramsey *et al* (1994) will be used.

Ranking of Risks and Resultant Scores

FEATURE	DESIGN AND DEVELOPMENT STAGE	POST EVALUATION STAGE	
	ORIGINAL DESIGN DECISION	**NEW DESIGN DECISION**	**RATIONALE**
Scoring	• Provide a scoring system for each parameter of each group. • Provide a mechanism for the comparison of scores between parameters to identify possible heat stress causal factors • Provide visual feedback about potential levels of risk of each parameter.	The ranking system needs to be exponential and not linear. This would increase the differences between ranks and thereby increase the difference between environments. Not all ranks need to be included. (*NOTE: For this project however, linear ranks are being used in the prototype. It is recommended that future ranks are agreed by a panel of experts and validated in the field.*)	• The users felt that the use of only 3 scoring "zones" above the neutral ZERO was insufficient as it suggested an equal weighting to all those appearing in each zone. Perhaps additional ratings could be included, with parameters such as high radiation, high humidity, etc having a much higher rating than hot air temperature. • There was significant difference between environments although there was a significant similarity within an environment.
Score as a measure of Overall Risk	• To provide an easy to understand overall estimation of the risk of heat stress. • To provide this as a SINGLE NUMBER representing a position on a qualitative scale of risk of heat stress.	Not to provide an estimate of overall risk at this time.	• Further investigation will provide the basis for evaluating possible ways of calculating an overall risk estimate. The only way to ensure that this accurate and valid is to compare qualitative risk data with objective environments and physiological measures.

Environmental Parameters

FEATURE	DESIGN AND DEVELOPMENT STAGE	POST EVALUATION STAGE	
	ORIGINAL DESIGN DECISION	NEW DESIGN DECISION	RATIONALE
Air Temperature	• To use descriptions or categories of air temperature instead of ranges based on measurements.	To keep the use of categories of air temperatures. Not to adopt Malchaire's use of ranges based on air temperature ranges.	• No air temperature measures were available during the user trials and therefore they could not allocate an answer to Malchaire's method.
Thermal Radiation	• To adapt the radiation descriptions as used by Malchaire.	To discard the descriptions adopted from Malchaire and to introduce more descriptions and examples of types of thermal radiation.	• Occasional users did not understand what was meant by the word "radiation", while the experts considered the descriptions to not go far enough.
Humidity	• To adapt the radiation descriptions as used by Malchaire.	To discard the descriptions adopted from Malchaire and to introduce more descriptions and examples of humidities.	• Users stated that confusion occurred when describing the humidity in terms of skin wetness because sweating may result in erroneous observations. • A paper by McIntyre (1978) showed that people have difficulty in estimating humidity between 20 and 70%, although if humidity changed over time, people could detect it. Therefore it was decided to describe humidity in terms of vapour producing processes and not on subjective estimation of humidity. Fewer options would be given to reduce the risk of confusing the user.
Air Movement	• To adapt the radiation descriptions as used by Malchaire.	To improve on the descriptions given by including examples of different types of air movement.	• Users understood the descriptions provided but it was felt that the task may be made easier by introducing examples. • Several of the users stated that the air velocity categories described by Malchaire were too narrow and did not take into account incidences where high temperature air movement was found. This they said was inconsistent with the rest of his method, e.g. intense burning on skin for radiation.

