The effects of protective clothing and its properties on energy consumption during different activities: literature review

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THE EFFECTS OF PROTECTIVE CLOTHING AND IT'S PROPERTIES ON ENERGY CONSUMPTION DURING DIFFERENT ACTIVITIES

-Literature Review-

Lucy Dorman and George Havenith

Loughborough University, Environmental Ergonomics Research Centre.

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Preface

There are many industrial situations where workers are required to wear personal protective clothing and equipment (PPC), for example, firefighters, chemical workers, cold store workers, army personnel and those working in the steel and forestry industries. Although this protective clothing may provide protection from the primary hazard, for example heat or chemicals, it can also create ergonomic problems.

In recent years many PPC product standards have been introduced, these have helped to improve the quality of the protective clothing and so increased the safety of the workers. However, information on the effect of the clothing on the wearer and the interactions between PPC, wearer and environment are limited. Most PPC is designed for optimal protection against the hazard present, but this protection in itself can be a hazard.

There are important side effects to protective clothing and typically with increasing protection requirements, the ergonomic problems increase. Often the main problem is the added load on the body in terms of weight. Also reduced mobility due to garment stiffness reduces the freedom of movement and may increase the risk of falls or getting caught in machinery. Even worse, the extra load and discomfort due to the protective clothing may tempt workers not to wear it when the primary hazard risk is low, leaving them unprotected if the hazard unexpectedly reappears or increases in strength.

The problems of protective clothing can be seen as thermal, metabolic and performance issues. By creating a barrier between the wearer and the environment, clothing interferes with the process of thermoregulation, particularly reducing dry heat loss and sweat evaporation. The main metabolic effects come from the added weight of the clothing and the ‘hobbling effect’ due to garment bulk and stiffness, both of which increase metabolic cost so the worker has to expend more energy when carrying out tasks. Loss of freedom of movement and range of motion due to PPC can also lead to reduced performance.

Current heat and cold stress standards consider the balance of heat production and loss but focus on environmental conditions and work rate metabolism. They also assume workers are wearing light, vapour permeable clothing. By failing to consider the metabolic effects of actual protective clothing, the standards underestimate heat production and therefore current standards cannot be accurately applied to workers wearing PPC.

The effects of protective clothing on workers have been studied across a number of industries but studies have mainly concentrated on the thermal effects of clothing, such as heart rate, core temperature responses to different garments and on performance decrements caused by wearing PPC. Very few studies have considered the metabolic effects.

Quantifying the effect of PPC on metabolic load based on the properties of the PPC was one of the objectives of the European Union THERMPROTECT project and the work undertaken for this thesis made up work package 4 of the EU project. The main objectives of the project were to provide data and models which allow the heat and cold stress assessment standards to be updated so that they need no longer exclude specialised protective clothing.

This thesis will consider the effects of protective clothing and its properties on energy consumption during work. The following is a review of the relevant background literature on metabolic rate, protective clothing, work environments, and standards. Previous research on PPC and its effects is also presented and evaluated.

1. Human thermal environment

Humans are homeotherms and require a stable internal (core) temperature. That the internal temperature should be maintained at around 37 ^{o}C dictates that there is a heat balance between the body and its environment. So, on average, heat transfer into the body and heat generation within the body must be balanced by heat outputs from the body. This process is not a steady state but a dynamic balance. The heat balance equation for the human body can be represented in many forms, however all equations involve terms for the heat generation within the body, heat transfer and heat storage.

$$M - W = E + R + C + K + S$$

<u>Heat generation within the body</u>

M metabolic rate of the body

The metabolic rate is the rate at which the body converts chemical energy, into mechanical (used to produce work (W)) and thermal energy (remainder that is released as heat (M - W)).

<u>Heat transfer from the body</u>

W energy released outside the body as mechanical work

E evaporation

R radiation

C convection

K conduction

Heat can be transferred from the body to the environment and vice versa via these 4 pathways.

Heat storage

S rate of heat storage

For the body to be in heat balance (constant temperature) the rate of heat storage must be zero. If there is a net heat gain, storage will be positive and body temperature will rise. If there is net heat loss, storage will be negative and body temperature will fall.

There are numerous proposed system models of human thermoregulation. Although they are different in composition, for most practical purposes they are almost identical and can explain human thermoregulatory responses. All models recognise that when the body becomes hot it loses heat by vasodilation of blood vessels and, if required, sweating (sweat is secreted over the body to allow cooling by evaporation). If the body becomes cold then heat is preserved by vasoconstriction of blood vessels and, if necessary, generated by shivering. Shivering can vary in intensity from 'mild' to 'violent' and can greatly increase metabolic heat production (Parsons 2003).

Air temperature, radiant temperature, vapour pressure and air velocity are the four basic environmental variables that affect the human response to thermal environments. Combined with the metabolic heat generated by human activity and the insulation of the clothing worn by a person, they provide the six fundamental factors that define human thermal environments (Parsons 2003).

It can be seen from the previous equation that metabolic rate is an important influence on heat load and in the overall heat balance. There are a number of factors that can influence the metabolic rate (heat load) of the worker, these are illustrated in Figure 1.1.

When a person performs a task, some energy will be used to perform the external work but energy for mechanical work will vary from about zero to no more than 25 % of total metabolic rate, the rest of the energy is given off as heat (Parsons 2003). The amount of heat produced will depend on the number and size of muscle groups involved, (for example, just the arms or a whole body effort) and intensity of the work.

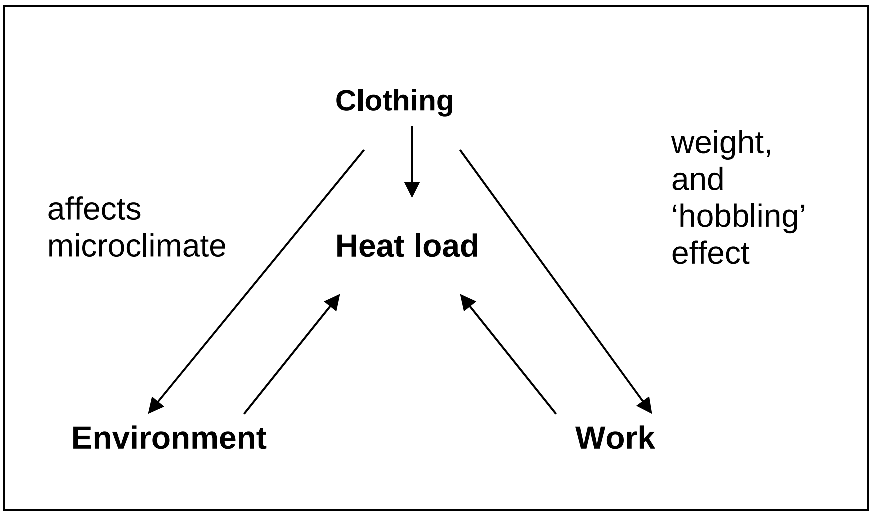

Figure 1.1. Factors affecting metabolic rate (heat load) of worker.

Clothing can influence the heat load as garments covering the body surface affect the microclimate of the body, interfering with the heat transfer pathways of conduction, convection, radiation and evaporation, the avenues through which excess heat is lost. Clothing also indirectly affects the heat load due to its properties. The weight of the clothing can increase the workload and the bulk/stiffness of the garments can have a 'hobbling effect', restricting movements and making them less efficient, and thus harder work.

These effects are detailed in BS 7963 'Ergonomics of the thermal environment - Guide to the assessment of heat strain in workers wearing personal protective equipment' (British Standards 2000), which states that although worn to protect against physical, chemical, biological and thermal hazards, PPC can negatively affect the heat balance of the body:

- metabolic rate can be increased by the weight of the PPC or by the restrictions it imposes on the movement of the wearer,

- convection to and from the skin can be affected by the amount of body covered by PPC and its thermal insulation properties. In general, the greater the proportion of the body covered and the greater the insulation, the less heat is lost by convection,
- evaporation of sweat from the skin is also an effective pathway for cooling the body but the more the body is covered and the greater the evaporative resistance of the PPC, the less is the heat loss by evaporation,
- radiation to and from the skin can be affected by the coverage of PPC over the body.

The standard also includes a table of typical incremental increases in metabolic rates when selected items of PPC are worn, suggesting these increments should be added to the activity related metabolic rate (British Standards 2000).

In her paper 'Heat stress in protective clothing: Interactions among physical and physiological factors' Nunneley (1989) concludes that “a better understanding is needed of the interactions between the environment, clothing, task and worker to support the development of predictive models which are valid over the entire spectrum of thermal conditions encountered among industrial and military applications”. The author goes on to suggest “particularly challenging areas needing improvement include quantification of changes to the metabolic cost of real-world tasks due to clothing, worker characteristics, thermal stress and fatigue”.

