# Empirical validation of a new heat stress index

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**Thermal stress is a well-recognised health hazard in the workplace. In addition to the health deficits, working in the heat can impact significantly on the productivity of some industries which are located in harsh environments. A long-standing dilemma in OHS has been the specification of what constitutes a safe working environment. The current indices used to evaluate the environment are either flawed or are difficult to implement. A new heat stress index, the thermal work limit, has now been developed which incorporates all needed inputs, and generates a single figure specifying a maximum work limit. Initial validation of the index demonstrates it to be simple to use, less prone to interpretive error, reliable and far superior to currently recommended indices as an indicator of thermal stress.**

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- HEAT STRESS
- HEAT STRESS INDEX
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- ACCLIMATISATION
- DEHYDRATION

## Introduction

It is now generally accepted that working in conditions of thermal stress has associated risks and consequences. From a health perspective, heat stroke (a serious condition with a mortality rate of around 80%) is the classical end point of the inability to maintain a stable core temperature. The lesser condition of heat exhaustion is relatively common and has recently been shown to have a clear biochemical and haematological profile.[1] In addition, chronic hypohydration leads to increased risk of renal calculi and bladder cancer.[2] From an economic perspective, high environmental stress contributes to safety incidents, lowered productivity and poor morale.

These considerations are particularly relevant to Australian industry, especially in the tropical northern region where operations are frequently located in areas of high ambient summer temperatures and humidity. Under the current OHS legislation there is a duty of care to protect workers in these environments. However, the guidelines to ensure this protection are scant, inappropriate and often non-specific. This situation has persisted as a consequence of minimal research into human thermal homeostasis in high stress environments and limiting technology. Currently, the most widely recommended index of thermal stress is the wet bulb globe temperature (WBGT). In common with other heat stress indices in use in industry, the WBGT is relatively insensitive to the cooling effect of air movement, although, due to its impact on both evaporative and convective cooling, increased ventilation is one of the most cost-effective ways of reducing physiological strain to the individual working in a thermal environment. In practice the WBGT is difficult to apply as it requires estimation of the workers' metabolic rates, which will not only vary throughout a shift with different tasks performed, but may be voluntarily altered by self-pacing workers. The measured WBGT, estimated metabolic rate and assessed acclimatisation status must be applied to a standard chart to arrive at a thermal index. Personnel with the necessary knowledge and training to correctly apply the WBGT are not present at all times in all workplaces, and in practice the index is often not used. An alternative is ISO 7933-1989: *Analytical determinator and interpretation of thermal stress using calculation of required sweat rate*, but it is extremely difficult to apply and in reality is rarely used.[3]

Complicating the issue, many union award agreements use a single environmental parameter as the limiting factor to work, for example, many above ground operations have chosen ambient temperature whereas underground mining operations have mainly favoured wet bulb temperature. This has resulted in heat stress management protocols such as reduction in shift length or work termination when environmental conditions exceed a certain threshold. The consequences of this strategy, in terms of lost production, are severe and of questionable value in health protection.

The five main parameters that define the thermal environment are dry bulb temperature (DB), wet bulb temperature (WB), radiant temperature (Trad), air velocity or wind speed (WS) and atmospheric pressure (Patm). The heat strain experienced by an individual working in a given thermal environment may also be influenced by physiological and behavioural factors including age, sex, clothing, hydration, sweat rate, surface area, fitness, health and acclimatisation status. All of these factors, both environmental and individual, influence the ability to dissipate excess heat generated in the body as a result of metabolic activity. Whether or not an individual will be able to safely work in an environment for an extended period of time depends on the balance between heat gained from metabolism and heat lost to the environment. If the rate of heat production exceeds the rate at which heat can be lost, then heat storage occurs and the core temperature rises — potentially resulting in heat illness. In most situations the single most important factor influencing this balance is the rate of metabolic heat production, which is a function of the workload. There is therefore a maximum safe level of work for an individual working in a given environment.

