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# THE DEVELOPMENT OF A PERSONAL RESPONSE HEAT STRESS METER CALIBRATED TO THE PHYSIOLOGY OF THE RANGE OF EMPLOYEES WITHIN THE MINE WORKPLACE

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**ABSTRACT**

An evaluation of the use of air cooling power as an index of the thermal environment is discussed. A body temperature prediction model based on body temperature tests, a concept linked to a maximum safe body temperature and the predicted fourth hour body temperature which depends on the rate of heat accumulation (heat storage) within the body has been developed and tested. This has led to the conceptual development of a personal response heat stress meter calibrated to the physiology of the personnel within the workplace. The proposed heat stress meter will be able to measure workplace environmental parameters such as air temperature, humidity and air velocity and the user can either select or manually enter other heat stress parameters such as work rate, clothing type and subject's personal response to heat. With a built-in computer program, the meter will calculate the ACP of the workplace, the fourth hour body core temperature expected and the maximum safe working time allowed for a pre-defined limiting body temperature. A brief description of the work required for developing the meter is included. The potential benefits of such instrument to the mining industry are also evaluated.

## INTRODUCTION

Excessive heat stress causes discomfort, decreased productivity, increased accident rates, abnormal physiological strain and ultimately death due to heat stroke. Heat stress is influenced by work rate, personal factors such as age, weight and physical conditions and the environmental climatic effects of atmospheric temperatures, relative humidity and air velocity. Problems are found in the mining industry under various conditions, particularly in deep mining where high virgin rock temperatures provide difficult ventilation conditions in stopes and confined working areas and in open cut mines where employees need to work outside equipment cabs during hot summer months.

Current mining regulations or practices in Australia and overseas take an indirect approach to determining a safe heat stress limit (Gillies, 1991). Most of the approaches take some measurements of climatic factors such as air temperatures, humidity and velocity within the working environment. Some introduce aspects such as work rate, although quantification of work rate heat production is accepted to be very difficult. Approaches in use and adopted by one or more Australian states' statutory regulations include:

- the wet bulb temperature index;
- the effective temperature index;
- a modification of the predicted Four Hour Sweat Rate ($P_4SR$) index; and
- the air cooling power (ACP) index.

Other approaches to heat stress measurement in other major mining countries are well known, in particular the Wet Kata Thermometer index in South Africa and the Wet Bulb Globe Temperature index in the United States.

For a heat stress index or measure (not a comfort index) to be of practical use it must incorporate the work rate and allow for the effects of clothing and relevant climatic parameters as well as the physiological strain on the employee. This precludes, on their own, the use of wet bulb temperature, effective temperature and the more recently introduced wet bulb globe temperature indices. The $P_4SR$ index has been adequately validated for work in hot conditions and incorporates work rate and the effect of clothing. This index was used to develop the current six hour and stop job protocol at the Mount Isa Mine, Australia and has been proven to be suitable in practical situations. Since this work was undertaken, the ACP index has been developed and, because of its greater generality and more rigorous development, has in places superseded the $P_4SR$ index concept (Howes, 1992).

Previous work on ACP indices including "Scale A" Cooling Power graphs and tables has been based on experiments performed on assessing the heat stress of male nude acclimatised mine workers in environments with wet bulb temperatures between 25 and 35°C and air velocities from 0.2 to 4.5 m/s (Stewart, 1981). The cooling power values were calculated assuming the man's skin surface is fully wet with sweat. However, as clothing wetness can vary considerably for clothed employees, it is not possible to simply add on an additional constant clothing insulation value to the heat transfer equation (Murray-Smith, 1987). Current charts assume nude or near nude conditions and so wider use of the concept in Australian mining industry has been inhibited.

Recent investigations at The University of Queensland studied the effects of heat stress on a group of fit young students (Travers, 1990; Brumpton, 1993). The studies sought to establish the physiological and psychological reactions to half hour exercise programs in a heated and humidified room. The investigations found that physiological reactions were related to room temperature and the clothing worn. Psychological testing indicated that there was an increase in mental stress with increased temperature and this relationship was accentuated when subjects wore mine clothing. A reduction in the level of psychological arousal with increased room temperature was also found.

Based on these findings, conclusions have been drawn that there is a need for the development of a heat stress index for use in Australian mining (Travers, 1990; Gillies, 1991; Wu, 1994). A suggested method is to develop a direct approach for heat stress measurement, namely, a personal response heat stress meter calibrated to the physiology of the employee within the workplace.