In summary, the main effects of PPC on the heat balance of the worker are to increase the rate of metabolic heat production and reduce the convective, radiative and evaporative pathways for heat exchange.

2. Metabolic rate and its measurement

The metabolic rate, as a conversion of chemical into mechanical and thermal energy, measures the energetic cost of muscular load and gives a numerical index of activity. Metabolic rate is an important determinant of the comfort or the strain resulting from the exposure to a thermal environment (ISO 2004). Thus an estimate of metabolic heat production in the body is fundamental to the assessment of human thermal environments (Parsons 2003).

2.1 Basic principles

Humans require the substance, adenosine triphosphate (ATP) to supply energy for each cell, for use in membrane transport, chemical reactions and mechanical work. The ATP is generated from ADP (adenosine diphosphate) using the energy produced by combustion of glucose, ingested in food as carbohydrates, fats and proteins, and oxygen, with the release of carbon – dioxide (CO_2) and water. Carbohydrates are converted in the gut and liver to glucose before they reach the cell. Proteins are converted into amino acids and fats into fatty acids, which are then transported to the cell via the bloodstream. Within the cells, a number of enzyme driven reactions take place to produce ATP, which is steadily regenerated by 'burning' carbohydrates, fats and proteins with oxygen. The breakdown of ATP liberates energy, most of which is released as heat. The total energy produced is termed the metabolic rate (Parsons 2003).

2.2 Factors affecting metabolic rate

A number of factors are known to affect metabolic rate;

1. Activity level

   As the body shifts from rest to exercise, the energy needs increase, with the metabolic rate increasing in direct proportion to the increased rate of work (Wilmore and Costill 1999).

2. Environment

Metabolism is raised in the heat due to additional energy required for sweat gland activity and altered circulatory dynamics. Cold environments can also significantly increase energy metabolism during rest and exercise, with fivefold increases reported during extreme cold stress as shivering generates body heat to maintain a stable core temperature. The magnitude of the effect depends largely on body fat content and clothing (McArdle *et al.* 2001).

3. Body temperature

If the temperature of the body is increased the rate of cell chemical reactions increases by around 13 % for each 1 ^{o}C rise in temperature. (Parsons 2003).

4. Diet – induced thermogenesis

Food consumption generally increases energy metabolism due to the energy required digesting, absorbing and assimilating food nutrients, with the thermic effect of food generally reaching a maximum within an hour after a meal (McArdle *et al.* 2001).

5. Diurnal fluctuation

Even if other conditions are kept the same, e.g. food intake and environmental temperature, metabolic rate is subject to diurnal fluctuation, with an increase in the morning and a decline during the night (Frisancho 1993).

6. Pregnancy

An added energy cost to weight bearing locomotion, e.g. walking, jogging, stair climbing has been reported during pregnancy, resulting primarily from the additional weight of the foetus transported by the female (McArdle *et al.* 2001).

7. Body mass

Body mass determines the energy expended, particularly in weight bearing exercise like walking and running. The influence of body mass on energy metabolism occurs whether a person gains weight naturally as body fat or as an acute added load such as sports equipment or a weighted vest on the torso (McArdle *et al.* 2001).

8. Body composition and age

Metabolic rate is directly related to fat-free mass, with a greater fat-free mass resulting in a higher metabolic rate, because women tend to have a greater fat mass, they also tend to have lower metabolic rates than men of a similar weight. Metabolic rate tends to decrease with age, generally due to a decrease in fat-free mass (Wilmore and Costill 1999).

9. Stress and hormones

Stress increases the activity of the sympathetic nervous system, which increases metabolism. Thyroxine (from the thyroid gland) and epinephrine (from the adrenal medulla) are also known to increase metabolism (Wilmore and Costill 1999).

10. Drugs

Drugs taken may affect metabolic heat production, for example, antithyroids and hypoglycaemics are known to reduce metabolic heat production (Parsons 2003).

2.3 Measurement of metabolic rate

The different approaches, and levels of accuracy for the measurement of metabolic rate are detailed in ISO 8996 'Ergonomics. Determination of metabolic heat production' (ISO 2004) and summarised in Table 2.1. While measurement of metabolic rate via direct or indirect calorimetry is quite accurate for a specific condition, estimations of metabolic rate are prone to error. The main factors affecting the accuracy of the estimations are:

- Differences in work equipment and work speed
- Differences in work technique and skill
- Gender differences and anthropometric characteristics
- When using level 2, differences between observers and training
- When using level 3, accuracy of relationship between heart rate and oxygen uptake, as other stress factors also influence heart rate
- When using level 4, measurement accuracy (determination of gas volume and oxygen fraction).

The accuracy of the results, but also the costs of the study, increase from level 1 to 4. Measurement at level 4 gives the most accurate values. As far as possible, the most accurate method should be used (ISO 2004).

Table 2.1. Levels for the determination of metabolic rate (ISO 2004).

Level	Method	Accuracy
1. Screening	a)Classification according to occupation b)Classification according to activity	Rough information Very great risk of error
2. Observation	a)Tables of group assessment b)Tables for specific activities	High error risk Accuracy ± 20%
3. Analysis	Heart rate measurement under defined conditions	Medium error risk Accuracy ± 10%
4. Expertise	a)Measurement of oxygen consumption b)Doubly-labelled water technique c)Direct calorimetry	Errors within the limits of the accuracy of the measurement Accuracy ± 5%

At the ‘screening’ level the methods are easy to use and allow a mean workload for a given occupation or activity, to be estimated. The next level ‘observation’ details methods which could be used by people with a knowledge of the working conditions but no real training in ergonomics, to characterise an average working situation at a specific time. A procedure is described to record the activities with time and compute the time weighted average metabolic data, using tables of either group assessment or specific activities.

There are many tables and equations for calculating energy expenditure. In their book ‘Energy, Work and Leisure’, Durnin and Passmore (1967) provide detailed lists of energy expenditure values for various activities, particularly Chapter 4 which lists energy expenditure values (in kcal/min) for occupational activities, see also Spitzer *et al.* (1982) and Ainsworth *et al.* (1993). Givoni and Goldman (1971) using laboratory data and data from the literature on the energy cost of level or grade walking, with or without loads, also produced an empirical equation for the prediction of the metabolic cost of such activities.

The heart rate method described at the ‘analysis’ level is appropriate for people trained in occupational health and ergonomics of the thermal environment. It involves taking heart rate recordings over a representative period and allows an indirect determination of metabolic rate based on the relationship between oxygen uptake and heart rate which can be determined in the lab or for a specific individual. Finally at the ‘expertise’ level are the methods to be undertaken by experts to collect very specific measurements, (a) involves measuring oxygen consumption over relatively short periods 10-20 minutes, (b) uses doubly labelled water to characterise average metabolic rate over much longer periods of 1 to 2 weeks, (c) uses direct calorimetry.

For the work to be carried out in this thesis the 3 methods highlighted at the ‘expertise’ level were considered due to the need for highly accurate measurements. Direct calorimetry is based on the measurement of heat produced as all of the body’s metabolic processes ultimately result in heat production. Various heat-measuring devices have been developed to measure heat production in an appropriately insulated calorimeter. However accurate measurements in a calorimeter require considerable time, expense and engineering expertise, so remain inapplicable for most sport, occupational and recreational energy determinations (McArdle *et al.* 2001). The doubly-labelled water technique provides an isotope-based method to estimate energy expenditure but the expense of the doubly-labelled water and spectrometric analysis of the isotopes and the long time constant for this type of measurement make this method unsuitable for comparisons of large numbers of conditions and short work periods (McArdle *et al.* 2001).

The oxygen consumption method is based on indirect calorimetry. As all energy-releasing reactions in the body ultimately depend on oxygen, and since the human body can only store very small amounts, it must be continuously taken up from the atmosphere by respiration. Muscles can work for a short time without being directly provided with oxygen (anaerobic work), but for longer periods of work, oxidative metabolism is the major energy source. Therefore measuring a person's oxygen consumption during physical activities can give an indirect, but accurate estimate of energy expenditure (ISO 2004). The absolute rate of oxygen consumption is typically given in the units litres per minute (l/min) and this can easily be converted to a rate of energy expenditure using the Weir formula as the consumption of 1 litre of oxygen results in the liberation of approximately 5 kcal (20.9 kJ) of energy.

The most common method followed in humans is the open-circuit method, which is based on the collection and analysis of expired air, allowing the changes in oxygen and carbon dioxide percentages to be compared to the inspired ambient air (20.93 % oxygen, 0.03 % carbon dioxide, 70.94 % nitrogen) and thus indirectly reflecting the ongoing process of energy metabolism (McArdle *et al.* 2001). At its simplest this method requires the volume of expired air to be recorded (and the time frame over which it was recorded) and the oxygen and carbon-dioxide content analysed.