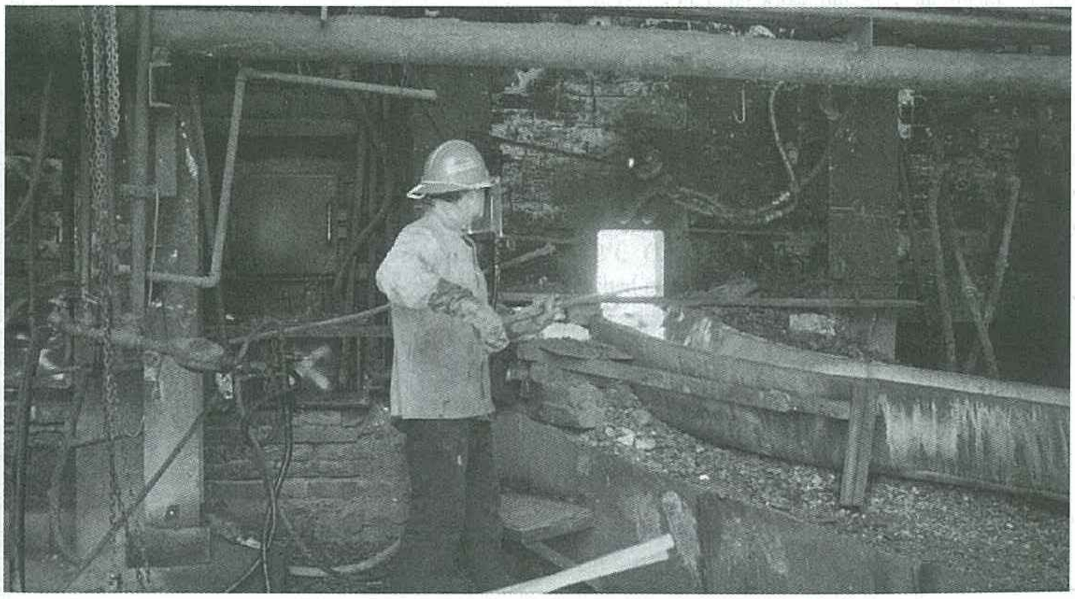
To date there have been few studies examining the effect of thermally stressful environments and different work rates on core body temperature, partly due to the technical difficulties associated with measurement of this parameter. The best approximation of the core temperature has, in the past, been given by the rectal temperature. However, continuous measurement of rectal temperature is not a practical undertaking in a working subject. With the advent of wireless sensor technology, it is now possible to continuously monitor the core temperature of an active subject by way of a Food and Drug Administration-approved ingested temperature sensor, which sends a signal to a small external monitor.

A new heat stress index — the thermal work limit (TWL) — has recently been developed, which utilises all five environmental parameters and accommodates for clothing characteristics to arrive at a prediction of a safe maximum metabolic rate for the conditions (Figure 1).[4] In conjunction, a hand-held heat stress meter (HSM) has been designed and produced which can simultaneously measure and integrate all five environmental parameters and be programmed to calculate the TWL or any other commonly used index of heat stress.[4]

Hand-held heat stress meters programmed to calculate the TWL have been trialled in the field at a number of Australian mine sites, and appropriate stop work, cautionary range and unrestricted work limits in terms of TWL have been recommended (see the Appendix).[4] These guidelines have been incorporated into working in heat protocols implemented at several sites and have resulted in a reduction in the incidence of heat illness and, in some instances, the costly production losses associated with previous protocols.[5]

The derivation of the algorithm used to calculate the TWL is principally rational rather than empirical and, although the results of its implementation have been encouraging, there is a need for experimental validation under controlled conditions. The present study was undertaken to validate the ability of the algorithm to accurately predict safe working limits.

**FIGURE 1**
**The TWL provides a comprehensive, easy to understand assessment of the thermal environment**



Subjects were exercised at near the TWL in an environmental chamber under controlled conditions of moderately high ambient temperature (DB) and humidity, such as would be encountered in many worksites, particularly during the summer months. The TWL algorithm was used to predict maximum safe workloads for the conditions, that is, workloads which should not result in increases in core body temperature above a selected limit of 38.2°C.[4] Core temperatures and heart rates were monitored throughout and the protocol required work to be stopped and the subject withdrawn from the chamber if a subject's core temperature reached 39°C.

The protocol was approved by the Curtin University Ethics Committee. The work was supported by a grant from Newcrest Mining Ltd.

## Methodology

### Subjects

All subjects were healthy young men (< 32 years). Prior to participation in the study, anthropometric data were collected and the subjects were assessed for health status, fitness level (predicted $VO_2max$), resting metabolic rate and work efficiency (cycling). These data are summarised in Table 1. The subjects were assumed to be at least partially acclimatised, as the trials were carried out in February when ambient temperatures are in the high 30s. However, the extent of the individual's acclimatisation depends on his lifestyle. No one was considered to be fully acclimatised to work in the conditions used in this study.