Clothing Parameters

FEATURE	DESIGN AND DEVELOPMENT STAGE	POST EVALUATION STAGE	
	ORIGINAL DESIGN DECISION	NEW DESIGN DECISION	RATIONALE
Materials	• Provide different descriptions of clothing based on the vapour and air permeabilities.	Do not use a materials category for describing clothing. Describe clothing by it's type (i.e. coverall, PVC, Fire fighting etc).	• The occasional users were confused by the material descriptions as they did not know whether clothing was vapour and or air impermeable/permeable. • All the users thought that general descriptions would be easier to use. • Descriptions of clothing ensembles will be adapted from BS ISO 9920 (1995), Annex A, Table A.1 and from ACGIH, TLV's and from BS 7963 (2000).
Hazard Protection	• Describe clothing based on the severity of the hazard from which it is protecting the worker (i.e. exposure could be fatal).	As above	• As Above
Movement	• Describe clothing in terms of any restrictions it may have on the workers ability to perform tasks.	As above	• As above
Weight	• Describe clothing in terms of its weight (i.e. lightweight, heavy etc).	As above	• As above
Reflective qualities of clothing material surface	• Describe reflective properties of clothing (i.e. black/dark clothing with no reflective properties).	As above	• As above

An overall design decision, based on the above findings was that the clothing described in BS ISO 9920 (1995) and the references provided needed to be categorised so that the different ensembles could be ranked according their insulative properties.

The "Checklist to identify possible personal risk factors" has been adapted from Goldman (1988), NIOSH (1992), Parsons (1993) and Ramsey *et al.* (1994)

CHAPTER 5
A PRACTICAL HEAT STRESS ASSESSMENT METHODOLOGY

5.1 PART 1: CHECKLIST TO IDENTIFY POSSIBLE PERSONAL RISK FACTORS.

The checklist below is associated with heat intolerance and heat stress susceptibility. A preliminary observation tool it is intended to aid in the identification of possible "**at added risk**" workers who, due to a personal risk factor, may have an increased susceptibility to heat stress. This checklist is not intended to replace a medical examination.

The indicators listed may be representative of temporary and/or permanent conditions and careful consideration of each individual case following a medical should be applied before restricting work. There may be additional indicators that are not listed that could increase the risk of the worker experiencing heat stress.

If in doubt, seek advice from a physician.

Apply checklist to those workers who are to be exposed to hot working environments. Tick checklist either YES or NO. Any YES answer may indicate an increased risk heat stress.

If in doubt, seek advice from a physician.

Personal Risk Factor Indicators	YES	NO
History of heat stroke		
History of inability to acclimatise		
Inexperience of working in the heat		
Not skilled at specific job		
Just returned from illness or leave		
Worker is not acclimatised		
Pre-existing or recent illness (e.g. Vomiting, diarrhoea etc.)		
On a restricted or low sodium diet		
Skin trauma such as sunburn, heat rash etc.		
Heat Stroke		
Heat Exhaustion		
Heat Syncope		
Heat Cramps		
Heat Rash		
Anhydrotic Heat Exhaustion		
Hyperventilation		
Heat Fatigue Transient		
Heat Fatigue Chronic		
Beta-blockers		
Antihistamines		
Diuretics		
Cholinergics		
Recreational		
Alcohol		
Other (check with physician for side effect)		
Cardiovascular disease		
Obesity Males >25% overweight		
Obesity Females >30% overweight		
Other (check with physician for effects of heat)		
Low physical fitness		
Inability to sweat		
Skin disease		
Pregnancy (poses potential risk to the unborn baby)		
Impaired mental capacity		
Other (check with physician for effects of heat)		

If in doubt, seek advice from a physician.

5.2 OBSERVATION CHECKLIST FOR HEAT STRESS RISK ASSESSMENT

5.2.1 Environmental Considerations

This section describes the four environmental parameters that make up the thermal environment. They are; radiant temperature, air temperature, humidity and air velocity.

Each table represents one of these parameters, which are described and explained. Each parameter is described according to a number of risk scores; where the higher the score the higher the risk that it may contribute to heat stress. Observe the environment, taking note of the descriptions provided, and tick the box (on the right) next to the description that best fits the workplace you are observing. This will provide you with a rank score for that parameter.

If you do not see a description that best fits the work situation you are assessing, or are unsure, then tick the "**Don't know**" box at the bottom of that table. This introduces an uncertainty into the assessment and requires that you conduct a more detailed qualitative assessment.