Historically, the measurement of oxygen uptake has been restricted to the laboratory or clinical settings due to cumbersome equipment (Wideman *et al.* 1996). Early scientists often employed large canvas or plastic Douglas bags to collect the expired air together with separate Haldane chemical analyses, but the need for faster and more efficient techniques fuelled the development of semi- and fully-automated systems (Macfarlane 2001). Although the Douglas bag method is still considered the gold standard, it has several disadvantages and its own sources of error. No breath-by-breath data can be obtained and the method is also time consuming due to the requirement of sampling and analysis after collection (Carter and Jeukendrup 2002).

Over the last 40 years, a considerable number of automated systems have been developed, with over a dozen commercial manufacturers producing in excess of 20 different automated systems. The quality of modern flow-sensing devices and gas analysers can permit highly valid and reliable measurements of oxygen consumption ($\dot{V}O_2$) to be made, but considerable care must be taken in the maintenance and particularly the calibration of these machines to facilitate acceptable results (Macfarlane 2001). In summary the three main open circuit methods of measuring oxygen consumption and their key details are included in the Table 2.2.

Table 2.2. Specific characteristics of three alternative methods of respiratory gas analysis (adapted from Roecker *et al.* 2005).

Approach	Field of application	Benefits	Drawbacks
Douglas bag	• indirect calorimetry • reference method for steady state conditions	• gold standard • accuracy • robust due to low technical complexity • inexpensiveness • all-purpose method	• low temporal resolution • method is laborious • PVC material of bags permeable to certain gases • analysis of inspired air is not included • difficult handling • additional artificial deadspace due to breathing-valve • additional weight on subjects' head from valve and air tubes
Mixing chamber	• exercise stress testing with regard to maximum criteria • measurement of absolute and stable values in gas exchange and indirect calorimetry	• accuracy • method performed automatically	• volume of mixing chamber and other factors influence measured gas concentrations irregularly • average technical complexity • analysis of inspired air is difficult • high amount of maintenance for some systems • additional artificial deadspace due to breathing-valve

			• additional weight on subjects' head from valve and air tubes
Breath-by-breath	• exercise stress testing with regard to submaximal criteria • analysis of gas exchange kinetics • intra-breath calculations	• high temporal resolution • direct implementation of the mass balance equation by measurement of inspired air • low additional weight on subjects' head	• interpretation often equivocal due to breath-by-breath variability and artefacts • depends on sophisticated computer algorithms

For the determination of metabolic effects of clothing, freedom of movement is crucial, and static oxygen uptake measurement systems cannot be used. Several ambulatory systems have become available over recent years, of which most are based on breath-by-breath technology.

2.4 Portable breath-by-breath systems

The validity of portable devices for gas exchange measurements has been evaluated by comparisons to Douglas bag measurements, by comparisons to other validated stationary devices, by assessing the reproducibility during repeated measurements and by quantifying the influence of the apparatus' weight during exercise (Meyer *et al.* 2005).

The two systems that are in most widespread use are those from Cosmed and Cortex, whose current models are the K4 b^2 and MetaMax 3B respectively. Accuracy of gas exchange measurements has most often been investigated using determinations from Douglas bags as a criterion measure (Meyer *et al.* 2005). Kawakami *et al.* (1992) found no significant difference in the calculated $\dot{V}O_2$ between the Cosmed K2 system and the Douglas bags when subjects were cycling to exhaustion. They also succeeded in using the Cosmed K2 to measure a variety of activities in the field, including playing soccer and rowing on the water. However, Peel and Utsey (1993) found that oxygen consumption measurements were significantly lower using the K2 system compared with a metabolic measurement cart, the respiratory rate was also lower for measurements made with the metabolic cart. The Cosmed systems use a different formula to calculate $\dot{V}O_2$ as the carbon dioxide content of expired air is not measured. The authors also suggest subjects breathe slower and deeper when using a mouthpiece system (as is common with most metabolic cart and Douglas bag systems) compared to a face mask (as is common with most of the portable systems), they conclude that exercising with the K2 system may facilitate a more natural breathing pattern because subjects are less affected by the gas collection system (Peel and Utsey 1993).

McLaughlin *et al.* (2001) compared a Cosmed system (K4 b^2) to Douglas Bags during cycle ergometry. Although they found no significant differences in $\dot{V}O_2$ at rest and cycling at 250 W, at work rates of 50 to 200 W the K4 b^2 values were significantly higher, although the magnitude of the differences were small. As McLaughlin *et al.* (2001) state the ideal experimental design would use simultaneous expired air collections, but when they tried during a pilot it proved too problematic. Also employing a cycling protocol but using submaximal exercise levels, Hausswirth *et al.* (1997) found no significant differences in $\dot{V}O_2$ between the Cosmed K4 system and a metabolic cart and they concluded that the K4 system was accurate for all oxygen uptake measurements from rest to maximal exercise levels.

Schulz *et al.* (1997) tested an earlier Cortex model, the Cortex X1 and concluded that it accurately measured oxygen uptake and carbon dioxide output, when compared with a standard breath-by-breath system. Using a graded cycle test with subjects exercising to volitional fatigue, the Cortex X1 accurately measured ventilation, even up to 288 l/min with no loss of linearity. They noted the main disadvantage of the Cortex system seemed to be the relatively high weight of the equipment. Similar studies have also been carried out on the Aerosport system (Wideman *et al*. 1996, McLaughlin *et al.* 2001) and Oxycon-Pro system (Rietjens *et al.* 2001, Carter and Jeukendrup 2002).

In their review of the literature on portable devices used for the measurement of gas exchange during exercise Meyer *et al.* (2005) conclude that the results from the validity studies are comparable to those for corresponding stationary systems. The mean differences to Douglas bag measurements are reported to be around 0.1 – 0.2 l/min in $\dot{V}O_2$, reach an acceptable accuracy and are not inferior to metabolic carts (Meyer *et al.* 2005).

The review of Meyer *et al.* (2005) highlights the lack of investigations addressing the reliability of gas exchange measurements from portable devices but they suggest the available evidence indicates that the devices produce sufficiently reproducible results, with no obvious inferiority compared to stationary metabolic carts. However, in contrast to stationary systems an additional factor that needs to be considered in portable devices is the extra weight that has to be carried by the subject (Meyer *et al.* 2005). But with current modern systems weighing as little as 1 kg and improvements in weight distribution, Meyer *et al.* (2005) highlight the superior weight distribution of the Cortex MetaMax 3B which hangs around the athletes' shoulders distributing weight more symmetrically to the front and back, the systems can be tolerated well.

In summary, Meyer *et al.* (2005) conclude that the two most often tested portable devices, the Cortex MetaMax and Cosmed K2/K4b^2 can be regarded as valid and reliable.

3. Personal Protective Clothing (PPC)

3.1 PPC overview

Millions of people world-wide work in environments which expose them to specific risks. In many industrial sectors, military and energy services, hospital environments, human beings are subjected to various types of risks and each setting has its own requirements for protective clothing (Shishoo 2002).

The end-use applications for protective clothing include:

- Chemical splash and vapour protection
- Clean-room apparel
- Cut resistant gloves
- Dirt and dust
- Fire fighting
- Heat and cold protection
- Ballistic protection
- Paint spray
- Puncture-resistant clothing
- Hospital textiles
- Dry chemical handling (Shishoo 2002).

The growing concern regarding health and safety of workers in various industrial sectors has generated regulations and standards, environmental and engineering controls, as well as tremendous research and development in the area of personal protective equipment. All clothing is protective to some extent, it is the degree of protection from a specific hazard that is of major concern (Raheel 1994).

3.2 PPC and thermoregulation

Clothing can protect workers from hazardous or unpleasant environments. The prime physiological objective for protective clothing is to enable the wearer to maintain their body temperature within acceptable limits (Parsons 1988). Successful protective clothing must allow the functions of the body to be maintained and account for its responses as well as protect it from environmental hazards and agents (Parsons 1994). Clothing functions as a resistance to heat and moisture transfer between the skin and environment by acting as a barrier, formed by the clothing materials, the air they enclose and the still air that is bound to its outer surfaces (Havenith 1999). So the clothing provides a microclimate between the body and the external environment and the nude body exists within and responds to this microclimate. To provide for thermal comfort and health, protective clothing should maintain an internal body temperature within acceptable limits and allow skin temperature and skin wettedness to be within comfort limits. That internal body temperature should be relatively constant at 37 - 38°C implies that heat production and any heat transfer into the body must be balanced by heat loss from the body, including that through clothing. The thermoregulatory responses of the body and the heat transfer and vapour permeation properties of the clothing determine the microclimate (Parsons 1994).