### Instrumentation and measurements

The study was conducted in a climate-controlled chamber permitting adjustment of DB and WB. Conditions were monitored throughout each trial.

In the chamber, external work was performed using Monark cycle ergometers, adjusted for the height of the subject to achieve optimum pedalling efficiency. Work rates used were 40 and 50 watts obtained by pedalling at 40 and 50 rpm respectively against a resistance of 1 kilopond. These workloads are relatively light and therefore unlikely to cause subject fatigue, but were chosen as they approximate the thermal work limit for the conditions.

Core temperature of the subjects was monitored by ingestion of a pea-sized temperature sensor/transmitter (HTI Technologies Inc) accurate to ±0.1°C. Once activated, these transmit a continuous radio signal corresponding to temperature which can be detected externally by a monitor worn by the subject. The transit time of these "pills" in the gut varies but, while some had been voided overnight, requiring ingestion of a second "pill", most were still transmitting data on the second day. Core temperature data were sampled every 15 or 30 seconds and stored. In addition, the sensor output read in real time from an LCD display was manually recorded every five minutes while the subjects were working in the chamber.

Each subject wore a Polar "sportstester" heart rate monitor. Heart rates were monitored every five minutes during periods of work as an indication of cardiovascular strain and were stored over the test session. Core temperature and heart rate data for the complete session were later downloaded for analysis.

**TABLE 1**

**Anthropometric and physiological data for the subjects**

| | *Age* | *Height (cm)* | *Weight (kg)* | *Surface area ($m^2$)* | *Body mass index* | *Fat %* | *Predicted $VO_2max$* | *Resting metabolic rate (watts/$m^2$)* | *Efficiency %* |
|---|---|---|---|---|---|---|---|---|---|
| Mean | 23.25 | 183.27 | 81.56 | 2.03 | 23.83 | 14.11 | 41.93 | 54.70 | 25.41 |
| Standard deviation | 5.31 | 7.40 | 14.12 | 0.18 | 3.17 | 4.70 | 9.00 | 7.29 | 1.02 |

Nude weights were recorded before and after sessions in the chamber using an electronic balance which was accurate to ±5 g (Salter). All fluids consumed and urine voided were measured and recorded to enable calculation of average hourly sweat rates.

Hydration status was assessed by measurement of the specific gravity (Atago urine refractometer) of a urine specimen collected before entering the chamber and all urine subsequently voided.

### Chamber trial protocol

On the first morning of the trial subjects were asked to swallow the core temperature sensor pill (the pill takes at least one hour to pass through the stomach and become insensitive to the effect of fluid ingestion). The subjects were then required to void their bladders. All subjects had been instructed to drink a large glass of water (500 mL) that morning and refrain from consuming caffeine-containing drinks or salty foods. Any subject who failed to produce a urine specimen with a specific gravity of less than 1.015 prior to any session was deemed to be hypohydrated and was required to consume 500 mL of water before commencing the trial.

Each subject completed three test sessions in the chamber, two on the first day, with a one hour break for lunch, and one on the morning of the following day.

Each session lasted a maximum of three hours and consisted of alternating periods of work (~ 30 minutes) and rest (~ 10 minutes). All subjects were instructed to drink water to replace sweat loss and maintain hydration, particularly during rest breaks.

On completion of each session the subjects voided their bladders of urine, which was collected and measured. Subjects then showered without wetting their hair, and towelled down as thoroughly as possible before nude re-weighing.

## Results

Conditions throughout the trial were maintained as closely as possible to 40°C DB and 30°C WB and with minimal air movement. Conditions for the seven sessions are summarised in Table 2. The wet bulb globe temperature was recorded regularly throughout and mean values for sessions ranged from 31.86 to 33.52. The thermal work limit was calculated for each session using the means of the recorded environmental parameters for the session and a clothing insulation factor of 0.08 clo. Values for the TWL ranged between 140 and 156 watts/m$^2$.

Typically, core temperatures increased during the first work period and most subjects then attained a steady state (Figure 2). On some occasions a subject showed a progressive rise in core temperature with repeat bouts of work, indicating that heat storage was occurring. In some cases this led to core temperatures slightly in excess of the TWL limit of 38.2°C being reached (Figure 3).