5.3 THERMAL ENVIRONMENT CONSIDERATIONS

This section describes the four environmental and two personal parameters that make up the thermal environment. They are;

- **Environmental Parameters** – Air Temperature, Radiant Temperature, Humidity and Air Velocity.
- **Personal Parameters** – Metabolic rate and Clothing

Each table represents one of these parameters, which are described and explained. Each parameter is described according to a number of risk scores; where the higher the score the higher the risk that it may contribute to heat stress. Observe the environment, taking note of the descriptions provided, and tick the box (on the right) next to the description that best fits the workplace you are observing. This will provide you with a rank score for that parameter.

If you do not see a description that best fits the work situation you are assessing, or are unsure, then tick the "**Don't know**" box at the bottom of that table. This introduces an uncertainty into the assessment and requires that you conduct a more detailed qualitative assessment.

5.3.1 Air temperature

AIR TEMPERATURE EXPLAINED

- The temperature of the air surrounding the human body

Estimate Risk of Air Temperature contributing to Heat Stress:

- Consider the temperature of the air surrounding the worker and read the subjective descriptions below.
- Can you provide a subjective estimation of the air temperature? **<u>YES / NO</u>**
  - If **YES,** tick the box that best fits the air temperature you are evaluating. If you think that more than one air temperature is present then tick more than one box.
  - If **NO,** tick "**Don't Know**" and <u>conduct a quantitative heat stress risk assessment.</u>

Description and things to look out for	**SCORE**	**Tick**
• Cool	**-1**	
• Neutral	**0**	
• Slightly warm	**1**	
• Warm	**2**	
• Hot	**3**	
• Very Hot	**4**	
	Don't know	

5.3.2 Thermal Radiation

THERMAL RADIATION EXPLAINED

- Thermal radiation is the heat that is given off from a warmer to a colder object.
- Radiant heat may be present if there are heat sources in an environment. <u>Examples</u> may include; the sun, fire and flares; electric fires; furnaces; steam rollers; ovens, walls in kilns, cookers, dryers; hot surfaces & machinery, exothermic chemical reactions, nuclear reactors, tunnel walls in deep mines, molten metals, etc.

Estimate Risk of Radiant Temperature contributing to Heat Stress:

- To obtain a measure of risk for thermal radiation, observe the surroundings and look for sources of heat. Also, consider how close the workers are to these heat sources, and whether they need to wear protective clothing to prevent burns etc. Read the subjective descriptions of radiant heat
- Can you provide a subjective estimation of the air temperature? **<u>YES / NO</u>**
  - If **YES**, tick the box that best fits the radiant temperature you are evaluating. If you think that more than one radiant temperature is present then tick more than one box.
  - If **NO**, tick "**Don't Know**" and <u>conduct a quantitative heat stress risk assessment.</u>

Description and things to look out for	**SCORE**	**Tick**
• Objects colder than the surrounding air are near to worker.	**-1**	
• There are no heat sources in the environment.	**0**	
• Heat source is present in the environment but the workers are not working in close proximity to it. • Heat source surface feels warm to the touch and you could keep your hand there indefinitely.	**1**	
• Heat source surface feels hot to the touch. • Worker is working in close proximity to the heat source • Heat source makes workers feel hot when they stand near it.	**2**	
• Heat source surface feels very hot to the touch and may burn the skin. • Workers cannot work in close proximity to the heat source for more than 10 minutes.	**3**	
• Contact with heat source will cause burning • Workers cannot work in close proximity to the heat source for more than 5 minutes.	**4**	
• Workers have to wear flame resistance clothing to protect their skin from burning. **Examples:** Flares, fires and furnaces, kiln walls, etc. • Workers are not permitted to work in the environment without PPE to protect them from the radiant heat in that environment.	**5**	
	Don't know	

5.3.3 Air velocity

AIR VELOCITY EXPLAINED

- Air velocity is the speed at which air moves across the worker. Air velocity may help cool the worker if it is cooler than the environment.