## THE PHYSIOLOGICAL HEAT STRAIN MODEL

The most important part of the development of the personal heat stress meter involves the definition of a heat strain model that completely satisfies requirements of the human body's physiological response to heat stress environments. A physiological heat strain computer model based on the concepts of ACP and the body core temperature has been conceptualised. As the body core temperature is the most direct indicator of the strain brought about by heat stress, it would be advantageous to develop a computer model that predicts the body core temperature rise under various heat stress environments. The model needs to consider all thermal parameters that contribute to heat stress including rates of metabolic heat production, clothing, individual factors (such as age, fitness, body size, acclimatisation and gender) and thermal environmental parameters.

A thermoregulation concept proposed by McPherson (1992) for assessing predicted climatic conditions was employed to calculate the ACP for a wide range of climatic conditions. With users entering other heat stress parameters including work rates, clothing types and personal heat response information for each subject studied, the outputs of the model should indicate the ACP of the thermal environment, the metabolic rate produced, the heat accumulated in the human body, the predicted maximum body temperature and the maximum safe working time (duration) allowed under the given thermal condition.

The concept is based on the definition of a maximum safe body temperature at which a person will experience negligible risk of suffering heat stroke. It follows then that individuals will be able to achieve a safe equilibrium body temperature in all conditions where the calculated ACP equals or exceeds the rate of metabolic heat generated by the individuals in question. Body temperature will only increase when the calculated ACP is less than the metabolic heat produced. The rate of body temperature increase depends on the rate of heat accumulation (heat storage) within the body. Different environmental conditions causing the same heat accumulation rate may be assessed as leading to the same heat stress, in that they will all be associated with the same body temperature elevation.

The prediction of maximum body temperature under heat stress conditions was developed based on the results of body temperature tests using a Cortemp thermometer conducted by Travers (1990) and Brumpton (1993). These experiments investigated the effects of heat stress on a group of fit young students at The University of Queensland. The study sought to establish the physiological and psychological reactions to half hour exercise programs in a heated and humidified room. In these tests, the exercise room was controlled at three temperature settings, namely, 35°C, 37°C and 39°C with 100 percent relative humidity (RH). The exercises conducted were rated as high activity level. Subjects wore either only shorts or overalls (mining coveralls) on successive sessions, together with normal mining accessories (boots, belts, hard hats, lamp and batteries). Body temperature changes were measured for all subjects orally and with an electronic internal body temperature monitor (Cortemp thermometer) which provided a continuous record before, during and after each exercise session.

The basis of the Cortemp thermometer tests is a "tablet" or "capsule" sized disposable temperature sensor that is swallowed by the subject being monitored. The capsule contains microcircuitry and battery power to enable temperature measurement over the 24 to 72 hours that it is expected to remain within the body's digestive system. Temperatures can be displayed and recorded at intervals between 30 seconds and one hour. The sensor capsule transmits to an external "Ambulatory Recorder" with indicator and large memory storage. This recorder can be attached to the miner's belt so as not to inhibit normal movement.

As a starting point for establishing a physiological heat strain prediction model, it is logical to note that changes in the body temperature may be brought about in two ways:

- by a change in the body's state of heat balance, or
- by a redistribution of heat stored within the body.

While it might be possible for a redistribution of stored heat to occur without there being a change in the body's overall state of heat balance, it is most unlikely that this would occur. Hence, this aspect can be ignored; and consideration will be given only to the conditions for heat balance of the body.

Heat exchange between the human body and the surrounding atmosphere occurs through a combination of processes. If the rate of body (metabolic) heat generation is M and heat losses from human body to the surrounding is defined as ACP, then the heat balance of the body can be described by the following equation:

$$S = M - ACP \qquad W/m^2 \qquad [1]$$

where S is the heat accumulation within the body under heat stress. The value of S can be either positive or negative depending on the values of M and ACP. The approach has been taken that it is possible to have negative ACP values (where there is a net heat flow from the surrounding atmosphere to the body) as well as positive (where there is a net heat loss from the body to the surrounding atmosphere). All situations gives negative S were ignored as these situations are not considered as “heat stress” conditions. Examples of the possible heat accumulated in the subjects' body for the body temperature tests at an estimated body metabolic heat output rate of 240 W/m$^2$ are given in Table 1.

