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British Occupational  
Hygiene Society

The Chartered  
Society for Worker  
Health Protection

# Student Manual: M502

## Thermal Environment

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## Version History

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M502	1.0	February 2024	Minor amendments to front matter, Course Overview and format including: - Renamed as M502 - Addition of M Series Copyright and Licence Information



**Feedback**

We welcome feedback on this manual. Comments should be sent to the BOHS Qualifications Team at [qualifications@bohs.org](mailto:qualifications@bohs.org).

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## ABBREVIATIONS

ACGIH	American Conference of Governmental Industrial Hygienists
AIHA	American Industrial Hygiene Association
AIOH	Australian Institute of Occupational Hygienists
ASHRAE	American Society of Heating, Refrigerating and Airconditioning Engineers
ATP	Adenosine Triphosphate
BOHS	British Occupational Hygiene Society
CCOS	Canadian Centre for Occupational Health & Safety
COP	Code of Practice
DLE	Duration Limited Exposures
ECG	Electrocardiogram
HR	Heart Rate
HSE	Health & Safety Executive
HVAC	Heating, Ventilation & Air Conditioning
IREQ	Index of Required Clothing Insulation
MOHAC	Mining Occupational Health Advisory Committee
NaCl	Sodium Chloride
OSHA	Occupational Safety & Health Administration (USA)
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
PPE	Personal Protective Equipment
RSA	Republic of South Africa
RT	Recovery Time
SG	Specific Gravity
TWL	Thermal Work Limit
UK	United Kingdom
USA	United States of America
WCI	Wind Chill Index
WHO	World Health Organisation

## **1. COURSE OVERVIEW**

### **1.1 INTRODUCTION**

This Course has been developed so that it follows the module syllabus M502 Thermal Environment available on the British Occupational Hygiene Society (BOHS) website at [www.bohs.org](http://www.bohs.org).

At the time of publication every care has been taken to ensure all topics covered in the syllabus for the subject (M502) have been included in this Student Manual.

The developers of this Student Manual take no responsibility for any material which appears in online versions of the syllabus for Module M502 which is not covered in this manual.

### **1.2 AIM OF COURSE**

To provide the student with a sound understanding of the effects of the thermal environment on people and the means of assessing and controlling the risks associated with thermal stress.

### **1.3 LEARNING OUTCOMES**

On successful completion of this module the student will be able to:

- Identify sources of thermal stress within the working environment;
- Understand the nature of thermal strain on the body;
- Make an assessment of the thermal environment through appropriate measurement and other means;
- Evaluate the likely risk from exposure to thermal stress;
- Suggest appropriate control approaches for the thermal environment.

## 1.4 **FORMAT OF MANUAL**

This manual has been specifically designed to follow the syllabus for this course as published on [www.bohs.org](http://www.bohs.org). Similarly, the material provided in this manual has been aligned with the presentations for each topic so students can follow the discussion on each topic.

It should be recognised that the format presented in this manual represents the views of the authors and does not imply any mandatory process or format that must be rigidly observed. Presenters using this manual may well choose to alter the teaching sequence or course material to suit their requirements. In this regard the case studies are provided as illustrative examples and alternate case studies relevant to a particular industry may be used if desired.

In the final outcome, the aim of this manual is to transmit the principles of the thermal environment to attendees and provide guidance as to how those principles should be applied.

## **2. THE THERMAL SPECTRUM**

### **2.1 INTRODUCTION**

Energy from the sun is a fundamental requirement for the existence of humans, plants, animals and other forms of organisms. Upon reaching the earth, energy from the sun is transferred from one place to another and from one form to another thus creating a wide range of environments.

Evolution has decided that humans are warm-blooded and whose biochemistry functions at an optimum temperature operations level. Humans are equipped with a very efficient control system to keep their internal environment at a relatively stable temperature. This temperature is above that of the usual environmental surroundings, however the inability of the body to maintain this operating level when the environmental surroundings are at temperatures either higher or lower than normal can give rise for concern in terms of physiological consequences.

Humans can thus be considered as homeotherms and attempt to maintain the internal body temperature near to 37°C. A deviation of a few degrees from this temperature can have serious consequences.

In order to maintain the internal body temperature within acceptable limits there is a need to understand and control those factors which may influence this process. As there can be considerable variations in the work environment, the work load, personal characteristics and susceptibilities, the application of any measurement index or control approach may result in some individuals suffering annoyance, aggravation of a pre-existing condition or in extreme cases physiological damage.

Notwithstanding these limitations, there are many strategies which can be adopted which limit the risk of adverse health effects by maintaining the internal body temperature at or near its theoretical operating level.

Another factor that needs to be considered in regard to work is the link between thermal comfort and accident rates and performance.

As far back as the First World War investigation of accident rates (especially in the munitions and mining industries) has shown a relationship between accident rates and higher than normal temperatures (BOHS 1996).

Smith (1984) used actual monthly production figures to demonstrate that significant productivity increases occurred in deep level gold mines in South Africa where improved refrigeration procedures resulted in a reduction in wet bulb temperatures. Moreover, the accident frequency rate showed a parallel decline and Smith proposed that heat stress degrades mental performance well in advance of any deterioration of physical performance.

OSHA (1999) suggested that at an atmospheric temperature of 35°C, a loss in work output of 45% and a loss in accuracy of 700% occurs, however no information is provided as to how these values were determined.

Strong support for the concept of Smith is provided by Knapik et al (2002) who reported on seasonal variations in injury rates during US army basic combat training.

Increased fatigue can result from thermal stress (Brake & Bates, 2001; Ganio et al 2011) and the negative impact of dehydration has been demonstrated in relation to cognitive function, visual attentiveness, short term memory psychomotor skills (Cian et al 2000; Ganio et al 2011).

The implications of such findings are significant and perhaps have not received the focus that they deserve, but these examples do serve to highlight that heat stress may well be linked to outcomes not generally apparent.

## **2.2 WORK IN EXTREME TEMPERATURES**

It is an ironic twist of fate that many of the world's resources are located in parts of the globe which enjoy extremes in climatic conditions (either hot or cold). Development of these resources has necessitated that persons are required to work in conditions of either heat or cold and thus adequate

precautions need to be taken to ensure any adverse health effects are minimised.

Examples of work in extreme temperatures include:

- Oil production in Alaska and the Middle East
- Mining in the Arctic regions of Canada and also in Central Africa

While the above are examples of the same activity in both cold and hot environments, other situations can occur. For example serious issues with excessive heat can arise in deep mines (South Africa, Canada and Australia) where the host rock is so hot that heat transfer to the ventilating air results in elevated temperatures. In such cases it is not uncommon for ventilation air to be refrigerated.

Other examples of work in extreme temperatures would be:

- Work in refrigerated areas like cool rooms and freezers.
- Work in areas of high radiant energy, eg foundries, steel plants, glass plants, coke ovens, brick firing and ceramic plants, smelters.
- Work in outdoor areas where there may be exposure to the sun's radiation or to wind chill.
- Military activities.

Consequently, when any work activity is conducted in areas of potential temperature extremes there is a need for an appropriate management plan which addresses those risk factors present.

### **2.3 WORK IN MODERATE TEMPERATURES**

The need for work activity in extreme temperature climates is not that uncommon these days. The mere fact that temperature extremes do occur forces attention on the issue and in the majority of cases the requirement to ensure any health risk is mitigated.



In more temperate climates such high level of awareness is not always apparent. In periods of “heat wave” conditions (or even moderately elevated temperatures) it is not uncommon for whole production facilities to be affected by heat induced illness.

It is highly likely that this also occurs to some degree with “cold snaps”; however this situation does not seem to be recorded that often.

In the case of hotter than normal (not necessarily heat wave) conditions, there are numerous reasons why these abnormal conditions could give rise to heat induced issues. For example:

- The body in moderate climates is thermoregulating within a narrow range of temperatures and any increase in that range may take time for the regulatory systems to adjust.
- Acclimatised workers who are overweight or obese would generally cope with working in a thermally challenging environment whereas unacclimatised workers (and the general populace) would find it difficult to adapt to sudden changes in the thermal environment (Desira, Gopaldasani & Whitelaw 2014).
- Workplaces in most moderate climates are designed for the normal environment, not extremes.
- Working intensity and clothing are key factors.

Activities where thermal stress may be an issue in moderate temperatures include but are not limited to:

- Rubber vulcanising plants
- Bakeries
- Commercial kitchens
- Laundries

- Food canneries
- Boiler rooms
- Fire fighting activities

Many of the issues arising from abnormal conditions in moderate climates can be easily managed provided a commonsense approach is adopted. For example, the introduction of more rest periods and increased liquid intake may ensure production can continue (albeit at a reduced rate) without harm to employees. This is a better option than total loss of production due to heat induced illness. Each case needs to be judged on its merits and managed accordingly.

At the other end of the scale, prolonged exposure to cold air or to immersion in cold water at temperatures well above freezing can lead to hypothermia.

### **3. PRINCIPLES**

#### **3.1 HEAT STRESS**

The Australian Institute of Occupational Hygienists (AIOH) defines heat stress (AIOH 2013) as:

*“The net heat load to which a worker may be exposed from the combined contributions of metabolism associated with work and environmental factors such as:*

- *air temperature,*
- *humidity,*
- *air movement*
- *radiant heat exchange and*
- *clothing requirements*

*The effects of exposure to heat may range from a level of discomfort through to a life threatening condition such as heat stroke. A mild or moderate heat stress may adversely affect performance and safety. As the heat stress approaches human tolerance limits, the risk of heat-related disorders increases”.* A discussion of these effects can be found in Section 4.1.

#### **3.2 HEAT STRAIN**

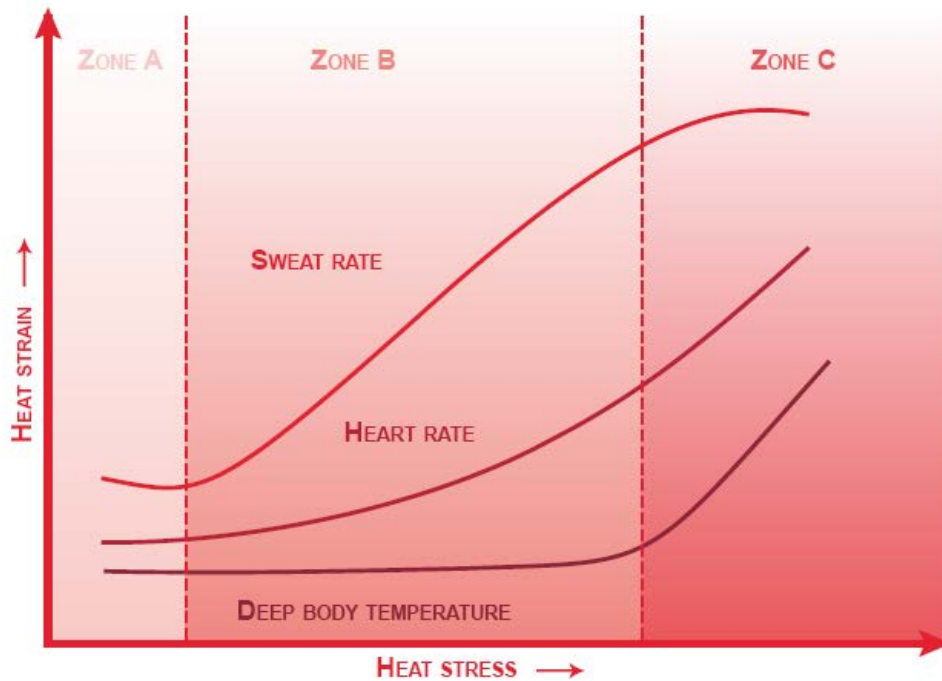
Heat strain can be defined (Taylor 2005) as:

*“The physiological impact of heat stress on the body, as expressed in terms of changes in tissue temperatures and compensatory changes in the activity of physiological systems (sweat rate, heart rate, skin blood flow).”*

An alternate definition is provided by the AIOH in their publication (AIOH 2013) where they define heat strain as:

*“The body’s overall response resulting from heat stress. These responses are focussed on removing excess heat from the body”.*”

The interaction between heat stress and heat strain can be demonstrated in graphical form (Figure 3.1).



(Source:

WHO 1969)

**Figure 3.1 – Relationship Between Heat Stress & Heat Strain**

From Figure 3.1 it is possible to make the following observations:

- Zone A - Body in state of homeostasis.
- Zone B - As the level of heat stress increases the deep body temperature is held constant by increasing the sweat rate.
- Zone C - As the level of heat stress continues to increase, the sweat rate can no longer increase to regulate deep body temperature and thus the body temperature increases.

Thus we can see an increase in heat strain on the body as the level of heat stress increases.

### 3.3 HOMEOSTASIS

#### 3.3.1 Definition

*“The process of keeping the internal environment (eg temperature, pH, blood pressure, blood gases) stable by modulating physical functions and behaviour (Taylor 2007)”.*

It is important to understand that homeostasis is actually a dynamic equilibrium in which continuous changes are occurring, the net effect of which is a relatively stable environment.

The concept of homeostasis can be demonstrated by considering the action of a thermostat in a room. Here a sensor determines the environmental conditions in a room and then informs the thermostat, which either increases or reduces energy flow (heat) to maintain a pre-set temperature.

In humans the process is much more complex and is controlled by a section of the brain called the hypothalamus, which adjusts, for example, breathing and metabolic rates, blood vessel dilation and blood sugar levels in response to changes caused by factors such as ambient temperature, hormones and disease.

#### 3.3.2 Typical Body Temperatures

In the previous section we discussed the concept of homeostasis whereby the body acts to maintain its internal environment within a narrow margin around the core body temperature of approximately 37°C. Failure to maintain the core body temperature within this margin will result in adverse health effects.

Taylor (2005) suggests the following core temperatures as being clinically significant.

46.5°C	Highest recorded survivable core temperature
43°C	Tissue damage (brain, liver)
41°C	Cessation of sweating
39°C	The threshold of hyperthermia
36.8°C	<i>Normal core temperature</i>

35°C	The threshold of hypothermia
33°C	Impaired muscle function, introversion, loss of mental alertness
30°C	Cessation of shivering and then unconsciousness
28°C	Possible ventricular fibrillation
26°C	Bradycardia and bradypnoea
24°C	Possible death without rewarming
14.4°C	Lowest recorded core temperature for a survivor of accidental hypothermia

The deep body or core temperature is normally maintained within a narrow range around 37°C. Core temperature represents a composite temperature of the deep tissues, but even in the core, temperature is not uniform because organs such as the liver and active muscles have a higher rate of heat production than other deep tissues.

The internal temperature of warm-blooded animals, including man, does not stay strictly constant during the course of a day even when keeping constant the generation of heat from food intake and physical activity. In humans it may be 0.5 – 1.0°C higher in the evening than in the early morning due to an inherent circadian temperature rhythm. Another natural internal temperature variation occurs in women at the time of ovulation when core temperature rises by 0.1 – 0.4°C until the end of the luteal (post-ovulatory) phase of the menstrual cycle.

Taylor (2005) also indicates that the following skin temperatures are clinically significant.

>50°C	Second-degree burn
>45°C	Tissue damage
41 – 43°C	Burning pain
39 – 41°C	Pain
33 – 39°C	Skin warmth through to discomfort (hot)
28 – 33°C	Thermal comfort

25 – 28°C	Cool through to discomfort (cold)
20°C	Impaired
15°C	Pain
10°C	Loss of skin sensation
5°C	Non-freezing cold injury: (time dependent, and can occur between 17 – 0.55°C)
<0.55°C	Freezing cold injury (frostbite)

Across the shell of the body, from the skin surface to the superficial layers of muscle, there is a temperature gradient which varies. This is dependent on the external temperature, the region of the body surface, and the rate of heat conductance from the core to the shell. This gradient determines the rate and direction of heat flow in the body.

When an individual is thermally comfortable, the skin of the toes may be at 25°C, that of the upper arms and legs at 31°C, the forehead temperature near 34°C while the core is maintained at 37°C.

### 3.4 THERMAL REGULATION

As discussed in previous sections there is a need for the body to maintain core temperature within acceptable limits and the process by which this requirement is achieved is the system of human thermoregulation.

One of the most prominent forms of human thermoregulation is that of behavioural change. For example humans can regulate their body temperature by actions such as:

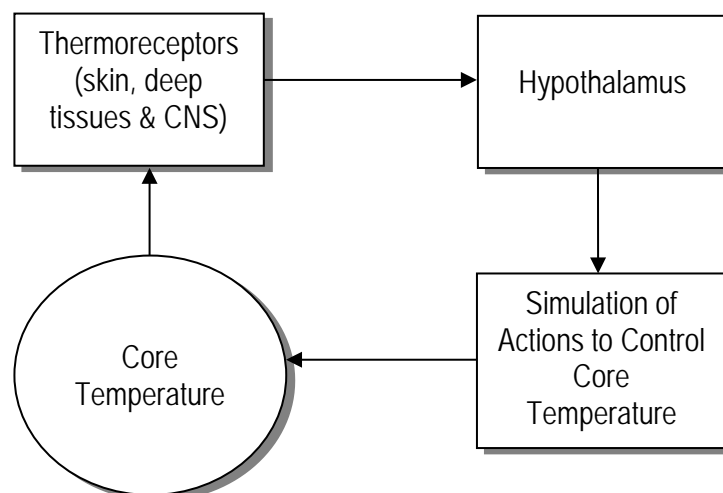
- Putting on or taking off clothes
- Changing posture
- Undertaking movement
- Taking shelter
- Personal protective equipment

The body also has a physiological system of thermoregulation. Both this and behavioural actions continually interact and respond to the changes in the surrounding environment in an attempt to ensure human survival and comfort.

Parsons (2003) indicates that there are numerous system models for human thermoregulation and goes on to discuss four in detail. He suggests that although they are different in composition, they are almost identical. These are based on the recognition that when the body becomes hot it loses heat via vasodilatation (and if required sweating). If it becomes cold then heat is preserved by vasoconstriction and if necessary heat is generated by shivering. All models agree that the primary control centre for thermoregulation is in the hypothalamus; a section of the brain just above the brain stem.

Relevant information is sensed by the body and transferred to the hypothalamus. Here it is processed and translated into signals that stimulate effective control of core temperature are unclear.

It has been suggested that thermoreceptors sensitive to thermal information from the skin, deep tissues and central nervous system provide the feedback signals to the central controller (hypothalamus) as illustrated very simplistically in Figure 3.2.



**Figure 3.2 – Feedback Control of Body Temperature**

While the above diagram has been provided so as to help describe the process of information collection and transmission to the hypothalamus, it should be



clearly understood that the actual individual mechanisms are not known at this stage.

For the purpose of this course it is sufficient to understand that the hypothalamus plays a key role in thermoregulation.

The body's control system is analogous to thermostatic control of temperature in a house with both heating and cooling capabilities. When body temperature rises above a threshold temperature, effector responses associated with cooling (sweating, increasing skin blood flow) are turned on. When body temperature falls below another threshold, heat gain responses (decreasing skin blood flow, shivering) are initiated. Unlike home heating/cooling systems however, the human thermoregulatory control system does not operate as a simple on-off system, but also has proportional control and rate-of-change control characteristics.

The operating temperature of the body is relatively stable but it is affected by work or ambient temperature. When the body rises above (or falls below) a critical threshold, a variety of behavioural and physiological responses are initiated.

This is sometimes thought of in terms of a load error (ie the difference between the operating temperature and the temperature resulting from the external factors). The size and direction of the load error determines the form and intensity of the behavioural and physiological responses.

### **3.5 PHYSIOLOGICAL RESPONSES TO HOT ENVIRONMENTS**

#### **3.5.1 Vasodilatation**

When information is received at the hypothalamus from the thermoreceptors that the body is getting hot, skin vasodilatation (widening of the blood vessels, increasing surface area) occurs increasing heat loss to reduce the heat load. In this way heat is transported from the hot core to the skin surface for dissipation.

### **3.5.2 Sweating**

When the body temperature rises, sweat is secreted over the body to allow cooling by the process of evaporation. An increase in sweat production leads to greater fluid availability for evaporation and hence a greater rate of cooling.

Two types of sweat glands exist in the body, ie apocrine glands (armpits and pubic regions) and eccrine glands which are distributed about the body in areas such as the forehead, neck, trunk, back of forearm and hand plus other areas. It is the eccrine glands that perform the thermoregulatory function and there are 2 – 4 million glands distributed over the entire body surface.

In a hot environment (ie when the air temperature is greater than the skin temperature) the evaporation of sweat is the only method of maintaining a stabilised core temperature (only until the sweating process cannot disperse the heat load).

### **3.5.3 Electrolyte Changes**

Heavy and prolonged sweating brings large volumes of body water and electrolytes (principally sodium) to the skin surface.

All cells that make up the various tissues and organs in the body are surrounded by a membrane. This cell membrane serves as both an insulator and a diffusion barrier to the movement of ions. These ions are both positive and negative ions thus creating an electrical gradient across the cell membrane. This electrical gradient is essential for proper functioning of all cells, tissues and organs in the body. Any disruption of this electrical gradient will result in a malfunction of the tissue or organ. For example disruption within the myocardium (muscle tissue of the heart) may result in abnormal heart contractions; disruption within the muscles of the gut may result in intestinal obstruction and disruption within the skeletal muscle may result in cramps (Hodgkin 1951, Coraboeuf 1978).

Thus, failure to maintain electrolyte levels (and hydration) often results in gastrointestinal disturbances and muscle cramps.

#### **3.5.4 Dehydration**

While sweating is a natural process of the body to control temperature, it presents a problem in that it sacrifices body fluid to cool the skin surface.

For people working hard in hot environments the maximum daily sweat rate can approach 10 – 15 litres/day (Taylor 2005) and the resultant dehydration diminishes the effectiveness of blood circulation for distributing heat in the body.

Dehydration can lead to the following consequences:

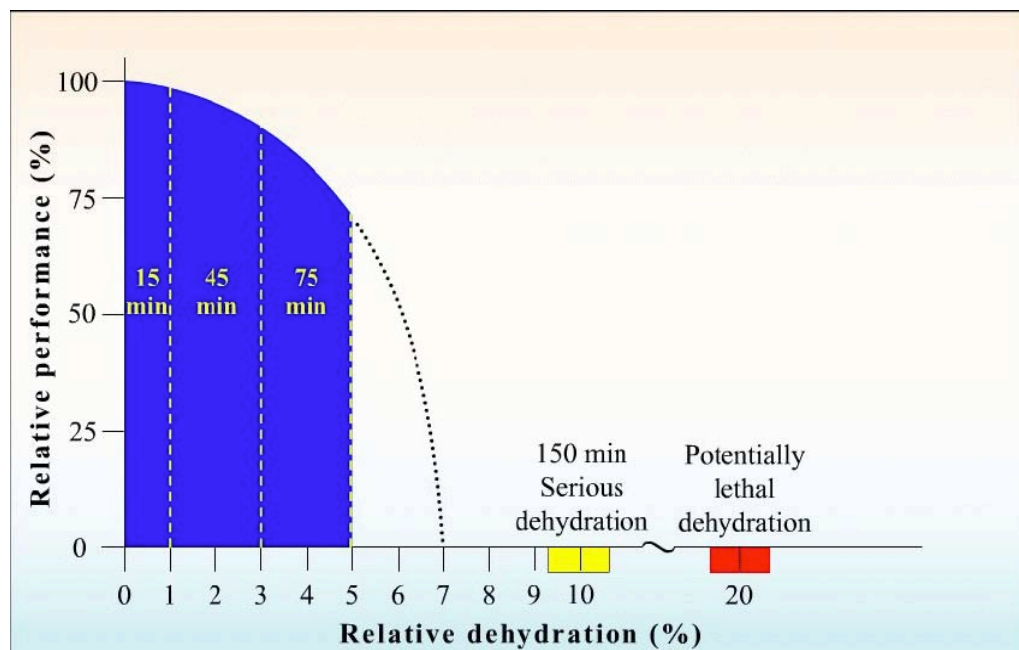
- Reduced blood volume
- Impaired cardiovascular stability
- Reduced physical and cognitive performance
- Reduced muscle and general endurance
- Elevated thermal strain at any given thermal stress
- Reduced heat tolerance
- Reduction in the benefits of heat adaption
- Increased risk of heat illness

Critical thresholds for dehydration as % of body weight, have been defined by Taylor (2005) as:

- 3% - Physical and cognitive performance starts to deteriorate (occurs in about 45 minutes during heavy work without fluid replacement).

- 5% - Severe degradation in physical and cognitive performance (occurs in about 75 minutes during heavy work if fluids are not replaced).
- 10 – 15% - Serious and dangerous dehydration approaching circulatory collapse (occurs in about 150 minutes during heavy work if fluids are not replaced).
- 20% - Potentially lethal dehydration associated with uncontrolled fluid loss (usually diarrhoea).

These thresholds are clearly demonstrated in Figure 3.3; however there is considerable variability among individuals for the attainment of these thresholds.



(Source: Taylor 2005 – reproduced with permission)

**Figure 3.3 – Impact of Dehydration on Physical and Cognitive Performance**

### **3.5.5 Heart Rate**

During rest the cardiac output is distributed among all the organs but preference is given to organs such as the brain, kidneys, digestive system and liver.

When the core body temperature increases, the cardiovascular system must now also (in addition to providing oxygenated blood to the organs) remove heat.

To achieve this, blood flow to the skin is increased at the expense of the less critical organs and the increased circulatory strain causes a corresponding increase in heart rate.

In humans the heart rate is highly variable but in most average adults a rate of 60 – 80 beats per minute is common (40 – 50 beats per minute in endurance athletes). Under thermal stress higher than normal heart rates are observed.

### **3.5.6 Respiration Rate**

Respiration provides a pathway by which heat can be lost to the atmosphere. This heat loss is due to evaporation of moisture in the respiratory tract.

## **3.6 PHYSIOLOGICAL RESPONSES TO COLD ENVIRONMENTS**

### **3.6.1 Vasoconstriction**

When the body senses that it is getting cold, the process of vasoconstriction is activated so as to reduce heat loss. During this process constriction of superficial veins occurs in the limbs so that cold blood from the skin returns along the accompanying vein (venal comitans) close to the artery thus gaining heat and returning it to the body core.

This process is the reverse of that which occurs during vasodilatation.

### **3.6.2 Shivering**

Shivering can be both a voluntary and involuntary process, the onset of which is related to both skin and core temperature. The process of shivering is designed to increase the metabolic heat production within the body as an offset against a drop in core temperature.

Shivering can vary in intensity from mild to violent and can increase metabolic heat production by a factor of up to five times the non shivering level for short periods.

Unfortunately in very cold environments or during cold water immersion, shivering can reduce the fall in body core temperature but it can also increase heat loss to the environment.

### **3.6.3 Piloerection**

Piloerection (also known colloquially as “goose bumps”) is the condition which occurs when the skin becomes cold and in an attempt to reduce heat loss the hairs of the body “stand on end” so as to maintain a layer of still air between the body and the environment.

As humans have relatively little hair and are generally clothed (which creates a layer of still air), this condition is not usually regarded as a significant factor in human thermoregulation. Some researchers do however believe it does play an active role for example during shivering and in still air environments.

### **3.6.4 Cold Diuresis**

One side effect of vasoconstriction is that of cold diuresis whereby the constriction of all skin blood vessels forces a large amount of blood to the body core. This causes a rapid increase in blood pressure and to compensate the kidneys quickly removes fluid from the blood stream so as to stabilise blood pressure. The effect of these changes is the resultant need to urinate.

### **3.6.5 Respiration**

Heat loss occurs by way of the respiratory tract; the actual amount is dependent on the temperature and humidity of the air and on the respiratory ventilation rate.

Cold may cause bronchospasm and adversely affect physical work performance and in some people may lead to exercise-induced asthma.

### **3.6.6 Heart Rate**

As discussed in Section 3.5.5, heart rate is influenced by an increased metabolic rate and heat load and can be considered as a general index of strain on the body caused by a number of factors, one of which is thermal stress.

In cases of hypothermia, atypical patterns can be observed on an electrocardiogram (ECG) suggesting a level of cardiovascular strain. There is also evidence of an increased level of angina attacks, coronary and cerebral thrombosis in cold environmental conditions. This is probably due to increased blood pressure (vasoconstriction), cardiac strain and increased blood viscosity.

It should be noted that people who have an abnormal heart function would also show non typical ECG patterns and would be at increased risk of a heart attack in cold conditions.

### **3.6.7 Dehydration**

As indicated in Section 3.6.5, heat is lost from the body under cold conditions via the respiratory tract. Water is also lost via this pathway and dehydration may occur due to water loss not only via the respiratory tract but from the skin and cold diuresis.

### 3.6.8 Psychological

Psychological responses to changes in the thermal environment have been studied in some detail (Parsons 2003) and it is generally accepted that a person's psychological state (eg mood and behaviour) can be influenced by thermal stress.

Studies have demonstrated that persons working in areas such as Antarctica suffered incidences of boredom, weariness, homesickness, bad temper, anxiety and disturbances of mood and self confidence.

Despite a great deal of evidence that thermal environments can significantly influence psychological responses, the underlying mechanisms are not understood.

### 3.6.9 Other Effects

There are a number of other physiological consequences to cold environments worthy of mention. These include:

- *Local cold injury* – Local cooling of the limbs can induce non-freezing cold injury or freezing injury (frostbite) with or without the presence of hypothermia. Trench foot (immersion foot) is an example of a crippling non-freezing cold injury with local damage to nerves and tissues due to the prolonged cooling of the feet in mud or water.
- Cold allergy occasionally develops on removal from the cold with widespread vasodilatation over the whole body, headache and hypertension.
- Acute paralysis of the facial nerve can sometimes occur as a result of a cold airstream directed onto the side of the face.



### 3.7 HEAT PRODUCTION AND HEAT EXCHANGE WITH THE SURROUNDINGS

#### 3.7.1 Basic Thermodynamics

The laws of thermodynamics are unique in that they were not developed (as were most other physical laws) to explain processes that humans experience in nature. In fact the laws of thermodynamics were designed to explain the absence of perpetual motion in nature.

The first law of thermodynamics can be stated as:

“The increase in the internal energy of a thermodynamic system is equal to the amount of heat energy added to the system minus the work done by the system on the surroundings.”

A simple summary of the first law is that *“Energy cannot be created or destroyed, it can only be transformed from one state to another”*.

The second law of thermodynamics is often stated as:

“The entropy of an isolated system not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium.”

Entropy is the dispersal of energy within a system or that part of the energy within the system not available to do work in the future.

To demonstrate the concept of increasing entropy, consider water overflowing a dam. When the water is at the top of the dam it has potential energy due to gravity, which can be used (for example to generate electricity). When the water is at the foot of the dam wall it has the same total energy as the water at the top of the dam wall (as falling over the dam wall heats the water thus increasing its thermal energy) but it no longer has the same capacity to do work. Thus the water has moved from an available (or free) energy state to an unavailable (or bound) energy state and this change is an increase in entropy.

A simple summary of the second law is that

*“Energy spontaneously tends to flow from being concentrated in one place to becoming diffused or dispersed and spread out”*. As an example a hot object will tend to cool by losing energy (heat) to its surroundings. This can be demonstrated in the cooling of a cup of hot coffee where various processes act to disperse energy (heat).

### **3.7.2 External Heat Sources**

The fundamental external source of heat for all life is the sun, which has an approximate temperature of 5500°C and delivers heat to the top of the atmosphere at an approximate rate of 1370 Wm<sup>-2</sup> and to the earth’s surface at a rate of 800 – 1000 Wm<sup>-2</sup>.

On the earth, this energy is transposed from one form to another in accordance with the laws of thermodynamics sustaining a wide range of biosystems including humans.

Air temperature and radiant temperature are the two major external sources of heat which can impose thermal loads (either hot or cold) on humans.

In regard to solar radiation it is important to realise that this varies throughout the day and the year due to the earth’s rotation on its own axis and the earth’s orbit around the sun. Orientation and posture of a person will also influence an individual’s solar load.

### **3.7.3 Internal Heat Sources**

Humans generate heat because they are homeothermic (warm-blooded) and do so from energy derived from food and oxygen. At the cellular level potential energy is provided to the cell in the form of adenosine triphosphate (ATP) derived from glucose (converted from carbohydrates in the gut and liver), proteins, amino acids and fatty acids in the presence of oxygen by enzyme action. The potential energy is released when the ATP is broken down in the cell.

The resultant energy may be converted into work (eg causing muscles to contract), however as this process is inefficient, heat energy is also produced (about 80%).

The heat energy released from the above process is distributed, mainly by the blood, around the body. Obviously, the more energy required by the body (heavy work, exercise, etc) the more heat released by the above process and thus transported throughout the body.

### 3.8 HEAT BALANCE EQUATION

Given that there is a physiological requirement that the body should maintain its core temperature around 37°C, this leads to the conclusion that there is a heat balance between the body and its environment. This is to say that on average, heat transfer into the body and heat generation within the body must be balanced by heat outputs from the body.

Thus if heat generation and inputs were greater than heat outputs the core body temperature would rise and if the heat outputs were greater the core body temperature would fall.

The human heat balance equation can be presented in many forms, however all equations involve the following heat processes, ie:

- Heat generation in the body
- Heat transfer
- Heat storage

One means is to represent the human heat balance equation as:

$$M - W = E \pm R \pm C \pm K \pm S$$

Where

- M = Rate of metabolic heat production
- W = External work performed by or on the body
- E = Heat exchange via evaporation
- R = Heat exchange via radiation

C = Heat exchange via convection

K = Heat exchange via conduction

S = Rate of heat storage (heat gained or lost by the body)

Note: M - W is always positive

E, R, C, K, S (positive value is heat loss, negative value is heat gain)

This equation can be re-written as:

$$M \pm W \pm K \pm C \pm R - E = S$$

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

While the units of rates of heat production or loss are  $\text{Js}^{-1}$  or Watts (W), it is traditional to standardise over persons of different sizes by using units per square metre of the total body surface area (ie  $\text{Wm}^{-2}$ ).

Using the conceptual heat balance equation it is possible to derive a number of further equations for which terms can be either measured or estimated. These include such calculations as:

- Heat loss at the skin
- Evaporative heat loss from the skin
- Heat loss from respiration

In regard to heat loss from respiration it should be noted that this is most prominent in cold environments because expired air is warmer and has a higher absolute humidity than inspired air. For example a person expending energy at  $400 \text{ Wm}^{-2}$  at  $-10^\circ\text{C}$ , the respiratory heat loss would be about  $25 \text{ Wm}^{-2}$  but for normal activities (seated/standing) at  $20^\circ\text{C}$  the heat loss would only be about  $2 - 5 \text{ Wm}^{-2}$ .