As most protective clothing, by definition of its purpose, will be less permeable to heat and vapour than normal work clothing it is obvious that thermal stress is quite likely with these types of garments (Havenith 1999). Impermeable clothing prevents any sweat evaporation and is a potential hazard to the wearer even at moderate environmental temperatures (Nunneley 1989).

It is usually thought that heat strain only occurs in warm or hot conditions. This is incorrect. Any heat generated by working which cannot escape because protective clothing is being worn, is stored in the body, and as a consequence the body temperature rises. Heat strain therefore occurs whenever the body generates more heat than it can lose, even in cold conditions (Crockford 1999). Working in NBC clothing can cause variations in core and skin temperatures even at –10°C (Rissanen and Rintamaki 1994). That said performing work in a warm or hot environment is in general more stressful than in a neutral or cool environment. The physical load of the work, added to the heat exposure, can increase the risk to the worker's health and safety. If protective clothing is worn in such conditions it may have a detrimental effect on the workers ability to lose heat to the environment and lead to intolerable heat strain. Protective clothing causes a downward shift in the temperature level at which heat stress occurs. Military data on soldiers wearing chemical protective garments undertaking medium heavy to heavy work indicate the temperature threshold above which heat stress is observed falls well below 20°C (Havenith 1999).

Firefighters, workers engaged in toxic cleanup, foundry workers, miners and soldiers on the chemical-biological battlefield may all be exposed to uncompensable heat stress. This occurs when working in oppressively hot and/or humid areas, or when working in protective clothing. Uncompensable heat stress exists when the evaporative cooling requirement exceeds the environment's cooling capacity. Under these conditions, individuals are unable to achieve thermal steady state and will continue to store heat until exhaustion occurs (Montain *et al.* 1994). Evaporation of sweat normally provides a powerful physiological cooling mechanism for humans under warm work conditions, but clothing inhibits evaporation by creating a humid microclimate (Nunneley 1989).

3.3 PPC and energy cost

Protective clothing also increases the metabolic cost of performing a task by adding weight and by otherwise restricting movement. The binding or hobbling effect of multilayered clothing adds measurably to work. Clothing can also require added movement to compensate for problems such as restricted visual fields and failure of communication due to a gas mask or loss of manual dexterity due to gloves. The effect of added weight on work load depends in part upon the task, e.g. a heavy suit poses little problem for a stationary worker but presents a severe handicap for a firefighter climbing a ladder or stairwell (Nunneley 1989).

There is a very limited number of papers considering the influence of PPC on metabolic rate / energy expenditure. Studies on the energy expended by the soldier were among the earliest non-clinical investigations in the area of applied physiological research (Goldman 1965) and because of the need to wear protective clothing and still be able to perform tasks effectively much of the research is still military based.

3.4 PPC, task and environment

Nunneley (1988) introduced the ‘heat stress triad’ arguing that heat stress may result from one or more of three factors; work rate, clothing, environment. The triad can also be applied to effects other than heat stress, such as reduced productivity and comfort, and increased physiological strain (Adams *et al.* 1994).

Montain *et al.* (1994) tried to determine the influence of exercise intensity, protective clothing level and climate on physiological tolerance to uncompensable heat stress. 7 subjects attempted 180 minute treadmill walks at metabolic rates of approximately 425 and 600 W (representing moderate and heavy exercise for soldiers wearing chemical protective clothing) while wearing full or partial protective clothing (US military MOPP 4 and 1 level protection respectively) in both a desert and tropical climate. The study found that full encapsulation of subjects in protective clothing reduced physiological tolerance and partial encapsulation of subjects resulted in a physiological tolerance similar to that reported for unclothed persons. Increasing the metabolic rate from approximately 400 to 600 W when dressed in full clothing did not alter physiological tolerance, with the rectal temperature at exhaustion, 38.5 – 38.7°C when subjects were wearing protective clothing in desert and tropical climates with the same wet bulb globe temperature (WBGT) (Montain *et al.* 1994).

However predicting garment effects on worker performance is difficult because relationships of garment properties and human responses are not well understood. In an expanded model by Adams *et al.* (1994), a systematic approach for studying the effects of PPC properties on various aspects of worker performance is presented with thermal balance being affected by four causal factors; clothing, task requirements, environmental conditions and worker traits.

(i) clothing

It is necessary to identify those garment properties that potentially affect worker performance, from the subcomponents (yarn, seams, openings) to the garment components (fabric, design and fit), and the garment properties (stiffness, weight, insulation and vapour permeability).

(ii) task requirements

It is necessary to identify what movements must be made for each task and the characteristics of the movements. Worker movement also causes clothing to move or change form. Resistance to change in form imposes additional force requirements on the wearer and may compromise movement capability.

(iii) environmental conditions

Environmental conditions often require the use of PPC, but may also affect the wearer's performance directly.

(iv) worker traits

Differences among workers in three characteristics help determine the effects of PPC on performance, these are anthropometry (how well the garment fits), physiology (rate of metabolic heat generation and level of sweating) and motivation (affects the rate and duration of work and the choice of movements involved).

Three of these factors; clothing, task requirements and worker traits also determine changes in garment form and position that accompany movement. The processes of maintaining thermal balance and changing garment form cause immediate effects on movement capability, physiological balance and sensory feedback. These immediate effects may in turn produce the net effects of reduced productivity, increased physiological strain and reduced comfort (Adams *et al.* 1994). It is also known that working in a hot environment creates greater physiological strain than working in a thermoneutral environment and greater strain is also apparent when working in protective clothing than in normal clothing (Smith and Petruzello 1998).

4. Work environment

The previous section established that the human body responds to the microclimate between the skin and the clothing and any risk of heat strain will be as a response to that climate (Parsons 2000). The microclimate is the primary environment that impacts the body and it is altered by humans when adding or removing clothing with different properties. When any material, such as encapsulating protective clothing covers the body the microclimate quickly becomes warmer and more humid than the ambient environment. Therefore a worker can experience heat strain even in a cold environment if he/she is producing a high metabolic heat load and wearing heavy insulative clothing (Bishop *et al.* 2000).

Metabolic heat production is directly proportional to the work demands, so metabolic rate and clothing characteristics may combine with environmental factors to cause heat stress (Bernard and Matheen 1999). High levels of activity with protective clothing should always be regarded as high risk. The ability to vary the pace of the work will provide a major method for reducing thermal strain. However, there will be some jobs with a limited exposure time and hot environment, where protective clothing must be worn and the task completed, which will obviously be high risk (Parsons 2000).

Three possible contributing factors to heat stress were highlighted in the previous section; work rate, environment and clothing. Unacceptable heat stress may be produced by one of these factors or by two or three of them in combination. For example, the rise in core temperature which normally accompanies sustained work is not in itself a threat, but problems develop when environmental conditions and/or clothing prevent dissipation of excess metabolic heat and thus interfere with achievement of a tolerable steady-state condition (Nunneley 1988).

Working in a hot environment such as in a foundry, glass works, mine or in the ceramics industry can put considerable heat stress on workers. The greater risks occur in this country with indoor workers. Generally a comfort zone exists which is the range of environmental conditions in which it is possible to work without undue strain or discomfort. Temperatures of between 16 and 24 ^{o}C appear to be acceptable with heavier workloads at the lower end of the temperature range and sedentary tasks at the upper end. But this temperature zone needs adjustment for heavy physical work or work requiring the use of protective equipment (Williams 1993).

The human body compensates well for moderate climatic heat stress, but artificial environments often block or overwhelm physiological defence mechanisms. Examples from industry include combinations of high air temperature and extreme radiant load in smelters, foundries and glassworks or elevated humidities which cause problems in very deep mines (coal and gold), ship engine compartments and textile drying rooms (Nunneley 1988).

MacDougall *et al.* (1974) had subjects treadmill running under three thermal conditions; a condition in which the active hyperthermia induced by the exercise would be similar to that experienced by an individual undergoing heavy exercise in a non-laboratory setting at a “normal” ambient temperature (23$\pm$1 ^{o}C). A “hyperthermal” condition was induced by infusing a water-perfused suit worn by the subject with hot water to accelerate the rate of active hyperthermia, cold water was then used for the “hypothermal” condition. While treadmill speed was identical under each condition, work tolerance was significantly reduced in the hyperthermal condition and significantly prolonged in the hypothermal. Slight but significant increases in $\dot{V}O_2$ occurred over time under each condition, the greatest increase in $\dot{V}O_2$ occurred in the hyperthermal condition, where it became higher than in the hypothermal condition after only 15 minutes of running. In summary, it is apparent that during exercise where normal heat dissipation mechanism are curtailed, or when heavy exercise under comfortable ambient conditions (where no restrictions are made on heat dissipation mechanisms) is prolonged, a condition of metabolically induced hyperthermia develops, becoming a limiting factor to performance time (MacDougall *et al.* 1974).