Table 1 ACP and accumulated heat calculated during the Cortemp thermometer tests conducted by Travers and Brumpton.

| Thermal Conditions & Clothing types | ACP* (W/m$^2$) | M (W/m$^2$) | S (W/m$^2$) |
|---|---|---|---|
| 35$^o$C, 100% RH, 0.5 m/s, Overall | 4 | 240 | 236 |
| 37$^o$C, 100% RH, 0.5 m/s, Overall | -31 | 240 | 271 |
| 39$^o$C, 100% RH, 0.5 m/s, T-shirt & short | -107 | 240 | 347 |

* calculated based on McPherson’s ACP model.

The body temperature increase over time at three different heat accumulation rates are given in Figure 1. The curve from the thermal condition (39$^o$C, 100 percent relative humidity, 0.5 m/s, Shorts and T-shirt) is plotted using the average body core temperature increase rates from two male subjects completing exercise programs in Brumpton's Cortemp tests.

It is assumed that when the excess heat accumulated in the human body is zero (thermal equilibrium), there is no body temperature change. Based on this assumption, the body temperature changes over time for four heat accumulation rates are listed in Table 2 for an initial body core temperature of 37.5$^o$C (the average initial temperature measured for subjects studied).

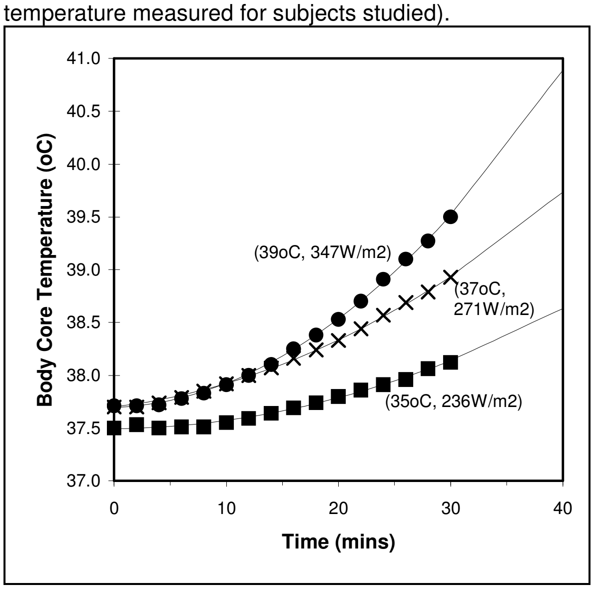



Figure 1 Body core temperature changes at different thermal conditions (data complied from Travers, 1990; Brumpton, 1993).

Table 2 Prediction of body temperature increase over time at various heat accumulation levels.

| Accumulated Heat Rate (W/m$^2$) | Body core temperature ($^o$C) | | | | | |
|---|---|---|---|---|---|---|
| | Time (minutes) | | | | | |
| | 10 | 20 | 30 | 40* | 50* | 60* |
| 0 | 37.50 | 37.50 | 37.50 | 37.50 | 37.50 | 37.50 |
| 236 | 37.58 | 37.79 | 38.14 | 38.64 | 39.27 | 40.04 |
| 271 | 37.72 | 38.13 | 38.74 | 39.53 | 40.01 | 41.69 |
| 347 | 37.76 | 38.39 | 39.41 | 40.80 | 42.58 | 44.61 |

* predicted values from curves in Figure 1.

Figure 2 shows six body temperature curves corresponding to times of 10 to 60 minutes after exposure to indicated thermal conditions. By interpolating these curves, the body temperature increase at any given heat accumulation rate can be obtained (For example, body temperature increase at 30 minutes under conditions of 100 W/m$^2$ heat accumulation is 0.08$^o$C).

Subsequently, the body temperature increases at the heat accumulation rate of 10, 20, 30, 40, 50, 100, 150, 200, 250, 300 and 350 W/m$^2$ were established for 10 and 60 minute periods. Re-interpreting (transposing) these data, the curves of body temperature increases over time at various heat accumulation conditions are illustrated in Figure 3.