### 3.9 METABOLIC HEAT PRODUCTION AND EFFICIENCY

#### 3.9.1 Metabolic Heat Production

As indicated in Section 3.7.3, the human body may be considered to be a chemical engine, and foods with different energy content, the fuel. At rest, some of the chemical energy of food is transformed into mechanical work, eg in the heart beat and respiratory movements. This accounts for less than 10% of the energy produced at rest, the remainder being used in maintaining ionic gradients in the tissues and in chemical reactions in the cells, tissues and body fluids. About 80% of energy is ultimately lost from the body in the form of heat and the balance of intake and loss maintained during daily physical activity. In general, energy intake from food balances energy expenditure, except in those cases where body weight is changing rapidly. In the absence of marked weight changes, measurement of food consumption may be used in assessing habitual activity or energy expenditure, though in practice, energy balance is only achieved over a period of more than one week.

Energy released in the body by metabolism can be derived from measurements of oxygen consumption using indirect calorimetry. The value of metabolic heat production in the basal state with complete physical and mental rest is about  $45 \text{ Wm}^{-2}$  (ie per  $\text{m}^2$  of body surface area) for an adult male of 30 years and  $41 \text{ Wm}^{-2}$  for a female of the same age. Maximum values are obtained during severe muscular work and may be as high as  $900 \text{ Wm}^{-2}$  for brief periods. Such a high rate can seldom be maintained and performance at  $400 - 500 \text{ Wm}^{-2}$  is very heavy exercise but an overall rate that may be continued for about one hour.

Metabolic heat is largely determined by muscle activity during physical work but may be increased at rest in the cold by involuntary muscle contractions during shivering.

In the heat balance equation given previously,  $M - W$  is the actual heat gain by the body during work, or  $M + W$  when negative work is performed.

External work ( $W$ ) is that part of the total energy produced by the body which is not given off as heat.

In positive work, some of the metabolic energy appears as external work so that the actual heat production in the body is less than the metabolic energy produced. With negative work, eg 'braking' while walking downstairs, the active muscle is stretched instead of shortening so that work is done by the external environment on the muscles and appears as heat energy. Thus the total heat liberated into the body during negative work is greater than the metabolic energy production.

In an attempt to reduce the individual variability in estimates of metabolic heat production for a specific activity, the value is usually related to surface area of the body or body mass.

Thus the units of metabolic heat production are  $Wm^{-2}$  or kcal/min/kg. A unit used in some publications is the Met, where 1 Met = 50 kcal/m<sup>2</sup>/hr or 58.15  $Wm^{-2}$  and is said to be the metabolic rate of a seated person at rest.

Frequently values of 1.84 m<sup>2</sup> are assumed for the surface area and 65 – 70 kg for the mass of a man and 1.6 m<sup>2</sup> is assumed for the surface area and 55 kg for a woman.

These are approximate only and the use of the surface area to mass ratio would be more appropriate.

### 3.9.2 Typical Values of Metabolic Heat Production

The following table (Table 3.1) gives an indication as to how metabolic rates change with varying activity.

**Table 3.1 – Examples of Metabolic Rates**

Level of Activity	Metabolic Rate Range ( $Wm^{-2}$ )	Typical Examples ( $Wm^{-2}$ )
Resting	<65	Sleeping (35) Seated – quiet (50) Standing – relaxed (60) Office work (50 – 60) Driving car in light traffic (60)
Low	65 -130	Pushing a wheelbarrow (125) Washing dishes (80) Shop assistant (100) Laboratory activities (70 – 110)
Moderate	130 - 200	Using a pneumatic hammer (160) Driving a heavy vehicle (160) Gymnastics (150 – 200) Machine fitter (140)
High	200 - 260	Sawing by hand (200 – 240) Using a pick and shovel (200 – 240) Playing tennis (230)
Very High	>260	Planing wood by hand (280 – 320) Hot metal furnace operator (340) Digging trenches (300) Wrestling (435)

Another approach is that whereby the individual component physical movements are taken into account to calculate the overall metabolic rate.

**Table 3.2 – Metabolic Rates for Body Position & Movement**

<b>A. Body Position and Movement</b>	<b>Wm<sup>-2</sup></b>
Sitting	10
Standing	25
Walking	80 – 120
Walking up hill	Add 32 per metre rise

(Source: AIOH 2003 – reproduced with permission)

**Table 3.3 – Metabolic Rates for Component Movements**

<b>B. Type of Work</b>		<b>Average Wm<sup>-2</sup></b>	<b>Range Wm<sup>-2</sup></b>
Hand work	light	15	5 – 50
	heavy	40	
Work with one arm	light	35	25 – 100
	heavy	75	
Work with both arms	light	65	40 – 140
	heavy	105	
Work with body	light	125	100 – 600
	moderate	190	
	heavy	280	
	very heavy	390	

(Source: AIOH 2003 – reproduced with permission)

In this approach the average values of metabolic rates during different activities is added to the basal metabolism of 40 Wm<sup>-2</sup>. For example, a person standing doing light work with one arm would have a metabolic rate of

$$40 + 25 + 35 = 100 \text{ Wm}^{-2}$$



### 3.10 DRY OR NON-EVAPORATIVE HEAT TRANSFER

#### 3.10.1 Conduction

Heat is conducted between the body and static solids or fluids with which it is in contact. Conduction occurs due to internal temperature gradients causing vibrational motions of free electrons (solids) and molecules (liquids and gases) causing the transfer of heat from higher to lower temperatures. All effects are at the microscopic level and there is no appreciable motion of the substance.

This process can be expressed as:

$$K = k (t_1 - t_2)$$

$K$  = Conductive heat loss ( $\text{Wm}^{-2}$ )

$t_1$  = Temperature of the body ( $^{\circ}\text{C}$ )

$t_2$  = Temperature of the environment ( $^{\circ}\text{C}$ )

$k$  = Thermal conductivity of medium ( $\text{Wm}^{-2} \text{ } ^{\circ}\text{C}^{-1}$ )

Some typical values of thermal conductivity are:

Air at  $0^{\circ}\text{C}$  =  $0.024 (\text{Wm}^{-1} \text{ } ^{\circ}\text{C}^{-1})$

Blood at  $37^{\circ}\text{C}$  =  $0.51 - 0.53 (\text{Wm}^{-1} \text{ } ^{\circ}\text{C}^{-1})$

Water at  $0^{\circ}\text{C}$  =  $0.57 (\text{Wm}^{-1} \text{ } ^{\circ}\text{C}^{-1})$

Stainless Steel at  $0^{\circ}\text{C}$  =  $16.2 (\text{Wm}^{-1} \text{ } ^{\circ}\text{C}^{-1})$

Copper at  $0^{\circ}\text{C}$  =  $356 (\text{Wm}^{-1} \text{ } ^{\circ}\text{C}^{-1})$

Clearly immersion in water at  $0^{\circ}\text{C}$  will result in a much higher conductive heat loss than exposure to air at  $0^{\circ}\text{C}$ .

#### 3.10.2 Convection

When the surface temperature of a person is higher than that of the surrounding air, heated air close to the body will move upwards by natural convection (ie hot air rises) as colder air takes its place.

The expression for heat exchange by convection is:

$$C = h_c (t_1 - t_2)$$

$C$  = Convective heat loss ( $\text{Wm}^{-2}$ )

$t_1$  = Temperature of the body ( $^{\circ}\text{C}$ )

$t_2$  = Temperature of the air ( $^{\circ}\text{C}$ )

$h_c$  = Convective heat transfer coefficient ( $\text{Wm}^{-2} \text{K}^{-1}$ )

Natural (free) convection is considered to apply when the relative air velocity is  $<0.1 \text{ ms}^{-1}$  and has a typical  $h_c$  of  $5 - 25 \text{ Wm}^{-2} \text{K}^{-1}$ .

As the relative air velocity increases (eg through movement such as walking), the  $h_c$  increases and convective losses are said to be “forced” convection. Obviously, the use of a fan increases the  $h_c$  even further. Typical  $h_c$  values for forced ventilation of gases ranges from  $25 - 250 \text{ Wm}^{-2} \text{K}^{-1}$  and  $50 - 20,000 \text{ Wm}^{-2} \text{K}^{-1}$  for solids.

### 3.10.3 Radiation

All bodies above a temperature of absolute zero emit thermal radiation and heat transfer occurs in the form of electromagnetic waves between two opaque solids at different temperatures.

Thus if we have two similar objects (1 & 2) the radiation transfer is given by:

$$R = \sigma \varepsilon (T_1^4 - T_2^4)$$

$R$  = Radiation transfer ( $\text{Wm}^{-2}$ )

$\sigma$  = Stefan-Boltzmann Constant ( $5.67 \times 10^{-8} \text{ Wm}^{-2} \text{K}^{-4}$ )

$\varepsilon$  = Emissivity of the objects

$T_1$  = Temperature of object 1 ( $^{\circ}\text{K}$ )

$T_2$  = Temperature of object 2 ( $^{\circ}\text{K}$ )

### 3.11 EVAPORATIVE HEAT LOSS

At rest in a comfortable ambient temperature an individual loses weight by evaporation of water diffusing through the skin and from the respiratory passages. Total water loss in these conditions is approximately 30 gh<sup>-1</sup>. Water diffusion through the skin will normally result in a heat loss equal to approximately 10 Wm<sup>-2</sup>. This is termed “insensible perspiration”.

The latent heat of vaporisation of water is 2453 kJ kg<sup>-1</sup> at 20°C and a sweat rate of 1 litre per hour will dissipate about 680 W. This value of heat loss is only obtained if all the sweat is evaporated from the body surface; sweat that drips from the body is not providing effective cooling.

Evaporation is expressed in terms of the latent heat taken up by the environment as the result of evaporative loss and the vapour pressure difference which constitutes the driving force for diffusion

$$E = h_e (p_{sk} - p_a)$$

Where E is the rate of heat loss by evaporation per unit area of body surface (Wm<sup>-2</sup>), h<sub>e</sub> the mean evaporation coefficient (Wm<sup>-2</sup> kPa<sup>-1</sup>) and p<sub>sk</sub> and p<sub>a</sub> the partial pressures of water vapour at the skin surface and in the ambient air (kPa).

The direct determination of the mean evaporation coefficient (h<sub>c</sub>) is based on measurement of the rate of evaporation from a subject whose skin is completely wet with sweat. Since the production of sweat is not even over the body surface this requires that total sweat rate must exceed evaporative loss by a considerable margin – a state that is difficult to maintain for any length of time.

Air movement and body posture are also important in making the measurement.

### 3.12 ACCLIMATISATION

Heat acclimatisation is acquired slowly over several days or weeks of continued activity in the heat. While the general consensus is that heat acclimatisation is gained faster than it is lost, less is known about the time required to lose acclimatisation. Caplan (1944) concluded that, in the majority of cases he was studying, “there was sufficient evidence to support the contention that loss of acclimatization predisposed to collapse when the individual had absented himself for ... two to seven days”, although it was “conceivable that the diminished tolerance to hot atmospheres after a short period of absence from work may have been due to the manner in which the leave was spent, rather than loss of acclimatization.” Brake *et al* (1998) suggest that 7 to 21 days is a consensus period for loss of acclimatisation. The weekend loss is transitory and is quickly made up, such that by Tuesday or Wednesday an individual is as well acclimatised as they were on the preceding Friday. If, however, there is a week or more of no exposure, loss is such that the regain of acclimatisation requires the usual 4 to 7 days (Bass, 1963). Some limited level of acclimatisation has been reported with short exposures of only 100 minutes per day such as reduced rectal (core) temperatures, reduced pulse rate and increased sweating (Hanson & Graveling, 1997).

The improvement in heat tolerance is due to an increased ability to sweat and a reduced pulse rate; sweating commences at lower core and skin temperatures and the salt content of the sweat is reduced.

Acclimatisation in cold environments is less well understood but humans learn to behave in cold environments such that they can survive and keep warm. Physiological acclimatisation is difficult to demonstrate and the evidence for such processes is inconclusive.

There is however evidence of local acclimatisation to cold of the fingers and hands. It is often observed that people whose hands are regularly exposed to cold (fishermen, Eskimos) maintain hand temperature. This is thought to be caused by less vasoconstriction and more cold-induced vasodilatation,

however it may be simply that the hands have become damaged and restrict the ability to vasoconstrict.

## 4. EFFECTS OF TEMPERATURE EXTREMES

### 4.1 EFFECTS OF EXCESSIVE HEAT STRAIN – HOT ENVIRONMENTS

The human body operates within a very narrow core temperature band typically ranging from 36.8°C to 37.2°C. The level of this range is a balance between the heat exchange with the thermal external environment and the internal generation of heat generated by metabolic processes and clothing. As detailed earlier in section 3.8, this process can be represented by the heat balance equation in its simplified form of:

$$M \pm C \pm R - E = S$$

Where

- M = Rate of metabolic heat production
- C = Convective heat loss or gain
- R = Radiant heat loss or gain
- E = Evaporative heat loss
- S = Heat gained or lost by the body

W and K are usually small and not considered so the simplified form is often used.

The combined effect of external thermal environment and internal metabolic heat production constitutes the thermal stress on the body. The levels of activity required in response to the thermal stress by systems such as cardiovascular, thermoregulatory, respiratory, renal and endocrine constitute the thermal strain. Thus environmental conditions, metabolic workload and clothing, individually or combined, create heat stress for the worker. The body's physiological response to the stress, for example, sweating, increased heart rate and elevated core temperature, is the heat strain.

When the body is unable to adequately regulate core temperature heat illness or heat strain as a consequence of the heat stress may result.

Working in a hot environment places the body and in particular the cardiovascular system under load. The body must ensure that working muscles have an adequate supply of blood, but the blood must also be

distributed to the skin to allow heat exchange through conduction and convection. A disproportionate amount of blood is shunted to the skin for heat exchange. This reduces the volume of blood returning to the heart and thus decreases the amount of blood pumped per heart beat stroke (stroke volume).

In hot conditions heat loss is increased firstly by vasodilatation which increases the flow of blood to the skin and raises skin temperature. If this is insufficient to control core temperature, body temperature will rise further and sweating begins to increase the heat loss by evaporation. Repeated exposures to heat leads to modified responses in the cardio vascular system the sweating mechanism (earlier onset, increased sweat rate and more dilute sweat) ie acclimatisation.

When the environment is hot and humid, ie the air is saturated with water vapour, such as in underground coal mines, laundries and paper mills, excessive fluid loss can occur during a work shift. This is primarily due to sweating and often inadequate hydration. Excessive fluid loss can also occur in hot and dry conditions, albeit that this is not as noticeable to the person who again may be inadequately hydrated. Depending on the severity of the fluid loss, the total blood volumes can decrease to such a level where the stroke volume is reduced.

The AIOH in their publication on heat stress (AIOH 2003) gives a review of heat illness which is reproduced below with permission.

### **Acute Illnesses**

Incorrect management of exposure to elevated thermal environments can lead to a number of acute illnesses which range from:

- prickly heat,
- heat cramps,
- heat syncope (fainting),
- heat exhaustion, to
- heat stroke.

The most serious of the heat-induced illnesses requiring treatment is heat stroke, because of its potential to be life threatening or result in irreversible tissue damage. Of the other heat-induced illnesses, heat exhaustion in its most serious form can lead to prostration and can cause serious illnesses as well as heat syncope. Heat cramps, while debilitating and often extremely painful, are easily reversible if properly and promptly treated. These are discussed in more detail below.

The physiologically related illnesses resulting from the body's inability to cope with an excess heat load are usually considered to fall into three or four distinct categories. It has been suggested (Hales & Richards, 1987) that heat illnesses actually form a continuum from initial symptoms such as lethargy through to heat-related stroke. It is important to note that the accepted usual symptoms of such heat illness may show considerable variability in the diagnosis of the individual sufferer, in some cases requiring appropriate skilled medical assessment. The broad classification of such illnesses is as follows.

- **Heat Stroke**

Heat stroke, which is a state of thermoregulatory failure, is the most serious of the heat illnesses. Heat stroke is usually considered to be characterised by hot, dry skin; rapidly rising body temperature; collapse; loss of consciousness; and convulsions. If deep body temperature exceeds 40°C (104°F), there is a potential for irreversible tissue damage. Without initial, prompt and appropriate medical attention, including removal of the victim to a cool area and applying a suitable method for reduction of the rapidly increasing body temperature, heat stroke can be fatal. Whole body immersion in a cold / ice water bath has been shown to remove heat from the body the quickest (Casa et al, 2007). If such equipment is not available, immediate cooling to reduce body temperature below 39°C is necessary. Other methods of cooling may include spraying with cool water and/or fanning to promote evaporation. Irrespective of the cooling method, a heat stroke victim needs immediate, experienced medical attention.



- **Heat Exhaustion**

Heat exhaustion, while serious, is initially a less severe illness than heat stroke, although it can become a preliminary to heat stroke. Heat exhaustion is generally characterised by clammy, moist skin; weakness or extreme fatigue; nausea; headache; no excessive increase in body temperature; and low blood pressure with a weak pulse. Without prompt treatment, collapse is inevitable.

Heat exhaustion most often occurs in persons whose total blood volume has been reduced due to dehydration (i.e. depletion of total body water as a consequence of deficient water intake). Individuals who have a low level of cardiovascular fitness and/or are not acclimatised to heat have a greater potential to become heat exhaustion victims, particularly where self-pacing of work is not practised. Note that where self-pacing is practised, both fit and unfit workers tend to have a similar frequency of heat exhaustion. Self-paced workers reduce their work rate as workplace temperatures increase, hence hyperthermia in a self-paced setting is generally due to exposure to extreme thermal environments (external heat) rather than high metabolic loads (internal heat) (Brake & Bates, 2002c).

Depending on the extent of the exhaustion, resting in a cool place and drinking cool slightly saline solution (Clapp et al, 2002) or an electrolyte supplement will assist recovery, but in more serious cases a physician should be consulted prior to resumption of work. Salt-depletion heat exhaustion may require further medical treatment under supervision.

- **Heat Syncope (Fainting)**

Exposure of fluid-deficient persons to hot environmental conditions can cause a major shift in the body's remaining blood supply to the skin vessels in an attempt to dissipate the heat load. This ultimately results in an insufficient supply of blood being delivered to the brain (lower blood pressure) and consequently fainting. The latter condition may also occur even without significant reduction in blood volume in conditions such as

wearing impermeable encapsulating clothing assemblies, or with postural restrictions (Leithead & Lind, 1964).

- **Heat Cramps**

Heat cramps are characterised by painful spasms in one or more skeletal muscles. Heat cramps may occur in persons who sweat profusely in heat without replacing salt losses, or unacclimatised personnel with higher levels of salt in their sweat. Resting in a cool place and drinking cool slightly saline solution (Clapp et al, 2002), or an electrolyte supplement, may alleviate the cramps rapidly. Use of salt tablets is undesirable and should be discouraged. Thereafter, such individuals should be counselled to maintain a balanced electrolyte intake, with meals if possible. Note that when heat cramps occur, they occur most commonly during the heat exposure, but can occur sometime after heat exposure.

- **Prickly Heat (Heat Rash)**

Heat rashes usually occur as a result of continued exposure to humid heat with the skin remaining continuously wet from unevaporated sweat. This can often result in blocked glands, itchy skin and reduced sweating. In some cases, depending on its location on the body, prickly heat can lead to lengthy periods of disablement (Donoghue & Sinclair, 2000). When working in conditions that are favourable for prickly heat to develop (eg. exposure to damp situations in tropical or deep underground mines), control measures to reduce exposure may be important to prevent periods of disablement. Keeping the skin clean, cool and as dry as possible to allow the skin to recover is generally the most successful approach to avoid prickly heat.

### **Chronic Illness**

While the foregoing acute and other shorter term effects of high levels of heat stress are well documented, less data are available on chronic, long-term effects and appear generally less conclusive. Psychological effects in subjects from temperate climates, following long-term exposure to tropical conditions, have been reported (Leithead & Lind, 1964). Following years of daily work

exposures at high levels of heat stress, chronic lowering of full-shift urinary volumes appears to result in a higher incidence of kidney stones despite greatly increased work shift fluid intake (Borghini et al, 1993).

In a review of chronic illnesses associated with heat exposure (Dukes-Dobos, 1981) it was proposed that they can be grouped into three types:

- Type 1 - The after effects of an acute heat illness; i.e. reduced heat tolerance, reduced sweating capacity.
- Type 2 - Occur after working in hot conditions for weeks, months or a few years (similar to general stress reactions); i.e. headache, nausea, hypertension, reduced libido.
- Type 3 – Tend to occur more frequently among people living in climatically hot regions of the world; i.e. kidney stones, heat exhaustion from suppressed sweating (anhidrotic) (NIOSH, 1997).

A study of heat waves in Adelaide indicated that men aged between 35 to 64 years of age had an increased hospital admission rate for kidney disease (Hansen et al, 2008).

Some studies have indicated that long-term heat exposure can also contribute to issues relating to liver, heart, digestive system, central nervous system, skin illnesses and gestation length (Porter et al, 1999; Wild et al, 1995). Evidence to support these findings are inconclusive.

Consideration may be required of the possible effects on human reproduction. This is in relation to temporary infertility in both females and males [where core temperatures are above 38°C (100.4°F)] (NIOSH, 1997). There may also be an increased risk of malformation of the unborn foetus when during the first trimester of pregnancy a female's core temperature exceeds 39°C (102.2°F) for extended periods (AMA, 1984; Edwards et al, 1995; Milunsky et al, 1992;). Note that no published cases of the latter effect have been reported in an industrial setting.

In addition to the illnesses, previous occurrences of significant heat induced illnesses can predispose an individual to subsequent incidents and impact on

their ability to cope with heat stress (Shibolet et al, 1976; NIOSH, 1997). In some cases, workers may develop intolerance to heat following recovery from a severe heat illness (Shapiro et al, 1979). Irreparable damage to the body's heat-dissipating mechanisms has been noted in many of these cases.

## 4.2 EFFECTS OF EXCESSIVE HEAT STRAIN – COLD ENVIRONMENTS

Four factors contribute to cold stress: cold temperatures, high or cold winds, dampness and cold water. A cold environment (see Table 4.1 for various air temperatures of cold occupational environments) forces the body to work harder to maintain its core temperature band.

**Table 4.1 – Air Temperatures of Various Cold Occupational Environments**

Air Temp °C	
-90	Lowest temperature at south pole base - Vostock
-55	Cold store for fish meat and production of frozen, dried products
-40	"Normal" temperature at polar base
-28	Cold store for frozen products
-50 to -20	Average January temperature of northern Canada and Siberia
-20 to -10	Average January temperature of southern Canada, northern Scandinavia & central Russia
-10 to 0	Average January temperature of northern USA, southern Scandinavia, central Europe, parts of middle and far East, Central and northern Japan

The first effects of excessive heat strain due to cold environments is pain, then numbness of the extremities especially the fingers and toes. This is due to the body shunting warm blood to the core of the body, away from the non-vital areas such as the hands, feet, nose, cheeks and ears.

The effects include:

- Frostbite
- Trenchfoot

- Hypothermia
  - Mild
  - Moderate
  - Severe

- **Frostbite**

Frostbite is the medical condition whereby damage is caused to the skin and other tissues due to extreme cold. At or below 0°C core temperature may be reduced and blood vessels close to the skin start to narrow (constrict) thus helping to preserve the core body temperature. In extreme cold or when the body is exposed to cold for long periods and core temperature reduced, this protective strategy can reduce blood flow in some areas of the body to dangerously low levels. The combination of cold temperatures and poor blood flow can cause severe tissue injury by freezing the tissue.

Frostbite is most likely to occur in body parts farthest from the heart and in those with a lot of surface area exposed to cold. The initial stages are sometimes referred to as “frostnip”, some people can feel these, some not.

Generally frostbite is accompanied by discoloration of the skin, along with burning and/or tingling sensations, partial or complete numbness and possibly intense pain. If the nerves and blood vessels have been severely damaged, gangrene may follow and amputation may eventually be required. If left untreated, frostbitten skin gradually darkens after a few hours. Skin destroyed by frostbite is completely black and looks loose and flayed, as if burnt.



(Source: BP International Ltd)

**Figure 4.1 – Example of Early Stages of Frostbite of the Extremities**

- **Trenchfoot**

Trenchfoot or immersion foot as it is now referred to is a medical condition caused by prolonged exposure of the feet to damp and cold. It was a particular problem for soldiers engaged in trench warfare during the winter months of World War I, World War II and also during the Vietnam conflict.

Trenchfoot occurs when feet are cold and damp while wearing constricting footwear. Unlike frostbite, immersion foot does not require freezing temperatures and can occur in temperatures up to 16°C. Immersion foot can occur with only twelve hours of exposure. When affected by immersion foot, the feet become numb, followed by a change in colour to red or blue. As the condition worsens, the feet may swell. Advanced immersion foot often involves blisters and open sores, which lead to fungal infections. In such cases immersion foot can be referred to as "jungle rot". If left untreated, immersion foot usually results in gangrene, which can require amputation. If treated properly and quickly, complete recovery is normal, but recovery is marked by severe short-term pain as feeling returns. Like other cold injuries, those who experience immersion foot are more susceptible to it in the future.

Immersion foot is easily prevented by keeping the feet warm and dry, and changing socks frequently when the feet cannot be kept dry. British

soldiers in World War I were advised to keep multiple pairs of clean socks on hand, and change them at least three times daily. During World War I, soldiers were provided with whale grease and told to apply it to their feet as part of a bid to reduce the prevalence of this condition in the trenches. The idea was to make the feet waterproof. It was also discovered that a key measure was regular foot inspections by officers.

Trenchfoot made an unwelcome reappearance in the British Army during the Falklands War in 1982. The causes were the cold wet conditions and the type of boot worn by soldiers which was insufficiently waterproof. Large numbers of soldiers were incapacitated by the condition and it was rumoured that had the war not ended when it did the British advance would have ground to a halt.

- **Hypothermia**

Hypothermia refers to any condition in which the temperature of a body drops below the level required for normal metabolism and/or bodily function to take place. In warm-blooded animals, core body temperature is maintained at or near a constant level through biologic homeostasis. When the body is exposed to colder temperatures, however, its internal mechanisms may be unable to replenish the heat that is being lost to the body's surroundings.

Hypothermia is the opposite of hyperthermia. Because the words sound alike, they are easily confused.

Signs and symptoms of hypothermia

- Mild hypothermia 36.5 – 32 °C
  - Shivering
  - Lack of coordination, stumbling, fumbling hands
  - Slurred speech
  - Memory loss
  - Pale, cold skin
- Moderate hypothermia 32 – 30°C

Shivering stops  
 Unable to walk or stand  
 Confused or irrational

- Severe hypothermia 30 – 25.5°C  
 Severe muscle stiffness  
 Very sleepy or unconscious  
 Ice cold skin  
 Death

Some authors (Dembert 1982) have provided more defined criteria at various temperatures including:

30 – 29°C	Progressive loss of consciousness, muscular rigidity increases, respiratory rate decreases
27°C	Voluntary motion ceases
24°C	Pulmonary oedema
20°C	Cardiac standstill

What should be understood is that the above is not applicable to all individuals and a case of a hypothermia victim with a core temperature of 18°C is reported in the literature as recovering. This is a rare event and core temperatures in the range 30°C – 25.5°C are fatal in the majority of cases.

### **4.3 PREDISPOSING FACTORS**

The effects and severity of heat strain on individuals depends naturally enough on the physiological capacity of the individual and these personal factors include age; gender; general health (including medical conditions, weight and general fitness etc); state of hydration; alcohol, caffeine and diet; nicotine use; medications and non prescription drugs; acclimatisation and protective clothing and other protective equipment.



- **Age**

Age as such is not necessarily the important feature when assessing a persons' susceptibility to heat strain. The physical condition of a person rather than the debilitations often and typically associated with age is more significant. As we all know there are some people in a higher age group who are a lot "fitter" or capable of withstanding a heat stress situation than some members of a much younger age grouping.

Individuals of any age who have suffered peripheral nerve injuries may also have reduced sweating ability and reduced vasomotor control.

As people get older, the personal factors of general good health and level of physical fitness are more important than simply age itself. A reasonable expectation for someone who has normal cardiovascular, respiratory and sweating reflexes and who is in general good health, and is fully hydrated will be no more endangered by heat stress than anyone else.

Some physical disabilities associated with ageing can reduce a persons' response to heat stress. Anything that affects the circulatory system and its ability to distribute heat in the body and bring it to the surface of the skin, as do compromised abilities to maintain full hydration. Chronic illnesses that reduce cardiac output or reduce circulating blood volume are also adverse effects when coping with heat stress.

- **Gender**

Research has demonstrated (AIHA 2003) that in matched (cardiorespiratory fitness levels) groups there was no difference in the tolerance levels of males and females.

In contrast, it appears that for very low work rates, such as inspection or supervision tasks, gender differences in cold tolerance should be considered and the female worker offered additional protection. For work rates eliciting substantial amounts of metabolic heat production, gender

responses are somewhat different, but the net effect is a similar overall response, regardless of gender.

- **General Health**

Some medical conditions can contribute to the risk of developing heat related illness. Examples include past episodes of heat related illness, chronic cardiovascular disease, diabetes and skin disorders.

If a person has experienced heat related illness in the past, they are at higher risk for developing it again. Cardiovascular conditions and diabetes affect blood flow; skin conditions such as sunburn and psoriasis can inhibit the body's ability to cool itself by sweating.

Having excess body fat affects the body's ability to cool itself in two ways. Firstly, body fat is a good thermal insulator. It is not as heavily perfused with blood as are other tissues and has comparatively low density. Skin has a thermal conductivity of about 95% and muscle about 86% when compared to water, while fat heat conduction is at about 36%. While this insulation is an advantage in cold stress it is a disadvantage during heat stress.

Besides providing thermal insulation, fat is also heavy and requires a greater expenditure of energy by a person to move around. Typically people who are obese are not in ideal physical condition and often demonstrate comparatively higher heart rates during exercise and physical work. It is this extra effort that muscles must make generates more internal heat that must be removed.

Also, excess body fat can result from an inactive lifestyle, which lowers the general level of work that will cause a person to be out of breath and makes it harder to get use to hot conditions.

Lack of sleep and fatigue also affects how the body cools itself, since one of the things that happens during sleep is that the brain resets the point

at which your body's cooling mechanisms (blood vessels widening, skin sweating etc) start to work. Without proper sleep and rest, these cooling mechanisms don't start working when they should, which allow too much heat to build up in the body.

It is again necessary to reiterate the importance of assessing each person's unique characteristics when trying to evaluate job safety and comfort in a situation where heat stress is likely to be encountered.

- **State of Hydration**

Ensuring a worker maintains an adequate level of hydration is essential when working in conditions of heat stress. It has been shown (Brake 2001) that workers typically only replace one half of the water they are losing as sweat (a physiological phenomenon called "voluntary dehydration"), unless they are "programme drinking", i.e. stopping typically every 15 minutes to drink 250 ml of water. Waiting an hour or more and then attempting to drink a litre of cold water, when very thermally stressed, is likely to lead to nausea, vomiting or headache.

It has also been found that, once dehydrated by more than about 2%, it is difficult to rehydrate merely by drinking water. This emphasises the importance of not becoming dehydrated in the first place.

Workers should carry personal containers of perhaps 4 litres and a supply of cool drinking water should be available so individuals can replenish their personal containers.

Water/fluids should not be drunk ice cold; a temperature of 10 to 12°C is suggested. Although it could be assumed that this would cool the body faster, the stomach is not part of the body core and the cold has the effect of constricting the stomach. As a result, flow to the intestines from where the fluid is absorbed is reduced and rehydration delayed.

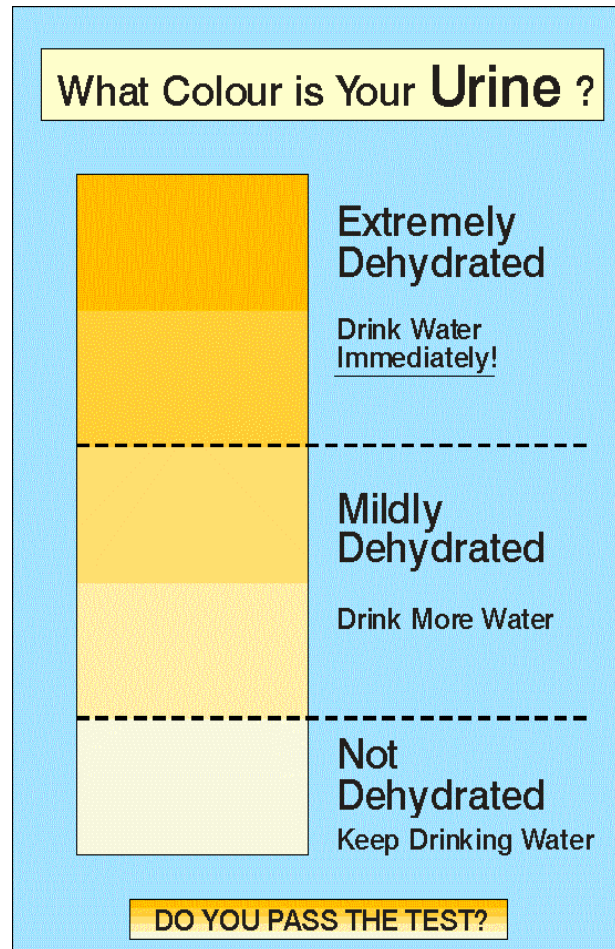
Hydration status is generally estimated from urinary specific gravity although it may be in error where the subject is experiencing diuresis due to alcohol intake, or is taking vitamin supplements or some drugs. A study of underground miners (Brake 2001) considered a euhydrated (properly hydrated) state to be a urinary specific gravity (SG)  $\leq 1.015$ , while a urinary SG  $> 1.030$  was considered to be clinically dehydrated. In that study a value of 1.022 was an arbitrary value selected approximately half-way between a euhydrated (1.015) and dehydrated (1.030) states to provide a suitable “buffer” to ensure that workers who are “nearly” clinically dehydrated were not exposed to heat stress until rehydrated.

The National Trainers Association in the U.S. have indicated that a urine specific gravity of greater than 1.020 would indicate dehydration of the individual as indicated in table 4.2.

**Table 4.2 National Athletic Trainers Association  
index of hydration status** (adapted from Casa *et al* (2000))

	Body Weight Loss (%)	Urine Specific Gravity
Well Hydrated	<1	1.010
Minimal dehydration	1 - 3	1.010 – 1.020
Significant dehydration	3 - 5	1.021 – 1.030
Severe dehydration	> 5	> 1.030

Charts have been developed to qualitatively assess hydration status by urinary colour. These are effective but caution must be exercised as some drugs and vitamin supplements can change urine colour (Figure 4.2).