Estimate Risk of Air Velocity contributing to Heat Stress:

- Think about the temperature of the air moving across the worker. Remember that the temperature is important, as it will affect the heat loss or heat gain to the worker.
- To aid your subjective estimation of the air velocity, four categories of air velocity are provide. They are **Still**, **Low**, **Moderate** and **High**
  - ⇨ **Still** air, is where there is no noticeable flow of air.
  - ⇨ **Low** air speed, is when you can just feel the air movement, but it is not as obvious as a breeze may be.
  - ⇨ **Moderate air speed,** is when you can feel the air movement (e.g. a light breeze) on exposed flesh.
  - ⇨ **High** air speed may be similar to the air speed on a windy day, or at or near fans or other machines or equipment that generate air movement.
- In considering the air movement in the work area, look for the following:
  - ⇨ Is there a wind source?
  - ⇨ Have fans been introduced to reduce the temperature (e.g. during specialist maintenance work?)
  - ⇨ Can the workers feel hot or warm air blowing on any exposed skin?
  - ⇨ Is the moving air colder or warmer that the ambient air temperature?
- Read all the categories before deciding on your score.
- Can you estimate the air velocity and it's temperature: <u>**YES / NO**</u>
  - If **YES** give a ranking to the air velocity below.
  - If **NO**, tick "**Don't Know**" <u>conduct a quantitative heat stress risk assessment.</u>.
  - If more than one air velocity is observed, or if the temperature of the moving air is changing, then either tick more than one category or tick "**Don't Know**" and <u>conduct a quantitative heat stress risk assessment.</u>

Description and things to look out for	**SCORE**	**Tick**
• Cold air at a high air speed (e.g workers standing in front of an air conditioning unit, compressed air supply into clothing for cooling of worker – Breathing apparatus compressed air does not fall into this category)	**-3**	
• Cold air at a moderate air speed • Cool air at a high speed	**-2**	
• Cold air & low movement • Cool air at moderate air speed	**-1**	
• Still air movement in a neutral environment	**0**	
• Warm air & low movement	**1**	
• Still air movement in a warm environment	**2**	
• Still air movement in a hot environment.	**3**	
• Warm air at a moderate speed • Still air movement in a very hot environment • Hot air and moderate air movement	**4**	
• Very hot air at a high speed.	**5**	
	Don't know	

5.3.4 Humidity

HUMIDITY EXPLAINED

- If water is heated and it evaporates to the surrounding environment, the resultant amount of water in the air of that environment will provide humidity. High humidity environments have a lot of vapour in the air and this prevents the evaporation of sweat from the skin.
- If workers are wearing **vapour impermeable PPE**, then the humidity inside the garment increases as they sweat because the sweat cannot evaporate. Therefore, if workers are wearing high protection PPE that is vapour impermeable (e.g. asbestos, chemical protection suits etc) the humidity within the microclimate of the garment may be high.

<u>Examples</u>. Humidity in indoor environments will probably vary greatly, and may be dependent on whether there are drying processes (paper mills, laundry etc) where steam is given off. Indoor environments that are susceptible to outdoor conditions may also be humid on humid days. Where workers wear vapour impermeable PPE.

NOTE: Humidity is very difficult to estimate. Observing worker sweat rates to see if there is profuse sweating with sweat dripping from the person may be an indication of high humidity. However, it is also easy to confuse this with the sweating that occurs as a result of hard work.