Twenty-seven valid subject sessions were conducted, each consisting of several alternating work and rest periods. In eight of these sessions the subject's core temperature exceeded the TWL limit of 38.2°C (Table 3). However, two subjects accounted for five of the eight occasions, with one exceeding 38.2°C in all three sessions. On no occasion did a subject's core temperature exceed 38.2°C during the first hour in the chamber; typically this occurred when subjects were into at least the second or third hour of the session.

During most sessions the external workload was increased from 40 to 50 watts in the third or fourth work period, producing a further rise in core temperature in most subjects but not exceeding 38.2°C. Only those subjects who had either already reached or exceeded this level at 40 watts or else had failed to attain a steady state core temperature at 40 watts were likely to exceed 38.2°C at 50 watts, but this could not be clearly attributed to the increase in workload. A far more important factor appeared to be the issue of heat storage, with individuals whose core temperatures rose progressively with each work period eventually exceeding 38.2°C irrespective of workload (Figure 3).

**TABLE 2**

**Environmental conditions during the seven sessions for which results are reported. Data are means and standard deviations for readings recorded approximately every five minutes throughout each session**

| *Session* | *Dry bulb (°C)* | *Wet bulb (°C)* | *Wind speed* | *WBGT* | *TWL* |
|---|---|---|---|---|---|
| 1 | 39.84<br>±2.50 | 28.68<br>±1.45 | 0.24<br>±0.06 | 33.78<br>±1.55 | 156 |
| 2 | 39.60<br>±2.03 | 29.55<br>±1.29 | 0.22<br>±0.07 | 33.21<br>±1.80 | 140 |
| 3 | 39.79<br>±1.48 | 29.41<br>±2.52 | 0.24<br>±0.10 | 33.52<br>±1.11 | 147 |
| 4 | 39.47<br>±1.37 | 29.76<br>±0.80 | 0.23<br>±0.07 | 32.94<br>±1.00 | 140 |
| 5 | 41.36<br>±1.52 | 29.68<br>±1.15 | 0.26<br>±0.06 | 33.33<br>±1.12 | 142 |
| 6 | 40.26<br>±0.97 | 29.02<br>±1.04 | 0.24<br>±0.04 | 31.68<br>±1.00 | 150 |
| 7 | 39.58<br>±1.89 | 29.38<br>±1.28 | 0.24<br>±0.05 | 32.50<br>±1.34 | 148 |

## Discussion

In pre-trial testing, all subjects demonstrated an efficiency of approximately 25% for cycling with resting metabolic rates of approximately 55 watts/m$^2$, and had body surface areas of approximately 2 m$^2$ (Table1). At an external workload of 40 watts and 25% efficiency the metabolic heat load generated by the external work is approximately 120 watts or around 60 watts/m$^2$. The heat load due to resting metabolism plus the 40-watt workload is therefore approximately 115 watts/m$^2$. At 50 watts external work the total heat load is approximately 130 watts/m$^2$.

The TWL values calculated from the environmental conditions (140–156 watts/m$^2$) assume that subjects are fully acclimatised. The partially acclimatised nature of the subjects studied reduces the TWL by a variable amount depending on the degree of acclimatisation. For completely unacclimatised subjects in these conditions, the TWL is lowered to approximately 110 watts/m$^2$. It was therefore expected that for partially acclimatised subjects the selected workloads would be equivalent to or in excess of the TWL and that their ability to work in the environment without an excessive rise in core temperature would depend to some degree on individual acclimatisation status.

In 19 of the 27 sessions conducted the subjects were able to disperse the additional heat generated during periods of work without an excessive rise in core temperature (Figure 2). However, five of the eleven

**TABLE 3**

**Maximum core temperatures (°C) of subjects during work sessions**

| *Subject* | *Day 1 am* | *Day 1 pm* | *Day 2 am* |
|---|---|---|---|
| 1 | | | 37.7 |
| 2 | | | 38 |
| 3 | | | 37.8 |
| 4 | 38.4 | 38 | 38.2 |
| 5 | 38.4 | 38.5 | 38.65 |
| 6 | 37.8 | 38.1 | 38.5 |
| 7 | 37.3 | 37.55 | 38.05 |
| 8 | 38.1 | 38.25 | 38.45 |
| 9 | 38.2 | 37.4 | 38.1 |
| 10 | 37.7 | 37.9 | 37.9 |
| 11 | 38.4 | 38 | 38.1 |