(Source: BHP Billiton – reproduced with permission)

**Figure 4.2 – Urine Guidance Chart**

- **Alcohol and Diet**

The consumption of alcohol prior to or even the night before undertaking hot work should be discouraged. Alcohol is a diuretic and hence increases urine output and therefore fluid loss, significantly contributing to dehydration. Carbonated drinks may cause bloating and thus prematurely induce a sensation of satiety and hence inhibit water replacement.

The consumption of a high protein meal can place additional demands on the body's water reserves, as some water will be lost in excreting nitrogenous waste. High fat foods take longer to digest, diverting blood supply from the skin to the gut, thus reducing cooling potential.

- **Caffeine**

Caffeine is present in a range of beverages and is readily absorbed by the body, with blood levels peaking within 20 minutes of ingestion. One of the effects of caffeinated beverages is that they may have a diuretic effect in some individuals (Pearce, 1996); particularly when ingested at rest. Thus, increased fluid loss resulting from the consumption of caffeinated products could possibly lead to dehydration and hinder rehydration before and after work (Armstrong et al, 1985; Graham et al, 1998; Armstrong, 2002). There have been a number of recent studies (Roti et al, 2006; Armstrong et al, 2007; Hoffman, 2010, Kenefick & Sawka, 2007) that suggest this may not always be the circumstance when exercising. In these studies, moderate chronic caffeine intake did not alter fluid-electrolyte parameters during exercise or negatively impact on the ability to perform exercise in the heat (Roti, 2006; Armstrong et al, 2007) and in fact added to the overall fluid uptake of the individual. There may also be inter-individual variability depending on physiology and concentrations consumed. As well as the effect on fluid levels, it should also be noted that excessive caffeine intake can result in nervousness, insomnia, gastrointestinal upset, tremors and tachycardia (Reissig et al, 2009) in some individuals".(AIOH, 2013)

- **Nicotine Use**

Using nicotine tightens your blood vessels so the blood vessels in the skin cannot widen to let heated blood reach the surface to release heat and thus may make you more susceptible to heat related illness.

- **Medications**

If prescriptions or over the counter drugs are being taken it should be confirmed with a medical practitioner that they do not affect the body's ability to regulate temperature. Some medications are known to do this with some common ones being diuretics (increases urination and can

compound dehydration), tranquilisers, antidepressants and antihistamines. This is by no means a comprehensive list and specialist advice from an occupational physician should be sought for more detailed guidance.

- **Acclimatisation**

An acclimatisation period is recommended for new workers or those onsite from cooler climates such as during maintenance and shutdowns. Acclimatisation is a physiological adaptation which occurs with repeated exposure to hot environments. The heart rate decreases, sweating increases, salt levels of sweat become more dilute, and body temperature will be lower. The ability to acclimatise varies among workers. Generally, individuals in good physical condition acclimatise more rapidly than those in poor condition.

Approximately one week of gradually increasing the workload and time spent in the hot environment will usually lead to full acclimatisation. Acclimatisation is lost when exposure to hot environments does not occur for several days.

After a one week absence, a worker needs to reacclimatise by following a schedule similar to that for initial acclimatisation. The acclimatisation occurs more rapidly, reaching normal work conditions by day four.

- **Protective Clothing and Other Protective Equipment**

Protective clothing for performing hazardous jobs, such as encapsulating suits, impede sweat evaporation and heat loss and significantly increase the risk of heat illness. The effect increases from liquid/vapour/air permeable fabrics to liquid/vapour impermeable fabrics (cotton to Tyvek). The advantage of a vapour permeable/liquid impermeable fabric such as Gortex may be lost at high metabolic load when a lot of sweat is produced. With liquid/vapour impermeable fabrics a microclimate may be set up between the skin and the fabric, whereby the sweat evaporates

from the skin and condenses on the inner surface of the fabric. These conditions preclude the use of environmental monitoring indices and demand a health assessment for job fitness and physiological monitoring.

It is important to ensure that sweat can be evaporated off the skin to obtain the maximum cooling effect. Hence, slightly loose fitting clothing allows for good ventilation and air circulation. A pumping and/or thermal gradient effect, whereby air is moved into and out of the space between the skin and the clothes is known to improve the sweat evaporation. This phenomenon is demonstrated by the robes of the Bedouins in the Sinai deserts (Shkolnik et al 1980)

Where personal protective equipment (PPE) such as a breathing apparatus harness, fall protection harness or belt is worn over clothes the pumping effect is prevented. Caution must be exercised with loose clothing if working near machinery.

Where there are high radiant heat loads, insulation will play an important role in the clothing factor. The best type of clothing will be a natural fibre such as cotton drill which will provide insulation and some protection from contact burns. However, the higher the insulation factor, the more difficult it will be for the body to dissipate heat.

Respirators may restrict breathing while air supplied respirators may alter the temperature of air breathed. The loading of the PPE depends on whether the worker is active or sedentary. The need to work in hot environments should be considered when assessing a worker's ability to wear respiratory protection.



## 5. THERMAL SURVEYS

### 5.1 MEASUREMENT EQUIPMENT

#### 5.1.1 Air Temperature

Comment on the weather is an acceptable opening to any polite conversation and it is interesting to observe that such comment is often accompanied with a comparison of the temperature to the day before or the time of the year.

It was the beginning of the 17<sup>th</sup> century when a primitive type of air thermometer was thought to be introduced by Galileo. In about the year 1714 Fahrenheit devised the first satisfactory thermometric scale and it was about 30 years later before the introduction of the Centigrade scale by Celsius.

Parsons (2003) defines air temperature as:

*“The temperature of the air surrounding the human body which is representative of that aspect of the surroundings which determines heat flow between the human body and the air.”*

Air temperature is important in any assessment of thermal stress as it affects the convection heat transfer from an individual.

Measurement of air temperature is usually made with one of the following techniques:

- Mercury-in-glass thermometer
- Thermocouple
- Platinum resistance thermometer
- Thermistor

The accuracy of these techniques varies, ranging from  $\pm 0.1^{\circ}\text{C}$  for a calibrated mercury-in-glass thermometer to  $\pm 2^{\circ}\text{C}$  for a thermocouple.

Irrespective of what technique is used, it is important to establish a calibration with temperature change as no technique is truly linear with temperature change. This is especially the case with thermistors, where electronic instrumentation must be matched to specific thermistors.

When using a thermometer care must be taken to prevent the thermometer from being affected by radiation from heat sources. This can be achieved by:

- Reducing the emissivity of the sensor (ie make it silver), use of a polished metal sensor.
- Shielding the sensor from heat sources, eg by placing a polished metal tube or film around the sensor – the shield should be separated from the sensor by an air space large enough to allow air to circulate.
- Increasing the air velocity around the sensor by forced ventilation.

### 5.1.2 Radiant Temperature

Two radiant temperatures are commonly used to summarise the radiant heat exchange between the human body and the environment. These are:

- Mean radiant temperature ( $t_r$ ) – overall average value.
- Plane radiant temperature ( $t_{pr}$ ) – gives variations in direction of the mean radiant temperature.

Thus the mean radiant temperature is defined (Parsons 2003) as:

“The temperature of a uniform enclosure with which a small black sphere at the test point would have the same radiation exchange as it does with the real environment.”

ISO 7726 (1998) defines plane radiant temperature as:

“The uniform temperature of an enclosure where the radiance on one side of a small plane element is the same as in the non-uniform actual environment.”

Measurement of the mean radiant temperature can be derived from the readings of a black globe thermometer. This consists of a hollow black globe usually made of copper (due to its high conductivity) in the centre of which is placed a temperature sensor (Figure 5.1).



(Source: BP International Ltd)

**Figure 5.1 – Typical Black Globe Thermometer**

In theory the globe can have any diameter, however a diameter of 150 mm is generally recommended as the use of small globes can lead to large errors in estimates of mean radiant temperature.

The standard 150 mm black copper globe takes about 20 minutes to reach equilibrium but this can be reduced by increasing air movement within the globe and using thermocouples instead of mercury-in-glass thermometers. Because of its high inertia, the black globe thermometer cannot be used to determine the radiant temperature of environments that vary rapidly.

Mean radiant temperature can be calculated using the following equations:

a) For natural convection (ie  $v \leq 0.15 \text{ ms}^{-1}$ )

$$t_r = \left[ (t_g + 273)^4 + \frac{0.25 \times 10^8}{\epsilon} \left( \frac{t_g - t_a}{d} \right)^{\frac{1}{4}} \times (t_g - t_a) \right]^{0.25} - 273$$

b) For forced convection (ie  $v > 0.15 \text{ ms}^{-1}$ )

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

Where:  $t_r$  = Mean radiant temperature ( $^{\circ}\text{C}$ )  
 $t_a$  = Air temperature ( $^{\circ}\text{C}$ )  
 $t_g$  = Globe temperature ( $^{\circ}\text{C}$ )  
 $v$  = Air velocity ( $\text{ms}^{-1}$ )  
 $\varepsilon$  = Emissivity of black globe  
 $D$  = Diameter of sensor (m)

For a standard globe of 150 mm, values of  $\varepsilon = 0.95$  and  $d = 0.15 \text{ m}$  may be used.

Measurement of plane radiant temperature can be accomplished by the use of a “net” radiometer. Plane radiant temperature measurements are rarely used in workplace assessments.

### 5.1.3 Humidity

The absolute humidity is defined as the mass of water vapour in air per unit volume of air/water vapour mixture and has units of  $\text{kg m}^{-3}$ .

If sweat is heated by the body and evaporates to a vapour and is lost (i.e. evaporated) to the surrounding environment, then heat has been transferred from the body to the environment with a resultant cooling of the body.

The process for this transfer is the difference in absolute humidity between that at the skin surface and that in the environment. For convenience, the driving force for this process is considered to be the difference in the partial vapour pressures between that at the skin and that in the environment.

The humidity of the environment can be expressed in a number of forms with relative humidity, partial vapour pressure and dew point being the most commonly used.

The partial pressure approach can be described mathematically as:

$$\text{Absolute humidity} = 2.17 \frac{P_a}{T}$$

Where:  $P_a$  = Partial vapour pressure (kPa)

$T$  = Temperature ( $^{\circ}\text{K}$ )

Relative humidity is defined as:

“The ratio of the prevailing partial pressure of water vapour to the saturated water vapour pressure.”

This is represented mathematically as:

$$\phi = \frac{P_a}{P_{sa}} = \text{RH (where expressed as a \%)}$$

The “dew point” is the temperature at which the air becomes saturated.

One of the most commonly used instruments for determining humidity is the whirling hygrometer, which is also called a sling psychrometer (Figure 5.2).



(Source: University of Wollongong)

**Figure 5.2 – Typical Sling Psychrometer**

Its operation is relatively simple. The sling psychrometer consists of two thermometers, a wet bulb and dry bulb. A “wick” or “sock” covers one of the thermometers (the “wet” bulb) and should be thoroughly wetted using distilled (de-ionised) water prior to taking any measurements. This involves filling the water reservoir at the end of the psychrometer and may also involve manually wetting the wick. Care should be taken not to contaminate the wick with dirty fingers or water that is not de-ionised.

Some precautions are as follows:

- The wet thermometer should be ventilated at least 4 m/s to 5 m/s.
- The wick on the thermometer should extend beyond the sensitive part of the thermometer (i.e. bulb) to avoid conductance from the non-sensitive section.
- The water wetting the wick should be distilled water as the water vapour pressure is less for water containing salts.
- The wick should not be soiled as this can affect the capillary action and the evaporation process particularly in low humidity environments.

The handle is then unclipped and the psychrometer is swung for at least 20 – 30 seconds. This will allow an air movement to pass over the wet bulb

thermometer and initiate evaporation of water from the wick. After 20 – 30 seconds, the aspirated wet bulb temperature is read first (then the dry bulb temperature). These values are noted and the measurements repeated three times. Optimally, the repeated measurements should be within  $\pm 1^\circ\text{C}$  of each other.

Obviously, at 100% relative humidity there will be no depression of the aspirated wet bulb temperature.

From the dry bulb and aspirated wet bulb temperature it is possible to calculate the partial vapour pressure ( $P_a$ ), relative humidity (RH) and dew point ( $t_{dp}$ ).

$$P_a = P_{swb} - 0.667 (t_a - t_{wb})$$

$$RH = \frac{P_a}{P_{sa}} \times \frac{100}{1}$$

$$t_{dp} = \frac{4030.18}{18.956 - \ln P_a} - 235$$

Where:  $t_a$  = Air temperature  $^\circ\text{C}$

$t_{wb}$  = Wet bulb temperature  $^\circ\text{C}$

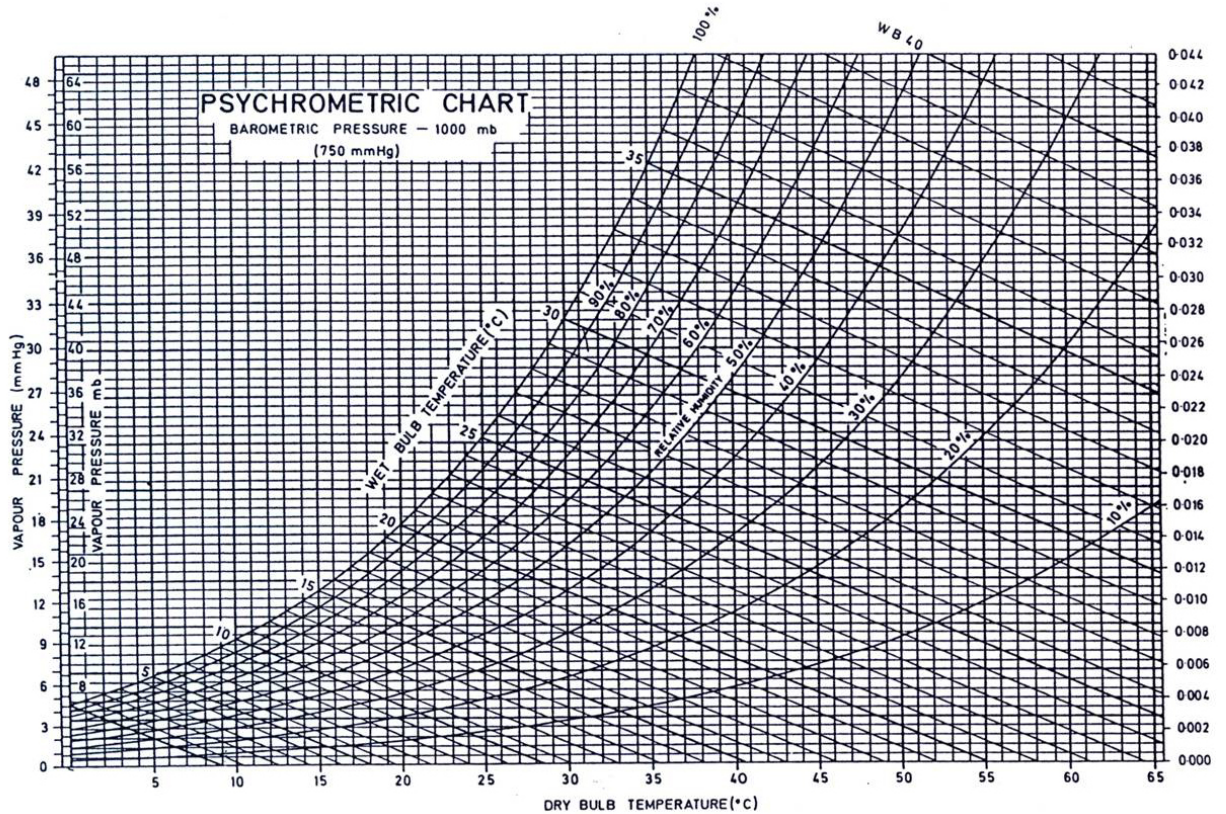
$P_{swb}$  = Saturated water vapour pressure at the wet bulb temperature (mb)

$P_{sa}$  = Saturated water vapour pressure at the dry bulb temperature (mb)

A simpler approach is to use the psychrometric chart supplied with the instrument (Figure 5.3) to calculate the relative humidity. The use of this chart will be demonstrated during the practical session.



Some sling psychrometers have a calibrated scale on their side and it is just a matter of matching the dry and wet bulb temperature to be able to read off the % relative humidity.



(Source: BJIM, 1972, Vol.29, Page 363 – reproduced with permission from the BMJ Publishing Group)

**Figure 5.3 – Relative Humidity Psychrometric Chart**

#### 5.1.4 Air Movement

Air movement across the body can influence heat flow to and from the body and hence body temperature. Any air movement will vary in time space and direction and thus air velocity is usually considered to be the “mean” air velocity over the body integrated over all directions and over an exposure time of interest.

The characteristics of air velocity measuring instruments should be such that they have a measuring range of  $0.1 - 5.0 \text{ ms}^{-1}$  for thermal stress evaluations or  $0.05 - 1.0 \text{ ms}^{-1}$  for thermal comfort evaluations. A major requirement is that the velocity sensor be omni-directional and should have an accuracy of



$\pm 0.05 \text{ ms}^{-1}$  (thermal comfort) or  $\pm 0.1 \text{ ms}^{-1}$  (thermal stress). The 90% response time should be as short as possible but no greater than 1 second.

Air velocity can be measured by a number of methods eg Hot-wire Anemometer (Figure 5.4), Vane Anemometer (Figure 5.5) and a Kata Thermometer (Figure 5.6).



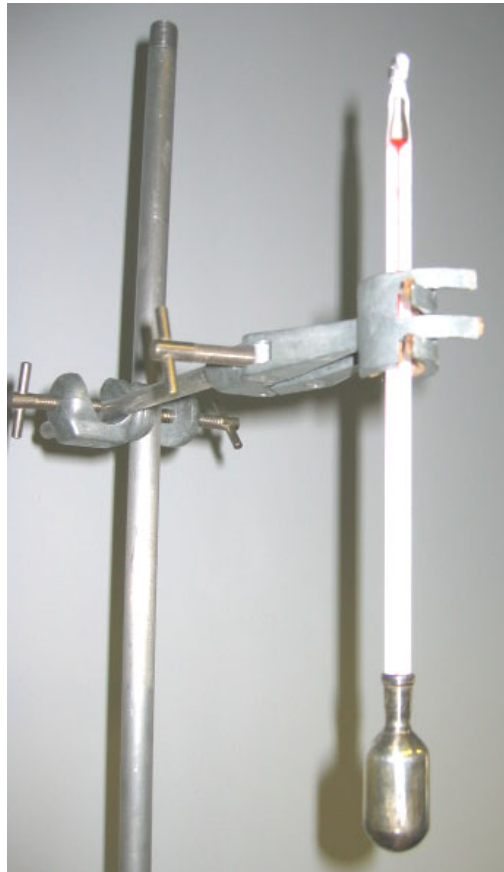
(Source: University of Wollongong)

**Figure 5.4 – Hot-wire Anemometer**



(Source: University of Wollongong)

**Figure 5.5 – Vane Anemometer**



(Source: BP International Limited)

**Figure 5.6 – Kata Thermometer**

The hot-wire anemometer works by an electrical current heating the sensor to a temperature above ambient and being cooled by air movement: the amount of cooling is dependent on the air velocity, the ambient air temperature and the characteristics of the heat element. These devices are directional and can be inaccurate in low air velocities due to natural convection of the hot wire.

The rotating vane anemometer consists of a number of blades that are configured to allow the air movement to rotate them in one direction. The number of rotations are then counted over a period of time (usually 1 minute) and converted to air velocity. These devices are not accurate at low air velocities, are not omni-directional and cannot be used where the direction of airflow is variable, hence have limited value in thermal stress evaluations.

To determine the air velocity associated with heat, the best device (although not the most practical in the field!) is the Kata thermometer. Its advantages are that it responds to many directions of airflow and it measures air velocity of a period of time.

The Kata thermometer (Figure 5.6) consists of a silvered bulb that has two levels marked on the thermometer, corresponding to a temperature drop of 3°C.

In operation, the thermometer is heated to above the temperature of the upper graduation, wiped dry and allowed to cool while still clamped in place. The time taken to cool over the marked temperature interval is measured. Air velocity may then be derived by formula or nomogram from three known quantities, ie the cooling time, the dry bulb temperature of the air, and a calibration factor for the particular Kata thermometer which represents the heat loss per unit surface area, as the thermometer cools.

The Kata thermometer has a long response time and hence averages air movement values over the measurement period. It is not suitable for detailed measurements of environments where large or rapid variations in air movement occur, not for determining turbulence intensity.

The Kata thermometer is rarely used for field measurements due to its fragile nature but remains in legislation in some parts of the world.

One other device that has been developed is the hot-sphere anemometer. This device uses a similar principle to the hot-wire anemometer but has design features to produce an omni-directional instrument.

### **5.1.5 Composite and Integrating Meters**

The development to modern day instrumentation can be attributed in part to Thomas Bedford who in 1940 recommended the introduction of a “measurement kit” into all British naval ships to monitor human performance below decks.

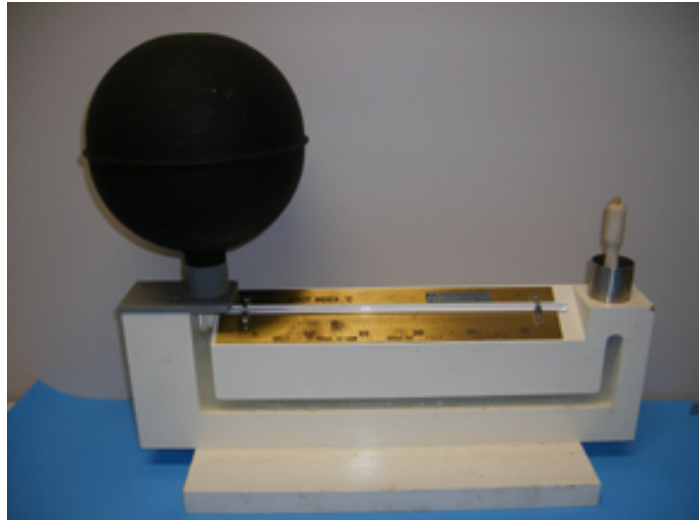
This became known as the “Admiralty Box” and consisted of a whirling hygrometer, Kata thermometer, globe thermometer, stop watch, vacuum flask and appropriate charts.

Over the intervening years other instrumentation has been developed, such as the “Indoor Climate Analyser” which was designed to satisfy the requirements of ISO 7726 (1985).

Perhaps the area of most rapid and sophisticated instrumentation development has been with units designed to measure thermal parameters and compute indices such as “Wet Bulb Globe Temperature” (WBGT) Thermal work limit (TWL) and Predicted heat strain (PHS).

These devices typically have the three normal sensors (dry bulb, wet bulb and globe bulb) in basic models but most modern instruments also have the ability to measure relative humidity and air velocity. In order to minimise the size of the instrument 40 mm globes are used (instead of the 150 mm) and thus a correction for globe size should be made. In practice however this correction is typically small and generally ignored.

Figure 5.7 shows a precursor to modern day instrumentation developed by Dobbie Instruments in the 1960's to measure WBGT.



(Source: University of Wollongong)

**Figure 5.7 – Dobbie Instruments Heat Stress Monitor**

Figure 5.8 shows a modern unit capable of measuring the required parameters of dry bulb, wet bulb and globe temperature plus relative humidity and velocity.



(Source: 3M – reproduced with permission)

**Figure 5.8 – Thermal Environment Monitor**

This device has the capacity to measure and store the following information:

- Dry bulb temperature
- Wet bulb temperature

- Globe temperature
- Relative humidity
- Air velocity
- Indoor WBGT index
- Outdoor WBGT index
- Head-Torso-Ankle weighted average WBGT (when multiple stage sensors are used)
- Stay time data
- Real time clock
- Overall summary data
- Detailed time history data

all of which can be downloaded into a software programme for display and model development.

Like all instrumentation, such devices provide information which is no better than its calibration value and thus the accuracy of such instrumentation should always be checked prior to use.

#### **5.1.6 Personal Monitoring**

Where workers are exposed to hot or cold environments, especially when wearing protective clothing and equipment, a method of assessing the level of risk may be for them to wear individual physiological monitoring devices.

These devices do not measure the environmental conditions leading to heat stress but rather the physiological indicators of heat strain. The usual factors monitored are body temperature and heart rate and sometimes skin temperature (particularly on hands and feet in the cold).

A number of issues need to be understood when using such devices. The method of core body temperature measurement (most measure skin temperature and calculate core temperature) needs to be known and the accuracy, sensitivity and reliability of the instrument understood.

More importantly, the interpretation of the data produced needs to be undertaken with significant care.

Notwithstanding the above issues, such devices offer a lightweight real time assessment of heat strain and most are fitted with data logging capabilities and audible alarms. One such device is provided in Figure 5.9. This device utilises an ingestible sensor in a capsule. The sensor transmits the individual's physiological parameters to an external receiver such as a data logger or laptop computer.

Interpretation of this data requires someone technically competent in this field of expertise.



(Source – Equivital UK – reproduced with permission)

**Figure 5.9 – Typical Personal Monitor**

## **5.2 SURVEYS**

### **5.2.1 Data Collection**

In any workplace situation many factors can impact on the thermal stress associated with a particular activity or environment. It is not possible to assess

such a situation using one single factor nor should reliance to assess such a workplace be placed on a sole index without due assessment of the individual situation.

The basic data required for any assessment of the thermal environment involves collection of data on the following six parameters. These are:

- Air temperature
- Mean radiant temperature
- Humidity
- Air movement
- Metabolic work rate
- Clothing

Not all six of these parameters may be required in an assessment as this will depend on the nature of the assessment and the index being used. Just measuring the above parameters on the other hand may not give the full picture of the thermal environment and a more detailed assessment may require information on factors such as:

- Air temperature gradients
- Surface temperature measurements
- Plane radiant temperature
- Local air movement
- Changing humidity conditions
- Variations in clothing and activity
- Physiological measurements

Other factors that may need to be collected (if possible) at the survey stage for inclusion in the assessment process include:

- Exposure period
- Confined space work requirements
- Task complexity
- Distance to rest area



- Distance to drinking water (heat stress conditions)
- Respiratory protection (negative pressure)
- Medication being used by workers
- Chronic medical conditions
- Acute infections
- Acclimatisation level
- Obesity
- Age
- Fitness
- Consumption of alcohol in last 24 hours

As with all data collection it is important that it is accurate and representative of the workplace situation. All instrumentation should be correctly calibrated and the results should not be distorted by the actions of the person collecting the data (eg through inadvertent shielding of sensors, etc).

### **5.2.2 Monitoring Strategies**

While there has been considerable evaluation of the various indexes available, a similar effort has not been expended in establishing the best workplace monitoring strategy. One reason for this is the wide variability in situations and conditions that are likely to be experienced, making standardisation difficult.

Notwithstanding this, a number of approaches are worthy of inclusion.

In the OSHA Technical Manual (1995) guidance is provided to compliance officers as to how they should evaluate a workplace following heat stress complaints. The steps suggested are:

- *Employer and Employee Interviews* – Establish the extent of the problem and what action has been taken to minimise the issue.

- *Walkaround Inspection* – To determine building and operation characteristics, identify potential sources of heat stress, determine if controls are operational.
- *Workload Assessment* – Establish the workload category (light, medium or heavy work) of each job.
- *Sampling* – Environmental heat measurements should be made as close as possible to the specific work area where the worker(s) is exposed. If a worker moves from one area to another of differing environmental conditions both work areas should be evaluated.

This information plus that obtained during interviews and the walkaround inspection is used to come to a conclusion as to the validity of the complaint. While the above approach may suit the role of an inspector, it does not provide the best overall assessment of a workplace.

Malchaire et al (1999) presented a structured protocol involving four successive stages. These are:

- *First Stage* – The majority of the risk factors have to be detected to get a first overview of the working conditions. This first stage involves the use of a “screening” method to cover the majority of factors related to safety, health and wellbeing.
- *Second Stage* – Consists of looking more closely at the climatic and working conditions over the entire year and/or any circumstances to search for straightforward solutions. This requires an “observation” method and clearly involves those involved with the working conditions.
- *Third Stage* – After the completion of Stages 1 & 2 well identified working conditions will be identified which require evaluation. This “analysis” phase will be targeted and performed by trained personnel.

- *Fourth Stage* – In situations that cannot be evaluated or resolved by Stage 3, further “expertise” may be required to fully understand the complexity of the situation.

This is a much more structured approach to that of the OSHA manual and has more relevance to the evaluation of workplace environments.

The Australian Institute of Occupational Hygienists (AIOH 2013) has adopted a similar approach to Malchaire et al (1999) and suggests the following three stage strategy:

1. A basic heat stress risk assessment incorporating a simple index (eg WBGT, BET, Apparent Temperature, etc).
2. If a potential problem is indicated from the initial step, then progress to a second level rational index to make a more comprehensive investigation of the situation and general environment. Ensure factors such as temperature, radiant heat load, air velocity, humidity, clothing, metabolic load, posture and acclimatisation are taken into account.
3. Where the calculated allowable exposure time is less than 30 minutes or there is an involvement of high-level personal protective equipment, then employ some form of physiological monitoring.

This approach is discussed in greater detail in Section 11.1.

Another strategy is that adopted by the South African Department of Minerals and Energy in their South African Mines Occupational Hygiene Programme Codebook (2002). This document details the mandatory requirements for an occupational health programme specific to thermal stress.

Under this code of practice the operator of a mine must categorise the thermal environment and suggests the following steps in relation to heat stress.

Step 1      Subdivide the mine into measurement areas

- Step 2     Subdivide the measurement areas into activity areas.
- Step 3     Evaluate the risk assessment undertaken.
- Step 4     Subject the data to an elementary but statistical analysis in order to categorise each defined activity area with a degree of confidence commensurate with the risk.
- Step 5     (optional) Depending on specific circumstances, needs or operations, mines may opt to implement heat stress management in terms of a heat stress index.

Other requirements are that monitoring be conducted on an annual basis and that accurate and meaningful results which are representative of all full working shifts for a specific thermal environment are obtained and documented. This approach is very complex and time-consuming, which may influence the degree to which it is implemented and administered.

While the above strategies are divergent in their approach, they all rely on the collection of accurate reliable data that is a true representation of working conditions. Any monitoring strategy that does not achieve this basic requirement is fatally flawed and of little value.

## **5.3           ASSESSMENT OF THE DEGREE OF RISK**

### **5.3.1       Introduction**

The primary object of monitoring any workplace is to collect data so as to establish the level of risk to human health and control it.

In terms of the thermal environment there is the aim of determining if the working environment is acceptable and if not whether workers are likely to suffer from discomfort or from the more serious effects of heat or cold stress.

If the thermal environment is shown to be unacceptable it is then necessary to identify the reason(s) so that remedial action can be taken.

In order to achieve the outcomes indicated above, there is a need to analyse the collected data in an appropriate manner so that it can be readily interpreted and appropriate actions taken.

### **5.3.2 Recording of Results**

Results from any monitoring exercise should be recorded clearly and precisely together with sufficient background information and description of the activity or process to enable interpretation. The form of data documentation will depend on the type of survey, type of issue being evaluated, nature of data collected and the type of instrumentation used.

Where possible the use of a spreadsheet format should be considered as this allows data to be appraised equally and easily and ensures none are omitted. Where appropriate, diagrams of the building or process showing where readings were taken should be attached to the data.

It is also important to note prevailing weather conditions at the time of the survey as these may be a factor in the overall assessment.

Also, if data is collected on “loggers” it should be converted to a common file type (eg Excel), clearly identified and retained.

### **5.3.3 Assessment of Risk**

Once all the collected data is available it can be analysed to determine the level of risk. The first step in this process is the selection of a suitable stress or comfort index which takes into account all relevant risk factors. These will include the measured environment, work rate, clothing and the physiological condition of the workers being assessed.

In practice, the choice of the assessment index usually comes before the data collection process so that you ensure that the required data is collected during the monitoring survey. Such judgements are influenced by the prevailing

conditions and the level of experience of the person conducting the monitoring survey. In general, there are six key measures that should be recorded, which will enable the utilisation of a large variety of assessment tools, these include:

- Dry bulb temperature
- Globe temperature
- Relative humidity
- Air velocity
- Metabolic load, and
- Clothing

Irrespective of when the assessment index is chosen, it should be related to an acceptable standard which has been validated by field trials. A number of these indices are detailed in the various International Standards (eg ISO 7730, ISO 7243), however some statutory authorities use indices that are relevant to local or industry conditions.

The AIHA (2003) provides two examples (one hot and one cold) of how workplaces should be evaluated. A simplified approach is provided below.

- *Preliminary Review* – Observation of the worksite, review of type of clothing worn and other job and worker characteristics obtained.
- *Select a Heat Index* – Select a heat index which best represents the hot work in question.
- *Select Instruments* – Depends to some degree on the index chosen but the basics (ie air temperature, globe temperature, wet bulb temperature and air velocity) should be measured as a minimum.
- *Measure the Thermal Environment* – Instruments should be placed in the actual working locations to ensure results are representative of the true exposure. Time should be allowed for instruments to become stabilised and repeat readings should be taken if the conditions change during the work day.

- *Calculate the Selected Index* – Use the data collected to calculate (or establish if using direct reading instrumentation) the selected index.
- *Estimate the Metabolic Heat Load* – Refer to charts or tables for this data.
- *Evaluate Recommended Limits (Exposure Limits)* – Use the calculated index and metabolic heat load to determine the level of risk by comparison to an appropriate exposure standard.
- *Determine Thermal Components* – Knowledge of the specific thermal components can provide diagnostic information which is very useful in the control of heat.
- *Modification of Hot Work Exposure* – If a workplace has a level of risk deemed to be unacceptable, actions need to be taken to mitigate the risk.
- *Re-evaluate Heat Limits* – After modifications to the hot workplace have been finalised the workplace should be re-evaluated to ensure that the modifications are appropriate.

For a cold workplace the following approach may be used:

- *Preliminary Review* – The cold work site should be inspected to establish the nature of the work, characteristics of work and warm up areas, type of clothing and other relevant job and worker information.
- *Decide the Type of Analysis* – Is a simple general analysis or a more detailed rational analysis required?
- *Measure the Thermal Environment* – The primary measurements are air temperature and wind speed. If a rational analysis is used, measures of mean radiant temperature and humidity must be obtained. Surface

temperatures should be measured when bare skin can contact cold surfaces.

- *Determine the WCI* – Calculate the WCI and also the equivalent chill temperature.
- *Estimate Metabolic Heat Load* – Refer to appropriate tables for this information.
- *Determine Insulation Required* – Using the available information refer to appropriate tables to establish the index of required clothing insulation (IREQ) or base judgement on experience for the prevailing climatic conditions.
- *Modification of Cold Work Exposure* – Ensure the required level of clothing is supplied and ensure that the worker is adequately educated and trained concerning all aspects of controlling and responding to cold environments.

Engineering controls should also be investigated and implemented if appropriate.