Consolazio *et al.* (1963) also had subjects exercise at three levels of physical activity in three different temperatures, and compared metabolic rates. Results indicated that as the environmental temperature increases there was also an increase in metabolic rate when performing a fixed activity. As no significant difference was seen in metabolic rates between temperatures of 21.2 ^{o}C and 29.4 ^{o}C, the significant threshold must occur in temperatures above 29.5 ^{o}C. The authors cite work by Eichna *et al.* (1950) and Christensen (1933) who suggest there is an approximate increase of 11.6 % in the metabolic rate for every 1 ^{o}C rise in body temperature.

So working in a hot environment creates greater physiological strain than working in a thermoneutral environment and greater strain is also apparent when working in protective clothing than in normal clothing (Smith and Petruzello 1998).

5. Standards

The heat balance equations are used in a number of standards to assess heat and cold stress for the worker in various climatic conditions. Typically these standards use climatic data (temperature, humidity, radiation, wind), clothing data (insulation and vapour resistance), and data on the work activity (metabolic heat production) to determine the heat/cold stress level. They deal with these factors in a relatively simple way, one insulation value for the clothing ensemble, an estimate for metabolic rate based on the work load and environmental conditions. However, they do not consider any effect the clothing may have on the metabolic heat production of the wearer.

This simple approach reduces the applicability of these standards, e.g. ISO 7933 ‘Ergonomics of the thermal environment. Analytical determination and interpretation of heat stress using calculation of the predicted heat strain’ (ISO 2004) includes a disclaimer “in its present form, this method of assessment is not applicable to cases where special protective clothing is worn”. The paradox is that it is these types of clothing, for example that include impermeable protection, that induce the most strain and therefore would benefit most from an accurate standard that could help to determine safe working limits.

Where heat stress may pose a risk to the worker, it must be assessed. Different methods for estimating potential heat stress have been developed including the Wet Bulb Globe Temperature (WBGT) index and the Required Sweat Rate index. However, these methods, covered in International Standards such as ISO 7243 (ISO 1989) and ISO 7933 (ISO 2004), assume that the worker is wearing light, vapour permeable clothing. As most forms of protective clothing (PPC) either have a higher insulative value or are water vapour impermeable, these standards cannot be accurately applied to workers wearing PPC (Hanson 1999). Thus whilst the method should apply to protective clothing and PPC use, further work is needed to provide guidance. As the WBGT index provides most weight to the natural wet bulb value, it is considered a representation of the response of a sweating worker in saturated clothing with free evaporation to the environment, therefore when impermeable clothing is worn it is debatable whether the WBGT index is appropriate (Parsons 1999). As many researchers have recognised that clothing plays an important role in heat stress, some adjustments and correction factors to the WBGT have been put forward for when different types of clothing are worn (Hanson 1999, Bernard *et al.* 2005).

All the heat and cold stress standards that have metabolic rate as an input parameter refer to ISO 8996 'Ergonomics. Determination of metabolic heat production' (ISO 2004) for detailed guidance on how to measure or estimate metabolic rate. However no reference is made to the effects of PPC on metabolic rate in ISO 8996. Furthermore, little information is provided concerning the insulative characteristics or moisture permeability of items of PPC in ISO 9920 'Ergonomics of the thermal environment. Estimation of the thermal insulation and evaporative resistance of a clothing ensemble' (ISO 1995) (Hanson 1999).

A working group from BSI identified a need to develop a British Standard which would allow interpretation of the existing standards for workers wearing PPC. Hanson and Graveling (1999) from the Institute of Occupational Medicine (Edinburgh) conducted the research comprising a literature review, discussions with experts, a questionnaire survey and consideration of reported physiological data, and produced a report "Development of a draft British Standard; The assessment of heat strain for workers wearing personal protective equipment".

The authors highlighted a number of studies which had considered the effects of PPC on metabolic heat production rate. But they also state that studies of the metabolic cost of clothing interpreted from heart rate data are difficult to interpret because heart rate is an indirect measure of metabolic heat production and it is very difficult to differentiate between heart rate increases attributable to increased metabolic heat production from clothing and increases due to thermal stress. Even where oxygen consumption data is available, the observed increase in metabolic cost may only be partly associated with the energy cost of the PPC (Hanson and Graveling 1999).

Based on the available literature, Hanson and Graveling (1999) produced a table of various forms of PPC and the magnitude of their effect on metabolic heat production, with values for individual items of PPC (where more than one item is worn, values should be added together), but the table is limited. They conclude that the effect of PPC on metabolic heat production rate will vary with the activity, but as the metabolic heat production rate due to the activity increases, the effect of the PPC will also increase. They suggest that ideally a series of percentage based corrections would be utilised to relate the metabolic cost of PPC to the metabolic heat production rate of the activity. But the data available to them was not considered sufficient to allow these to be compiled.

6. Previous research on PPC

A detailed review of the literature highlighted a significant lack of consideration of the effects of PPC on energy cost and metabolic rate. The existing papers focus particularly on the thermal effects of wearing PPC and comparisons of different garment designs / ensembles and are dominated by work on firefighting and Nuclear, Biological and Chemical (NBC) protective clothing.

6.1 Specific effects of PPC on energy cost

Teitlebaum and Goldman (1972) investigated the possible increased energy cost with multiple clothing layers. They used 8 subjects walking on a treadmill at 5.6 and 8.0 km/hr either wearing an additional 5 layers of arctic clothing over their standard fatigues or carrying the 11.2 kg equivalent weight of the five layers as a lead-filled belt. For every subject the energy cost at a given speed was always higher with the clothing than the weight belt. In conclusion, the authors suggest the significant increase on average of approximately 16 % in the metabolic cost of working in the clothing compared to the belt can most probably be attributed to 'friction drag' between the layers and/or a 'hobbling effect' of the clothing.

So during walking, multilayered clothing ensembles have been reported to increase oxygen uptake ($V0_2$), equivalent to metabolic rate, by an amount significantly in excess of that which can be accounted for by the increases in the clothed weight of the subjects. A study by Duggan (1988) investigated the effect of protective clothing ensembles (chemical agent and cold weather) on the energy cost of a bench stepping task. Using a step height of 0.305m and rate of 20 steps/min, subjects performed the task in military combat clothing and with long underwear, cold weather quilted thermal jackets/trousers and chemical agent protection as extra layers. To prevent subjects from overheating the task was performed at a controlled ambient temperature of 10 ^{o}C and was limited to 6 minutes duration. When corrected for clothing weight, $\dot{V}O_2$ was greater by an average of 9 %. The author also concludes that when protective clothing ensembles are worn, the increased energy cost of physical performance will reduce the time to the onset of fatigue and because of the increased metabolic heat production, could exacerbate problems of heat dissipation and thus increase the risk of overheating (Duggan 1988).

6.2 Firefighter PPC

The effects of work in heavy, impermeable clothing has been illustrated well by studies on men wearing firefighter outfits under mild and hot conditions (Nunneley 1989). Many studies have been conducted in the laboratory setting; Duncan *et al*. (1979), Skoldstrom (1987), Faff and Tutak (1989), Ilmarinen *et al*. (1994) and Smith *et al*. (1994). The effects of different garments, conditions and tasks have also been studied in the field; Romet and Frim (1987) used a training facility and Ilmarinen and Makinen (1992) a flashover facility with small burning houses. Smith *et al.* (1997) and Smith and Petruzello (1998) used fire houses whilst Budd (2001) looked at suppression of experimental bush fires. Shipboard fire fighting was also simulated in the studies of Bennett *et al.* (1995) and Bilzon *et al.* (2001).

Studies in the laboratory have tended to look at performance in cycling and walking exercises. The most common protocol is walking at a set speed and gradient over a specified time period with and without the fire fighting protective clothing (Duncan *et al*. 1979, Skoldstrom 1987, Ilmarinen *et al.* 1994, Smith *et al.* 1994, Baker *et al.* 2000). However maximal exercise tests (Louhevaara *et al.* 1995) and cycling to exhaustion (Gavhed and Holmer 1989) have also been employed by researchers. Simulated fire fighting tasks have been studied, especially in the field settings, Romet and Frim (1987) provided a scenario which required a group of fire-fighters with a truck to respond to an alarm, subjects were classified into 4 activity categories; crew captain, lead hand, secondary help and exterior fire fighting. Smith *et al.* (1997) simulated a ceiling overhaul whilst Smith and

Petruzello (1998) got subjects to complete 3 sets of 4 tasks; dragging a hose, carrying a 5 gallon pump, hoisting a hose and chopping on a block of wood. During shipboard fire fighting simulations Bennett *et al.* (1995) had subjects complete the following objective; to contain and extinguish a Class A material fire, whilst Bilzon *et al.* (2001) used tasks including a drum carry and boundary cooling.