**FIGURE 2**
**Changes in core temperature and heart rate for a euhydrated subject throughout a complete test session**

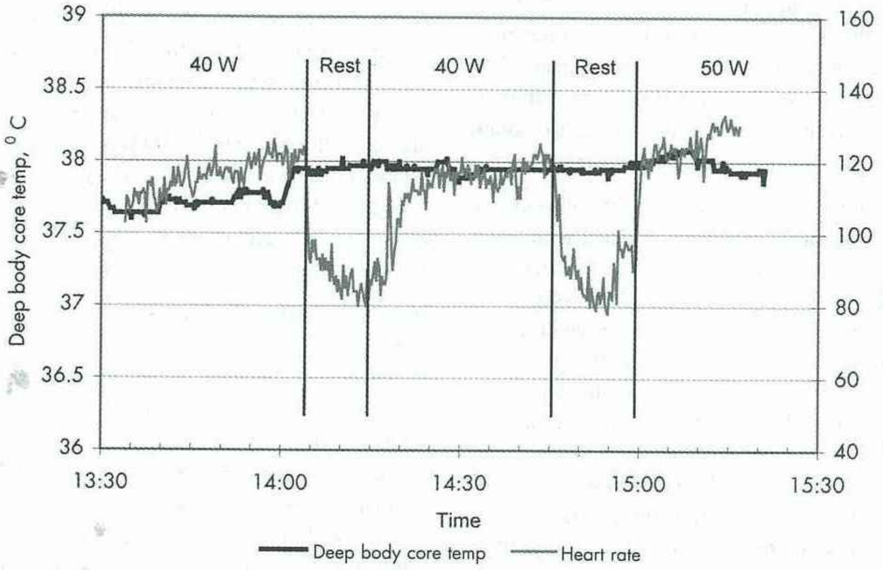
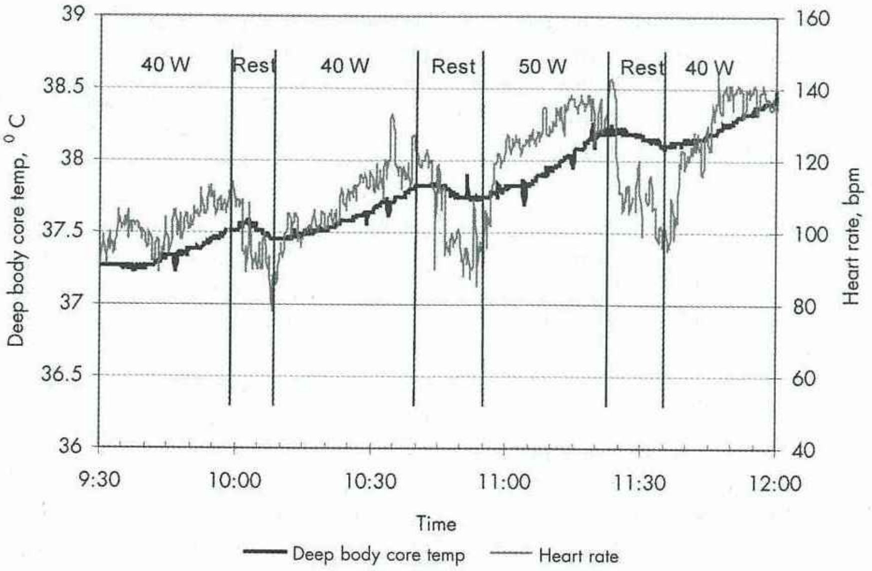


**FIGURE 3**
**Changes in core temperature and heart rate for the same subject as in Figure 2 during a test session in which the subject became hypohydrated (lost > 2.8% of body weight over the session)**



subjects did reach core temperatures in excess of 38.2°C in at least one of their sessions, and one did so in all three of his sessions as shown in Table 3.

With ambient temperatures in excess of 35°C, sweating is the only avenue of heat loss. To maintain the high sweat rates necessary to thermoregulate when working in these conditions, adequate hydration is essential. When fluid intake is inadequate to sustain high sweat rates, the core temperature rises.