The procedures suggested by the AIHA (2003) are a basis for understanding how to establish the level of risk in hot or cold environments. In the real world however, the assessment of workplaces in respect to the thermal environment more often than not requires the understanding and application of the broader principles of this subject. This is to say that each workplace needs to be assessed on its individual merits and that there are three key variables that must always be considered when assessing the thermal environment, these include the:

- work environment,
- task being undertaken
- individuals associated with that task

These parameters have a significant impact on the outcome of an individual assessment.



#### **5.3.4 Outcome of Surveys**

Once the data has been analysed and the level of risk established, appropriate steps need to be taken where the risk is deemed unacceptable. In general such steps include:

##### **a) Environmental Control Measures**

General precautions which can be taken to reduce temperature and control environmental conditions include control or elimination of the source of heat. This is the preferred method and is usually the most effective and economical.

This involves for example:

- i) Insulation of hot surfaces and pipework
- ii) Shielding of radiant heat sources
- iii) Maintenance of plant and pipework to eliminate steam leaks
- iv) Reduction of plant and pipework temperatures
- v) Increased ventilation, air movement and local cooling

##### **b) Personnel Selection and Monitoring**

In deciding whether a person is suitable for work in hot environments the following points should be considered:

- i) Overweight and physically unfit people have an increased risk of ill-effect. Those over 45 years old are also more susceptible to hot conditions.
- ii) Some chronic illnesses, especially those affecting the heart and circulatory system, may be aggravated by work at high temperatures. Chronic skin disorders may also be affected.
- iii) People suffering from minor illnesses such as influenza, or hangovers (especially if they are habitual heavy drinkers), or who are receiving certain medical treatment particularly involving diuretics, should avoid working in hot environments.

- iv) People who have previously suffered from heat stress are often more susceptible to further attacks.

People who may be required to work in very hot or cold environments should be assessed by an occupational physician before undertaking such work. In addition, physiological monitoring may sometimes be necessary. The form of monitoring will be determined by the degree of risk. In moderately hot conditions it may be sufficient to ensure that workers look out for each other so that if one is unwell he can be removed from the hot environment and treated immediately.

If the environment is very hot or cold, supervision by medically trained personnel may be necessary. No person should be permitted to work alone in a very hot or cold environment.

**c) Work-Rest Regimes**

Work may be permitted at very high temperatures for short periods followed by a period of rest either in the work area or, if conditions are very hot, in a cooler environment. It should be noted that recovery is significantly improved if rest is taken in a cooler environment. The body is able to accumulate a certain amount of heat before the deep body temperature reaches an unacceptable level, and if exposure ceases before that level is reached there will be no harm. This approach should be a last resort and control of the environment should always be the first choice.

**d) Clothing**

When it is necessary to work at temperatures which are extremes of hot or cold so that even very short exposure can lead to adverse health effects, then the workers themselves must be protected by wearing clothing appropriate to the prevailing conditions.

This can present issues in itself in that some clothing may restrict heat loss by sweat evaporation in hot conditions.

Extreme care must be taken when selecting protective clothing to ensure detrimental effects are not inadvertently introduced. The use of heat stress indices in such situations is not recommended and personal physiological monitoring should be considered.

## **6. THERMAL COMFORT**

### **6.1 WHAT IS THERMAL COMFORT?**

In his introduction to the topic Parsons (2003) states that thermal comfort is often described as “that condition of mind which expresses satisfaction with the thermal environment”.

This statement used by both the American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE) and in the ISO Standard 7730 (Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria) is considered to be a goal for achieving thermal comfort by Heating, Ventilation and Air Conditioning (HVAC) engineers, ie the people who design buildings.

Why a person reports thermal comfort or discomfort or related feelings of warmth, freshness, pleasure etc are complex and not known. The effect of the thermal environment on people is shown when the conditions of thermal comfort are not met. When people are not content with their thermal environment and especially in the workplace they will express their feelings of discomfort by often vehement complaint, which affects both individual and group morale, general job dissatisfaction, effects on productivity and may even lead to a refusal to work.

For a group of people it is the interaction of the environmental factors of:

- Air temperature
- Radiant temperature
- Air velocity
- Humidity

plus the personal factors of:

- Metabolic heat generated by human activity and
- Clothing worn ie insulation

which produces comfort.

Any deviation from these conditions is likely to cause dissatisfaction amongst a percentage of the workforce.

### **6.1.1 Why Thermal Comfort Can Be Important**

Comfort is a subjective phenomenon. Comfort requirements can and do vary from person to person. It seems to be related to job satisfaction or job dissatisfaction, employer – employee relations and other psychological factors. For example foundry workers, most of whom have high job satisfaction, will tolerate very hot and dirty conditions without complaint, while employees in air conditioned offices, when they do not have sufficient work to keep them occupied or interested, will initiate the most bitter complaints of discomfort. It has been found by NSW WorkCover (1989) that workers in sub-basement offices will complain of suffocation and lack of air when the air temperature, humidity and air movement are identical with those of ground floor offices where most workers are comfortable. They also found an employee who sits in a closed-in area on their own will be quite happy with almost stagnant air, while workers in a general office, with good air movement will complain of lack of air.

The Health & Safety Executive (HSE) in the UK states that because thermal comfort is psychological it may affect morale (HSE 2007). Employee complaints may increase, productivity may fall and in some case people may refuse to work in a particular environment. Some aspects of the thermal environment, such as air temperature, radiant heat, humidity and air movement, may also contribute to the symptoms of sick building syndrome.

## **6.2 SCALES FOR SUBJECTIVE EVALUATION OF COMFORT**

In practice when asking people how they feel with regard to temperature or do they feel comfortable the responses are very subjective and range from one extreme through a middle zone to the other extreme - with most people often reporting somewhere around the middle range.

There have been a number of rating scales developed with probably the Bedford Scale (Table 6.1a) or the ASHRAE Psycho-Physical Scale (Table 6.1b) being the most widely used.

**Table 6.1a - The Bedford Scale**

<b>Bedford Scale</b>	
Much too warm	7
Too warm	6
Comfortably warm	5
Comfortable	4
Comfortably cool	3
Too cool	2
Much to cool	1

(Source: Chrenko 1974)

**Table 6.1b – ASHRAE Psycho-Physical Scale**

<b>ASHRAE Psycho-Physical Scale</b>	
Cold	-3
Cool	-2
Slightly cool	-1
Neutral	0
Slightly warm	+1
Warm	+2
Hot	+3

(Source: Fanger 1972)

In general the two scales are similar and are not affected by immediately previous thermal experience. It should be noted that in ISO 7730 the ASHRAE Psycho-Physical Scale is referred to as the “Seven Point Thermal Sensation Scale”.

### **6.3 ACTUAL IDEAL INDOOR ENVIRONMENTS**

When considering thermal comfort studies around the world, it is important to understand where the study was undertaken. In hot climates, the consideration is generally on how to cool the indoor environment to provide conditions of thermal comfort by use of increase air movement or air conditioning. In cold environments the attention is to how to heat the environment.

In the USA much of the research work into thermal comfort in the indoor work environment has been led by ASHVE (American Society of Heating and Ventilation Engineers) – later ASHRAE (American Society of Heating, Refrigeration and Air-conditioning Engineers) into the relative importance of air temperature and humidity which is of great interest in the hot and humid climates experienced in much of the USA. In Europe, humidity has not been considered in such detail nor air conditioning requirements. In the UK the emphasis has been on environmental warmth and freshness.

### **6.4 AN INTRODUCTION TO THE WORK OF FANGER**

#### **6.4.1 The Fanger Equation**

The first classic textbook on thermal comfort was the publication in 1970 of the book “Thermal Comfort” by Fanger (1970) who recognised that it was the combined effect of all (ie the six basic parameters) physical factors which determines human thermal comfort. This original text was written in Danish and was reproduced in English in 1972 (Fanger 1972).

In his study of the physiological response of the thermoregulatory system has been related statistically to thermal sensation votes collected from 1,296 subjects.

Fanger stated that three conditions needed to be met for a person to be in whole body thermal comfort:

1. The body is in heat balance
2. Sweat rate is within comfort limits, and

3. Mean skin temperature is within comfort limits.

From his basic heat balance equation of:

$$M - W = \underbrace{(C + R + E_{sk})}_{\text{"skin"}} + \underbrace{(C_{res} + E_{res})}_{\text{"breathing"}}$$

where M = Metabolic rate

W = Work

C = Heat transfer by convection from clothing surface

R = Heat transfer by radiation from clothing surface

$E_{sk}$  = Evaporative heat exchange at skin

$C_{res}$  = Respiratory convective heat exchange

$E_{res}$  = Respiratory evaporative heat exchange

We can see that heat is generated in the body and lost through the skin and from the lungs. It is transferred through clothing where it is lost to the environment. His logical considerations, reasonable assumptions and a review of the literature provided equations for each of the terms such that they can be calculated from six basic parameters which are:

- Air temperature
- Mean radiant temperature
- Relative humidity
- Air velocity
- Clothing insulation
- Metabolic rate

#### 6.4.2 The Predicted Mean Vote (PMV)

Fanger provided a complex set of equations for evaluating predicted mean vote (PMV) of a large group of subjects if they had rated their thermal sensation in that environment on the ASHRAE Psycho-Physical Scale (Table 6.2):



**Table 6.2 – ASHRAE Psycho-Physical Scale**

-3	Cold
-2	Cool
-1	Slightly cool
0	Neutral
+1	Slightly warm
+2	Warm
+3	Hot

(Source: Fanger 1972)

The derivation of these equations is beyond the scope of this course but it is important to note that Fanger considered factors such as:

- Metabolic rate
- Effective mechanical power
- Clothing insulation
- Clothing surface area
- Air temperature
- Mean radiant temperature
- Air velocity
- Water vapour pressure
- Convective heat transfer
- Clothing surface temperature

in his equations.

The PMV index is based on heat balance of the human body. Thermal balance is obtained when the internal heat production in the body is equal to the loss of heat to the environment. In a moderate environment, the human thermoregulatory system will automatically attempt to modify skin temperature and sweat secretion to maintain heat balance and thus thermal comfort.

Fanger (1972) indicated that the PMV index was derived in environmental conditions only slightly different from thermal neutrality (slight discomfort) and

thus for PMV values less than -2 or greater than +2 care should be exercised. He also suggested that in the hot end of the scale significant errors can occur due to issues associated with the evaporation of sweat.

### 6.4.3 Predicted Percentage Dissatisfied

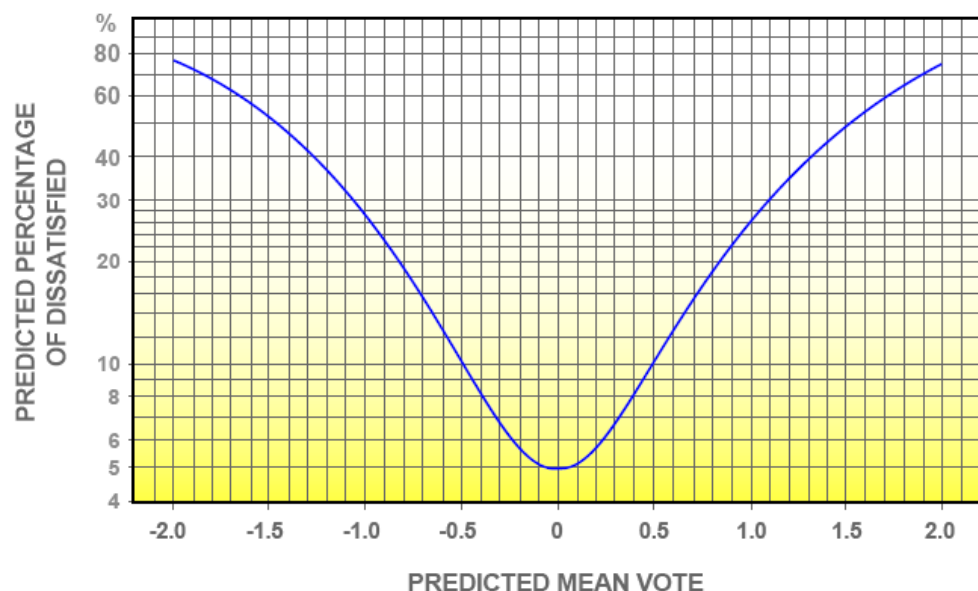
The PMV predicts the mean value of the thermal votes of a large group of people exposed to the same environment. But individual votes are scattered around this mean value and it is useful to be able to predict the number of people likely to feel uncomfortably warm or cool.

The predicted percentage dissatisfied (PPD) is an index that establishes a quantitative prediction of percentage of thermally dissatisfied people who feel too cool or too warm.

The PPD can be calculated using the equation below.

$$PPD = 100 - 95 e^{(-0.03353.PMV^4 - 0.2179.PMV^2)}$$

and demonstrated graphically as seen in Figure 6.1.



(Source: Fanger 1972)

**Figure 6.1 – PPD as a Function of PMV**

From Figure 6.1 it can be observed that the PPD increases rapidly the more the mean vote deviates from zero. The graph also indicates that it is impossible to satisfy all individuals in a large group as demonstrated by the fact that in a perfect environment ( $PMV = 0$ ) there will still be a 5% PPD.

In practice this point is often overlooked and complaints (no matter how few) are seen as an indicator that the temperature system is defective or not operating properly. This leads to people changing the room temperature, often resulting in even more complaints.

#### **6.4.4 A Standard for Thermal Comfort**

The most widely accepted standard for the optimum thermal comfort of workers is ISO 7730 first published in 1984 and subsequently revised in 1994. In 2005 it was technically revised and renamed to “Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.” As the title suggests much of the Standard is based on the work by Fanger. In addition to the determination of PMV and PPD it offered advice on local thermal discomfort.

A method for long term evaluation has been added, as well as further information on local thermal discomfort, non steady state conditions and adaptation, and an annex stating how thermal comfort requirements can be expressed in different categories.

#### **Local Thermal Discomfort**

The PMV and PPD express warm and cold discomfort of the body as a whole but thermal dissatisfaction can also be caused by unwanted cooling or heating of one particular part of the body. This is known as local discomfort.

The most common causes of local thermal discomfort are:

- Draught
- Thermal radiation asymmetry
- Vertical air temperature difference
- Floor temperature
  
- **Draught**
  - Unwanted local convective cooling of the body.
  - Dependent on the velocity, the fluctuations in velocity and the air temperature.
  - Calculations are provided in ISO 7730 (mean air velocity  $<0.5 \text{ ms}^{-1}$ ).
  
- **Thermal Radiation Asymmetry**
  - Warm ceilings and cold windows are the most uncomfortable.
  - Warm walls and cold floors seemed to be less uncomfortable.
  - Calculations are provided in ISO 7730 (windows  $<10^\circ\text{C}$ , warm ceiling  $<5^\circ\text{C}$ ).
  
- **Vertical Air Temperature Difference**
  - Generally unpleasant to be warm around the head while being cold at the feet.
  - Calculations are provided in ISO 7730 ( $<3^\circ\text{C}$  between head and ankles).
  
- **Floor Temperature**
  - Depends on the thermal conductivity and specific heat of the floor material.
  - Depends on footwear.
  - Calculations are provided in ISO 7730 (between  $19\text{-}26^\circ\text{C}$ ).

## 6.5 CONTROLS FOR THERMAL COMFORT

As we have seen earlier:

- Much of current understanding of thermal comfort is based on work of Fanger (1970) which uses mathematical (heat balance equation) and physical methods to relate physiological responses to comfort.
- Fanger's work applies to moderate thermal environments (offices, schools, homes, most factories, transport) but NOT to heat or cold stress environments
- Fanger's work forms the basis of ISO 7730 (2005) - "Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of PMV and PPD indices and local thermal comfort criteria"
- The other commonly used Standard is from ASHRAE 55-1992, Thermal environmental conditions for human occupancy".

Such standards have received widespread use and while there have been many studies undertaken it is still apparent that people in buildings suffer from thermal discomfort.

This discomfort, while not manifesting itself in life threatening heat stress effects, still impacts on the individuals. It can also impact productivity and the economic consequences of having a dissatisfied workforce.

Factors or likely problem areas that can influence the thermal conditions of internal environments in buildings and in particular offices have been reported by the BOHS (1996).

Any one or a combination of the factors may require attention to improve unsatisfactory conditions of thermal comfort and any investigation may require those responsible for the design, operation and maintenance of buildings and

building services plant and equipment. A number of these are described by the BOHS (1996) and are reproduced below with permission.

**a) Building Fabric**

The fabric of a building can influence thermal conditions

- Poor or inadequate thermal insulation will result in low surface temperatures in winter and high ones in summer with direct effect on radiant conditions. Variations and asymmetry of temperatures will also be affected.
- Single window glazing will take up a low internal surface temperature when it is cold outside causing both discomfort and radiation asymmetry. The effects are reduced, but not eliminated with double glazed windows.
- Cold down draughts of air from glazing due to cold window surfaces can be counteracted by the use of heat emitters under glazing or by the installation of double or triple glazing.
- Direct solar gain through glazing can be a major source of discomfort. This can be reduced or controlled by:
  - Modifications of the glazing type ie use of 'solar control glass' (a laminated glass with a spectrally selective film encapsulated between 2 or more plies of glass) or the application of window tinting
  - Use of internal blinds, preferably of a light reflecting colour. This provides localised protection for individuals, but the majority of the heat still enters the area or space
  - Use of external shutters or shades is by far the most effective method

It should be noted that the glazing itself may absorb heat and therefore rise in temperature causing an increase in the radiant temperature. This is particularly relevant with 'solar control glass'. Also use of such glass often means that internal lighting levels are reduced, leading to more use of artificial light and hence additional heat gain to the space which can then contribute to thermal discomfort.

- Unwanted air movement (and local low air temperatures) in winter time can arise from poor window and fabric seals, external doors etc. Draught proofing should be used to reduce this effect.
- The siting, style and nature of internal partitions of open plan offices can affect local conditions. If the interior of a space has high thermal mass (thermal capacity) then temperature fluctuations are reduced.

## **b) Heating Systems**

A range of factors need to be checked to ensure that a heating system is designed and functioning correctly and advice from suitably qualified engineers may be required.

Examples are:

- Overall output from central boiler plant or local output from heat emitters in individual spaces need to match the building and its requirements.
- The position of heat emitters can assist in counteracting discomfort eg siting of radiators under windows counteracts cold window surfaces and cold down draughts.
- Poor siting can lead to radiation asymmetry and increased draughts.

- Noise (eg from fan units and grilles) can be a contributing nuisance factor.
- The heat output from emitters should be appropriately controlled. Control systems may vary from a simple thermostat in one room to multiple sensors and computer control throughout the building.

**c) Ventilation Systems (heating only)**

When assessing a system pertinent points to note are:

- Identify air input grilles/diffusers to the room and check volume flow, velocity, circulation and distribution of supply air.
- Check the supply air temperature. Note that increased air movement may mean higher air temperature requirements for given comfort conditions.
- Look for air temperature gradients, particularly arising from air distribution patterns. If the supply temperature is too high buoyancy effects may lead to large temperature gradients and poor supply air distribution.
- Air volumes: if ventilation is providing heating, then air volume flow (and air temperature) must be sufficient to counteract heat losses in the space.
- Ensure local adjustments in one area do not adversely affect adjacent or overall plant operation.
- Low levels of relative humidity may result during winter heating. Humidification may be provided in central plant. If so, check that it is operating and being controlled correctly.



**d) Air Conditioning Systems, Heating, Cooling and Humidity Control**

Building air conditioning systems can be very complex and sophisticated and it is likely that specialist expertise is required in their assessment. The types of points to be considered and required checking are:

- What is the principle of operation? There are many types, eg
  - Fixed air volume, variable temperature
  - Variable air volume, fixed temperature
  - Fan assisted terminals
  - Fan coil unit – local control
  - Induction units
  - Twin duct
  - Chilled ceilings, chilled beams
  - Displacement ventilation: floor air supply

These issues typically fall into the domain of the building services engineer, but the basic principles of operation and control needs to be established.

- If conditions are not satisfactory, check for under or over capacity in both the main plant and local emitters. This is especially relevant with cooling systems which usually have little excess capacity.

Also check or have checked, the operation of local valves to heater and chiller batteries, these may jam, may allow bypass or operate incorrectly.

- Assess the temperature and velocity of air leaving the grills. Are the levels likely to lead to local discomfort, and is there sufficient air distribution?

Adjustments made for summer conditions (eg increasing air movement) may lead to discomfort in winter and vice versa

Also the air distribution is likely to differ for cooling and heating modes.

- Establish whether relative humidity is controlled (humidification and/or dehumidification). Measure the levels. Check control logic and sensors and whether plant is in operation/operational. Humidity sensors are prone to drift and malfunction.

**e) Control Systems (heating, cooling, humidity and airflow)**

Again, many questions will need to be asked to establish the principle of operation of control systems, and whether they are actually working as intended. Again much of this requires expert advice.

- What is the mode of control? Space sensors, return air sensors? How many sensors are involved? Do they operate independently or do they average detected readings?
- Are sensors suitably positioned to control the occupied space? Are they responding primarily to air or surface temperatures?
- Are sensors set at appropriate control values (eg return air sensor control set point should be higher than the room temperature required)? What are the set point values?
- Control may be fully automatic, localised or operated by individuals.
- The type of control provided may influence “perceived” comfort eg adjustments of a thermostat may induce a perceived improvement of conditions even if the thermostat is disconnected and has no effect.
- Check functioning and calibration etc of sensors, particularly relative humidity and duct air pressure sensors in variable air volume systems.

- Plant may be controlled by an Energy/Building Management System. Functional logic needs to be established.

Overall plant control, start up times, temperature values etc are often controlled by such systems or by a localised optimum start and stop controller. Check set point values and operational logic.

**f) Plant Maintenance**

Plant must be checked and maintained on a regular basis to ensure correct operation. Daily inspection is recommended for large plant. Air handling systems including duct work require periodic inspection and cleaning. This may be required under local legislation or recommended in Codes of Practice.

- Plant should be fully documented so that the nature of operation; and system and control logic can be ascertained.
- Maintenance and condition monitoring records should be kept and be available for inspection. Building management systems are of value here although sometimes too much information becomes available.
- There may be difficulty in obtaining all the explanations/answers concerning the building and its services. In this case the services and expertise of outside consultants may be required to assess the systems.
- It may be necessary to recommend complete reassessment and recommissioning of the mechanical systems although this will be an expensive process.

## **7. EVALUATION OF HOT ENVIRONMENTS**

### **7.1 THE USE OF HEAT STRESS INDICES**

A heat stress index is a single number that attempts to reflect the effects of basic parameters in any thermal environment. It aims to correlate the number with thermal strain experienced by the exposed person. It is important to recall the difference between *heat stress* and *heat strain*. Heat stress is the total heat load on the body from all sources. Heat strain relates to the physiological response of the imposed stress.

A mild or moderate heat stress may cause discomfort and may adversely affect performance and safety, but it is not harmful to health. As the heat stress approaches human tolerance limits, the risk of heat related disorders increases.

The aim of heat stress indices is to provide an approximation of worker's physiological state at any time of the exposure. This will then allow assessment of the permissible duration of the exposure and the length of rest breaks. While there has been a great deal of work done in the development of a number of indices there is no single index that has been accepted as both an accurate indicator of risk and universally applicable.

While much research has gone into determining the definitive index there is still much debate on which is best. Many indices do not consider all six basic parameters, although all have taken them into consideration in application. The use of particular indices will depend on individual situations hence the reason for so many.

Most heat indices consider, directly or indirectly, that the main strain on the body is due to sweating. The more sweating required to maintain heat balance and hence internal core body temperature, the greater the strain on the body.

The indices **most commonly used today** to manage the risk of heat stress are:

- Effective temperature (ET)
- Corrected effective temperature (CET)
- Predicted 4-hour sweat rate (P4SR)
- Wet bulb globe temperature (WBGT)
- Heat stress index (HSI)
- Predicted Heat Strain (PHS)
- Thermal Work Limit (TWL)

Heat stress indices typically fall into two types:

- Empirical or those that have been developed by assessing the physiological effects (often subjectively) on a test group of people under varying environmental test conditions, and include the ET, CET, P4SR and WBGT.

Empirical indices do not readily allow the detailed consideration of the individual components of the thermal environment, but assess the overall effect and being simple and practically derived they are more widely used as the basis for standards.

- Theoretical or rational indices which have been derived by consideration of the effects of the environment etc on the body's heat balance. The HSI was modelled on the heat balance equation and is based on a comparison of evaporation required to maintain heat balance with the maximum evaporation that could be achieved in that environment.

Further development of the HSI resulted in the Required Sweat Rate ( $SW_{req}$ ) index which was accepted as ISO 7933 in 1989.

This index calculated sweating required for heat balance from an improved heat balance equation, but more importantly allowed the

interpretations of the calculations with what is required with what is possible and acceptable in humans.

Further improvements to the Required Sweat Rate have resulted in the Predictive Heat Strain Method which has been adopted in revised and renamed ISO 7933:2004. The original Required Sweat Rate is not in general use today.

Another rational index of thermal stress, the Thermal Work Limit (TWL), has been developed in Australia in an attempt to overcome the shortcomings of some indices (eg ET and WBGT) that do not adequately take into account the effects of wind speed and does not rely on the estimation of metabolic rates (eg  $SW_{req}$ , and PHS).

## **7.2 EFFECT OF HEAT STRESS AND EVALUATION OF THERMAL STRAIN BY DIRECT PHYSIOLOGICAL MEASUREMENTS**

There are a number of physiological parameters that can be used to assess effects of heat stress on the human body. ISO 9886:2004 describes methods for measuring and interpreting these physiological parameters:

- Body core temperature
- Skin temperatures
- Heart rate
- Body-mass loss

### **7.2.1 Body Core Temperature**

The “core” refers to all tissues located at a sufficient depth not to be affected by a temperature gradient through surface temperature. The core temperature is not a unique temperature may be measured at different points of the body:

- Oesophagus
- Rectum
- Gastrointestinal tract

- Mouth
- Tympanum
- Auditory canal
- Urine temperature

ISO (ISO 9886:2004) have proposed a number of limits for core temperature which should be observed and these are summarised below.

***Hot Environments:***

*In the case of slow heat storage ie increase by about 1°C in more than one hour, the limit must be set at an increase of 1.0°C or 38.0°C whichever comes first, in the following cases:*

- *If core temperature is measured intermittently, whatever technique is used.*
- *For auditory canal temperature and tympanic temperature, because of uncertainty of constant correct positioning of transducer.*
- *In absence of competent medical personnel.*
- *Where no other physiological parameter is measured.*

*In the case of rapid heat storage, ie increase by about 1°C in less than one hour, the same limit applies as well when rectal or intra-abdominal temperatures are used, as they rise at a lower rate than the temperatures of the thermoregulation centres.*

*In other conditions and in particular when oesophageal temperature as well as heart rate is monitored continuously, higher limit values can be tolerated, such as increase of 1.4°C or 38.5°C, whichever comes first.*

*Still (non-varying) temperatures above 38.5°C may be tolerated provided the following conditions are observed:*

- *The subjects are medically screened.*
- *They are acclimatised to heat through repeated exposure to that environment and to the particular work task.*
- *Continuous medical surveillance is provided and emergency resources are readily available.*
- *Oesophageal temperature is continuously monitored.*
- *Other physiological parameters, in particular heart rate are monitored simultaneously.*
- *The exposure can be stopped as soon as intolerant symptoms, such as sensations of exhaustion, dizziness or nausea appear.*
- *The worker is allowed to leave the work situation as he/she pleases.*

*Any increase of the core temperature above 39°C is NOT recommended.*

#### **Cold Environments:**

*Only oesophageal temperature, rectal temperature and intra-abdominal temperature are relevant in this case.*

*The lower limit for these temperatures should be fixed at 36.0°C:*

- *When these temperatures are monitored intermittently*
- *When exposure is going to be repeated the same day*

*In exceptional circumstances, lower temperatures can be tolerated for short periods provided:*

- *Subjects have been medically screened.*
- *Local skin temperatures are simultaneously monitored and the relevant limits are respected.*
- *The worker is authorised to leave the work situation as he/she pleases.*



### 7.2.2 Skin Temperatures

Skin temperature varies widely over the surface of the body and especially when the ambient conditions are cold. Distinction should be made between:

- Local skin temperature measured at a specific point, and
- Mean skin temperature which cannot be measured directly, but can be estimated by weighting an ensemble of local skin temperatures

Skin temperature is influenced by:

- The thermal exchanges by conduction, convection, radiation and evaporation at the surface of the skin
- The variations of blood flow and of the temperature of the arterial blood reaching the particular part of the body

ISO have also proposed limits for skin temperature as summarised below.

The limits listed concern only the threshold of pain and according to these criteria, in a hot environment the maximum local skin temperature is 43°C.

In cold situations, the minimum local skin temperature is 15°C (in particular for the extremities: face, fingers and toes) (ISO 9886:2004).

### 7.2.3 Heart Rate

Heart rate (HR) typically measured in beats per minute (bpm) provides a guide to stress on the body (or anticipated exertion, pleasure, etc) which can be brought about by a number of factors including activity, thermal strain and psychological responses.

Heart rates can be used as an effective measure of heat strain and this is due to the way in which the body responds to increased heat loads. Blood circulation is adjusted to move more blood around the body to dissipate heat. This in turn results in an increased pulse rate.

There are a number of recommendations for heart rate as an indicator of thermal strain. These have been summarised below.

- **ISO 9886**

In ISO 9886 it is suggested that the increase in heart rate due to thermal strain is on the average 33 bpm per degree of temperature rise of the body core. However this varies greatly from one individual to another.

In situations in which a risk assessment suggests the thermal strain is likely to be very high, an accompanying measure of core temperature is required. In addition, the system used should allow heart rate to be measured in real time during the exposure.

HR at the workplace should not exceed the maximum value of the person reduced by about 20 bpm. This should ideally be determined by means of an individual test.

If this is not possible, the Heart Rate Limit (HRL) can be predicted by:

$$\text{HRL} = 185 - 0.65 \times \text{age}$$

The sustained heart rate over a work period should not exceed:

$$\text{HRL}_{\text{, sustained}} = 180 - \text{age}$$

- **ACGIH**

The ACGIH (2015) have also provided guidelines relating to heart rate where the WBGT TLVs are exceeded, or if water vapour impermeable clothing is worn.

They suggest an individual's exposure to heat stress should be discontinued when any of the following occur:

- *Sustained (several minutes) heart rate in excess of 180 bpm minus the individuals age in years (180 – age), for individuals with assessed normal cardiac performance; or*

- *Body core temperature is greater than 38.5°C for medically selected and acclimatised personnel; or greater than 38°C in unselected, unacclimatised workers; or*
- *Recovery heart rate at one minute after a peak work effort is greater than 120 bpm; or*
- *There are symptoms of sudden and severe fatigue, nausea, dizziness or light-headedness.*

For example, the sustained peak heart rate for a 40 year old person would be 140 bpm. These values represent an equivalent cardiovascular demand of working at about 75% of maximum aerobic capacity.

- **Heart Rate Recovery Approach**

Another approach was suggested by Brouha (1960), where a recovery rate method involved using a specific procedure as follows:

At the end of a cycle of work, a worker is seated and temperature and pulse rate are measured

- P1 pulse rate counted from 30 to 60 seconds
- P2 pulse rate counted from 90 to 120 seconds
- P3 pulse rate counted from 150 to 180 seconds

The ultimate criterion in terms of heat strain is an oral temperature of 37.5°C.

1. If P3 <90 bpm job situation is satisfactory.
2.  $P3 \leq 90$  bpm and  $P1 - P3 < 10$  bpm

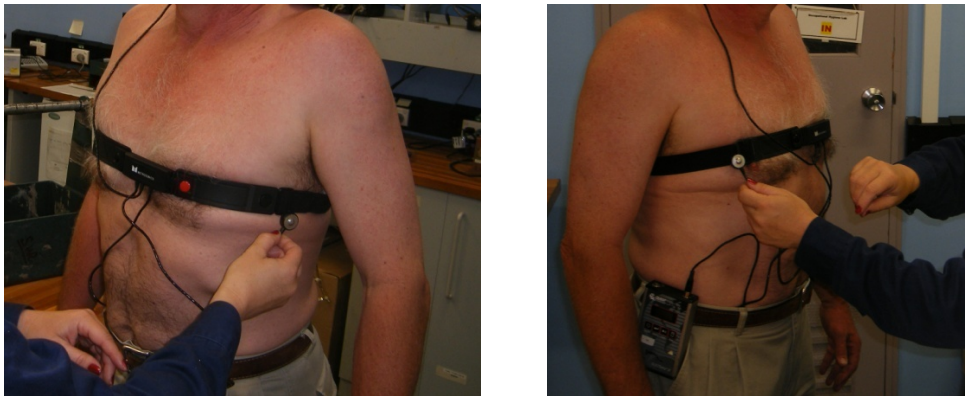
This indicates work level is high, but there is little likelihood of an increase in body temperature.

3.  $P3 > 90$  bpm and  $P1 - P3 < 10$  bpm

The stress (heat + work) is too high and action is needed to redesign the work.

All three approaches discussed above essentially aim to minimise the thermal strain on the body via controlling the HR so that the core temperature doesn't remain elevated. It should be appreciated that these approaches are guides only and individual variability may restrict their use.

An example of the fitting of instrumentation to measure personal heart rate is shown in Figures 7.1 and 7.2.



(Source: University of Wollongong)

**Figure 7.1 & Figure 7.2 – Personal Heart Rate/Data Logger**

#### **7.2.4 Body-Mass Loss Due to Sweating**

In a warm environment, the sweat loss can be considered as an index of the physiological strain from thermal origin, including not only the sweat that evaporates at the surface of the skin, but also the fraction dripping from the body surface or accumulating in the clothing.

In accordance with the requirements of ISO 7933, the sweat rate should be limited to 1.0 litre/hour for non-acclimatised subjects and up to 1.25 litres/hour for acclimatised subjects.

As far as the total body-water balance is concerned the limit should be set at 5% of the body mass to avoid dehydration.

### **7.3 EFFECTIVE AND CORRECTIVE EFFECTIVE TEMPERATURES**

#### **7.3.1 Effective Temperature Index**

The Effective Temperature (ET) was developed by Houghton and Yaglou in 1923 as a comfort scale. It combines the effects of air temperature, humidity and air movement into one scale to be used as a basis for comparisons. Three subjects judged which of two climatic chambers were warmer by walking between the two. Using different combinations of air temperature and humidity lines of equal comfort were determined. Immediate impressions were made so the transient response was recorded. This had the effect of over emphasising the effect of humidity at low temperatures and underestimating at high temperatures when comparing it to steady state conditions.