Many of the studies also compared performance in sports kit and a fire fighting clothing ensemble (Duncan *et al.* 1979, Skoldstrom 1987, Baker *et al.* 2000) or between different garments (House 1994, Ilmarinen *et al.* 1994, Smith *et al.* 1994, Smith and Petruzello 1998, Ftaiti *et al.* 2001, Taylor *et al.* 2001, Rossi 2003).

The literature can best be divided into those studies that have looked at

1. Physiological effects of wearing firefighter PPC
2. Comparisons of different firefighter PPC ensembles

The studies have focused on physiological responses (cardiovascular and thermoregulatory) including; heart rate, core temperature, oxygen uptake, skin temperature, ECG, energy expenditure, body mass loss, blood pressure, sweat loss and ratings of perceived exertion.

6.2.1 Physiological effects of wearing firefighter PPC

The physiological strain inherent in fire fighting activities is a result of the combination of physical activity, heavy clothing and/or thermal stress. The physical workload is dependent on the task being done, tools used and protective gear worn (Smith *et al*. 1997). The thermal strain results from the external stress of heat radiating from the fire and the exercise-induced metabolic heat stress that is trapped due to the encapsulation provided by protective clothing (Skoldstrom 1987, Smith *et al*. 1997). It is known that working in a hot environment creates greater physiological strain than working in a thermoneutral environment. Greater cardiovascular and thermal strain is also apparent when working in protective clothing than in normal clothing (Smith and Petruzello 1998).

Modern firefighters' clothing appears to be very effective in fulfilling its primary purpose, that of protecting the firefighter against the direct effects of the severe environments in which they may have to work. But research by Graveling and Hanson (2000) has, however, demonstrated and quantified the negative aspect of this protection, that the clothing itself increases the physiological cost of working whilst wearing it, and that the clothing can create a risk of heat stress through its considerable disruption of the thermoregulatory pathways. In summary, during the laboratory trials, standard firefighter clothing typically increased physiological cost (oxygen consumption) by 15 % over control sessions (Graveling and Hanson 2000).

UK fire fighting clothing weighs approximately 10 kg (excluding breathing apparatus) which inevitably incurs an energy cost (Baker *et al.* 2000). According to previous findings and the reports of other authors, protective equipment weighing 15-26 kg causes a rise in energy cost of walking or climbing by about 20 % or more (Faff and Tutak 1989). Ftaiti *et al.* (1989) state that the weight of protective clothing and equipment can increase energy demands by as much as 40 %. Also Goldman (1990) quotes a weight of 10.9 kg for the full fire fighting ensemble plus 10.5 kg for the self-contained breathing apparatus (SCBA) and asserts that the hobbling effect of arm and leg movement in such thick, heavy clothing can increase the working heat production by about 30 % over that of the same task done wearing only a station uniform. Previous research has found that the energy cost of moderate work while wearing the fire fighting clothing and protective equipment was elevated 33 % over that required to perform the same work without protective clothing and equipment (Davis *et al.* 1982). Bilzon *et al.* (2001) note the increase in energy cost of moderate intensity work of 33 % and explain that the high metabolic demand of fire fighting is a result of intrinsic metabolic and physical demands of various tasks combined with additional extrinsic stressors (clothing, equipment and environment).

In the field of fire fighting, the insulation of the clothing is so high that storage of heat can often not be avoided, with the weight of the equipment representing an additional load for the fire-fighter. The structure of the clothing and number of textile layers also increase the energy consumption and thus the required heat loss (Rossi 2003).

Duncan *et al.* (1979) reported significant ($p<0.01$) increases in oxygen uptake when subjects wore a turnout uniform compared to wearing a blue uniform (lightweight shirt and trousers) walking at 4 km/hr, 10 % gradient on a treadmill. After 15 minutes of exercise, mean oxygen uptake values were 7.13 ± 0.41 and 10.47 ± 0.75 ml/kg/min for the blue and turnout uniform respectively. The authors concluded that the additional weight and insulating properties of the turnout clothing imposed significant stress on firefighters especially while working in the heat. Skoldstrom (1987) also compared treadmill walking, 60 minutes at 3.5 km/hr, with and without turnout gear (standard 'blue' uniform of shirt and cotton trousers plus thick sweater, impermeable trousers, coat, boots, helmet and breathing apparatus) in a 15°C and 45°C climate. Oxygen uptake without turnout gear and breathing apparatus was 0.8 l/min, with the influence and weight of the additional clothing and equipment significantly increasing oxygen uptake by 0.4 l/min to 1.2 l/min. There was no significant effect on oxygen uptake when increasing the ambient temperature from 15°C to 45°C. Heart rate and rate of perceived exertion were significantly affected by both temperature ($p<0.001$) and equipment ($p<0.001$). Although the lack of a significant effect with increasing temperature is perhaps surprising it should be noted that absolute workloads were very low in this study.

Baker *et al.* (2000) compared the cardiorespiratory and thermal responses of two intensities (5 km/hr and 7 km/hr) of treadmill exercise over brief periods (12 minutes). Sports kit composed one ensemble (SE); shorts, vest and sports footwear and the firefighter kit (FE) of helmet, flash hood, GoreTex tunic and breeches, cotton underwear, gloves and leather boots the other. When walking at 7km/hr, heart rate (171 bpm and 146 bpm) and

$\dot{V}O_2$ (39.9 ml/kg/min and 36.1 ml/kg/min) were significantly ($p<0.05$) higher when wearing the FE compared to the SE respectively. The results of this study showed that walking at a moderate intensity in FE in a temperate environment (21 ^{o}C, 55 % RH) can involve up to 75 % of maximal oxygen consumption.

Faff and Tutak (1989) used a different work mode (cycle ergometry) but two clothing conditions (standard uniform (SU) and fire fighting protective clothing (FE)) The FE was aluminised, fire-resistant, impermeable clothing with self contained breathing apparatus. Subjects were instructed to cycle with a work load of 1.5 W/kg until a point of subjective fatigue and overheating that would cause them to stop working during real fire fighting. Heart rate recorded at the end of the exercise was independent of clothing but the working time until fatigue was much shorter for the FE trials, approx 15 minutes compared to the SU, approx 27 minutes (durations read off graph in the paper). Throughout the trial FE heart rate was higher than SU, the difference ranging from 5–19 bpm, the heart rate rose progressively throughout the exercise, but the increase in the SU condition was consistently smaller than in the FE (Faff and Tutak 1989).

6.2.2 Comparisons of different firefighter PPC ensembles

Smith and Petruzello (1998) compared different configurations of protective fire fighting gear. On separate days subjects wore (a) the NFPA (National Fire Protection Agency) 1500 (1987) standard configuration and (b) a hip-boot configuration and completed 3 firefighting drills. The NFPA 1500 configuration included bunker pants with low boots compared to ¾ hip boots and full length turnout coat. The NFPA 1500 gear did not perform as well as the hip-boot configuration, on average the subjects took 38 secs, 35 secs and 51 secs longer to complete the tasks in the NFPA gear than in the hip-boot configuration (time to complete trials 5:39, 5:34 and 5:38 minutes respectively). A repeated measures ANOVA for tympanic temperature revealed a significant effect for time ($p<0.001$) and a significant gear x time interaction effect ($p<0.042$) as it rose by 0.9 ^{o}C above pre-task levels in the hip-boot configuration and 1.5 ^{o}C in the NFPA gear (Smith and Petruzello (1998).

Five jackets were compared by Ftaiti *et al.* (2001), one leather and four textile ones, during treadmill running. In general, exercise in the jackets resulted in a higher tympanic temperature, heart rate and body mass loss compared to a condition in which no jacket was worn, with the magnitude of these changes dependent on the type of jacket. Exercise in the leather jacket resulted in the highest tympanic temperature (2.2 ^{o}C increase compared to 0.7 ^{o}C increase for no jacket, 1.6 - 1.9 ^{o}C for the textile jackets) and heart rate (end of test HR, 161 bpm for no jacket, 176–187 bpm other jackets, highest recorded in leather jacket), which was significantly ($p<0.001$) different from all the other conditions. The textile jackets induced less heart rate and tympanic temperature stress than the leather one and the magnitude of the physiological responses induced by the textile jackets could be correlated to jacket weight.

Ilmarinen *et al.* (1994) found no significant differences in cardiorespiratory or thermal strain during submaximal work in the heat wearing a turnout suit with or without a microporous water barrier. Regardless of the suit worn, heart rate and rectal temperature increased steadily during the work period, up to individual tolerance limits.