Estimate Risk of Humidity contributing to Heat Stress:

- Think about the humidity of the environment within which the worker is working. Remember that the humidity is vitally important, as it will affect the heat loss through evaporation.
- Is the environment susceptible to outdoor conditions, especially in summer? Are there any dryers? Do workers complain about the humidity?
- Read all the categories before deciding on your score.
- Can you estimate the humidity? <u>**YES / NO**</u>
  - If **YES,** give a ranking to the humidity below.
  - If **NO**, tick "**Don't Know**" <u>conduct a quantitative heat stress risk assessment.</u>.
    - If more than one humidity is observed, or if the humidity may be changing (i.e. outdoors), then either tick more than one category or tick "**Don't Know**" and <u>conduct a quantitative heat stress risk assessment</u>
  - If workers are donning and removing PPE please only select **ONE** option that best described the environment you are observing and <u>conduct a quantitative heat stress risk</u>

Description and things to look out for	**SCORE**	**Tick**
• No humidity. Air is dry, with no drying processes or other mechanisms for increasing the humidity in the workplace.	**0**	
• Humidity seems to be somewhere between very humid and very dry.	**2**	
• Air is very humid. Examples may be near drying machines, laundry machines, chemical processes where steam is given off.	**5**	
• Vapour impermeable PPE is worn	**6**	
	Don't know	

5.3.5 Work Rate

WORK RATE EXPLAINED

- Work rate is also called metabolic rate and is essential for a heat stress risk assessment.
- This is used to describe the heat that the worker may be producing inside their body as they work. The more physical work they perform, the more heat they produce and the more heat they need to lose so that they don't overheat.

Use ISO 8996 (1990), estimation of metabolic heat production for more information.

Estimate Risk of Metabolic Rate contributing to Heat Stress:

- Observe the workers, tacking careful note of their movements, posture, speed, effort, weight of materials they may be handling, parts of their bodies that are responsible for their movement etc?
- To aid your subjective estimation of the metabolic rate, five categories of metabolic rate are provide. They are **Resting**, **Low**, **Moderate**, **High** and **Very High**. Descriptions are provided for each.
- If in doubt, review your manual handling assessment for information of the components of the task.
- Read all the categories before deciding on your score.
- Can you estimate the Metabolic Rate? **YES / NO**
  - If **YES,** give a ranking to the metabolic rate below.
  - If **NO,** tick "**Don't Know**" and conduct a quantitative heat stress risk assessment..
  - If more than one task is being performed then either tick more than one category or tick "**Don't Know**" and conduct a quantitative heat stress risk assessment

Description and things to look out for	SCORE	Tick
Resting. • Worker is resting as part of a work/rest schedule or is awaiting instructions etc. • Worker is not involved in any tasks at all.	**-2**	
Low. • Sitting or standing to control machines. • Light hand work (writing, drafting, sewing, bookkeeping, drafting etc). • Hand and arm work (small bench work, using tools such as table saws; drills, inspecting, assembling or sorting light materials, operating control panel, turning low torque hand wheels, very light assembly operation etc). • Standing with light work at machine or bench while using mostly arms (drill press, milling machine, coil taping, small armature winding, machine with light power tools, Inspecting or monitoring hot processes). • Arm and Leg work (driving a car, operating foot pedals or switch). • Walking in easily accessible areas (can walk upright). • Lifting: 4.5Kg loads for fewer than 8 lifts/min; 11kg fewer than 4 lifts/min	**0**	
Moderate. • Hand and arm work (mailing filing). • Arm and leg work (off-road operation of trucks, tractors and construction equipment). • Arm and trunk work (operating air hammer, tractor assembly, cleaning or clearing light debris spillage, plastering, heavy welding, scrubbing while standing up, intermittently handling heavy objects/, weeding, hoeing, picking fruit and vegetables.) • Carrying, lifting, pulling and pushing light loads (lightweight carts and wheelbarrows); • Operating heavy controls (e.g. opening valves); • Walking in congested areas (limited headroom), walking at 2 to 3 mph. • Lifting: 4.5kg fewer than 10 lifts/min; 11kg fewer than 6 lifts/min	**2**	
High. • Intense arm and trunk work, (carpenter sawing by hand or chiselling wood, shovelling wet sand, transferring heavy materials, sledge hammer work, planting, hand mowing, digging). • Intermittent heavy lifting (such as pick-and-shovel work). • Pushing or pulling heavy loads (pallet trucks, skips, loaded cages, heavy wheelbarrows) • Heavy manual handling and lifting (e.g. laying concrete block, and clearing heavy debris (e.g. cleaning and relining reactor vessels)). • Heavy assembly work on a non-continuous basis. • Lifting: 4.5kg 14 lifts/min; 11kg 10 lifts/min	**4**	
Very High. • Work at this rate cannot be sustained for long periods. • Very intense activity at a fast maximum pace (e.g. intense shovelling, axe work, running). • Heavy assembly, building or construction work; (climbing stairs, ramps or ladders rapidly) Walking faster than 4mph • Lifting 4.5kg more than 18 lifts/min. 11kg more than 13 lifts/min.	**6**	
	Don't know	