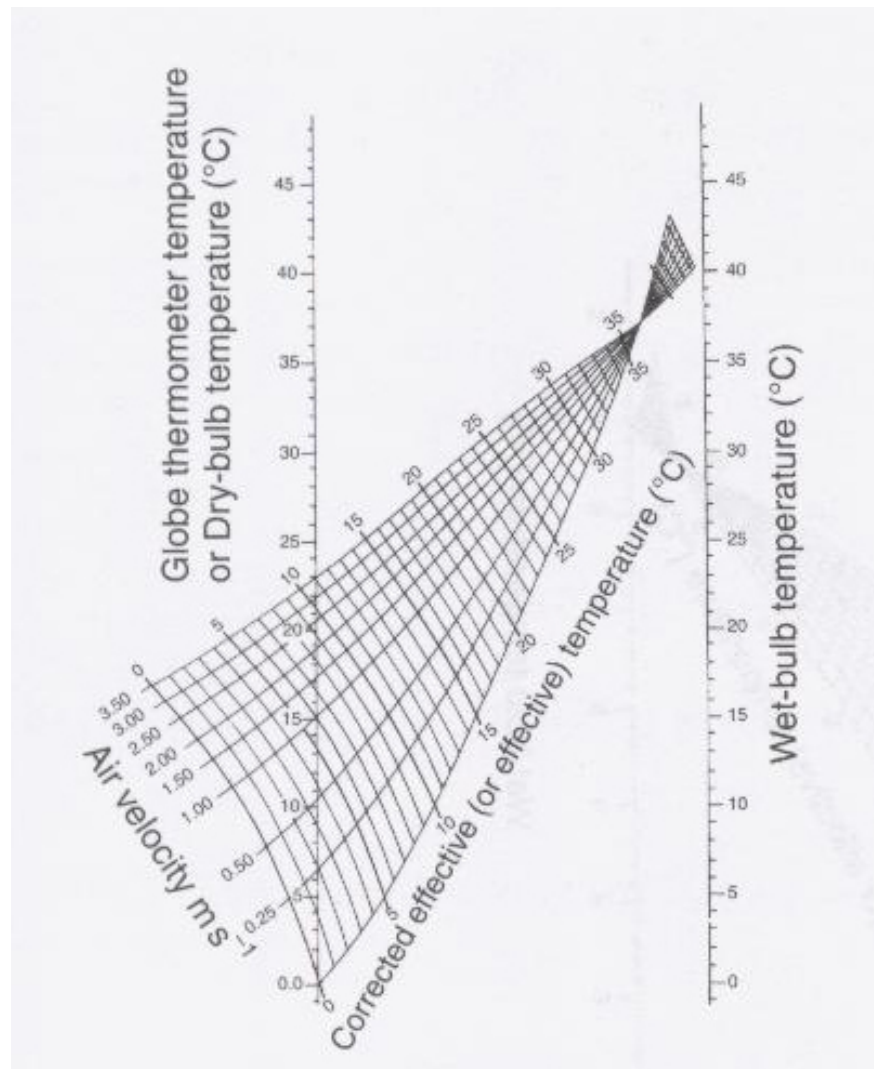
The ET index uses the concept of the temperature of a standard environment as the index value. ET is the temperature of a standard environment that contains still, saturated air that would provide the same sensation of warmth as in the actual environment. The person in the standard environment would have the same clothing and activity as in the actual environment.

Two charts were developed. One for persons naked to the waist Basic Effective Temperature (BET) - see Figure 7.3; and another for normally clothed people Normal Effective Temperature (NET) - see Figure 7.4.

To obtain effective temperature, draw a line between the dry bulb and wet bulb, note where it crosses the air velocity line, which slopes down to the right – this gives the effective temperature.

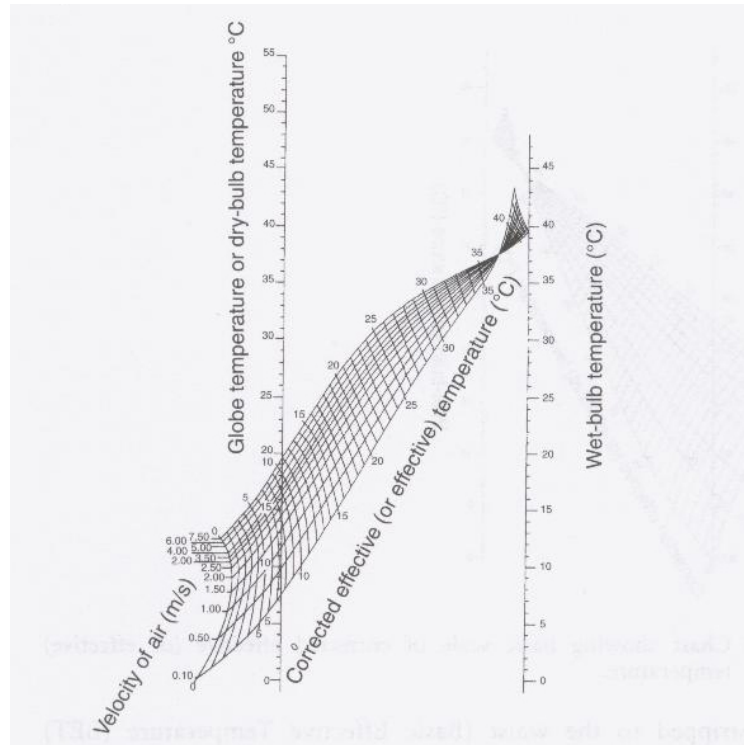
For example, if the dry and wet bulb temperatures and air velocity of an environment are 30°C, 20°C and 2.0 m/sec respectively the corresponding NET value for this environment is 23°C.

This means that the standard man wearing ordinary summer clothing will sense a thermal environment of 30°C dry bulb temperature, 20°C wet bulb temperature and 2 m/sec air velocity as equivalent to 23°C dry bulb temperature environment of still, saturated air (ie zero air velocity and 100% relative humidity).



(Source: BJH, 1972, Vol.29, Page 370 – reproduced with permission from the BMJ Publishing Group)

**Figure 7.3 - Basic Scale of Corrected Effective (or Effective) Temperature**



(Source: BJH, 1972, Vol.29, Page 371 – reproduced with permission from the BMJ Publishing Group)

**Figure 7.4 - Normal Scale of Corrected Effective (or Effective) Temperature**

### 7.3.2 Corrected Effective Temperature Index

The ET was limited in that it did not take into account the effects of radiant heat. It was later modified to form the Corrected Effective Temperature (CET). The basis for this index was to use a 150mm diameter globe temperature measurement on the scale in place of the dry bulb temperature.

The ET index was the first heat index and in revised form the ET and CET is still used around the world as a comfort index. While replaced by a number of other indices it is still a useful measurement technique in underground mines and other places where the humidity is high and the radiant heat low.

The ET and CET make limited allowance for the effects of clothing worn and no allowance for the level of physical activity. Under severe conditions approaching the limits of tolerance, wet bulb temperatures become the major determinant of heat strain and these scales may underestimate the severity of conditions.

A recommended maximum CET of 27°C was suggested for fit, acclimatised workers doing continuous light work was made by the early researchers.

However Parsons (2003) states that Bedford Proposed CET as an index of warmth, upper limits being CET of 34°C for reasonable efficiency and 38.6°C for tolerance.

#### 7.4 PREDICTED 4-HOUR SWEAT RATE

The Predicted 4-Hour Sweat Rate (P4SR) was established in climate chambers in London and evaluated extensively in Singapore. The P4SR index measures sweat rate as a function of climate stress. It uses a nomogram (Figure 7.5) to predict the quantity of sweat given off by fit, acclimatised young men exposed to the environment for four hours.

The P4SR is one of the few indices which take into account all the environmental factors plus the personal factors of metabolic rate and clothing. A disadvantage is that it covers only a moderate range of physical activity. It is also important to note that it was developed for naval personnel loading guns with ammunition during a naval engagement.

This empirical index and the steps taken to obtain the index are as follows:

1. If  $t_g \neq t_a$ , increase the wet bulb temperature by  $0.4 (t_g - t_a)$  °C
2. If the metabolic rate  $M > 63 \text{ Wm}^{-2}$ , increase the wet bulb temperature by the amount indicated in the table below or the graph in the nomogram (Figure 7.5).

**Table 7.1 – Wet Bulb Correction Factors For Metabolic Work Rate**

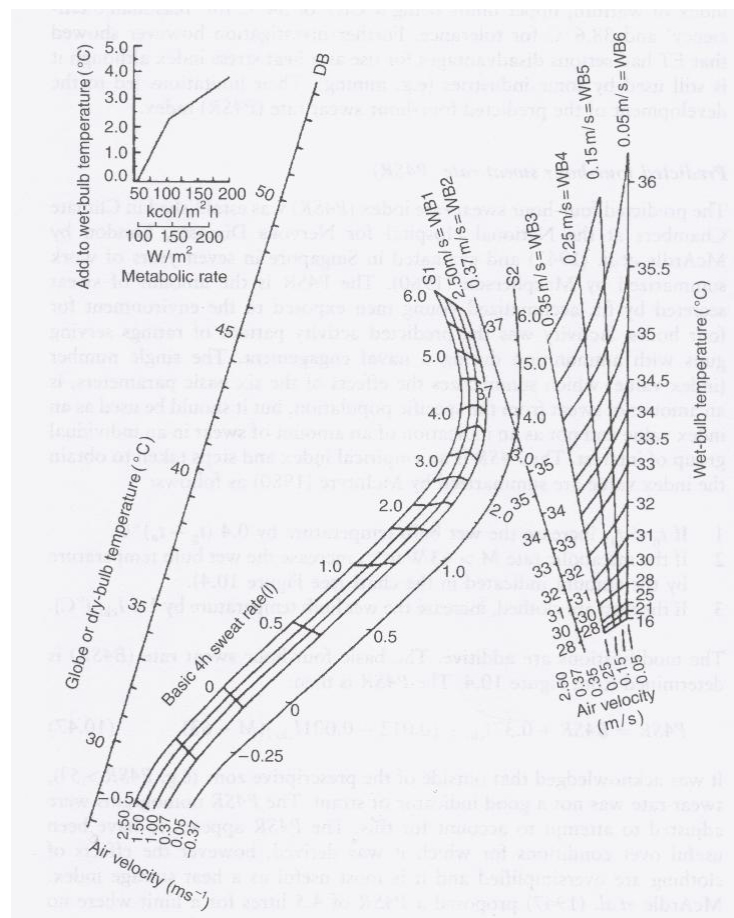
Activity	Approx Metabolic Rate $\text{Wm}^{-2}$	Correction °C
Sedentary	76	0.6
Light	116	2.2
Moderate	192	3.3
Heavy	262	4.2

(Source: Derived from Ellis 1972)



3. If the person is clothed, increase the wet bulb temperature by  $1.5 \times I_{clo}$  ( $^{\circ}\text{C}$ )
4. Using the chart, draw a straight line between the globe (if there is a radiant heat load) or dry bulb temperature (if there is no radiant heat load) which appears on the extreme left hand side of the chart and the intersection between the modified wet bulb temperature and the air velocity appearing in the block on the right hand side. The Basic 4-hour Sweat Rate (B4SR) can then be read from the intersection of this line with the air velocity lines on the B4SR block appearing in the centre of the nomogram.
5. The P4SR can then be calculated:  

$$\text{P4SR} = \text{B4SR} + 0.37I_{clo} + (0.012 + 0.001 \times I_{clo}) (M - 63)$$



(Source: BJIH, 1972, Vol.29, Page 373 – reproduced with permission from the BMJ Publishing Group)

**Figure 7.5 - Nomogram for Calculating Basic P4SR**

The P4SR index value which summarises the effects of the six basic parameters is an amount of sweat from the specific population and should be used as an index value and not as an indication of sweat in an individual group of interest.

It was acknowledged that outside of the prescriptive zone (eg P4SR >5 litres) sweat rate was not a good indicator of strain. A number of limits for P4SR have been proposed – an absolute maximum of 4.5 litres, and a maximum of 3 litres for regular exposure.

## 7.5 WET BULB GLOBE TEMPERATURE

The Wet Bulb Globe Thermometer (WBGT) is probably the most widely accepted index. It was originally developed for use in controlling heat casualties at military training centres as an approximation to the more cumbersome CET and modified to account for solar loading.

The WBGT combines the effects of the four main thermal components affecting heat stress: air temperature, humidity, air velocity and radiation as measured by the dry bulb, natural wet bulb and globe temperatures.

The WBGT values are calculated from one of the following equations:

- ***With direct exposure to sunlight***

$$\text{WBGT}_{\text{out}} = 0.7 \text{ NWB} + 0.2 \text{ GT} + 0.1 \text{ DB}$$

- ***Without direct exposure to the sun***

$$\text{WBGT}_{\text{in}} = 0.7 \text{ NWB} + 0.3 \text{ GT}$$

Where:

NWB = Natural wet bulb temperature

GT = Globe temperature

DB = Dry bulb (air) temperature

The ACGIH provide additional detail on the use of the WBGT and limit values (TLV's)© based on the WBGT index. The specified TLV's refer to heat stress conditions under which it is believed that nearly all adequately hydrated, unmedicated, healthy workers, wearing light weight summer clothing may be repeatedly exposed without adverse health effects. In most standards (including ACGIH's), maintenance of the core body temperature below 38°C is the criteria for ensuring no adverse health effects, although some consider this value conservative.

The recommended TLV values believed to delineate acceptable from non-acceptable thermal environments should be treated with caution, particularly in the tropics and arid areas. A number of studies have indicated that the WBGT may not be appropriate in all scenarios as it does not characterise the environment sufficiently to enable control effectiveness ( Bethea et al 2002, Budd 2008, d'Ambrosio Alfano et al, 2014, Desira, M., 2014).

When measuring the thermal environment, care should be taken to account for any variation in the heat stress index around the body. In this regard ISO 7243 (1989) suggests that readings be made at three positions corresponding to the height of the head, abdomen and ankles in relation to the ground.

- **NIOSH & ISO 7243**

The WBGT index was adopted by both NIOSH (1972) and ISO 7243 (1982) and is also incorporated into ISO 7243:1989 "Hot environments – Estimation of the heat stress on working man based, on the WBGT-index (wet bulb globe temperature)".

The WBGT has also been used as the basis for the ACGIH recommendations for their first order index of the environmental contribution to heat stress.

- **ACGIH Screening Criteria for TLV® and Action Limit for Heat Stress Exposure**

The guidance provided by the ACGIH (2007) in both their booklet and the accompanying Documentation of the TLV represents conditions under which it is believed that nearly all heat acclimatised, adequately hydrated, unmedicated, healthy workers may be repeatedly exposed without adverse health effects. The Action Limit is similarly protective of unacclimatised workers and represents conditions for which a heat stress management program should be considered. The guidance is not a fine line between safe and dangerous levels.

Since WBGT is only an index of the environment, the screening criteria are adjusted according to the contributions of work demands and clothing as well as the state of acclimatisation. Table 7.2 provides Screening Criteria for TLV based on WBGT values and Action Limit for heat stress exposure. For clothing types listed in Table 7.3 adjustments can be made to the environmental WBGT.

As metabolic rates increase, (ie work demands increase), the criteria and action limit values in Table 7.2 decrease to ensure that most workers will not experience a core body temperature above 38°C. Table 7.4 provides broad guidance for selecting the work rate category to be used in Table 7.2.

**Table 7.2 - Screening Criteria for TLV and Action Limit for Heat Stress Exposure**

Allocation of Work in a Cycle of Work and Recovery	TLV <sup>®</sup> (WBGT values in °C)				Action Limit (WBGT values in °C)			
	Light	Moderate	Heavy	Very Heavy	Light	Moderate	Heavy	Very Heavy
75% to 100%	31.0	28.0	—	—	28.0	25.0	—	—
50% to 75%	31.0	29.0	27.5	—	28.5	26.0	24.0	—
25% to 50%	32.0	30.0	29.0	28.0	29.5	27.0	25.5	24.5
0% to 25%	32.5	31.5	30.5	30.0	30.0	29.0	28.0	27.0

Notes to Table 2:

- See Table 3 and the *Documentation* for work demand categories.
- WBGT values are expressed to the nearest 0.5°C.
- The thresholds are computed as a TWA-Metabolic Rate where the metabolic rate for rest is taken as 115 W and work is the representative (mid-range) value of Table 3. The time base is taken as the proportion of work at the upper limit of the percent work range (e.g., 50% for the range of 25% to 50%).
- If work and rest environments are different, hourly time-weighted average (TWA) WBGT should be calculated and used. TWAs for work rates should also be used when the work demands vary within the hour, but note that the metabolic rate for rest is already factored into the screening limit.
- Values in the table are applied by reference to the “Work-Rest Regimen” section of the *Documentation* and assume 8-hour workdays in a 5-day workweek with conventional breaks as discussed in the *Documentation*. When workdays are extended, consult the “Application of the TLV<sup>®</sup>” section of the *Documentation*.
- Because of the physiological strain associated with Heavy and Very Heavy work among less fit workers, regardless of WBGT, criteria values are not provided for continuous work, and for up to 25% rest in an hour for Very Heavy work. The screening criteria are not recommended, and a detailed analysis and/or physiological monitoring should be used.

(Source: ACGIH<sup>®</sup>, 2007 TLVs<sup>®</sup> and BEIs<sup>®</sup> Book. Copyright 2007 – reprinted with permission)

WBGT based heat exposure assessment was developed for a traditional work uniform of a long sleeve shirt and pants. Additions to the measured WBGT values for some clothing assemblies are provided in the ACGIH TLV Booklet (ACGIH 2007).

**Table 7.3 - Clothing Adjustment Factors for Some Clothing Ensembles\***

Clothing Type	Addition to WBGT [°C]
Work clothes (long sleeve shirt and pants)	0
Cloth (woven material) coveralls	0
Double-layer woven clothing	3
SMS polypropylene coveralls	0.5
Polyolefin coveralls	1
Limited-use vapor-barrier coveralls	11

\* These values must not be used for completely encapsulating suits, often called Level A. Clothing Adjustment Factors cannot be added for multiple layers. The coveralls assume that only modesty clothing is worn underneath, not a second layer of clothing.

(Source: ACGIH<sup>®</sup>, 2007 TLVs<sup>®</sup> and BEIs<sup>®</sup> Book. Copyright 2007 – reprinted with permission)

**Table 7.4 - Metabolic Rate Categories and the Representative Metabolic Rate with Example Activities**

Category	Metabolic Rate [W] *	Examples
Rest	115	Sitting
Light	180	Sitting with light manual work with hands or hands and arms, and driving. Standing with some light arm work and occasional walking.
Moderate	300	Sustained moderate hand and arm work, moderate arm and leg work, moderate arm and trunk work, or light pushing and pulling. Normal walking.
Heavy	415	Intense arm and trunk work, carrying, shoveling, manual sawing; pushing and pulling heavy loads; and walking at a fast pace.
Very Heavy	520	Very intense activity at fast to maximum pace.

\* The effect of body weight on the estimated metabolic rate can be accounted for by multiplying the estimated rate by the ratio of actual body weight divided by 70 kg (154 lb).

(Source: ACGIH®, 2007 TLVs® and BEIs® Book. Copyright 2007 – reprinted with permission)

The simplicity of the index and its use by influential bodies has led to its widespread acceptance. Like all direct indices it has limitations when used to simulate human response and WBGT should be used with caution in practical applications.

Portable electronic instruments for measuring WBGT are commercially available (Figure 7.6).



(Source: 3M – reproduced with permission)

**Figure 7.6 - Questemp°36 For Measuring WBGT**

## 7.6 HEAT STRESS INDEX (HSI)

The HSI was developed by Belding & Hatch and is based on heat exchange. It is a comparison of evaporation required to maintain heat balance ( $E_{req}$ ) with the maximum evaporation that could be achieved in that environment ( $E_{max}$ ).

$$HSI = E_{req} / E_{max} \times 100$$

$$\text{Allowable exposure time} \quad AET = 2440 / (E_{req} - E_{max}) \text{ mins}$$

Where:

$$\begin{aligned} E_{req} &= \text{Required evaporative (ie sweat) loss (Wm}^{-2}\text{)} \\ &= M - R - C \end{aligned}$$

ie is the sum of metabolic work rate, radiation heat loss and convective heat loss

$$\begin{aligned} E_{max} &= \text{maximum evaporative (ie sweat) loss Wm}^{-2}\text{)} \\ &= 7.0v^{0.6}(56 - p_a) \quad \text{clothed} \\ &= 11.7v^{0.6}(56 - p_a) \quad \text{unclothed} \end{aligned}$$

An upper limit of  $390 \text{ Wm}^{-2}$  is assigned to  $E_{\max}$  – this corresponds to a sweat rate of 1 litre/hour for a typical man over an 8 hour work day.

$$\begin{aligned}
 M &= \text{Metabolic rate (Wm}^{-2}\text{)} \\
 R &= \text{Radiant heat loss rate (Wm}^{-2}\text{)} \\
 &= 4.4(35 - t_r) \quad \text{clothed} \\
 &= 7.3(35 - t_r) \quad \text{unclothed} \\
 C &= \text{Convective heat loss rate (Wm}^{-2}\text{)} \\
 &= 4.6v^{0.6}(35 - t_a) \quad \text{clothed} \\
 &= 7.6v^{0.6}(35 - t_a) \quad \text{unclothed}
 \end{aligned}$$

and

$$\begin{aligned}
 p_a &= \text{Water vapour pressure} \quad (\text{mb}) \\
 t_r &= \text{Mean radiant temperature} \quad (^\circ\text{C}) \\
 t_a &= \text{Dry bulb (ie air) temperature} \quad (^\circ\text{C})
 \end{aligned}$$

A HSI of 100 represents the upper limit of the prescriptive zone and is the maximum sweating that can be achieved. If  $E_{\text{req}} > E_{\max}$  the body cannot maintain equilibrium and its temperature begins to rise.

If  $\text{HSI} > 100$ , there is body heat storage and allowable exposure times need to be calculated.

If  $\text{HSI} < 20$  there is mild cold strain.

The range of possible effects for an 8 hour exposure can be summarised as follows (Table 7.5):



**Table 7.5 – Range of Possible Effects Vs HSI Values**

<b>HSI</b>	<b>Effect of 8 Hour Exposure</b>
0	No thermal strain
10-30	Mild to moderate heat strain
40-60	Severe heat strain, involving threat to health unless physically fit
70-90	Very severe heat strain – personnel should be medically assessed and steps taken to ensure adequate fluid intake
100	Maximum strain tolerated daily by fit acclimatised young men
Over 100	Exposure time is limited by the rise in core body temperature

The application of HSI can be shown by the following example.

A worker is exposed to the following conditions:

$$t_a = 30^\circ\text{C}$$

$$t_{wb} = 20^\circ\text{C}$$

$$t_r = 45^\circ\text{C}$$

$$v = 0.5\text{m/s}$$

$$M = 165\text{Wm}^{-2}$$

Calculate the HSI and interpret the results.

$$\begin{aligned} C &= 4.6v^{0.6}(35 - t_a) \quad \text{clothed} \\ &= 4.6(0.5)^{0.6}(35 - 30) \\ &= 15.17\text{Wm}^{-2} \end{aligned}$$

$$\begin{aligned} R &= 4.4(35 - t_r) \quad \text{clothed} \\ &= 4.4(35 - 45) \\ &= -44\text{Wm}^{-2} \end{aligned}$$

$$\begin{aligned} E_{\text{req}} &= M - R - C \\ &= 165 - (-44) - 15.17 \\ &= 194\text{Wm}^{-2} \end{aligned}$$

$$\begin{aligned}
 E_{\max} &= 7v^{0.6}(56 - p_a) \quad \text{clothed} \\
 &= 7(0.5)^{0.6}(56 - 16.3) \\
 &= 183
 \end{aligned}$$

$$\begin{aligned}
 \text{HSI} &= E_{\text{req}}/E_{\max} \times 100 \\
 &= 194/183 \times 100 \\
 &= 106
 \end{aligned}$$

Interpretation: Exposure time limited by rise in deep body temperature.

$$\begin{aligned}
 \text{AET} &= 2440 / (E_{\text{req}} - E_{\max}) \text{ mins} \\
 &= 2440 / (194 - 183) \\
 &= 222 \text{ minutes}
 \end{aligned}$$

Although the HSI considers all environmental factors and work rate, it is not completely satisfactory for determining an individual worker's heat stress and is also difficult to use. Although HSI is a rational index based on the heat balance equation, limited assumptions have been made for varying clothing levels.

## 7.7 REQUIRED SWEAT RATE

A further theoretical and practical development of the HSI and another related index, the Index of Thermal Stress (which is not discussed here) was the Required Sweat Rate ( $SW_{\text{req}}$ ) and hence is also based on the heat balance equation.

The Required Sweat Rate is a comprehensive, albeit complex, index that considers many factors that affect the body's response to heat and was subsequently adopted in ISO 7933:1989 - Hot Environments – Analytical determination and interpretation of thermal stress using calculation of required sweat rate.

It describes a method for calculating the heat balance as well as the required sweat rate that the human body should produce to maintain this balance in equilibrium.

The information required includes measurement of dry bulb temperature, wet bulb temperature, humidity, air velocity, globe temperature, together with estimates of factors relating to thermal insulation, property of clothing, metabolic work rate and posture. This allows the calculation of the required sweat rate (for the maintenance of thermal equilibrium) from the adaptation of the basic heat equation

$$E_{\text{req}} = M - W - C_{\text{res}} - E_{\text{res}} - K - C - R$$

combined with

$$SW_{\text{req}} = E_{\text{req}} / r_{\text{req}}$$

where

M = metabolic power

W = mechanical power

$C_{\text{res}}$  = respiratory heat loss by convection

$E_{\text{res}}$  = respiratory heat loss by evaporation

K = heat exchange on the skin by conduction

C = heat exchange on the skin by convection

R = heat exchange on the skin by radiation

$SW_{\text{req}}$  = required sweat rate for thermal equilibrium

$E_{\text{req}}$  = required evaporation for thermal equilibrium

$r_{\text{req}}$  = evaporative efficiency at required sweat rate

It subsequently predicts the sweat rate, evaporation rate and skin wettedness. If thermal equilibrium is maintained, there should not be a risk of heat stress. If it is not established, then the amount of time to reach an upper limit of heat storage should be determined.

The required sweat rate is compared with the maximum limit values for skin wettedness and required sweat rate which can be achieved by persons. These were provided in the ISO Standard for acclimatised and non-acclimatised persons at work and rest.

Where thermal equilibrium could not be maintained heat storage and therefore body core temperature will rise and limiting values were also provided for warning and danger levels of core temperature and maximum allowable water loss.

The predicted sweat rate can be determined from the required sweat rate and the limit values. If the required sweat rate can be achieved by persons and it will not cause unacceptable water loss, then there is no time limit due to heat exposure over an 8 hour shift. If this is not the case then an allowable exposure rate can be calculated from appropriate equations.

Calculation of the required sweat rate if done manually can take over an hour to perform and typically the data is entered into a spread sheet and calculated by computer.

## **7.8 PREDICTED HEAT STRAIN INDEX**

The method for calculating the Required Sweat Rate ( $SW_{req}$ ) of ISO 7933 1989 was further developed by Malchaire et al (2001) and led to the development of the Predictive Heat Strain Index (PHS).

In 1983 laboratories from Belgium, Italy, Germany, the Netherlands, Sweden and the UK carried out European research (BIOMED) to design a practical strategy for heat stress assessment based on the thermal balance equation. A number of studies (Kampmann et al 2000, Bethea et al 2002) tested the method and identified limitations in a number of different industrial environments in the field. In 1999 Malchaire et al. undertook a major review of the methodology based on 1113 files of responses to people in hot conditions. From this, numerous major modifications were made to take into account the increase in core temperature associated with activity in neutral environments. The prediction of maximum wetness and maximum sweat rates was also revised, as well as the limits for maximum water loss and core temperature. The revised model was renamed the "Predicted Heat Strain"

(PHS) model, derived from the Required Sweat Rate (SWReq). The inputs to the method are the six basic parameters, dry bulb temperature, radiant temperature, air velocity and humidity, metabolic work load and clothing. The required evaporation for the thermal balance is then calculated using a number of algorithms from:

$$E_{req} = M - W - C_{res} - E_{res} - C - R - S_{eq},$$

This equation expresses that the internal heat production of the body, which corresponds to the metabolic rate (M) minus the effective mechanical power (W), is balanced by the heat exchanges in the respiratory tract by convection ( $C_{res}$ ) and evaporation ( $E_{res}$ ), as well as by the heat exchanges on the skin by conduction (K), convection (C), radiation (R), and evaporation (E), and by the eventual balance, heat storage (S), accumulating in the body (ISO 7933:2004).

The maximum allowable exposure duration is reached when either the rectal temperature or the accumulated water loss reaches the corresponding limits (Parsons, 2003). Applying the PHS model is somewhat complicated and involves the utilisation of numerous equations.

These improvements to the Required Sweat Rate have resulted in the Predictive Heat Strain Method which has been adopted in revised form and renamed ISO 7933:2004.

The theoretical and practical considerations and empirical modelling provided modified equations and methods that lead to an improved model for  $SW_{req}$  with such significant change for it to be a new index (Predicted Heat Strain) which was subsequently adopted in the revision and renaming of ISO 7933:2004 – “Ergonomics of the thermal environment – Analytical determination and interpretation of heat stress using calculation of the predicted heat strain.”

The modifications to the required sweat rate index included: modifications to the respiratory heat loss, introduction of mean body temperature, distribution

of heat storage in the body, prediction of rectal temperatures, exponential averaging for mean skin temperature and sweat rate, evaporative efficiency of sweating,  $w_{max}$  limits for non acclimatised subjects, maximum sweat rate, increase of core temperature with activity, limits of internal temperature, maximum dehydration and water loss, influence of radiative protective clothing and the inclusion of the effects of ventilation on clothing insulation.

The Predicted Heat Strain Model of ISO 7933, in summary, adopted the following criteria for estimating acceptable exposure time in a hot work environment:

- **Acclimatised and non-acclimatised subjects**

Acclimatised subjects sweat more abundantly, more uniformly and earlier than non-acclimatised subjects. This results in lower heat storage, lower core temperature and lower cardiovascular constrain. It affects maximum skin wettedness and maximum sweat rate

- **A maximum skin wettedness**

The maximum skin wettedness is set for 1.0 acclimatised subjects (assumed to be able to evaporate sweat from 100% of the skin surface when needed), and 0.85 for non-acclimatised workers (assumed to perspire less efficiently and therefore able to evaporate sweat, at the maximum, on 85% of the skin surface).

- **A maximum sweat rate**

Can be estimated using equations provided and can range from 650 – 1,000 g/hour.

For acclimatised subjects, the maximum sweat rate is approximately 25% greater than for non-acclimatised.

- **A maximum dehydration and water loss**

Maximum water loss set at 7.5% for an average subject and 5% of the body to protect 95% of the working population.

- **A maximum rectal temperature**

Set at 38°C, the limit which assures that the probabilities of a worker reaching 39.2°C and 42°C are lower than  $10^{-4}$  and  $10^{-7}$  respectively.

The program to calculate the Predicted Heat Strain can be downloaded free of charge on request from Malchaire's web site at <http://www.deparisnet.be/DROPBOX.htm#eng> and also as a mobile phone application called "PHS" from the Apple App Store free of charge.

A case study from the steel industry using the PHS model will be undertaken as an exercise.

## **7.9 THERMAL WORK LIMIT (TWL)**

Another rational heat stress index called the Thermal Work Limit (TWL) has been proposed by Brake & Bates (2002) who consider the heat stress indices currently in use are either difficult to apply or poorly applicable in many situations.

For any set of environmental conditions, there is a maximum rate at which an individual can dissipate heat, ie a limiting metabolic rate, and therefore a maximum rate at which they can work safely.

A means of identifying conditions where excessive thermal stress places health at risk is required for easy application in workplaces. ISO 7933 2004, a rational heat stress index, uses the Predicted Heat Strain index, but it is complex to use. In common use is the empirical index WBGT which the ACGIH uses as the basis for their Heat Stress TLV.

The WBGT does not adequately take into account wind speed and the difficulties of estimating metabolic rates indices, a process that is difficult and subject to considerable error especially for workers who are mobile and work at varying tasks and metabolic rates during their shift.

Advances in instrumentation have enabled these shortcomings to be overcome by using the TWL. TWL uses five environmental parameters (dry bulb, wet bulb and globe temperatures, wind speed and atmospheric pressure) and accommodates for clothing factors to arrive at a prediction of a safe maximum continuously sustainable metabolic rate ( $Wm^{-2}$ ) for the conditions (ie the TWL). The TWL is defined as the limiting (or maximum) sustainable metabolic rate that euhydrated (well hydrated), acclimatised individuals can maintain in a specific thermal environment, within a safe deep body core temperature ( $<38.2^{\circ}C$ ) and sweat rate (1.2 kg/hr).

The thermal limit algorithm index has been developed using published experimental studies of human heat transfer and established heat and moisture transfer equations through clothing. Clothing parameters can be varied and the protocol can be extended to unacclimatised workers. The index is designed specifically for self-paced workers and does not rely on estimation of actual metabolic rates, a process that can be difficult and subject to considerable error. Work areas are measured and categorised based on a metabolic heat balance equation, using dry bulb, wet bulb and air movement to measure air-cooling power ( $W/m^2$ ).

Table 7.6 shows typical TWLs over a range of conditions.

**Table 7.6 - TWL Values at Various Environmental Conditions and Clothing Ensembles**

MRT = DB + 2°C						MRT = DB						MRT = DB + 3°C					
Wind speed = 0.2 m/s <sup>-1</sup>						Wind speed = 0.5 m/s <sup>-1</sup>						Wind speed = 1.5 m/s <sup>-1</sup>					
Barometric pressure = 101 kPa						Barometric pressure = 115 kPa						Barometric pressure = 80 kPa					
I <sub>cl</sub> = 0.45, i <sub>cl</sub> = 0.45						I <sub>cl</sub> = 0.69, i <sub>cl</sub> = 0.4						I <sub>cl</sub> = 0.35, i <sub>cl</sub> = 0.45					
WB						WB						WB					
DB	24	26	28	30	32	DB	24	26	28	30	32	DB	24	26	28	30	32
34	175	157	136	114	n/p	34	181	161	140	118	n/p	34	288	260	229	193	154
36	170	151	131	109	n/p	36	176	156	136	113	n/p	36	282	254	222	187	148
38	164	145	125	103	n/p	38	171	152	131	109	n/p	38	276	248	216	181	141
40	158	140	120	n/p	n/p	40	166	147	126	104	n/p	40	270	242	210	174	135
42	152	134	114	n/p	n/p	42	161	142	122	n/p	n/p	42	264	235	203	167	128

MRT = mean radiant temperature, °C; DB = dry bulb temperature, °C; WB = wet bulb temperature, °C; I<sub>cl</sub> = intrinsic clothing thermal resistance, clo; i<sub>cl</sub> = clothing vapor permeation efficiency, dimensionless; n/p = heat stress too extreme even for (continuous) light work. Permit required.