While protective clothing is being continually improved and lightened, the requirement for adequate environmental protection is generally contradictory. One option that has been implemented by the New York City Fire Department and is being considered for implementation by the Toronto Fire Service is the replacement of the long pants that are worn under the protective overpants with shorts, tested by McLellan and Selkirk (2004). To the authors knowledge the findings are the first to document the reductions in cardiovascular and thermal strain for firefighters while wearing shorts under their protective overpants during exercise in a warm environment.

It should be noted that differences between suits observed in these studies often represent the combined effects of variations in insulation, vapour resistance, clothing weight and their effect on the metabolic rate.

6.2.3 Summary

The physiological strain experienced by fire-fighters results from several factors a) metabolic heat produced by working muscles, b) heavy insulative protective gear that adds to metabolic work that must be done, c) insulative properties of clothing that trap metabolic heat next to body, d) radiant heat associated with the fire. However firefighters spend a considerable amount of time attending to tasks other than fighting fires, although required to wear the fire fighting ensemble, little attention has been directed at the energy cost and thermoregulatory changes that occur while working in fire kit in a non-fire environment.

6.3 Nuclear Biological Chemical (NBC) clothing

It is well reported that wearing chemical warfare (CW) protective combat clothing (often made up of an encapsulating protective garment, overboots, rubber gloves and gas mask) may protect the wearer but also results in impairment of human performance. Many studies including combined arms exercises, field trials, and laboratory studies have documented the degradation of both individual and unit performance, these have been thoroughly reviewed by Taylor and Orlansky (1993) in their comprehensive overview of the literature. Even when heat stress was not an important factor, the performance of many combat and combat support tasks was degraded when CW clothing was worn. The performance degradation was due to reduced manual dexterity, reduced vision, reduced communication, respiratory stress and psychological stress. The degree to which the combat effectiveness of an individual or a unit will be degraded by wearing CW clothing is a function of a number of variables including;

1. the ambient conditions of the workplace
2. the type and extent of the protective clothing

3. the length of time the protective clothing is worn
4. the level of physical activity
5. the physical conditions of the individuals in the unit
6. the work/rest cycles
7. the training level of the unit (Taylor and Orlansky 1993).

The protective clothing ensemble worn by the US forces, known as the ‘Mission Orientated Protective Posture’ (MOPP) provides 4 levels of increasing chemical (and some biological) protection ranging from slight (MOPP-I) to complete encapsulation (MOPP-IV). MOPP-IV consists of a chemical protective overgarment (suit), hood, gloves, boots and mask with special filter (Fine 2002). There are two main areas of concern regarding functional efficiency of troops clad in the MOPP-IV configuration; limitations imposed by the climate in which the protective clothing is worn and limitations imposed by the design of the clothing itself. Of necessity, the protective garment must be impenetrable by outside agents, chemical or biological. Thus the wearer is enclosed in an artificial environment that severely limits the evaporation of body sweat and thus reduces the body’s ability to maintain normal thermoregulation (Fine 2002).

There are a number of different acronyms and abbreviations for different types and levels of chemical protective garments. Most provide chemical protection and some also protection against nuclear and biological threats. As the descriptor NBC (nuclear, chemical, biological) is probably better known this will be the term used for the protective garments described in this section.

The literature can best be divided into those studies that have looked at

1. Physiological effects of wearing NBC garments
2. Comparisons of different NBC ensembles

The energy cost and metabolic demands of wearing NBC clothing have been considered (Henane *et al*. 1979, Patton *et al*. 1995, Murphy *et al.* 2001), although these parameters are not always measured, with heart rate and core temperature more commonly reported. Implications of wearing NBC clothing in the cold (Rissanen and Rintamaki 1994, Young *et al.* 2000) and the added issues of armoured vehicles (Millard 1994) and fighter jet pilots (Frim *et al.* 1992) with their poor ventilation and confined spaces, can also be found in the literature.

6.3.1 Physiological effects of wearing NBC garments

White *et al*. (1991) examined the physiological and subjective responses when wearing light work clothing with a self contained breathing apparatus (SCBA) or a chemical protective ensemble (NBC) with a self contained breathing apparatus in three different thermal environments (cool, neutral and hot). The results of this investigation demonstrate the interaction of thermal environment and clothing ensemble on the physiological and subjective responses, and the ability to perform low intensity work. While working at a fixed low work rate in the cool environment work performance did not appear to be limited nor did heat stress appear to be a problem in either ensemble. In the neutral environment work performance was not significantly limited wearing the NBC clothing, however the observed increases in heart rate, skin temperature, rectal temperature and subjective ratings suggest the ensemble does cause additional stress to the worker. The shortest total work time was in the hot environment wearing the NBC ensemble (White *et al.* 1991).

Using two work rates, two environmental conditions and three levels of clothing protection, the effects on work tolerance time were also studied by McLellan *et al.* (1993). The various levels of NBC protective clothing exerted a minimal impairment on work times when the metabolic rate of the task was light and the environmental temperature was cool (less than 20°C). As the metabolic rate and/or the environmental temperature increased, work times were progressively reduced while wearing the different levels of protective clothing with the greatest reduction in the full NBC ensemble.

6.3.2 Comparisons of different NBC ensembles

Possible solutions to the problem of heat strain associated with wearing protective clothing include implementing work/rest schedules, using microclimate cooling or designing new protective clothing layers (McLellan *et al.* 1994).

Cadarette *et al.* (2001) evaluated the physiological heat strain from two developmental toxic agent protective systems (Self-Contained Toxic Environment Protective Outfit–STEPO) compared with the standard Toxicological Agent Protective suit (TAP) during exercise-heat stress. STEPO was designed for personal protection in highly toxic, unknown or oxygen deficient environments, it is totally encapsulated and self contained, not relying on filtered air (like the TAP suit). A new generation of STEPO was designed in terms of reduced heat stress, improved load carriage and improved flame resistance, as well as both industrial chemical and chemical warfare agent protection. The study compared 2 STEPO suits, one with a tethered airline and one with a self-contained breathing apparatus. Although the thermal and performance parameters; heat storage, core temperature and endurance time were favourable for the STEPO suits compared to the TAP, the time weighted mean energy costs were higher in the STEPO suits (298 W and 299 W compared to 222 W).

The new generation of toxic chemical protective uniform systems can effectively reduce heat strain and increase work capabilities, because of the micro-climate cooling. It has not yet been determined what cooling system will provide the most favourable ratio of heat removal to equipment weight. All of the improvements to the STEPO systems, which make them a safer alternative to wearing the TAP suit, also come with a significant weight and therefore metabolic burden to the wearer (Cadarette *et al.* 2001).

The findings of an investigation from McLellan (1996) revealed a very significant reduction in heat strain associated with the removal of the combat clothing layer (normally worn under NBC garments) during light intermittent exercise. Therefore, the removal of the combat clothing prior to donning an NBC overgarment, gloves, boots and respirator would be recommended for extended operations in hot environments. The data also showed further reductions in heat strain associated with wearing a new protective NBC-BDU but these additional changes are small in comparison to the effect of removing the combat layer by itself.

6.3.3 Energy cost of NBC clothing

Despite the large body of knowledge on the performance effects of chemical protective clothing, little quantitative information exists about the energy cost and related physiological changes during dynamic exercise under conditions where heat stress is not a significant factor. Wearing standard BDU (battledress uniform), BDU with a M17 protective mask or NBC clothing (chemical protective clothing with a mask, overgarment, gloves and boots) Patton *et al.* (1995) had subjects walk at 5.6km/hr on a treadmill at 3 grades; 0, 5 and 10 %. Laboratory environmental conditions were maintained at 18-22°C and 40-55 % relative humidity to minimise the possible effects of heat on the physiological and perceptual responses to exercise in the NBC clothing (Patton *et al.* 1995). $\dot{V}O_2$ was significantly ($p<0.01$) increased in NBC clothing compared to BDU at all grades. No differences were seen between the BDU and BDU with mask conditions at any level of exercise. Over the range of exercise intensities (approximately 30-60 % $\dot{V}O_{2max}$), $\dot{V}O_2$ increased between 13 and 18 % while wearing NBC clothing. Since the contribution of the mask to this response was slight, the increased energy cost was assumed to be due to the overgarment, overboots and gloves. $\dot{V}O_2$ was corrected for clothing weight but was still greater by 6–11 % across exercise intensities in the NBC clothing suggesting that factors other than clothing weight were responsible for the increase.

The high insulation and low permeability of NBC clothing is an inherent problem that compromises the body's evaporative and convective cooling mechanism. The physical and psychological performance decrements while wearing NBC have also been extensively documented; decreased task performance, decreased work tolerance, increased time for task completion (Murphy *et al.* 2001). The study by Murphy *et al.* (2001) was conducted in a thermoneutral environment where heat stress was not a factor. Energy cost ($\dot{V}O_2$) was measured during the performance of physical tasks, categorised as stationary, intermittent or continuous, whilst wearing BDU or NBC. As the exercise intensity and mobility of the tasks increased so did the physiological impact of wearing NBC, with the difference in the energy cost between NBC and BDU significantly ($p<0.05$) higher in the continuous task category. After normalising the data for clothing weight, approximately 8 -10 % of the additional energy cost was attributed to the hobbling effect and the weight NBC added to the extremities.