5.3.6 Clothing

CLOTHING EXPLAINED

- Clothing interferes with our ability to lose heat to the environment.
- Heat stress is a risk in situations where workers may be wearing Personal Protective Equipment, even if the environment is not considered warm or hot. It is important therefore, to identify whether the clothing the worker is wearing may be contributing to the risk of heat stress.
- Examples of different types of clothing are provided below.

Use BS EN 29920 (1992), "*Estimation of the thermal characteristics of a clothing ensemble.*" for more information

Estimate Risk of Clothing contributing to Heat Stress:

- It is impossible to list or describe in this method all the clothing that may be worn in industry. Therefore, general descriptions of clothing are provided. Observe the worker and look through the list for an ensemble that may best describe the type of clothing they are wearing.
- Additional information may be obtained by contacting the manufacturer or a supplier of the PPE for further advice.
- Read all the categories before deciding on your score.
- Is the relevant Clothing described below? **YES / NO**
  - If **YES** give a ranking to the clothing.
  - If **NO,** tick "**Don't Know**" conduct a quantitative heat stress risk assessment..
  - If workers don and remove clothing then tick more than one category or tick "**Don't Know**". Conduct a quantitative heat stress risk assessment

Description of clothing	**SCORE**	**Tick**
• Shorts and a T-shirt. No protective or work clothing worn.	**-2**	
• Light work clothing	**0**	
• Cotton coverall, jacket	**1**	
• Winter work clothing, double cloth coveralls, water barrier materials	**2**	
• Light weight vapour barrier suits	**4**	
• Fully enclosed suit with hood and gloves	**6**	
	Don't know	

5.4 RESULTS OF OBSERVATION CHECKLIST FOR HEAT STRESS RISK ASSESSMENT

Referring back to each of the parameters you have just observed, please tick the subjective score below that corresponds to score you gave to each parameter. The black squares indicate that that score was not available for a particular category.

	SCORES									
	-3	-2	-1	0	1	2	3	4	5	6
Air temperature	■	■				🟥	🟥	🟥	■	■
Radiant heat	■	■				🟥	🟥	🟥	🟥	■
Air velocity						🟥	🟥	🟥	🟥	■
Humidity	■	■	■		■	🟥	■	■	🟥	🟥
Metabolic rate	■		■		■	🟥	■	🟥	■	🟥
Clothing	■		■			🟥	■	🟥	■	🟥

Those scores higher than 1 may contribute to heat stress. The more scores you that have that are higher than 1, the greater the risk. As the scores increase (also shown by colour shading from light red to dark red) so the potential of that parameter contributing to heat stress increases. If three or more of your scores are greater than 1, there may be a risk of heat stress.

CHAPTER 6
APPENDICES

6.1 TABLES FOR ESTIMATING METABOLIC RATE FROM ITS COMPONENTS.(TAKEN FROM ISO 8996)

Table 74 Metabolic rate for body posture, values excluding basal metabolic rate.