("From *Applied Occupational and Environmental Hygiene*, Limiting Metabolic Rate (Thermal Work Limit) as an Index of Thermal Stress, 17(3): pages 176-186. Copyright 2002. ACGIH®, Cincinnati, OH. *Reprinted with permission*")



It is important to note that the TWL is designed for workers who are well educated about working in heat, have control over their work rate, are healthy and are well hydrated.

Recommended guidelines for TWL limits with the corresponding interventions are provided below in Table 7.7. These guidelines are based on the hierarchy of safety controls, and include a range of engineering, procedural and personal protective equipment (PPE) interventions.

**Table 7.7 - Recommended TWL Limits and Interventions For Self Paced Work**

TWL limit ( $W/m^{-2}$ )	Name of limit/zone	Interventions
<115 (or DB > 44°C or WB > 32°C)	Withdrawal	<ul style="list-style-type: none"> <li>• No ordinary work allowed</li> <li>• Work only allowed in a safety emergency or to rectify environmental conditions</li> <li>• Permit to work in heat must be completed and authorized by manager beforehand</li> <li>• Dehydration test at end of shift</li> <li>• Personal water bottle (4-liter capacity) must be on the job at all times</li> </ul>
115 to 140	Buffer	<ul style="list-style-type: none"> <li>• Rectify ventilation or redeploy workers if possible</li> <li>• No person to work alone</li> <li>• No unacclimatized person to work</li> <li>• If work does continue, a corrective action request must be completed and signed by the manager within 48 hrs</li> <li>• Wind speed must be increased to at least <math>0.5 \text{ m/s}^{-1}</math></li> <li>• Dehydration test at end of shift</li> <li>• Personal water bottle (4-liter capacity) must be on the job at all times</li> </ul>
140 to 220	Acclimatization	<ul style="list-style-type: none"> <li>• Acclimatized persons allowed to work, but not alone</li> <li>• Personal water bottle (4-liter capacity) must be on the job at all times</li> </ul>
>220	Unrestricted	<ul style="list-style-type: none"> <li>• No limits on work due to thermal stress</li> </ul>

("From *Applied Occupational and Environmental Hygiene*, Limiting Metabolic Rate (Thermal Work Limit) as an Index of Thermal Stress, 17(3): pages 176-186. Copyright 2002. ACGIH®, Cincinnati, OH. *Reprinted with permission*")

At high values of TWL, the thermal conditions impose limits on the level of work that can be undertaken. At moderate values, adequately hydrated self paced workers will be able to accommodate to the thermal stress by adjusting their work rate. At low TWL values, heat storage is likely to occur.. At very low values no useful work may be sustained and only work in an emergency safety situation should be allowed.

With TWL, the higher the number, the higher the sustainable work rate (in terms of thermal stress). The use of the TWL algorithm provides an estimate of the limiting metabolic rate from simple measurements of environmental conditions.

In controlled conditions the TWL was originally validated in underground environments (Brake & Bates 2002) where there is no solar load or radiant heat, however, recently (Miller & Bates 2007) confirmed these results and their study extends the applicability of TWL to outdoor environments and generates management guidelines for its implementation. It should be noted that the programme is privately managed and does not have support of a formal standard such as WBGT (ISO 7243) and PHS (ISO 7933).

A thermal strain meter is available for determining aspects of this index (Figure 7.7).



(Source: Romteck Pty Ltd – reproduced with permission)

**Figure 7.7 - Heat Stress Monitor (HSM)**

## **7.10 SUMMARY OF INDICES FOR HOT ENVIRONMENTS**

The indices previously discussed can be placed broadly into two groups, ie Empirical and Rational Indices. These are summarised in Tables 7.8 and 7.9.

**Table 7.8 – Summary of Empirical Indices**

<b>Index</b>	<b>Parameters Measured</b>	<b>Other Factors</b>	<b>Uses</b>	<b>Other Information</b>
Effective Temp (ET)	Dry bulb, wet bulb, air velocity	Two clothing levels, basic and normal	Thermal comfort	No account of radiant heat and no allowance for metabolic rate
Corrected Effective Temp (CET)	Globe thermometer, wet bulb, air velocity	Two clothing levels, basic and normal	Thermal comfort	No allowance for metabolic rate
Predicted 4-hour Sweat Rate (P4SR)	Globe thermometer or dry bulb, wet bulb, air velocity	Corrections applied for metabolic rate and clothing	Heat stress	Absolute max 4.5 litres, normal limit of 3 litres
Wet Bulb Globe Temperature (WBGT)	Globe thermometer, wet bulb, (dry bulb if outside)	Correction applied for clothing, different metabolic rates	Heat stress – derives work-rest regimes. Fairly simple – instruments available	Two formulae (inside and outside). Two limits, action levels and TLVs

**Table 7.9 – Summary of Rational Indices**

<b>Index</b>	<b>Parameters Measured</b>	<b>Other Factors</b>	<b>Uses</b>	<b>Other Information</b>
Heat Stress Index (HSI)	Globe thermometer, dry bulb, wet bulb, air velocity, metabolic rate	Limited assumptions made for clothing levels	Heat stress – difficult to use. Derives allowable exposure times	100 max >70 very severe heat strain >40 severe heat strain
Predicted Heat Strain (PHS)	Globe thermometer, dry bulb, wet bulb, air velocity, metabolic rate and clothing	Many other factors included	Heat stress – very complex. Computer program available	Can be used to estimate work/rest regimes and effectiveness of controls
Thermal Work Limit (TWL)	Dry bulb, wet bulb, air velocity	Acclimatised and unacclimatised plus clothing taken into account	Heat stress – fairly straightforward – combined instruments available	Does not require estimation of metabolic rate. Workers self-pace

## **8. CONTROL OF HOT ENVIRONMENTS**

### **8.1 PERSONAL FACTORS MITIGATING AGAINST 'HOT' WORK**

As we have seen earlier in Chapter 4 (Effects of Temperature Extremes) there are number of predisposing factors that may influence a person susceptibility to both hot and cold environments. The severity of heat related disorders from these personal factors can be reduced.

#### **8.1.1 Obesity**

Those people who are overweight or unfit are more likely to experience ill effects when working in hot environments. The greater the level of fitness of the worker the more the worker will adapt to or tolerate both the heat and the cold. Physical fitness leads to better thermal tolerance because fitness leads to increased blood volume and cardiovascular capabilities. Aerobic fitness is known (AIHA 2003) to increase blood volume, cardiac stroke volume, maximal cardiac output and capillarisation of the muscles. These changes lower the cardiovascular strain for any given work rate, as well as increase the physiological reserves. The increased blood volume, for example, becomes important when blood must simultaneously supply the muscles with oxygen at the same time it must transport heat to the skin for dissipation.

Body size and fatness also influence tolerance to heat. The larger the person, the greater the energy required to perform a task and hence the higher the metabolic heat production, particularly for weight supported activities such as walking. Also, the bigger the person, the lower the surface area-to-mass ratio, so the person's ability to dissipate heat is reduced and it takes longer for the person to cool down after heat exposure.

It must be noted however that there is much individual variation in the influence of obesity and size on both heat and cold tolerance.

Maintenance of a healthy lifestyle can assist in the mitigation of the effects from working in a hot environment.

### **8.1.2 Medication**

Many therapeutic and social drugs can have an impact on a worker's tolerance to heat. A weekend of social drinking can leave a person dangerously dehydrated. Some therapeutic drugs, such as heart-rate controlling (beta blocking) drugs will compromise work ability in jobs with high heat strain, such as moderate or hard work in hot environments.

Any worker who is taking any medication should receive medical clearance before being exposed to hot conditions.

Sick workers, especially those with a fever, are at special risk in stressful work environments because body temperature is regulated to higher temperature than normal. This means that the same amount of work produces the same heat storage, but at a higher, more dangerous temperature. A worker who normally tolerates the heat will, therefore, likely to be impaired.

Any disease that that may affect cardiovascular or kidney function or state of hydration (eg diarrhoea results in dehydration) may impact on heat tolerance.

Generally it is dangerous for the ill too work in hot environments.

### **8.1.3 Age**

The AIHA (2003) suggest that although not well studied, thermal tolerance to heat tends to be only slightly affected by age, although some earlier studies suggest that heat tolerances decrease in older people. Observed declines in thermal tolerance with age may be related to decreased physical capacity rather than ageing as such. However there is a definite decline in maximal work capacity with age. The fall in maximal cardiac output with age probably contributes to reduced work capacity and greater susceptibility to heat injury as well.

### **8.1.4 State of Acclimatisation**

In heat acclimatisation the body adapts in a number of ways:

- Increase in the amount of sweat which increases the potential for evaporative cooling.
- Earlier onset of sweating which reduces heat storage prior to activation of evaporative cooling.
- More dilute sweat (ie lower salt concentration) which reduces electrolyte (sodium and chloride) losses.
- Increased skin blood flow which provides greater convective heat transfer between deep body and skin.
- Reduction in heart rate at any given work rate, which lowers cardiovascular strain and the oxygen requirements of the heart.
- Greater use of fats as fuel during heavy work which conserves carbohydrates that are useful when very high rates of energy production are needed.
- Reduction in skin and deep body temperature at any given work rate which maintains a larger heat storage reserve and permits the worker to work at a higher rate.

These adaptations work together to reduce the deep body temperature and skin temperature ie heat strain for a given amount of work, providing a greater reserve for emergency or prolonged work requirements.

Heat acclimatisation occurs very rapidly with substantial adaptation apparent after only two hours of heat exposure per day for eight consecutive days (AIHA 2003). Additional acclimatisation continues to occur with additional exposure and is complete by 14 days.

If the seasonal changes are gradual, people working outside make a natural adaptation to either the heat or cold. However, sudden weather changes especially those of heat stress may result in dangerous levels of stress.

Workers beginning to work in hot environments for the first time need to have enough time to acclimatise. Acclimatisation to one heat level may only partially acclimatise the individual to higher heat exposures. Similarly acclimatisation can be lost to some degree after a long weekend and is almost extinguished after a vacation of four weeks or more. The longer a person spends away from the heat, the longer the time required for readaptation.

## **8.2 A SIMPLE INTRODUCTION TO CONTROL BY ENGINEERING AND ORGANISATIONAL MEASURES**

As with any exposure the principles of the hierarchy of control should be applied to exposures to hot environments. This applies in particular to work activities that are not “normal” or “regular or routine” and may include activities such as breakdown repair of hot equipment, the maintenance and repair of hot plant and equipment, replacement of thermal insulation materials etc. The work can be both of varying duration and to varying levels of heat exposure.

If exposure is unavoidable then the risk should be controlled to acceptable limits as determined by the risk assessment. Where, despite all reasonable environmental controls, temperatures continue to exceed the recommendations of the ACGIH, ISO 7243, ISO 7933, AIOH or other local or statutory recommendations, then additional precautions will be required to reduce risk to personnel including:

### **8.2.1 Environmental Controls**

#### **a) Control of the Source**

- Where heat is released from a particular process is it possible to reduce the temperature of the source of heat?

This can often be achieved where the exposures are of a relative short time during repair and maintenance type operations involving



hot equipment and insulating materials. It may be possible to isolate the section of plant or equipment, and allow it to cool before work commences. Alternatively it may be possible to reduce the temperature of steam and water in pipe work and plant before work commences.

- Can hot surfaces be insulated?

Insulation can reduce surface temperature and hence emission of radiant heat from the surface. A variety of insulation materials are available. Where existing insulation is to be replaced caution should be exercised in case the material contains asbestos.

The use of insulation can also provide protection from contact burns.

- Radiant heat

Radiant heat from surfaces depends on the nature of the surface itself. Bright surfaces have lower emissivities (ie lower radiant heat output) than dark or dull surfaces at the same temperatures. For example, a flat black surface (emissivity of 1.0) emits the most heat while a smooth polished surface (emissivity of zero) emits the least. The emissivity of oxidised aluminium is 0.1 whilst that of rusted steel is 0.85 and rough brickwork is 0.93. Therefore radiant heat emission from steel or brick surfaces can be reduced by cladding them with aluminium or tin.

- Radiant heat barriers

Where it is not possible to reduce radiant heat at the source, radiant heat barriers positioned between the source and worker will reduce direct radiant heat.

The barriers should be made of a material with good insulation properties and have surfaces of low emissivity/high reflectivity so they themselves do not become hot. Transparent materials such as partially silvered glass or selectively absorbing clear plastics can be used when it is necessary to view the heat source.

## **b) Ventilation, Air Conditioning and Air Movement**

Ventilation can be achieved by two ways

- By removing or diluting hot/humid air and replacing it with cooler/drier air.

This is the most efficient method and can be achieved by either forced mechanical ventilation or naturally. It is especially important in hot and humid environments.

Mechanical ventilation can be achieved with forced draft whereby air is taken from a cool place outside the immediate area and blown into the area to displace the hotter air.

Hot air (and also dust and gas emissions from a process) can also be exhausted or extracted from the area or above the process and removed directly into the atmosphere or into a fume collection system.

Push – pull systems i.e. a combination of the above methods can also be utilised.

Natural ventilation utilising air movement through open windows and doors can also be advantageous in removing heat from the workplace. Thermal updrafts above the pouring of molten metal for example rise to the top of the building and is typically allowed to escape through roof louvres.

- **Increasing air movement**

In general increasing the air velocity increases the rate of heat loss from the body by both convection and evaporation. Under certain conditions at temperatures above 35°C convective heat transfer can become a heat gain to the body. Unless the humidity is high the evaporative heat loss still outweighs the convective heat gain. At very high temperatures and/or humidities this is reversed. The net effect of increasing air velocity can be calculated from indices such as ISO 7933 and HSI. As a rule of thumb the BOHS (1996) suggest, if the wet bulb temperature is below 36°C, increasing air velocity is beneficial; if above 36°C, it is detrimental. The reasons for this are obvious as air above 37°C blown over workers will, in the absence of other controls, add to their thermal load.

**c) Artificial Cooling**

Often there is no real advantage in using ambient air if the temperature of this air is not significantly different to that of the work area and the use of artificially cooled air is required.

Evaporative cooling reduces air temperature by spraying water into the air stream or passing the air over a wetted element. Other methods include the use of chillers and vortex tubes.

In some circumstances, eg furnace shutdowns where people have to go into the furnace as soon as possible, large capacity mechanical chillers and air condition units can be set up to reduce the air and radiant temperature prior to entry.

## **8.2.2 Administration Controls**

A variety of administration controls can also be used:

- **Worker Selection**

Worker selection can raise moral and ethical issues.

For example, excluding women from some hot jobs may be unethical and illegal sex discrimination, but exposing known pregnant women to jobs that threaten heat strain is certainly unethical. What do you do with workers with heart conditions? Stopping them from performing certain jobs may be highly ethical in some situations circumstances and unethical in others, depending on the circumstances. Ethical issues must be considered on a case by case basis.

Workers may be selected on the basis of the nature of the work and selecting workers based on obvious factors seems reasonable. For example, an acclimatised, fit, lean worker generally would be expected to tolerate greater heat stress than an overweight, unfit, unacclimatised worker. Although this is generally true, the only way to assess worker tolerance is to observe workers. Over a period of time it may be possible to see who is most tolerant of a given workload and environmental condition. Personal monitoring would be preferable and desirable, but not is always practical.

- **Worker Training**

Training is required for all workers likely to be involved with work in hot environments, undertaking strenuous work at elevated temperatures and those required to work in impermeable protective clothing.

The AIOH (2013) guidance recommends that training should include the following:

- Mechanisms of heat exposure
- Potential heat exposure situations
- Recognition of predisposing factors
- Importance of fluid intake
- The nature of acclimatisation

- Effects of alcohol and drugs in hot environments
- Early recognition of symptoms of heat illness
- Prevention of heat illness
- First aid treatment of heat related illnesses
- Self assessment
- Management and control
- Medical surveillance programs and the advantages of employee participation in programs

This is a very comprehensive training guide and if implemented should significantly reduce the risk of heat stress.

Training of all personnel in the area of heat stress management should be documented.

- **Self Assessment**

Self assessment is critical key element. With the correct knowledge of the early signs and symptoms individuals will be able to take the appropriate actions to prevent the onset of more serious heat related illnesses. This may be as simple as taking a short break and having a drink of water.

- **Scheduling of Work**

Often it is not possible to schedule when work will have to be undertaken in hot environments especially in breakdown situations. But where annual forward planning is possible factors to consider include:

- Time or season of year.
- Time of day especially for outdoor work – can it be done at night rather than at midday.

- Outdoor work requiring protective clothing should, when practical be done in the cooler months.

- **Work–Rest Intervals**

Work-rest intervals are often used to control the exposure of workers to heat as recommended in ISO 7243 (1989) and by the ACGIH (2015). As heat strain increases the ratio of work to rest must fall. But this is not as simple as it seems. Use of a rational index can be useful in determining approximate work/rest durations. However caution must be exercised when high levels of PPE are utilised. For example if the worker is required to wear protective clothing they often do not take it off during the rest period and hence do not cool off properly before resuming work. Rest periods should be spent in preferably in a cool place with a plentiful supply of cool water for fluid replacement.

- **Fluid Replacement**

Fluid replacement is critical when working in a hot environment especially where their hard work (metabolic work) is being undertaken. Guidelines from the AIHA (2003) for fluid replacement include:

- Workers should be careful to consume a well balanced diet and drink plenty of non-alcoholic beverages in the day preceding a severe heat exposure.
- Workers should avoid diuretic drinks immediately prior to work.
- During work workers should try to drink small volumes and as frequently as possible.
- Workers should be provided cool drinks that appeal to them. .
- Workers should be encouraged to rehydrate between work shifts.

- Body weight should be monitored at the start and end of each shift to ensure that progressive dehydration is not occurring.

Specific gravity of urine is also a useful tool as an indicator of overall hydration and is increasingly being utilised in industry and mining. The approach and further detail has been discussed in Section 4.3.

### **8.2.3 Personal Protective Clothing and Equipment**

Clothing and particularly protective clothing can often have an adverse effect on the body's heat balance in hot environments by insulating the body and reducing evaporative heat loss. Impervious clothing especially impedes heat loss and the wearing of such clothing may present some risk if physically demanding work or exercise is carried out at air temperatures as low as 21°C, particularly if the worker is not acclimatised, is unfit or otherwise susceptible.

Clothing and especially protective clothing can contribute to the overall heat storage of the body especially if it has a high insulation factor ( $I_{clo}$ ). The unit of insulation is the clo and by definition 1 clo is the insulation provided by clothing sufficient to allow a person to be comfortable for a seated or sedentary person at 21°C, Relative Humidity of 50% in still air.

Using this definition, typical clothing ensembles can be rated as listed in Table 8.1.

**Table 8.1 – Typical Clothing Insulation Values**

<b>Clothing Ensemble</b>	<b>I<sub>clo</sub> (clo)</b>
Naked	0
Shorts	0.11
Long trousers	0.22
Daily non-work clothing (underpants, shirt, light-weight trousers, socks & shoes)	0.6
Work Clothing (Underpants, shirt, trousers, socks & shoes)	0.75
Indoor clothing – suit	0.96
Heat protective clothing (briefs, shirt, trousers, aluminized hip length coat, socks & shoes)	1.36
Heavy suit with vest	1.49
Chemical resistant coverall with hood, respirator, helmet, rubber gloves & boots and full length underwear	2.0
Cold protective clothing (expedition suit)	3 – 4

Source: Corletto 2015 (Based in part on IOS 9920)

In some circumstances, clothing may provide protection against heat. Protective clothing, especially if made from natural fibre, will provide some protection against contact burns and radiation. Dark colours, especially black absorb most direct and reflected radiant heat energy and there could well be an increased risk of heat strain. Light colours, especially white, and reflective clothing (e.g. aluminised) absorbs comparatively little radiant heat energy and there could be a reduced risk of heat strain.

For protection against contact with very hot surfaces, or from molten metal splash, special clothing assemblies may be required and may be specified in local or International Standards.

Heat resistant protective clothing will only give protection for limited periods and may have a detrimental effect if exposure continues. If continued



exposure is necessary in circumstances where it would not otherwise be permitted, the use of cooled or conditioned personal protective clothing may allow for longer exposures.

There are a number of different systems and devices available and used in industry for personnel and have been described by the AIOH (2013) and include:

- **Air Circulating Systems**

Air circulating systems usually incorporate the use of a vortex cooling tube. Depending on the size of the vortex tube, they may be used to cool a large volume system such as a tank or may be utilised as a personal system whereby the vortex is worn on the belt and cool air is fed into an air supplied helmet and/or vest. The balance of air volumes and temperature is important.

Breathing quality air should only be used for such air supplied systems. While often providing cool air to the wearer, air supplied systems as such suffer from the obvious disadvantage of being attached to an airline and the air lines can become caught, entangled or air lines can come into contact with hot surfaces and become damaged.

The systems can be quite effective and are considerably less expensive than water circulating systems.

- **Liquid Circulating Systems**

These systems rely on the principle of heat dissipation by transferring heat from the body of the liquid and then the heat sink (which is usually an ice water pack). Liquid (water) cooling suits must be worn close to the skin and the chilled liquid is pumped through fine capillary tubing from either a battery powered pump worn on the belt or through an “umbilical cord” from a remote cooling unit.

## **Ice Cooling Systems**

Traditionally ice cooling garments involved the placement of ice in pockets in an insulating garment, typically a vest, worn close to the skin such that heat is conducted away. This in turn cools the blood in the vessels close to the skin surface, which then helps lower the core temperature.

One of the principle benefits of these systems is the increased mobility afforded the wearer and it is also less costly than the air or liquid circulating systems.

Ice has recently been replaced with other “phase change” materials such as n-tetradecane type liquids which freeze at 10°C - 15°C resulting in several immediate benefits.

- it is not as cold on the skin, and hence more acceptable to the wearer,
- The chill factor is reduced hence minimising the vaso constriction of the blood vessels on contact, and
- to freeze the solution it only requires a standard refrigerator or an insulated container full of ice water.

## **• Reflective Systems**

Reflective clothing is utilised to help reduce radiant heat load on an individual. It acts as a barrier between the person’s skin and the hot surface reflecting away the infrared radiation. The most common configuration of reflective clothing is an aluminised surface bonded to a base fabric.

In some situations only the front of the body is exposed such as in a furnace inspection and hence an apron would be suitable. In other jobs a full suit may be required. Caution must be exercised when using a full suit as it will affect evaporative cooling of the individual. The suit should be worn as loose as possible with minimal other clothing to facilitate air circulation to aid evaporative cooling.

It may also be possible to combine the use of a cooling vest under a reflective jacket to help improve “stay times”. However once combinations of PPE are used they may become too cumbersome to use. Such combinations of PPE should be trialled before undertaking the required tasks to ascertain their suitability.

A suggested strategy for the wearing of personal protective equipment in heat is:

Can you:

- Do without it?
- Wear it for less time?
- Cover less of body?
- Reduce thermal insulation?
- Increase wicking and moisture permeability?
- Reduce weight?
- Reduce number of layers/bulk?
- Use auxiliary cooling system?

*but* consider the weight.

#### **8.2.4 AIHA Checklist for Heat Exposures**

The AIHA (2003) provide a convenient checklist for work in hot environments:

- Are adequate supplies of palatable cool drinks available?
- What is the major source of heat stress and how can it be mitigated (eg protective clothing requires particular strategies)?
- If radiant shielding (including shade) is possible, is it in the most strategic location?
- Is temperature monitoring equipment available at the work site?
- Are work guidelines that are appropriate to the situation available to workers and supervisors?

- Are first aid supplies available that are appropriate to heat/cold emergencies?
- Has an appropriate work rate been determined, and is there sufficient manpower to stay on schedule despite a slower work pace?
- Have supervisors been instructed to remove workers at the first sign of problems?
- Have workers been properly and thoroughly acclimatised (or reacclimatised after a time away from the stressing environment)?
- Is a cool recovery/rest area available?
- Are workers and supervisors trained in recognising the symptoms, and providing first aid treatment of heat injury?
- Is there a means of calling emergency medical support? Do workers know how and where to call emergency medical support?
- Is the clothing appropriate (minimal obstruction of sweat evaporation and maximal protection from radiant heat ie use the lightest, most permeable clothing that provides adequate safety)?
- Is the air velocity as high as practical?
- Are workers well hydrated at the beginning of work?
- Is spot cooling available?
- Is microclimate cooling (eg cool type vests) available as needed?
- Have workers who might be pregnant, or those with cardiovascular problems, previous heat injuries, on problematic medications and who have fever, been protected from elevated internal body temperatures?

- Have workers been reminded of appropriate safety precautions?

*(Used with permission of the American Industrial Hygiene Association – 2007)*

While it may be argued that other factors should be included in the list (workplace monitoring, work-rest schedule, documented risk assessment) it does serve to highlight the various factors that need to be considered before commencing work in hot environments.

### **8.2.5 Refuges**

Refuges can also be used a method of for workers to seek shelter in to escape from the effects of a hot environment. These shelters are typically insulated structures or cabins which need to be air conditioned to reduce the effects of the radiant heat of the environment.

## **8.3 HOT SURFACES**

### **8.3.1 Introduction**

When human skin comes into contact with a hot surface the skin temperature rises. This causes a reaction that can vary from local vasodilatation and sweating to pain sensations and physical damage (ie burning) to the skin.

Whether or not burns occur depends on a number of factors including:

- The temperature of the surface
- The material of the surface
- The period of contact between the skin and the surface
- The structure of the surface
- The sensitivity of the person who comes into contact with the hot surface (eg adult or child)

Touching a hot surface may take place intentionally, (eg to operate a machine or tool) or unintentionally, when a person is near a hot object. The period of contact with the hot surface will be different if the object is touched intentionally

than if it is touched unintentionally. Considering human reaction times 0.5 seconds is the minimum applicable contact period for unintentional touching of a hot surface.

- **Skin Burns**

At temperatures above around 43°C, damage can begin to occur if exposure to that temperature is long enough. It is generally true therefore, that if skin temperature in contact with a solid surface is below about 43°C, discomfort and pain sensations will be avoided and no skin damage will occur.

Note that this applies to local skin temperatures. If the whole body were at 42°C then there would be a serious breakdown in thermoregulation, since “safe upper limit” levels for internal body temperature are less than around 38.5°C.

There are a number of methods for classifying skin burns and all are based on the extent of skin damage to the different layers of skin.

- **Solid Surfaces**

Skin reactions to contact with a hot solid surface will depend upon the rate at which heat transfers from the surface to the skin. Metals, for example will “give up” heat more easily than wood, for similar circumstances. Factors relating to the solid surface that may, on contact, affect heat transfer to the skin include: number of layers, surface roughness, wet or dry, surface temperature, thermal conductivity, specific heat, density, material thickness and surface cleanness.

### 8.3.2 ISO 13732-1

A number of empirical, mathematical models of heat transfer and other comprehensive models have been used as the basis for the setting of standards and limits around the world by different standard setting organisations.

Recently the ergonomics standard committee of ISO has released a series of Standards in this area of human skin reaction to contact with solid surfaces for hot (Part 1), Moderate (Part 2) and Cold surfaces (Part 3).

ISO 13732-1:2006 – “Ergonomics of the thermal environment – Methods for the assessment of human responses to contact with surfaces - Part 1 Hot surfaces.”

The standard provides detail advice on:

- Burn thresholds
- Assessment of risk of burning
- Protective measures

and is summarised briefly below.

- **Burn Thresholds**

The burn threshold is defined as the temperature values of hot surfaces of products which, when in contact with the skin, lead to burns.

Burn threshold data is provided for three different contact periods namely:

- Between 0.5 seconds to 10 seconds
- Between 10 seconds and 1 minute
- Between 1 min and longer (8 hour and longer)

This data, in graphical form, is provided in the Standard for:

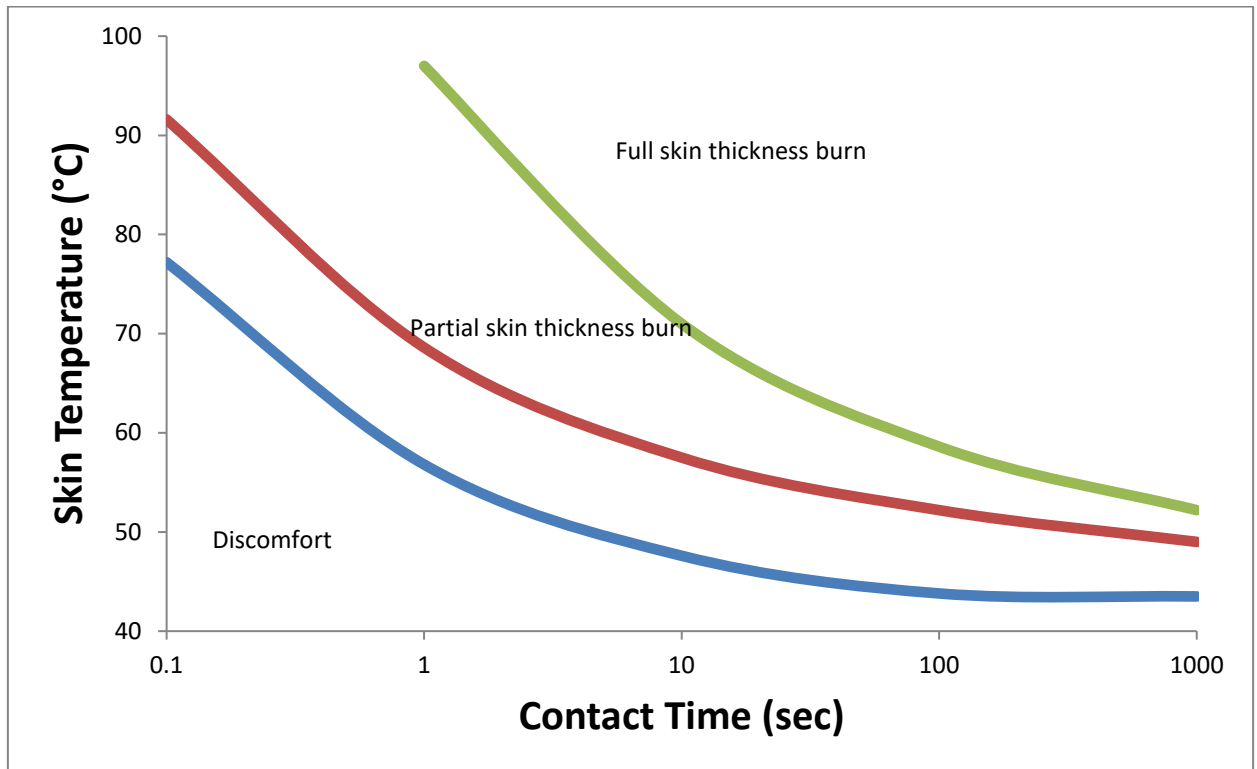
- Hot, smooth surface made of bare (uncoated) metal
- Coated metals
- Ceramics, glass and stone materials
- Plastics
- Wood

As an example, coated metal has burn thresholds for contact periods of 1 minute (51°C), 10 minutes (48°C), and 8 hours and longer (43°C).

It should be noted that the value of 43°C used for all materials for a contact period of 8 hour and longer applies only if a minor part of the body (less than 10% of the entire skin surface of the body) or if a minor part of the head (less than 10% of the skin surface of the head) touched the hot surface. If the touching area not only local or if the hot surface is touched by vital areas of the face (eg the airways), severe injuries may occur even if the surface temperature does not exceed 43°C.

Curves relating to temperature and contact time to burns have been developed as guides. An example from the work of Lawrence and Bull (1976) is illustrated in Figure 8.1.





**Figure 8.1: The relation of time and temperature to cause discomfort and thermal injury to skin**

(in AIOH 2013: adapted from Lawrence & Bull, 1976)

- **Assessment of Risk of Burning**

The following procedures should be carried out:

- Identification of hot, touchable surfaces
- Task analysis
- Measurement of the surface temperature
- Choice of applicable burn threshold value
- Comparison of the surface temperature and the burn threshold
- Determination of the risk of burning
- Repetition of the assessment

- **Protective Measures Against Burns**

- Engineering Measures***

- Reduction of surface temperature
    - Selection of surface materials and textures with high burn thresholds
    - Insulation (eg wood, cork, fibre coating)
    - Applying guards (screens or barriers)
    - Surface structuring (eg roughening, use of ribs or fins)
    - Increasing the distance between parts of a product which are intentionally touched and hot surfaces of the product

- Organisational Measures***

- Fixing of warning signs
    - Actuating warning signals (visual and acoustic alarm signals)
    - Instruction and training of users
    - Technical documentation, instructions for use
    - Setting of surface temperature limit values in product standards and regulations

- Personal Protective Measures***

- Use of individual protective equipment (eg clothing, gloves etc)

## **9. EVALUATION OF COLD ENVIRONMENTS**

### **9.1 INTRODUCTION**

Cold stress is defined as a thermal load on the body under which greater than normal heat losses are anticipated, and compensatory thermoregulatory actions are required to maintain the body thermally neutral.

In air environments, cold stress generally produces severe discomfort before any effect on health occurs. Thus, there is a strong behavioural reaction to cold whereby actions such as increased clothing, increased activity or shelter area taken to avoid the effects.

Care needs to be exercised when describing what a “cold” environment is. For those environments where the loss of heat from the body occurs, the description of “cold” is common, however there are circumstances where the air temperature may be considered cold but the thermal environment may in fact be considered hot. As an example consider the case of a person who is heavily clothing performing heavy work in a “cold” air temperature of 5°C. This person in all likelihood is hot and sweating into their heavy clothing in an attempt to lose heat. When the person rests, then the previously warm to hot human thermal environment of 5°C air temperature, becomes cold and heat loss and discomfort are exacerbated by damp clothing. In human thermal environment terms, the person has gone from a hot to a cold environment, whereas the air temperature has not changed.

Unfortunately, standards relating to the performance of work, thermal regulation and exposure duration in cold environments are less well validated than those for persons working in hot environments. The objectives of cold exposure standards are to avoid the core body temperature falling below 35°C and also to prevent cold injury to the extremities of the body.

Much of the investigation into cold stress indices has been associated with military and expedition type activities and in respect to working outdoors. There is increasing interest in working indoors, particularly in freezer rooms.