Rissanen and Rintamaki (1997) had subjects dressed in an impermeable rubber suit (IP) or a semipermeable activated carbon suit (SP) performing work/rest cycles in an ambient temperature of -10°C. During work they found the oxygen consumption was 13 % higher in the IP ensemble than in the SP ensemble, with $\dot{V}O_2$ 30 % higher in the IP ensemble during rest periods.

6.3.4 Summary

A number of studies have considered the physiological effects of working in NBC ensembles, however few have considered the metabolic implications, with a greater focus on the thermal consequences of the protection.

For the NBC clothing the major contributing factor to the increased heat load and energy cost is probably the encapsulation of the wearer, creating a microenvironment that severely compromises the ability of the body to thermoregulate, particularly through evaporation of sweat. By inhibiting the dissipation of internally produced metabolic heat, NBC garments can be seen to cause heat stress and illness at relatively moderate ambient temperatures.

6.4 Other Personal Protective Clothing

In hot working environments thermal radiation often accompanies high air temperature and in such conditions it is necessary to use protective clothing against radiation. This type of clothing is typically aluminized and therefore greatly disturbs heat dissipation from the human body, resulting in excessive heat strain. In many industrial operations, radiation protective clothing is often used in resting conditions during surveillance tasks like the quality control of molten metals. Marszalek *et al.* (1999) studied the effect of wearing aluminized protective clothing, which when worn at rest in the heat (WBGT 29°C) caused a higher sweat rate and higher subjective ratings of sweating and thermal sensation. The aluminized clothing was impermeable to water vapour, hampering sweat evaporation, the greater sweating in the protective clothing condition represented the failure to dissipate the heat by evaporation due to the clothing barrier.

Due to the asbestos exposure risk, workers in the asbestos removal industry are also advised to wear protective clothing. Respiratory protective devices prevent inhalation of asbestos fibre and protective clothing prevents contamination of personal clothing. Moreover asbestos removal workplaces are characterised by a very high air humidity resulting from covering the floor, ceiling and walls with vinyl sheets and spraying water to reduce the amount of asbestos in the air. To be able to work safely and effectively, Threshold Limit Values (TLV) for work in the heat are widely used. Since these TLV's are applicable to normally clothed workers, TLV's should be adjusted when applied to the asbestos removal workers who wear extra impermeable protective clothing. Although abbreviated guidelines for heat stress exposure have been proposed including characteristics of the clothing, literature advocating their use in the asbestos removal industry is limited (Ohnaka *et al.* 1993).

The study by Ohnaka *et al.* (1993) looked at wearing disposable asbestos removal clothing during work/rest cycles in varying environmental conditions. They reported a five-fold increase in sweat rate in the hot compared to the cool conditions, rectal temperature increased after the first work period in both the hot and hot/cool conditions, and positive heat storage during recovery in the hot condition suggested body temperature was increasing even during recovery. They concluded it is necessary not only to take a rest when working in the heat but also to consider using a countermeasure of passive cooling, for example cool rooms in the workplace.

Heat stress can also be a significant problem for pilots wearing protective clothing during flights, because the extra insulation they provide prevents evaporative heat loss. As heat stress can influence human cognitive activity this might be critical in a flying situation, requiring efficient and error-free performance. Sea King helicopter pilots are obliged to wear survival suits all year round when operating in areas with low sea temperatures, but wearing a survival suit results in higher discomfort ratings and significant rises in skin temperatures and sweat rates (Faerevik and Reinertsen 2003).

Protective clothing can be as simple as waterproof jackets. Australian soldiers may be required to perform prolonged activity in tropical conditions. It is important that soldiers be supplied with wet weather jackets which offer protection while still allowing for heat loss. A study by Malcolm *et al.* (2000) has shown that during physical activity in tropical conditions any design of wet weather garment worn over a standard uniform will impair heat loss and increase physiological stress. Comparing no jacket to a poncho and a ¾ length wet weather jacket, both layers caused increased body temperature and physiological work load with decreased thermal comfort. Measures of oxygen consumption and metabolic rate were significantly higher when wearing the poncho compared to the jacket and when wearing the jacket compared to no jacket. In conclusion wearing any form of wet weather garment in hot, humid conditions restricts heat loss and results in greater body heat storage, it seems when wearing the poncho, the heat trapped

between the poncho and the skin, despite being circulated by the pumping action of the arms did not contribute to additional heat loss but rather resulted in increased body heat storage (Malcolm *et al.* 2000).
In summary, protective clothing decisions in many industries are based on the need to reduce the risk of skin contact with chemical or physical hazards. But sometimes over-protection of the skin results in a secondary hazard, heat stress.

6.5 Summary of previous research on PPC

The physiological effects of protective clothing have been well studied. The volume of research reviewed illustrates a focus in the literature on firefighter and NBC garments, with considerably fewer papers on other workers and industries, for example those working in asbestos removal.

It is the thermal effects of the protective clothing that have been emphasized with the most commonly reported physiological parameters: core temperature, heart rate and sweat loss. It is known that wearing protective garments and/or performing in the heat causes greater increases in these parameters, indicating a degree of heat stress. Although some studies have reported energy cost or oxygen consumption, there is limited data on the pure metabolic effects of protective clothing and the data that is available is confined to a narrow range of protective garments, most notably fire fighting and NBC ensembles.

A wider knowledge is required of the metabolic costs of protective clothing worn in other industries, e.g. steel workers, cold store workers, those working in asbestos removal and with industrial kilns, for example in the ceramics industry. This information is crucially important as the heat and cold stress standards currently being used in industry to assess the working environment may be significantly underestimating the heat stress workers are exposed to as they assume light, vapour permeable clothing. More data on the metabolic costs of a wider range of protective garments with different properties will allow a greater understanding of the causes of the extra energy costs. Predicting garment effects on worker performance up to now has been limited because the relationships between garment properties and human responses are not well understood

7. Conclusions

From the literature review the following conclusions can be drawn:

- Information on the effect of PPC on the wearer and the interactions between PPC, wearer and environment is limited.
- There are important side effects to PPC, including added weight of the clothing and reduced mobility due to garment bulk and stiffness, which are not well understood.
- Current heat and cold stress standards assume workers are wearing light, vapour permeable clothing.
- Metabolic rate is the rate at which the body converts chemical energy into mechanical and thermal energy and is an important influence on heat load and in the human heat balance.
- The main effects of PPC on the heat balance are to increase the rate of metabolic heat production and reduce the convective, radiative and evaporative pathways for heat exchange.
- Measuring a person’s oxygen consumption during work can give an indirect, but accurate estimate of energy expenditure (metabolic rate).
- Newer portable breath-by-breath analysis systems have been well validated against the gold standard Douglas bag method for measuring oxygen consumption.
- Studies of the effects of PPC on workers have concentrated predominantly on the thermal implications of the clothing, little quantitative information exists about the energy costs.
- Literature on the effects of PPC is dominated by studies on firefighting and NBC garments.
- Clothing weight, a binding or hobbling effect and friction drag between clothing layers have all been put forward by authors in an attempt to try and explain increased energy costs with PPC, but none of these theories have been thoroughly investigated.

- Predicting garment effects on worker performance is difficult because relationships between garment properties and human responses are not well understood.

A number of research questions are raised from the literature,

- How much of an effect does PPC have on metabolic rate?
- Do different garments have greater effects on the wearers metabolic rate?
- Is the effect on metabolic rate the same across a number of activities?
- What is the relationship between garment weight and metabolic rate?
- Does clothing bulk have a 'hobbling' effect, reducing the range of movement for the wearer?
- Can wearing a number of layers increase metabolic rate due to friction between layers?
- Can we predict the metabolic effect of a PPC garment from its properties, for example, weight, stiffness, number of layers?

The aim of the work conducted in this thesis is to quantify the effects of wearing a range of PPC garments on metabolic rate whilst performing different activities. Further work will then consider the properties of the PPC such as weight, bulk, stiffness, number of layers and the scale of their contributions to increases in metabolic rate recorded.

It is important to establish the effects of PPC on metabolic rate as current heat and cold stress standards do not take this into account and so currently cannot accurately be applied to situations in which PPC is worn. It is hoped that the results from this thesis will provide a greater understanding into the interactions between the clothing and the wearer and that the data collected will be used to improve the application of heat and cold stress standards when PPC is worn.

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