Body Posture	**Posture W.m^2**
Sitting	10
Kneeling	20
Crouching	20
Standing	25
Stranding stooped	30

Table 75 Metabolic rate for different types of work, values excluding basal metabolism

	Metabolic rate W.m^2	
	Mean value	**Range**
Handwork		
light	15	<20
moderate	30	20 to 30
heavy	40	>35
One arm work		
light	40	<45
moderate	55	45 to 65
heavy	75	>65
Two arm work		
light	65	<75
moderate	85	75 to 95
heavy	105	>95
Trunk work		
light	125	<155
moderate	190	155 to 230
heavy	280	230 to 330
very heavy	390	>330

Other data used was that was not included in these tables but that can be found in the standard include:

- Slow walking speed (about 2km/h) = 120 W.m^2
- Basal metabolic rate = 44 W.m^2

6.2 MALCHAIRE’S OBSERVATION METHODOLOGY

Scoring scales for the "Observation" method

Score	Condition
AIR TEMPERATURE	
-3	- generally freezing
-2	- generally between 0 and 10°c.
-1	- generally between 10 and 18°C
0	- generally between 18 and 25°C
1	- generally between 25 and 32°C
2	- generally between 32 and 40°C
3	- generally greater than 40°C
HUMIDITY	
-1	- dry throat/eyes after 2-3 hours
0	- normal
1	- moist skin
2	- skin completely wet
THERMAL RADIATION	
-1	- cold on the face after 2-3 minutes
0	- no radiation discernible
1	- warm on the face after 2-3 minutes
2	- unbearable on the face after more than 2 minutes
3	- immediate burning sensation
AIR MOVEMENTS	
-2	- cold strong air movements
-1	- cold light air movements
0	- no air movements
1	- warm light air movements
2	- warm strong air movements
WORK LOAD	
0	- office work: easy low muscular constraints, occasional movements at
1	normal speed.
2	- moderate work with arms or legs: use of heavy machines steadily walking
	- intense work with arms and trunk: handling of heavy objects shovelling,
3	wood cutting, walking rapidly or while carrying a heavy load
	- very intense work at high speed: stairs, ladders.
CLOTHING	
0	- light, flexible, not interfering with the work
1	- long, heavier, interfering slightly with the work
2	- clumsy, heavy, special for radiation, humidity or cold temperatures
3	- special overalls with gloves, hoods, shoes
OPINION OF THE WORKERS	
-3	- shivering, strong discomfort for the whole body
-2	- strong local discomfort; overall sensation of coolness
-1	- slight local cool discomfort
0	- no discomfort
1	- slight sweating and discomfort; thirst
2	- heavy sweating, strong thirst, work pace modified
3	- excessive sweating, very tiring work, special clothing

4.2.3. Report the results in the table below

Table of scores for the present situation

	-3	-2	-1	0	1	2	3
Air temperature							
Humidity	▨	▨					▨
Thermal radiation	▨	▨					
Air movements	▨						▨
Work Load	▨	▨	▨				
Clothing	▨	▨	▨				
Opinions of the workers							

4.2.4. If the situation is not ideal (scores outside -1 to 1), identify the reason for this and describe the importance of the problem (sources, surfaces, location…).

The scales above are designed so that the optimum situation is zero in each case. When one or several parameters deviate from this optimum, prevention measures should be taken, and, the greater the deviation, the higher the need for solutions.

If the industrial process does not strictly impose the thermal parameters, look for ways to improve the situation, considering the examples of prevention measures given in the annexe 1.

Determine, if necessary, the measures to be taken in the short-term: hot or cold drinks, recovery periods, work organisation, clothing…. Short-term measures should remain temporary measures. They indicate the need for a further ***"ANALYSIS"*** to solve technically the problem.

Estimate what the scores might be if the situation was improved as envisaged. Judge, on the scales described in table 1, the condition in the future, taking into account the prevention/control measures. When this prediction of the future situation is difficult to do or does not appear to be reliable, this indicates the need for a further ***"ANALYSIS"*** to estimate the residual risk and identify the additional control measures.