## 9.2 WIND CHILL INDEX & EQUIVALENT CHILLING TEMPERATURE

The wind chill index (WCI) can be described as the cooling power of the atmosphere and combines the effects of air temperature and air velocity into a single index. The WCI was first considered in Antarctica of the freezing time of 250 g of water in a plastic cylinder suspended freely in variable atmospheric conditions whose temperature and wind velocity were known (MacPherson 1962). To determine the effects of cooling on humans, numerous simultaneous observations of the time required for the freezing of normal human flesh exposed in the path of cold wind were made by a medical officer (Parsons 2003). Approximately twenty separate subjects took part in the experiments and almost all exhibited freezing of the nose with additional freezing of the eyelids, cheeks, wrist, side of temple and chin. From this a scale of cooling power of the atmosphere to human effects was constructed. An equation was derived to estimate the rate of cooling of exposed skin, which is commonly expressed in SI units as:

$$\text{WCI} = 1.16 (10\sqrt{v} + 10.45 - v) (33 - t_a)$$

Where: WCI = Wind Chill Index in  $\text{Wm}^{-2}$

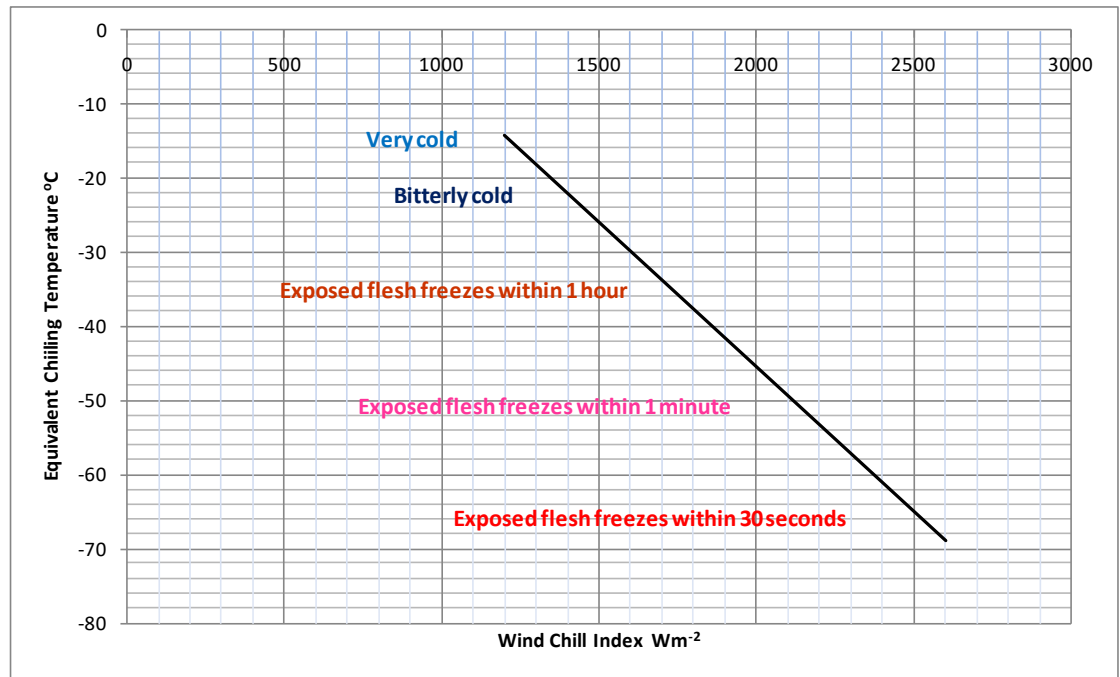
$v$  = Air Velocity in  $\text{ms}^{-1}$

$t_a$  = Temperature of the Atmosphere  $^{\circ}\text{C}$

The WCI reflects the cooling power of the wind on exposed flesh and is commonly expressed as an equivalent chilling temperature ( $t_{\text{ch}}$ ). The  $t_{\text{ch}}$  is the temperature under calm wind ( $v = 1.8 \text{ ms}^{-1}$ ) which would provide cooling of the skin (ie the same WCI) equivalent to that found with other combinations of temperature and wind. This can be restated as:

$$t_{\text{ch}} = 33 - \frac{\text{WCI}}{25.5} \text{ } ^{\circ}\text{C} \quad \text{if WCI is expressed in } \text{Wm}^{-2}$$

The effect on exposed flesh, at various WCI and  $t_{\text{ch}}$ , is provided in Figure 9.1.



**Figure 9.1 – Effect on Exposed Flesh**

The WCI is the most widely used cold stress index despite its theoretical limitations. The WCI does not recognise the amount of clothing being worn, but relates instead to bare skin such as the face and hands. The WCI does provide a comparative scale for the cooling power of the wind, but because of exaggerated importance of wind for people dressed in heavy clothing and having face and hand protections, is conservative for such situations.

### 9.3 REQUIRED CLOTHING INSULATION INDEX

The concept of an index of required clothing insulation (IREQ) was first developed by Holmer (1984) and is the resultant clothing insulation required to maintain the body in thermal equilibrium under steady state conditions when sweating is absent and peripheral vasoconstriction is present.

In effect the important role of clothing insulation omitted in the WCI is used in IREQ to express cold stress in terms of general body cooling and the insulation required to maintain thermal balance.

The method for calculation of IREQ is defined in terms of the heat balance equation in ISO document ISO 11079 (2007), however the calculation is

complex and requires a computer programme and is beyond the scope of this course.

Two indices are proposed; clothing insulation required for heat balance ( $IREQ_{min}$ ) and clothing insulation required to provide comfort ( $IREQ_{neutral}$ ). These indices are based on physiological strain and are defined as:

$IREQ_{(min)}$ : A minimal thermal insulation to maintain body thermal equilibrium at a subnormal level of mean body temperature. This represents the highest admissible body cooling in occupational work.

$IREQ_{(neutral)}$ : A neutral level of insulation required to provide body thermal equilibrium at a normal level of body temperature. This represents no or minimal cooling of the human body.

Thus for a given situation, choice of a clothing ensemble with resultant insulation values below the  $IREQ_{min}$  would result in a risk of progressive body cooling while values higher than  $IREQ_{neutral}$  conditions would be considered warm and overheating may occur.

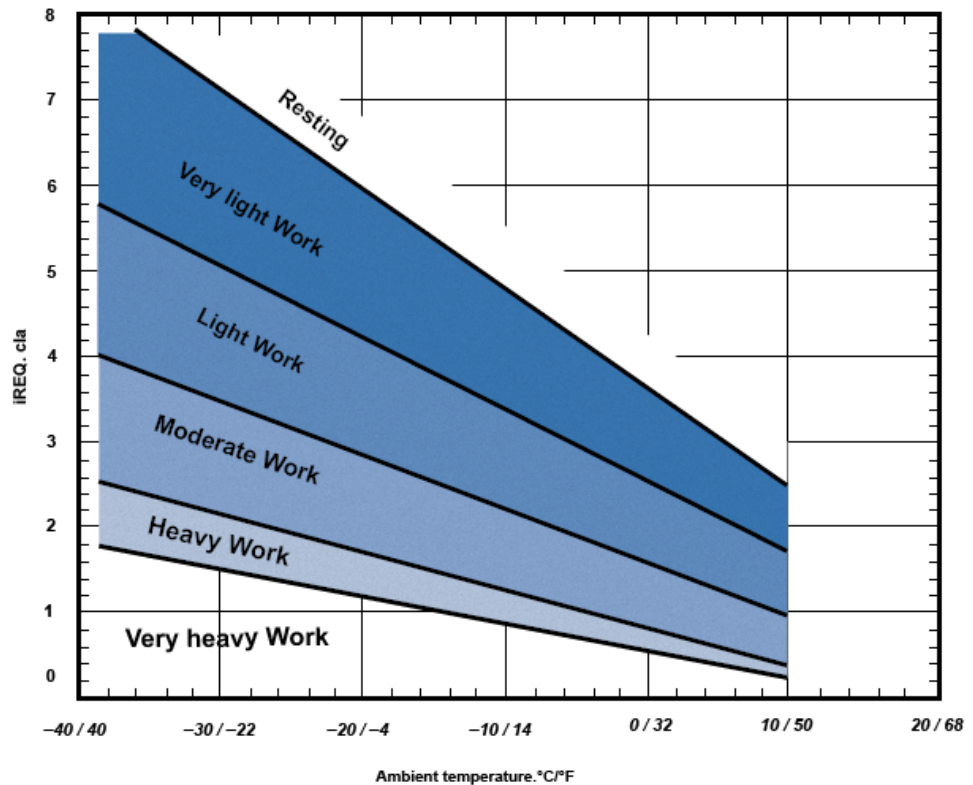
When the resultant insulation value of the selected clothing ensemble (Section 10.4.2) is less than  $IREQ_{min}$  exposure has to be time limited to prevent progressive body cooling. For these conditions, allowable exposure times (called duration limited exposures ( $D_{lim}$ )) can be calculated from:

$$D_{lim} = \frac{Q_{lim}}{S}$$

Where:  $Q_{lim}$  = Heat storage limit ( $Whm^{-2}$ )  
 $S$  = Rate of heat storage

After exposure to cold, a recovery period should be allowed to restore normal body heat balance. Recovery time (RT) may be calculated in the same way as  $D_{lim}$  if  $S$  is the rate of heat storage for the thermal conditions during the recovery period.

The AIHA (2003) depicts typical relationships between IREQ and metabolic rate at various ambient temperatures (Figure 9.2). This can be used to select the appropriate clothing ensemble necessary to control body cooling in cold conditions.



(Used with permission of the American Industrial Hygiene Association [2007])

**Figure 9.2 – IREQ at Varying Levels of Activity**

Parsons (2003) states that the usefulness of the IREQ in practical applications is yet to be determined. It is commonly thought that tolerance to cold is dominated by local skin temperatures (hands, face, feet) and problems occur due to sweating in clothing when working and gives rise to subsequent problems when resting.

From the above, it is possible to see that application of the IREQ as an index of cold environments requires significant knowledge, expertise and information and should only be applied by those experienced in this area.

#### **9.4 ACGIH TLV STANDARDS**

The intention of the ACGIH Cold Stress TLVs is to protect workers from hypothermia and cold injury to the extremities and to describe exposures to cold working conditions under which it is believed that nearly all workers can be repeatedly exposed without adverse health effects. The basis of the ACGIH TLVs is therefore defined in terms of preventing the core body temperature from falling below 36°C and to prevent cold injury to body extremities with emphasis on hands, feet and head.

For a single occasional exposure to a cold environment, the ACGIH proposes that a drop in core temperature to no lower than 35°C should be permitted but offers the caution that when the core temperature has reached 35°C this must be taken as a sign of danger to workers. Moreover exposure should be terminated immediately for any workers when severe shivering becomes evident.

Thus, the ACGIH TLVs recommended for properly clothed workers in cold environments are calculated on workload and wind speed and presented as a work/warm-up schedule for a four hour work shift.



Air Temperature - Sunny Sky °C (approx)	No Noticeable Wind		5 mph Wind		10 mph Wind		15 mph Wind		20 mph Wind	
	Max Work Period	No. of Breaks	Max Work Period	No. of Breaks	Max Work Period	No. of Breaks	Max Work Period	No. of Breaks	Max Work Period	No. of Breaks
-26° to -28°	(Norm Breaks) 1		(Norm Breaks) 1		75 mins	2	55 mins	3	40 mins	4
-29° to -31°	(Norm Breaks) 1		75 mins	2	55 mins	3	40 mins	4	30 mins	5
-32° to -34°	75 mins	2	55 mins	3	40 mins	4	30 mins	5	Non-emergency work should cease	
-35° to -37°	55 mins	3	40 mins	4	30 mins	5	Non-emergency work should cease			
-38° to -39°	40 mins	4	30 mins	5	Non-emergency work should cease					
-40° to -42°	30 mins	5	Non-emergency work should cease							
-43° & below	Non-emergency work should cease									

**Notes:**

- Schedule applies to any 4-hour work period with moderate to heavy work activity, with warm-up period of ten (10) minutes in a warm location and with an extended break (eg lunch) at the end of the 4-hour work period in a warm location. For Light-to-Moderate Work (limited physical movement): apply the schedule one step lower. For example, at -35°C (-30°F) with no noticeable wind (step 4), a worker at a job with little physical movement should have a maximum work period of 40 minutes with 4 breaks in a 4-hour period (Step 5).
- The following is suggested as a guide for estimating wind velocity if accurate information is not available:  
5 mph: light flag moves; 10 mph: light flag fully extended; 15 mph: raises newspaper sheet; 20 mph: blowing and drifting snow.
- If only the wind chill cooling rate is available, a rough rule of thumb for applying it rather than the temperature and wind velocity factors given above would be: 1) special warm-up breaks should be initiated at a wind chill cooling rate of about 1750 W/m<sup>2</sup>; 2) all non-emergency work should have ceased at or before a wind chill of 2250 W/m<sup>2</sup>. In general, the warm-up schedule provided above slightly under-compensates for the wind at the warmer temperatures, assuming acclimatisation and clothing appropriate for winter work. On the other hand, the chart slightly over-compensates for the actual temperatures in the colder ranges because windy conditions rarely prevail at extremely low temperatures.
- TLVs® apply only for workers in dry clothing

(Note: 5 m/hr = 8 km/hr)

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**Figure 9.3 – ACGIH TLV as a Work/Warm-up Schedule for a 4 Hour Shift**

The ACGIH also suggests the use of equivalent chilling (or chill) temperature (see Section 9.2) for control of injury to exposed skin. In this case the ACGIH suggests that for exposed skin, continuous exposure should not be permitted when the equivalent chill temperature is below -32°C (Figure 9.4).

<b>WIND CHILL CHART</b>										
		Ambient Temperature (°C)								
		4	-1	-7	-12	-18	-23	-29	-34	-40
Wind km/h	Velocity mph	Equivalent Chill Temperature (°C)								
<b>Calm</b>										
0	0	4	-1	-7	-12	-18	-23	-29	-34	-40
8	5	3	-3	-9	-14	-21	-26	-32	-38	-44
16	10	-2	-9	-16	-23	-30	-35	-43	-50	-57
24	15	-6	-13	-20	-28	-36	-43	-50	-58	-65
32	20	-8	-16	-23	-32	-39	-47	-55	-63	-71
40	25	-9	-18	-26	-34	-42	-51	-59	-67	-76
48	30	-16	-19	-22	-36	-44	-53	-62	-70	-78
56	35	-11	-20	-29	-37	-46	-55	-63	-72	-81
64	40	-12	-21	-29	-38	-47	-56	-65	-73	-82

Source: Threshold Limit Values (TLV™) and Biological Exposure Indices (BEI™) booklet; published by ACGIH, Cincinnati, Ohio

<b>Little danger</b> in less than one hour exposure of dry skin	<b>DANGER</b> – Exposed flesh freezes within one minute	<b>GREAT DANGER</b> – Flesh may freeze within 30 seconds
---	---	--

(Note: 1 km/h = 0.28 ms<sup>-1</sup>)

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**Figure 9.4 – ACGIH Wind Chill Chart**

All the above recommendations are based on dry well-clothed workers. For those cases where immersion is a factor or clothing becomes wet, it is imperative at air temperatures of 2°C or less that a change of clothing is provided and the workers concerned be treated for hypothermia.

## 9.5 USE OF COLD STRESS INDICES

It is important to note that no one index can accurately account for the numerous variables associated with cold stress assessment and for that reason they should only be used as guidelines not safe or unsafe limits. Different indices have application in different thermal and work conditions and all have some limitations in terms of their ability to predict human response to the environment.

The most appropriate means of addressing cold stress issues is by directing most effort to controlling and managing the risk factors present in an individual scenario.

## **10. CONTROL OF COLD ENVIRONMENTS**

### **10.1 PERSONAL FACTORS**

Parsons (2003) provides a number of guidelines for work practices in cold thermal environments. One of these is the screening of workers and it is suggested that workers should be excluded who are suffering from diseases or taking medication which interferes with normal body temperature regulation or reduces tolerance to cold.

People who suffer from heart disease, especially in the older age group, are at greater risk of a coronary heart attack in cold conditions. The increased incidence of angina attacks and coronary and cerebral thrombosis in cold temperatures is probably due to increased blood pressure, cardiac strain and increased blood viscosity.

Respiratory disease is also enhanced in cold weather particularly when there are atmospheric pollutants with freezing fog or smog. Cold may cause bronchospasm and adversely affect physical work performance and in some may lead to exercise-induced asthma.

Cold allergy occasionally develops on removal from the cold with widespread vasodilatation over the whole body, headache and hypotension. Those with circulatory problems require special protection against cold. Individuals who suffer from Raynaud's phenomenon (constriction of blood supply to the extremities causing white finger or toe) are particularly sensitive to local cold, which causes intense vasospasm and numbness in the unprotected extremities. Raynaud's phenomenon in the hands is known to result from vibration ('vibration white finger') caused by the use of pneumatic tools so that this may be a particular hazard in cold conditions.

A cold air-stream directed onto the side of the face can sometimes induce an acute paralysis of the facial nerve. This arises from swelling entrapment of the

nerve in the bony facial canal and it results in a Bell's palsy on one side of the face which may take some weeks to resolve.

Employees should be excluded from work in cold at  $-1^{\circ}\text{C}$  or below if they suffer from disease of the thermoregulatory or cardiovascular systems or if they are taking any medication that may reduce their tolerance to work in cold environments. Proper medical screening of potential workers in cold conditions is therefore important. In this regard Parsons (2003) indicates that the knowledge of how medical disorders are affected by cold is incomplete. Notwithstanding this fact, some specific disorders are consistently used in screening as indicators that will increase risk.

Parsons (2003) provides a list of screening factors listed by the British Refrigerated Food Industry Confederation. Factors included in the list are:

- Heart or circulation problems
- Diabetes
- Thyroid problems
- Blood disorders
- Kidney or urine disorders
- Any kind of arthritis or bone disease
- Any infection including ear, nose and throat
- Lung function problems or asthma
- Chronic gastro-enteritis or acute diarrhoea or vomiting (must be notified the same day)
- Neurological (nerve) malfunction
- Psychological problems
- Eyesight or hearing difficulty
- Prescribed medication

Parsons (2003) describes the above list as "sensible" but lacking detail on interpretation which makes this application somewhat arbitrary.

Notwithstanding these issues the list should be used as guidance until a more detailed approach is available.

Further information on the interpretation of an individual's fitness for the tasks to be performed can be found in ISO 12894 (2001).

## **10.2 ENGINEERING CONTROLS**

Given that one of the most critical factors in the onset of cold stress is wind chill, any engineering process that can reduce exposure to the wind and thus the cooling power of the air is useful. The two common approaches are the use of wind barriers and refuges. Wind barriers (shields) have been found to be effective outdoors or against circulated air indoors in freezer rooms. The provision of local refuges, equipped with warm drinks and warm conditions so that workers can retreat to rest, are an essential engineering control. If the refuge can be constructed around the work area so that the required task is performed inside, this presents an excellent work environment. Other engineering controls that should be considered include:

- For work below 0°C, metal handles and bars should be covered by thermal insulating material. Avoid metal tools if possible.
- Provision of local heating, hot air jets, radiant heating if bare hands have to be used.
- The use of mechanical aids should be encouraged so as to reduce manual handling requirements (hence reducing the potential for perspiration).
- Machines and tools should be designed so that they can be operated without having to remove mittens or gloves.
- Designing workplaces so that operators are not required to sit or stand for long periods in cold conditions.

- Reducing air velocity in cool rooms/chillers while workers are required to work inside.

## **10.3 MANAGEMENT CONTROLS**

### **10.3.1 Monitoring**

The ACGIH (2007) suggests the following workplace monitoring strategy be adopted.

1. Suitable thermometry should be arranged at any workplace where the environmental temperature is below 16°C.
2. If the air temperature in a workplace falls below -1°C the dry-bulb temperature should be measured and recorded at least every four hours.
3. In indoor workplaces, the wind speed should be recorded at least every four hours whenever the velocity exceeds 2 ms<sup>-1</sup>.
4. In outdoor situations the wind speed should be measured and recorded together with the air temperature whenever the air temperature is below -1°C.
5. The equivalent chilling temperature ( $t_{ch}$ ) should be calculated (see Section 9.2 and Figure 9.4) in all cases where air measurements are required and recorded whenever the  $t_{ch}$  is below -7°C.

Parsons (2003) suggests that air temperature, air velocity and equivalent chill temperature should be monitored and in the absence of any formal requirements from statutory authorities either of the above approaches would be appropriate.

### **10.3.2 Work-Rest Regimes**

The concept of work-rest schedules was developed by the Saskatchewan Department of Labour in Canada and subsequently by the ACGIH as threshold limit values for cold stress (Figure 9.2).

The ACGIH Schedule applies for a four hour shift for moderate to heavy work activity with warm up breaks of 10 minutes in a warm location.

As an example; a worker exposed to conditions of  $-35^{\circ}\text{C}$  at a wind speed of 8 km/hr should have a maximum work period of 40 minutes with four breaks in a four hour period.

If a worker is undertaking a job that requires little physical movement (light to moderate work activity) then the schedule should be applied at one step lower than that for moderate to heavy work activity.

In the example above, a person undertaking light to moderate work should have a maximum work period of 30 minutes with five breaks in a four hour period.

The schedule of work-rest is only applicable for workers in dry clothing and several changes of clothing during the work period may be required.

Natural work-rest routines vary for workers of different ages and because of the metabolic cost of different tasks. It is therefore inappropriate to insist on rigid work recovery routine for all operatives but to tailor the system to suit the needs of the individuals involved.

### **10.3.3 Other Managerial Controls**

A number of other managerial controls are available so as to minimise the effects of exposure to cold. Such controls (and the others highlighted above) should be established via means of a detailed risk assessment prior to undertaking any tasks.

Examples of other managerial controls include:

- *Education* – Workers and supervisors involved with work in cold environments should be informed about the symptoms of adverse health effects from exposure to cold. Other information such as proper clothing



habits, safe work practices, physical fitness requirements and emergency procedures should be communicated.

- *Medical Screening of Workers* – Workers who are suffering from respiratory or cardiac diseases or taking medication which interferes with normal body temperature regulation should be excluded from work in cold environments.
- *An acclimatisation period* is recommended for new workers (eg a period of approximately one week is recommended). Persons who work regularly in a cold environment become acclimatised. Persons differ in their ability to acclimatise to cold. Extra attention should be paid to those returning to work after an extended absence from cold exposure situations due to illness.
- *Accurate verbal and written instructions, frequent training* and other information about the signs and symptoms of cold stress, emergency procedures and preventative measures, should be undertaken on a regular basis. This is to ensure individuals can identify signs and symptoms of cold stress in themselves and others at an early stage. Training is often most effective when reinforced during medical evaluations.
- *Regular supervision* to monitor for signs and symptoms of workers exposed to potentially hazardous cold conditions. This may involve asking workers if they are well. Workers who are showing visible signs of cold stress (ie shivering, cold and pale skin, 'puffy' face, signs of confusion, poor co-ordination, etc) must be removed from the cold conditions to rest in a warm and dry area. The occurrence of shivering and numbness or pain in fingers and toes may be used as an early warning of possibly more serious cold stress issues. Fingers and toes should be regularly checked to be sure they are dry and warm. Travel or work in extreme cold should be done in pairs or groups.

- *Encourage self-reporting* of illness, medication, alcohol intake and other factors that may influence susceptibility to cold stress.
- *Requirement for self-paced working* at temperatures below -12°C. Work rates should not be so high as to cause heavy sweating that will result in wet clothing, and encourage co-worker observation to detect signs and symptoms of cold stress in others. The signs or symptoms of cold stress in an individual, if noticed, should never be ignored.
- *Encourage health life-styles.* A good diet and physical conditioning help protect against abnormal cold. Cold temperatures require an increase in calorie consumption (should be high in carbohydrates) and regular water intake (eg 4-5 litres of warm, sweet, non-alcoholic drinks per day). Proper rest reduces the risk of fatigue, which can increase vulnerability to cold. Limit alcohol intake because alcohol speeds up body heat loss.
- *Administrative controls* such as arranging work in such a way that sitting still or standing still for long periods is minimised. Where possible work should be scheduled for the least cold part of the day (ie work with the highest exposure potential). Long shifts and excessive overtime should be avoided in the cold.

## **10.4 CLOTHING**

### **10.4.1 Introduction**

In the absence of shelter, clothing is the most important means of protection against cold stress. The thermal insulation provided by clothing is due to the air trapped between layers of clothing and in the fibrous structure. Insulation is proportional to the thickness of still air enclosed in the garments, on the capacity to trap air and on the compressibility of the fabric when in use. Clothing also has to protect against wind which can penetrate and destroy the insulating property of the trapped air. It is therefore necessary for an effective cold-weather assembly to be windproof by having an outside layer made of tightly woven or impermeable material.

Whole body protection must be provided in cold air or cold water immersion primarily to prevent the onset of hypothermia (core temperature  $<35^{\circ}\text{C}$ ). The aim is to maintain a core temperature above  $36^{\circ}\text{C}$  if possible. The equivalent wind chill temperature should be used when estimating the combined cooling effect of wind and low temperature on exposed skin or when determining insulation requirements to maintain deep core temperature.

Efficiently waterproofed clothing is essential in cold, wet environments because of the rapid cooling produced by combined evaporative and wind chill. A serious disadvantage of impermeability is that the clothing is also impermeable to water vapour escaping from the skin surface. If it cannot escape, water vapour from the skin will condense beneath the impermeable layer in cold weather and eventually eliminate the insulation provided by trapped air. This effect is increased if the individual is physically active and sweating. In environmental temperatures below  $0^{\circ}\text{C}$ , water trapped in clothing may freeze. Apart from necessary protection against wet conditions, impermeable clothing is mainly useful in cold, dry conditions for people who are not very active. Loosely fitted with openings round the neck, impermeable garments rely on a bellows effect to reduce water vapour concentration. For more severe work the outer layer should be water repellent but capable of allowing vapour movement so that water vapour can escape. (The outer layer should be changed if it becomes wetted due to water repellency properties being lost.) If adequate protective clothing is not available to prevent the development of hypothermia or cold injury, work practices should be modified or suspended until adequate clothing is available or weather conditions improve.

The other important clothing consideration is protection of the extremities and head. Thick insulating gloves are of little use when fine hand movements are required, and furthermore, insulation round small diameter cylinders like the fingers is difficult to achieve. Mitts, with all the fingers enclosed together and only the thumb separate, provide more effective insulation.

Under survival situations these weaknesses in insulation can be overcome by withdrawing the hands and arms into the body of the jacket (ensuring that loose sleeves are constrained and made air tight).

#### **10.4.2 Intrinsic Clothing Insulation**

Parsons (2003) describes intrinsic (or basic) clothing insulation ( $I_{cl}$ ) as a property of the clothing itself and represents the resistance to heat transfer between the skin and the clothing surface. The rate of heat transfer through the clothing is via conduction which depends on the surface area, the temperature gradient between the skin and the clothing surface and the thermal conductivity of the clothing.

The units for intrinsic clothing insulation are  $m^2 \text{ } ^\circ\text{C W}^{-1}$ , however in 1941 the clo unit was proposed to replace the more cumbersome physical unit.

By definition 1.0 clo is the insulation provided by clothing sufficient to allow a person to be comfortable when sitting in still air at a temperature of  $21^\circ\text{C}$ . 1.0 clo is equivalent to an  $I_{cl}$  of  $0.155 m^2 \text{ } ^\circ\text{C W}^{-1}$ . Examples of typical clothing insulation values are given in Table 8.1.

Thus it is possible to compare the intrinsic clothing insulation value for the clothing worn by a worker against the IREQ calculated for a particular activity and establish if the level of clothing being worn is sufficient.

#### **10.4.3 Selection and Use of Appropriate Clothing**

Protective clothing is needed for work at or below  $4^\circ\text{C}$ . Clothing should be selected to suit the temperature, weather conditions (eg wind speed, rain), the level and duration of activity, and job design.

When using protective clothing it is important to remember the following:

- Clothing should be worn in multiple layers which provide better protection than a single thick garment. Having several layers also gives you the option to open or remove a layer before you get too warm and start sweating or to add a layer when you take a break.

- The inner layer of clothing should provide insulation and be able to “wick” moisture away from the skin to help keep it dry.
- The additional layers of clothing should provide adequate insulation for the weather conditions under which the work is being done. They should also be easy to open or remove before you get too warm to prevent excessive sweating during strenuous activity.
- For work in wet conditions, the outer layer of clothing should be waterproof.
- A wool knit cap or a liner under a hard hat can reduce excessive heat loss.
- Clothing should be kept clean since dirt fills air cells in fibres of clothing and destroys its insulating ability.
- Moisture should be kept off clothes by removing snow prior to entering heated shelters.
- If fine manual dexterity is not required, gloves should be used below 4°C for light work and below -7°C for moderate work. For work below -17°C mittens should be used.

In respect to footwear, felt-lined, rubber bottomed, leather-topped boots with removable felt insoles are best suited for heavy work in cold since leather is porous, allowing the boots to “breathe” and let perspiration evaporate. Leather boots can be “waterproofed” with some products that do not block the pores in the leather.

However, if work involves standing in water or slush (eg fire fighting, farming), the waterproof boots must be worn.

In extremely cold conditions, where face protection is used, eye protection must be separated from the nose and mouth to prevent exhaled moisture from fogging and frosting eye shields or glasses.

## **10.5 AIHA CHECKLIST FOR WORKING IN COLD ENVIRONMENTS**

The AIHA (2003) provides the following checklist as a guide to help improve worker safety and productivity in extreme environments:

- Are workers and supervisors trained in recognising the symptoms and providing first-aid treatment of frostbite and hypothermia?
- Is there a means of calling emergency medical support? Do workers know how and where to call emergency medical support?
- Are appropriate clothing and replacements for wet items available?
- Is emergency warming available?
- Are there facilities available for drying clothing items that become damp or wet?
- Are windbreaks erected in the most beneficial locations?
- Is a windchill chart available?
- Have supervisors been instructed to remove workers at the first sign of problems?
- Are hand/foot warmers available?
- Has the work rate been modified as much as possible to avoid following very high work rates with very low ones (ie avoid causing workers to sweat, followed by very low work rates that might cause them to become hypothermic)?
- Is spot warming available?

- Are drinks available? (Avoid drinks high in caffeine since caffeine is a vasodilator.)

*(Used with permission of the American Industrial Hygiene Association – 2007)*

While it may be argued that other factors should be included in the list (workplace monitoring, work-rest schedule) it does serve to highlight the various factors that need to be considered before commencing work in cold environments.

## **11.0 APPROACHES TO RISK ASSESSMENT**

### **11.1 AIOH TIERED APPROACH**

The AIOH (2013) stated that assessment of both heat stress and heat strain can be used for evaluating risk to worker health and safety and suggested that a decision making process such as that shown in Figure 11.1 is required.

They suggested a structured, tiered risk assessment approach as a means for determining conditions under which it is believed that an acceptable percentage of adequately hydrated, unmedicated, healthy workers may be repeatedly exposed without adverse health effects.

Their approach in summary involved:

1. Using their Basic Thermal Risk Assessment – Figure 11.2

If the Assessment Point Total is less than 28, then the risk of thermal conditions is low. The NO branch in Figure 11.1 can be taken. Nevertheless if there are reports of symptoms of heat related disorders then the analysis should be reconsidered or proceed to more detailed analysis if appropriate.

If the Assessment Point Total is 28 or more, further analysis is required.

An Assessment Point Total greater than 60 indicates the need for immediate implementation of controls.

Screening for clothing that does not allow air and water vapour movement.

As most heat exposure assessment indices were developed for a traditional work uniform of a long-sleeved shirt and pants, screening based on these is not suitable for outer clothing ensembles more extensive than this, unless a detailed analysis method appropriate to permeable clothing requirements is available.



With heat removal hampered by clothing, metabolic heat may produce life-threatening heat strain even when ambient conditions are considered cool and the risk assessment determines “Low Risk”. If workers are required to wear outer clothing that does not allow air and water vapour movement, then the NO branch in Figure 11.1 should be taken. Physiological and behavioural monitoring described in point 3 should be followed to assess the exposure.

The Thermal Risk Assessment form is intended as an initial screening step.

No numerical screening criteria or limiting values are applicable where clothing does not allow air or water vapour movement. In this case, reliance must be placed on physiological monitoring.

## 2. Detailed Analysis

The screening criteria require a minimal set of data to make a determination. Detailed analyses require more data about the exposures, including clothing, air speed, water vapour content of the air (eg humidity), and globe temperature. Following Figure 11.1, the next question asks about the availability of such data for a detailed analysis. If these data are not available, the NO branch takes the evaluation to physiological monitoring to assess the degree of heat strain.

Detailed rational analysis should usually follow the International Standards Organisation (ISO) Predicted Heat Strain (ISO 7933 2004), although other indices with extensive supporting physiological documentation may also be acceptable (e.g. Thermal Work Limit (TWL) and Basic Effective Temperature (BET) for the underground mine environment. – see AIOH Documentation for details). While such a rational method (versus the empirically derived WBGT thresholds) is computationally more difficult, it permits a better understanding of the source of the heat stress and is a means to appreciate the benefits of proposed modifications in the exposure.

In the event that the suggested values are exceeded, ISO 7933 (Predicted Heat Strain) calculates an allowed exposure time.

If the exposure does not exceed the criteria of ISO 7933 of Predicted Rise in Core Temperature of 1.0°C or Predicted Maximum water loss (in one shift or less) of 5% body mass, then the NO Branch in Figure 11.1 can be taken.

Because the criteria of the Risk Assessment have been exceeded, general heat stress controls are appropriate as detailed earlier in Chapter 8 and as provided by the AIOH in their Standard and Documentation.

If the exposure exceeds the suggested limits from the detailed analysis, or set by the appropriate authority the YES branch leads to the reassessment of job specific control options and then implementation and assessment of these controls again.

If these are not available, or it cannot be demonstrated that they are successful, then the NO branch leads to physiological monitoring as the only alternative to demonstrate adequate protection is provided.

### 3. Physiological Monitoring

Where the allowable exposure time is less than 30 minutes or any task that requires the utilisation of high levels of personal protective equipment, such as encapsulated suits, then physiological monitoring should be considered.