All of the subjects were advised of the importance of adequate hydration and were provided with water *ad libitum*; nevertheless, several failed to maintain euhydration in all of their sessions as assessed by either a loss of more than 1.5% of body weight during the session, a post-session urine specific gravity of > 1.015, or a pre-session urine specific gravity of > 1.015 coupled with a loss of > 0.8% of body weight. Five of the eight occasions of core temperatures exceeding 38.2°C occurred in sessions where the subject was hypohydrated by these criteria. This is clearly shown in Figures 2 and 3. The same individual when euhydrated established a core temperature steady state independent of workload; however, when hypohydrated each successive work period resulted in a rise in core temperature. The other four individuals were not acclimatised to the heat, that is, they worked in airconditioning; additionally, two had poor cardiovascular capacity. These data illustrate the importance of acclimatisation and the essential need to maintain hydration when working in the heat. As with other indices, the TWL assumes euhydration of workers — thus the importance of sound education becomes clear.

Other individual factors that may influence thermal tolerance include body composition and general fitness. Individuals with a high body mass index generally thermoregulate less efficiently in the heat and are more prone to heat illness.[6]

The selection of 38.2°C as the limiting temperature in the TWL formulation is in line with other indices. As was expected with the metabolic heat load approximately equivalent to the TWL, a number of subjects exceed the 38.2°C limit. However, the highest core temperature recorded in the study was 38.65°C, which is still within the euthermic range. In many work situations the work is self-paced. One of the most important behavioural adaptations to thermal strain is to reduce the level of work — an option which was not available in this study. These subjects, although working at around the predicted thermal work limit and deprived of the opportunity to self-pace, showed little or no evidence of hyperthermia. This result implies that the TWL predicts the limiting metabolic heat load with a high degree of reliability, and that well-hydrated, acclimatised subjects working within the TWL are at a very low risk of developing hyperthermia.

Mean WBGT values for different sessions ranged from 31.86°C to 33.52°C (Table 2) which, according to NIOSH criteria, exceeds the recommended exposure limit even for fully acclimatised workers at a similar metabolic heat output (233 watts) working for 30 minutes in the hour.[7] The fact that our partially acclimatised subjects were able to work for ~ 45 mins/hr without hyperthermia suggests that the WBGT index is a poor indication of environmental stress and that the guidelines for its application are excessively conservative. The environmental conditions in this study included little or no air movement. The shortcomings of the WBGT as a heat stress index are amplified when ventilation is increased, as the index is largely insensitive to the substantial cooling effect of air movement.

The thermal work limit calculation requires and incorporates measurements of all relevant environment parameters including air movement (wind speed) to arrive at a single figure for the conditions. No interpretative skills are required as this figure can simply be matched against guidelines linked to a heat management protocol. Calculation of the TWL also yields a value for required sweat rate under the conditions, dictating a fluid replacement schedule to avoid dehydration. The TWL calculation can incorporate an adjustment for a range of clothing ensembles and potentially for the acclimatisation status of workers. Intended future work will provide the data to extend the application of the TWL to females as well as to workers of different age groups.

## Conclusion

It can be concluded from this study that:

- The TWL algorithm is able to accurately predict work rates that would be limiting under a given set of environmental conditions.
- The TWL is applicable to all situations where work is carried out in thermally stressful environments.
- The TWL performed better than the WBGT index and is considerably easier to use.
- The advantages of the TWL are increased where there is significant cooling related to air movement.
- Acclimatisation status is an important factor in determining an individual's ability to work in a thermally stressful environment, and management protocols must allow for this.
- Maintenance of adequate hydration is of paramount importance, particularly where workers are operating close to the thermal work limit. The TWL algorithm can be used to indicate fluid replacement guidelines.

Therefore, adoption of the TWL as a heat stress index has the potential to simplify the management of heat stress and reduce the impact of heat illness in industry.

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## APPENDIX

Field studies have suggested the following guidelines for heat stress management of self-paced workers using the TWL heat stress index:[4]

| TWL value | Suggested protocol |
|---|---|
| < 115 watts/m$^2$ | Withdrawal limit for self-paced, self-supervised workers as below this level even light work is not continuously sustainable even for fully acclimatised workers. Formal "permitting system" with management approval required to work. |
| 115 to 140 watts/m$^2$ | "Buffer zone" — work is restricted. This zone is to ensure consideration of any corrective action that would improve the environment. |
| 140 to 220 watts/m$^2$ | Work restricted to acclimatised workers. The acclimatisation period lasts for the first seven days back at work after an absence of > 14 days. |
| > 220 watts/m$^2$ | Unrestricted work. |