4.2.5. Report these scores on table below

Table of scores for the anticipated situation

	-3	-2	-1	0	1	2	3
Air temperature							
Humidity	▨	▨					▨
Thermal radiation	▨	▨					
Air movements	▨						▨
Work Load	▨	▨	▨				
Clothing	▨	▨	▨				

4.2.6. Decide whether a more detailed ***"ANALYSIS"*** is needed to quantify and to solve the problem. For this, consider the number of scores outside the range from -1 to 1 for the anticipated situation in the future.

At the end of the ***"OBSERVATION"***, the user must determine whether, for this working situation, a more thorough ***"ANALYSIS"*** is necessary.

6.2.1. ANNEXE 1 Examples of prevention measures

AIR TEMPERATURE

- Locate the sources of heat or cold in the periphery
- Eliminate the sources of hot or cold air
- Insulate the hot surfaces
- Exhaust hot or cold air locally
- Ventilate without draughts
- Use clothes with lower or higher insulation
- …

HUMIDITY

- Eliminate the leaks of vapour and water
- Enclose the surfaces cooled with water or any evaporating surface
- Use clothes waterproof but permeable to vapour
- …

THERMAL RADIATION

- Reduce the radiating surfaces
- Use reflecting screens
- Insulate or treat the radiating surface
- Locate workstations away from radiating surfaces
- Use special protective clothes reflecting radiation
- …

AIR MOVEMENTS

- Reduce or eliminate air draughts
- Use screens to protect locally against draughts
- Locate workstations away from air draughts
- …

WORK LOAD

- Reduce the movements during work
- Reduce displacements
- Reduce the speed of movements
- Reduce the efforts, use mechanical assistance…
- Improve the postures
- …

CLOTHING

- Improve the design of the clothing
- Select more suitable materials
- Look for lighter materials
- …

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CHAPTER 8 GLOSSARY OF TERMS

Symbol	TERM	Units
M	Metabolic power	Wm^{-2}
W	Mechanical power	Wm^{-2}
_C_res	Respiratory heat loss by convection	Wm^{-2}
_E_res	Respiratory heat loss by evaporation	Wm^{-2}
K	Heat exchange on the skin by conduction	Wm^{-2}
C	Heat exchange on the skin by convection	Wm^{-2}
R	Heat exchange on the skin by radiation	Wm^{-2}
E	Heat flow by evaporation at skin surface	Wm^{-2}
_E_req	Required evaporation for thermal equilibrium	Wm^{-2}
SW_{req}	Required sweat rate for thermal equilibrium	Wm^{-2}
w	Skin wettedness	ND
_w_req	Skin wettedness required	ND
r_{req}	Evaporative efficiency at required sweat rate	ND
t_a	Air temperature	°C
Pa	Partial vapour pressure	kPa
h_c	Convective heat transfer coefficient	$Wm^{-2}K^{-1}$
F_{cl}	Reduction factor for sensible heat exchange due to the wearing	ND
t_{sk}	Mean skin temperature	°C
H_r	Radiative heat transfer coefficient	$Wm^{-2}K^{-1}$
T_r	Mean radiant temperature	°C
$P_{sk,s}$	Saturated vapour pressure at skin temperature	kPa
R_t	Total evaporative resistance of limiting layer of air and clothing	m^2kPaW^{-1}
_E_max	Maximum evaporative rate which can be achieved with the skin Completely wet	Wm^{-2}
V_{ar}	Relative air velocity	ms^{-1}
V_a	Air velocity for a stationary subject	ms^{-1}
σ	Stefan-boltzman constant, 5.67 x 10-8	$Wm^{-2}K^{-4}$
E_{sk}	Skin emissivity (0.97)	ND
A_r/A_{du}	Fraction of skin surface involved in heat exchange by radiation	ND
F_{cl}	Ratio of the subject's clothed to unclothed surface area	ND
F_{pcl}	Reduction factor for latent heat exchange	ND
h_e	Evaporative heat transfer coefficient	$Wm^{-2}kPa^{-1}$
I_{cl}	Basic dry thermal insulation of clothing	Clo or $m^2{}^\circ CW^{-1}$

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