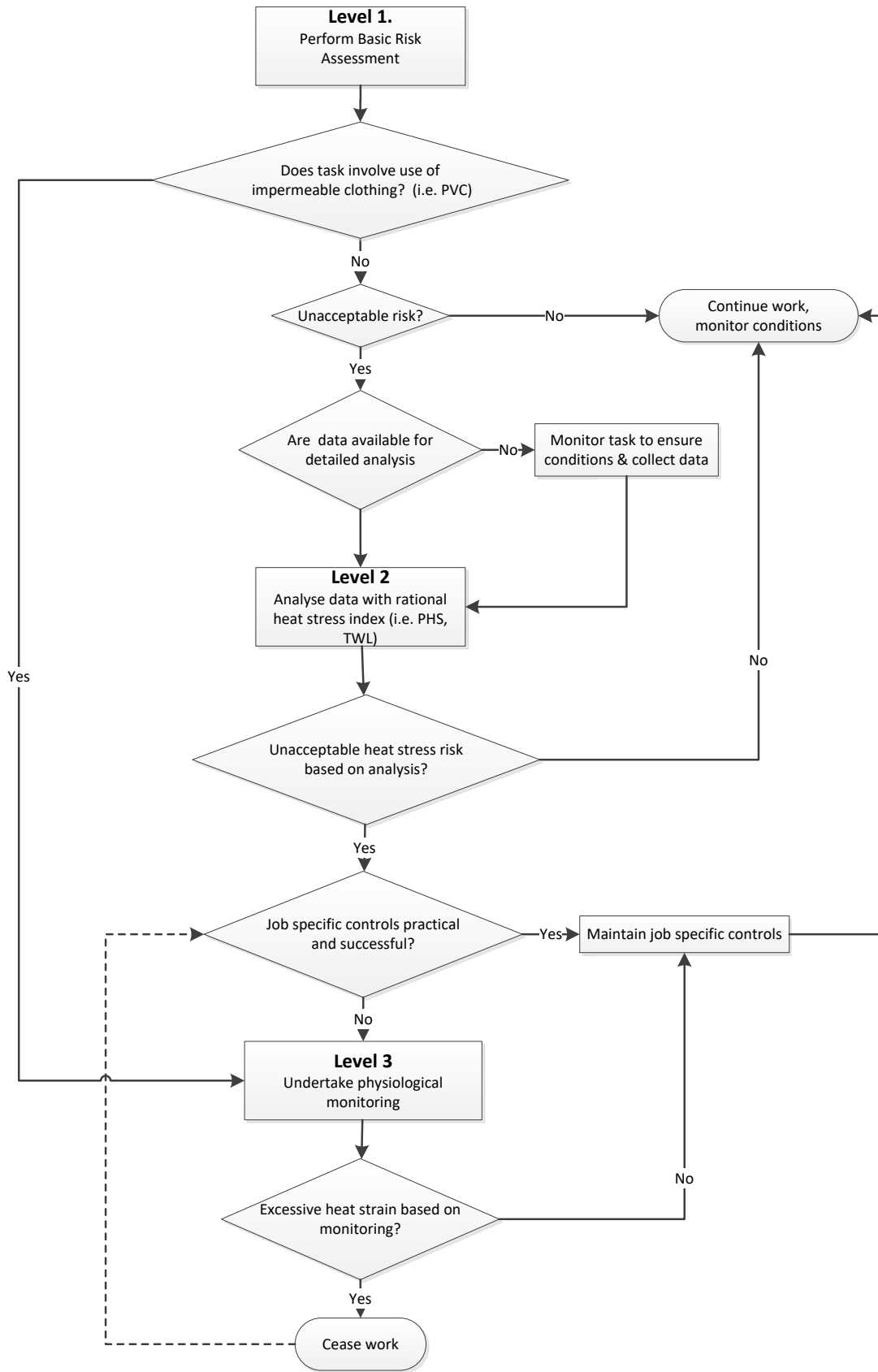
The AIOH suggests that excessive heat strain may be marked by one or more of the following measures, and an individual's exposure to heat stress should be discontinued when any of the following occur:

- “Heart Rate Limit” =  $185 - 0.65A$  (see ISO 9886), where A = Age in years; or
- “Thermal Heart Rate” increase is greater than 30 bpm per 1°C increase in core temperature; or
- Recovery heart rate at one minute after a peak work effort is greater than 124 bpm; or
- Body core temperature is greater than 38.5°C for medically selected and acclimatised personnel; or greater than 38°C in unselected, unacclimatised workers; or
- There are symptoms of sudden and severe fatigue, nausea, dizziness or lightheadedness.

With acceptable levels of heat strain, the NO branch in Figure 11.1 is taken. Nevertheless, if the heat strain among workers is considered acceptable at the time, the general controls are necessary. In addition, periodic physiological monitoring should be continued to ensure that acceptable levels of heat strain are being maintained.

If limiting heat strain is found during the physiological assessments, then the YES branch is taken. This means that the work activities must cease until suitable job-specific controls can be considered and implemented to a sufficient extent to control that strain. The job-specific controls include engineering controls, administrative controls and personal protection.

After implementation of the job-specific controls, it is necessary to assess their effectiveness, and to adjust them as needed.



(Source: AIOH 2013 – reproduced with permission)

**Figure 11.1 - Heat Stress Management Schematic**

	0	1	2	3	
Sun Exposure	Indoors <input type="checkbox"/>	Full Shade <input type="checkbox"/>	Part Shade <input type="checkbox"/>	No Shade <input type="checkbox"/>	
Hot surfaces	Neutral <input type="checkbox"/>	Warm on Contact <input type="checkbox"/>	Hot on contact <input type="checkbox"/>	Burn on contact <input type="checkbox"/>	
Exposure period	< 30 min <input type="checkbox"/>	30 min – 1hour <input type="checkbox"/>	1 hour - 2 hours <input type="checkbox"/>	> 2 hrs <input type="checkbox"/>	
Confined space	No <input type="checkbox"/>			Yes <input type="checkbox"/>	
Task complexity		Simple <input type="checkbox"/>	Moderate <input type="checkbox"/>	Complex <input type="checkbox"/>	
Climbing, up/down stairs or ladders	None <input type="checkbox"/>	One level <input type="checkbox"/>	Two levels <input type="checkbox"/>	> Two levels <input type="checkbox"/>	
Distance from cool rest area	<10 Metres <input type="checkbox"/>	10 - 50 Metres <input type="checkbox"/>	50-100 Metres <input type="checkbox"/>	>100 Metres <input type="checkbox"/>	
Distance from drinking water	<10 Metres <input type="checkbox"/>	10 - 30 Metres <input type="checkbox"/>	30-50 Metres <input type="checkbox"/>	>50 Metres <input type="checkbox"/>	
Clothing (permeable)		Single layer (light) <input type="checkbox"/>	Single layer (mod) <input type="checkbox"/>	Multiple layer <input type="checkbox"/>	
Understanding of heat strain risk	Training given <input type="checkbox"/>			No training given <input type="checkbox"/>	
Air movement	Strong Wind <input type="checkbox"/>	Moderate Wind <input type="checkbox"/>	Light Wind <input type="checkbox"/>	No Wind <input type="checkbox"/>	
Resp. protection (-ve pressure)	None <input type="checkbox"/>	Disposable Half Face <input type="checkbox"/>	Rubber Half Face <input type="checkbox"/>	Full Face <input type="checkbox"/>	
Acclimatisation	Acclimatised <input type="checkbox"/>			Unacclimatised <input type="checkbox"/>	
SUB-TOTAL A					
		2	4	6	
Metabolic work rate*		Light <input type="checkbox"/>	Moderate <input type="checkbox"/>	Heavy <input type="checkbox"/>	
SUB-TOTAL B					
		1	2	3	4
Apparent Temperature		< 27°C <input type="checkbox"/>	>27°C ≤ 33°C <input type="checkbox"/>	>33°C ≤ 41°C <input type="checkbox"/>	> 41°C <input type="checkbox"/>
SUB-TOTAL C					
TOTAL = A plus B Multiplied by C					

**\*Examples of Work Rate.**

**Light work:** Sitting or standing to control machines; hand and arm work assembly or sorting of light materials.  
**Moderate work:** Sustained hand and arm work such as hammering, handling of moderately heavy materials.  
**Heavy work:** Pick and shovel work, continuous axe work, carrying loads up stairs.

**Instructions for use of the Basic Thermal Risk Assessment**

- Mark each box according to the appropriate conditions.
- When complete add up using the value at the top of the appropriate column for each mark.
- Add the sub totals of Table A & Table B and multiply with the sub-total of Table C for the final result.
- If the total is **less than 28** then the risk due to thermal conditions are low to moderate.
- If the total is **28 to 60** there is a potential of heat-induced illnesses occurring if the conditions are not addressed. Further analysis of heat stress risk is required.
- If the total **exceeds 60** then the onset of a heat-induced illness is very likely and action should be taken as soon as possible to implement controls.

It is important to note that that this assessment is to be used as a guide only. A number of factors are not included in this assessment such as employee health condition and the use of high levels of PPE (particularly impermeable suits). In these circumstances experienced personnel should carry out a more extensive assessment.

(Source: AIOH 2013 – reproduced with permission)

**Figure 11.2 - Basic Thermal Risk Assessment**

The Basic Thermal Risk Assessment is used as follows:

- Mark each box according to appropriate conditions.
- When completed add up the totals using the assessment point values at the top of the appropriate column for each mark.
- Add the Sub Totals of Table A and Table B and multiply with the sub-total of Table C for the final result.
- If the total is **less than 28** then the risk due to thermal conditions are low to moderate.
- If the total is **28-60** there is a potential of heat induced illnesses occurring if the conditions are not addressed. Further analysis of heat stress risk is required.
- If the total **exceeds 60** then the onset of a heat induced illness is very likely and action should be taken as soon as possible to implement controls.

**NB:** This assessment is to be used as a **guide only**. A number of factors are not included in this assessment such as employee health condition and the use of high levels of PPE (particularly impermeable suits). In these circumstances experienced personnel should carry out a more extensive assessment.

An example taken from the AIOH (2013) publication of the application of the basic thermal risk assessment would be as follows and is reproduced with permission.

A fitter is working on a pump out in the plant at ground level that has been taken out of service the previous day. The task involves removing bolts and a casing to check the impellers for wear, approximately 2 hours of work. The pump is situated approximately 25 metres from the workshop, undercover and in the shade. The fitter is acclimatised, has attended a training session and is

wearing a standard single layer long shirt and trousers, is carrying a water bottle, and a respirator is not required. The work rate is light, there is a light breeze and the air temperature has been measured at 30°C, and the relative humidity at 70%. This equates to an apparent temperature of 35°C (see Appendix).

Using the above information in the risk assessment we have:

	0	1	2	3	
Sun Exposure	Indoors <input type="checkbox"/>	Full Shade <input checked="" type="checkbox"/>	Part Shade <input type="checkbox"/>	No Shade <input type="checkbox"/>	
Hot surfaces	Neutral <input checked="" type="checkbox"/>	Warm on Contact <input type="checkbox"/>	Hot on contact <input type="checkbox"/>	Burn on contact <input type="checkbox"/>	
Exposure period	< 30 min <input type="checkbox"/>	30 min – 1hour <input type="checkbox"/>	1 hour - 2 hours <input checked="" type="checkbox"/>	> 2 hrs <input type="checkbox"/>	
Confined space	No <input checked="" type="checkbox"/>			Yes <input type="checkbox"/>	
Task complexity		Simple <input checked="" type="checkbox"/>	Moderate <input type="checkbox"/>	Complex <input type="checkbox"/>	
Climbing, up/down stairs or ladders	None <input checked="" type="checkbox"/>	One level <input type="checkbox"/>	Two levels <input type="checkbox"/>	> Two levels <input type="checkbox"/>	
Distance from cool rest area	<10 Metres <input type="checkbox"/>	10 - 50 Metres <input checked="" type="checkbox"/>	50-100 Metres <input type="checkbox"/>	>100 Metres <input type="checkbox"/>	
Distance from drinking water	<10 Metres <input checked="" type="checkbox"/>	10 - 30 Metres <input type="checkbox"/>	30-50 Metres <input type="checkbox"/>	>50 Metres <input type="checkbox"/>	
Clothing (permeable)		Single layer (light) <input checked="" type="checkbox"/>	Single layer (mod) <input type="checkbox"/>	Multiple layer <input type="checkbox"/>	
Understanding of heat strain risk	Training given <input checked="" type="checkbox"/>			No training given <input type="checkbox"/>	
Air movement	Strong Wind <input type="checkbox"/>	Moderate Wind <input type="checkbox"/>	Light Wind <input checked="" type="checkbox"/>	No Wind <input type="checkbox"/>	
Resp. protection (-ve pressure)	None <input checked="" type="checkbox"/>	Disposable Half Face <input type="checkbox"/>	Rubber Half Face <input type="checkbox"/>	Full Face <input type="checkbox"/>	
Acclimatisation	Acclimatised <input checked="" type="checkbox"/>			Unacclimatised <input type="checkbox"/>	
SUB-TOTAL A		4	4	8	
Metabolic work rate*		2 Light <input checked="" type="checkbox"/>	4 Moderate <input type="checkbox"/>	6 Heavy <input type="checkbox"/>	
SUB-TOTAL B				2	
Apparent Temperature		1 < 27°C <input type="checkbox"/>	2 >27°C ≤ 33°C <input type="checkbox"/>	3 >33°C ≤ 41°C <input checked="" type="checkbox"/>	4 > 41°C <input type="checkbox"/>
SUB-TOTAL C				3	
TOTAL = A plus B					
Multiplied by C					
=					

A = 8; B = 2; C = 3; therefore

Total = (8+2) x 3 = 30

As the total lies between 28 and 60 there is a potential for heat induced illness occurring if the conditions are not addressed, and further analysis of heat stress risk is required.

A more complete explanation of the AIOH Tiered approach can be found in their “*A Guide to Managing Heat Stress: Developed for Use in the Australian Environment*” and should be referred to if undertaking this approach.

## **11.2 REPUBLIC OF SOUTH AFRICA DoM&E CODE OF PRACTICE**

Following a commission of inquiry into Safety & Health in the Republic of South Africa (RSA) mining industry, occupational health was identified as one of four major issues that needed to be addressed by the mining industry.

In an attempt to address this issue a tripartite subcommittee of the Mining Occupational Health Advisory Committee (MOHAC) was established and one of their tasks was to develop a guideline for a mandatory code of practice (COP) on thermal stress. This document was first issued by the Department of Minerals and Energy in February 2002 and became effective on 1 August 2002 (SADME 2002).

The objective of this guideline is to enable the employer at every mine to compile a COP, which, if properly implemented and complied with, would protect and improve the health of employees at the mine by monitoring and reducing their exposure to thermal stress. It provides guidance of a general nature on the required format and content for the COP and details sufficient technical background to enable the drafting committee at the mine to prepare a comprehensive and practical COP for their mine.

It sets out the two components of an Occupational Health programme to reduce the risk of thermal stress, namely:

- Occupational Hygiene
- Medical Surveillance

Under RSA law, failure by an employer to prepare or implement a code of practice in compliance with the guideline is a breach of the RSA Mine Health & Safety Act.

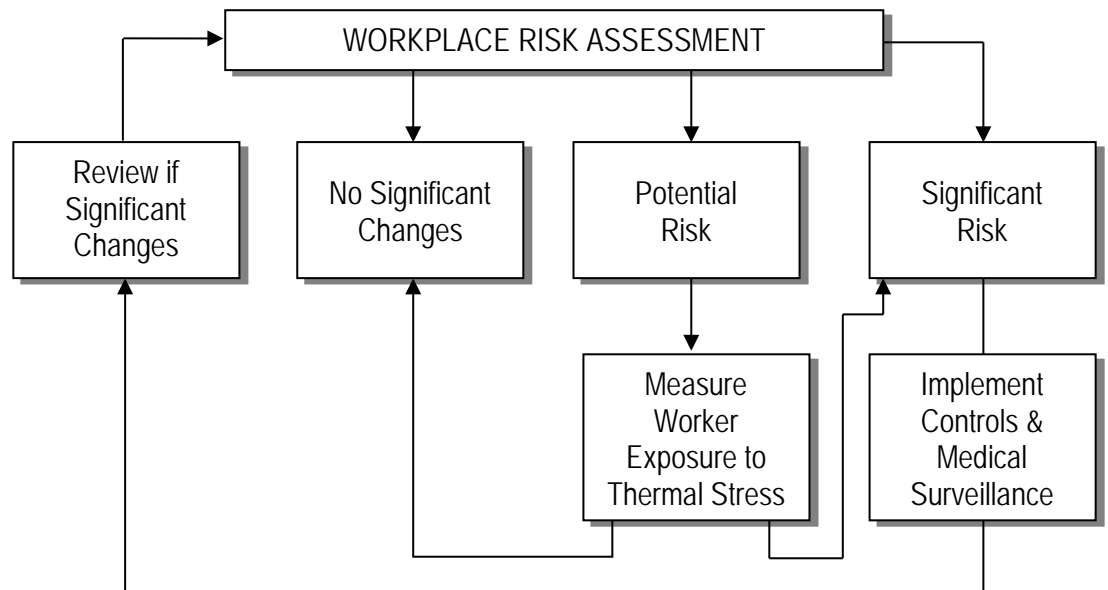


### 11.2.1 Aspects to be Addressed in the COP

Where the employer's risk assessment indicates a need to establish and maintain either a system of occupational hygiene measurements or a system of medical surveillance, or where either such system is required by regulation, the following key elements must be addressed in the COP:

- Risk assessment and control
- Monitoring programme
- Hierarchy of controls
- Medical surveillance
- Reporting and reviewing

The process as described in the COP can be summarised as follows (Figure 11.3).



**Figure 11.3 – Schematic of South African DME Thermal Stress Programme**

### **11.2.2 Occupational Hygiene**

Under the guideline an employer must, when developing a COP for an operation, ensure that the following steps are included:

- Step 1 - Risk Assessment and Control
- Step 2 - Categorisation of the Thermal Environments
- Step 3 - Thermal Stress Management (ie heat stress and/or cold stress management)
- Step 4 - Measurement Methodology
- Step 5 - Thermal Stress Monitoring
- Step 6 - Reporting and Recording

Details are provided in the guideline as to the requirements for each step in relation to both hot and cold stress. The requirements of the categorisation of the thermal environment are provided in Section 5.2.2. Routine monitoring programmes are then required to be developed in accordance with this categorisation and the measured indices relationship to prescribed limits. Appropriate measures must then be taken to mitigate excessive exposures.

### **11.2.3 Medical Surveillance**

Under the COP and the Mine Health & Safety Act medical surveillance is required. In terms of the COP this is dependent on the risk assessment and occupational hygiene data but may be overridden in some situations by the Mine Health & Safety Act.

Medical surveillance requirements in terms of:

- a) Initial examination
- b) Periodic examination
- c) Exit examination

are detailed in the guideline.

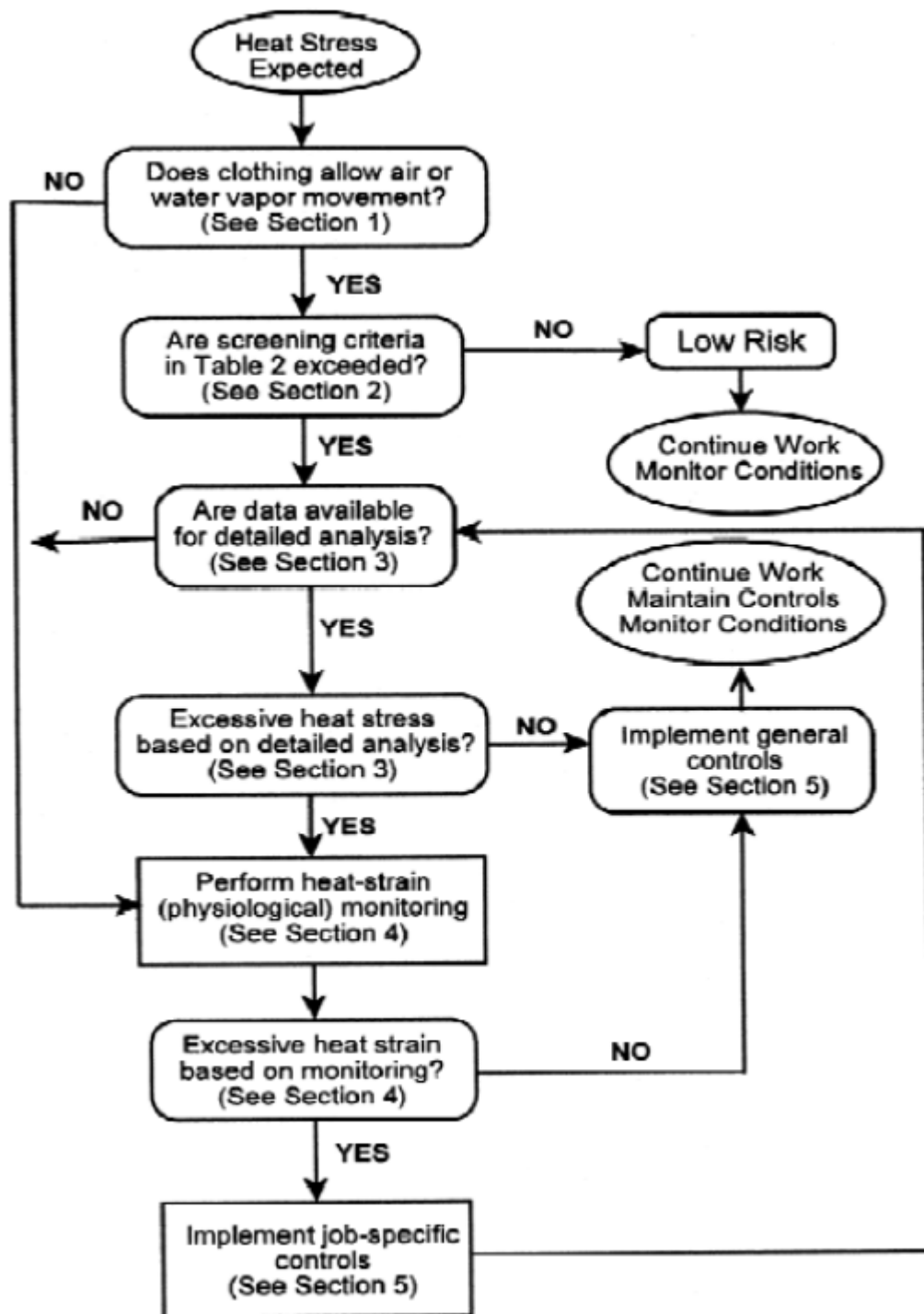
### 11.3 ACGIH THERMAL STRESS TLVs®

The goal of the ACGIH Thermal Stress TLV is to maintain body core temperature within +1°C of normal (37°C) temperature. Assessment of both heat stress and heat strain can be used for evaluating the risk to worker safety and health. Their guidance provided in Figure 11.4 and Figure 11.5 and in their associated documentation of the TLV (ACGIH 2007) represents conditions under which it is believed that nearly all heat acclimatised, adequately hydrated, unmedicated, healthy workers may be repeatedly exposed without adverse health effects.

The Action Limit is similarly protective of unacclimatised workers and represents conditions for which a heat stress management programme should be considered.

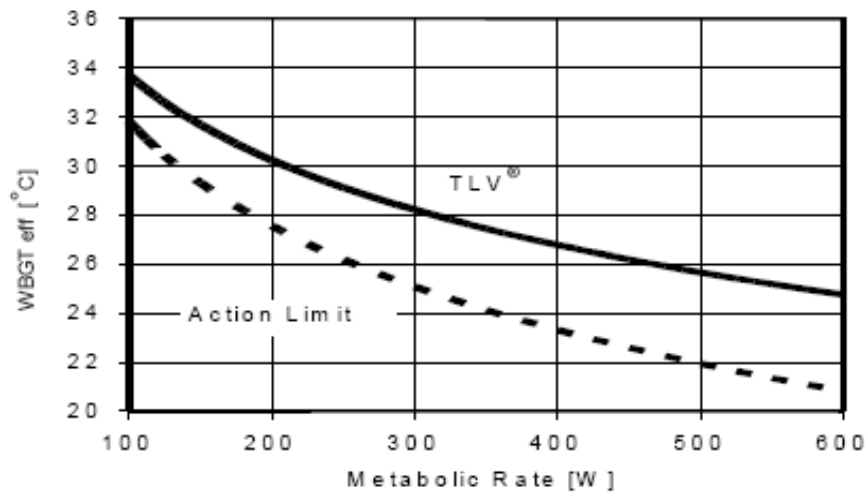
Their decision making process as outlined in Figure 11.4 should be started if:

- A qualitative exposure assessment indicates the possibility of heat stress,
- There are reports of discomfort due to heat stress, or
- Professional judgement indicates heat stress conditions.



(“ACGIH®, 2007 TLVs® and BEIs® Book. Copyright 2007. Reprinted with permission”)

**Figure 11.4 - Evaluating Heat Stress and Strain**



TLV (solid line) and Action Limit (broken line) for heat stress.

WBGT<sub>eff</sub> is measured WBGT plus the Clothing Adjustment Factor.

(“ACGIH<sup>®</sup>, 2007 TLVs<sup>®</sup> and BEIs<sup>®</sup> Book. Copyright 2007. Reprinted with permission”)

**Figure 11.5 – ACGIH Thermal Stress TLVs<sup>®</sup> and Action Limits**

### Section 1: Clothing

Figure 11.4 requires a decision about clothing and how it might affect heat loss. If the required clothing is adequately described by one of the ensembles in Table 11.1, or by other available data, then the YES branch is selected.

If workers are required to wear clothing not represented in Table 11.1, then the NO branch is selected. This decision is especially applicable for clothing ensembles that are:

- Totally encapsulating, or
- Multiple layers where no data are available for adjustment

In these circumstances, unless other data is available physiological and sign/symptoms monitoring described in Section 4 should be followed to assess the exposure.

**Table 11.1 - Clothing Adjustment Factors for Some Clothing Ensembles\***

<b>Clothing Type</b>	<b>Addition to WBGT [°C]</b>
Work clothes (long sleeve shirt and pants)	0
Cloth (woven material) coveralls	0
Double-layer woven clothing	3
SMS polypropylene coveralls	0.5
Polyolefin coveralls	1
Limited-use vapor-barrier coveralls	11

\* These values must not be used for completely encapsulating suits, often called Level A. Clothing Adjustment Factors cannot be added for multiple layers. The coveralls assume that only modesty clothing is worn underneath, not a second layer of clothing.

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#### 11.4 QUANTITATIVE Vs QUALITATIVE APPROACHES

When considering quantitative versus qualitative approaches we are essentially considering a measurement approach versus a risk assessment approach.

The measurement approach takes into account the variables (age, fitness, etc) of particular individuals and provides a more accurate estimate of an individual’s strain. This process also gives a greater level of confidence in relation to the impact on the individual regardless of the conditions and, importantly, includes the impact of personal protective equipment.

In respect to a measurement approach it must be realised that all indices have limitations to varying degrees and thus should be treated as guides not absolute divides between acceptable or unacceptable thermal environments.

The limitations of the measurement approach include:

- The need for equipment, some of which can be expensive. Basic measurements can be made with simple equipment but more detailed investigations are more easily conducted with instrumentation which can be expensive.
- The need to assess each person individually in order to obtain a profile of each person's level of strain. While this may be time-consuming it does provide an opportunity for the investigator to talk with individuals and clearly understand the workplace situation. However the results can be very individual specific and care needs to be taken that generalisations are not applied across groups of individuals with varied physiologies.
- The need for an increased level of technical expertise with the investigator being a person with specialist knowledge and skills.

The risk assessment approach is widely adopted as means by which people with limited technical expertise can assess or at least highlight the many different impacts associated with thermal assessments. As with all risk assessments the outcomes of such a process are totally dependent on the quality of the data inputted to the risk assessment process.

The limitations of the risk assessment approach include:

- The process is totally dependent on the available information and errors in that collection process can flow through the system leading to an incorrect outcome.
- Risk assessments in themselves cannot solve an issue of thermal stress but the actions arising from a risk assessment (if implemented) certainly can improve a workplace. Merely undertaking a risk assessment is not sufficient to protect a person's health and there is a need to ensure processes exist to implement the controls and required actions.

- There is a possibility of an unusual situation going unassessed due to the limited knowledge of the assessor. In the measurement approach such situations are more likely to be highlighted due to the increased skill level of the assessor.

While both approaches have their role to play, a review of the literature suggests a mixture of the risk assessment approach integrated with appropriate monitoring strategies as being the preferred model to assess workplaces at the present time. This brings together the benefits of both approaches and if undertaken in a stage approach (ie qualitative assessment to detailed monitoring exercise as required by the situation) can be both comprehensive and cost effective.

With the advancement of modern technology there are now a number of tablet and smart phone Apps available to carry out the basic risk assessment. They vary in content and approach but can be useful tools in the initial assessment process.

Examples include: The Thermal Risk App at:

**Android (Google play)**

<https://play.google.com/store/apps/details?id=com.Gopaldasani.thermalrisk>

**Apple (iTunes store)**

<https://itunes.apple.com/us/app/thermal-risk/id867920824?ls=1&mt=8>





## 11.5 PHYSIOLOGICAL ASSESSMENTS

Physiological assessments are simply a means by which to identify “at risk” individuals.

Susceptibility to heat varies from person to person and it is important that those who are more at risk from heat effects should not be exposed to unduly hot conditions. Factors which should be taken into account when assessing suitability for work in hot environments include:

- a) *Weight and physical fitness:* Those who are overweight or unfit are more likely to experience ill-effects.
- b) *Age:* The older a person is the more likely they are to suffer from the effect of heat; particular consideration should be given to individuals over 45 years of age.
- c) *Medical disorders:* Many disorders affect a person’s ability to work in hot conditions. These include disorders such as diarrhoea, vomiting, colds and influenza, and major disorders such as lung, heart and circulatory illnesses. Chronic skin diseases may be made worse by working in a hot environment and often predispose to heat illness. Low or high thyroid gland activity produce marked intolerance to cold and heat respectively.
- d) *Some medications* have an adverse effect on individuals exposed to heat. Habitual alcohol abuse has directly or indirectly contributed to the deaths of workers exposed to hot working conditions.
- e) *Previous heat intolerance:* Workers, who have shown themselves susceptible to the effects of heat in the past, even if no clear reason was evident, are likely to be at greater risk with further exposure.

Similarly for cold environments medical screening is important; however the knowledge of how medical disorders are affected by cold is incomplete (Parsons 2003).

As previously described (Section 10.1) Parsons (2003) provides a list of screening factors listed by the British Refrigerated Food Industry Confederation.

Factors included in the list are:

- Heart or circulation problems
- Diabetes
- Thyroid problems
- Blood disorders
- Kidney or urine disorders
- Any kind of arthritis or bone disease
- Any infection including ear, nose and throat
- Lung function problems or asthma
- Chronic gastro-enteritis or acute diarrhoea or vomiting (must be notified the same day)
- Neurological (nerve) malfunction
- Psychological problems
- Eyesight or hearing difficulty
- Prescribed medication

While this approach is very basic it can be considered good occupational health practice and thus worth consideration.

One novel approach (SIMRAC 2001) developed as a management tool in the South African gold and platinum mines, is the development of an individual employee risk profile against which overall fitness for work in hot environments is assessed. The profile consists of the following elements:

- Medical contraindications, ie a particular condition, treatment or even a medical history likely to lead to a critical job related reduction in heat tolerance.

- Age (50 years and above) in concert with full shift exposures to 'strenuous' work in heat.
- Obesity as measured by body mass index (BMI  $\geq 30$ ).
- Inherent heat intolerance.
- Strenuous work per se.
- A history of heat disorders.

In developing an employee risk profile on the above elements it is considered obvious that no hard and fast rules can be set and the estimation of risk may be imprecise. To address these shortcomings a threefold approach is recommended:

- A risk profile which features no more than one of the above elements should generally be regarded as 'acceptable'.
- The presence of any two factors (elements) should be viewed with concern and should not be condoned unless the situation can be ameliorated, for example through specially developed safe work practices.
- A profile containing more than two undesirable elements will constitute an unacceptable risk.

SIMRAC (2001) goes on to provide the following table of risk factor combinations (Table 11.6) which should not be condoned under any circumstances.

**Table 11.6 – Employee Risk Profile Matrix**

Primary Risk Factor	Secondary Risk Factor					
	Medical Contra-indication	Age ≥50 plus Strenuous Work	BMI ≥30	Heat Intolerance	Strenuous Work	History of Heat Disorders
Medical Contra-indication		X	O	O	O	X
Age ≥50 plus Strenuous Work	X		X	X		X
BMI ≥30	O	X		X	X	X
Heat Intolerance	O	X	X		X	X
Strenuous Work	O		X	X		X
History of Heat Disorders	X	X	X	X	X	

Where X = A combination of factors which generally should be viewed as a disqualification to work in particular hot and/or strenuous conditions.

O = A combination of factors which could be condoned if considered on merit.

*(Reproduced with permission from SIMRAC handbook of Occupational Health Practice in the South African Mining Industry, Chapter 8, 2001, Editor Dr A.J. Keilblock)*

SIMRAC (2001) suggests that there is a general attitude of complacency in South Africa towards the prevention of heat stroke. This assessment is based on a review of 121 cases of heat stroke in the South African mining industry which found that in 87% of cases two or more risk factors were present yet the worker had not been identified as an “at risk” person.

With the general rise in profile of “fit for work” programmes within major corporations throughout the world the role of physiological assessments is receiving significantly more attention. At the moment there does not appear to be significant co-ordination within industry to establish standardised schemes to assess “at risk” workers to extremes of thermal environments. Instead individual companies appear to be establishing specific company programmes (albeit along similar lines) with limited data or means available to judge their success.

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## APPENDIX

**Table 1 - Apparent Temperature Dry Bulb/Humidity Scale**

Align dry bulb temperature with corresponding relative humidity to determine apparent temperature in unshaded section of table. Numbers in ( ) refer to skin humidities above 90% and are only approximate.

Dry Bulb Temperature. (°C)	Relative Humidity (%)										
	0	10	20	30	40	50	60	70	80	90	100
20	16	17	17	18	19	19	20	20	21	21	21
21	18	18	19	19	20	20	21	21	22	22	23
22	19	19	20	20	21	21	22	22	23	23	24
23	20	20	21	22	22	23	23	24	24	24	25
24	21	22	22	23	23	24	24	25	25	26	26
25	22	23	24	24	24	25	25	26	27	27	28
26	24	24	25	25	26	26	27	27	28	29	30
27	25	25	26	26	27	27	28	29	30	31	33
28	26	26	27	27	28	29	29	31	32	34	(36)
29	26	27	27	28	29	30	30	33	35	37	(40)
30	27	28	28	29	30	31	33	35	37	(40)	(45)
31	28	29	29	30	31	33	35	37	40	(45)	
32	29	29	30	31	33	35	37	40	44	(51)	
33	29	30	31	33	34	36	39	43	(49)		
34	30	31	32	34	36	38	42	(47)			
35	31	32	33	35	37	40	(45)	(51)			
36	32	33	35	37	39	43	(49)				
37	32	34	36	38	41	46					
38	33	35	37	40	44	(49)					
39	34	36	38	41	46						
40	35	37	40	43	49						
41	35	38	41	45							
42	36	39	42	47							
43	37	40	44	49							
44	38	41	45	52							
45	38	42	47								
46	39	43	49								
47	40	44	51								
48	41	45	53								
49	42	47									
50	42	48									

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