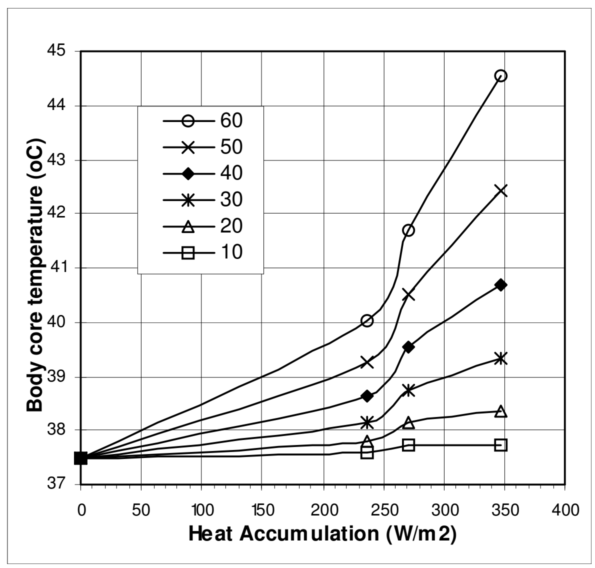
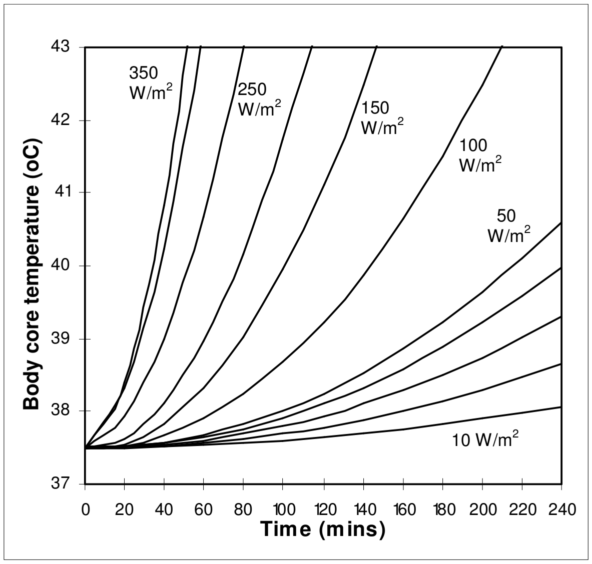



Figure 2. Predicted body temperature changes with heat accumulation for 10 to 60 minute periods.




**Y = Body core temperature (°C); X = time (minutes)**

$Y = 37.497 + 7.6925e^{-3}X + 1.8880e^{-3}X^2$ ($R^2$=1.000, 350 W/m$^2$)
$Y = 37.483 + 1.3418e^{-2}X + 1.3909e^{-3}X^2$ ($R^2$=0.998, 300 W/m$^2$)
$Y = 37.489 + 6.8393e^{-3}X + 7.7036e^{-4}X^2$ ($R^2$=1.000, 250 W/m$^2$)
$Y = 37.503 - 2.3979e^{-3}X + 4.4607e^{-4}X^2$ ($R^2$=1.000, 200 W/m$^2$)
$Y = 37.506 - 3.2282e^{-3}X + 2.7696e^{-4}X^2$ ($R^2$=0.999, 150 W/m$^2$)
$Y = 37.504 - 1.3332e^{-3}X + 1.3089e^{-4}X^2$ ($R^2$=0.997, 100 W/m$^2$)
$Y = 37.501 - 4.1393e^{-4}X + 5.5536e^{-5}X^2$ ($R^2$=0.999, 50 W/m$^2$)
$Y = 37.500 - 3.5386e^{-4}X + 4.4643e^{-5}X^2$ ($R^2$=0.998, 40 W/m$^2$)
$Y = 37.500 - 2.2093e^{-4}X + 3.2179e^{-5}X^2$ ($R^2$=0.997, 30 W/m$^2$)
$Y = 37.500 - 1.2929e^{-4}X + 2.0643e^{-5}X^2$ ($R^2$=0.996, 20 W/m$^2$)
$Y = 37.500 - 4.7143e^{-5}X + 1.0143e^{-5}X^2$ ($R^2$=0.996, 10 W/m$^2$)

Figure 3 Body core temperature increase rate at 10-350 W/m$^2$ heat accumulation conditions

The polynomial equations representing the curves are also included. From the curves, the possible maximum safe working time can be determined for the given heat accumulation condition. For example, with a limiting body temperature of 39.0°C, the possible maximum safe working time would be 165 minutes under a heat accumulation rate of 50 W/m$^2$ and about 110 minutes under heat accumulation rate of 100 W/m$^2$.

Figure 3 indicates that the relationship between body core temperature and time can be expressed in the following equation:

$$t_c = t_{ci} + Bt + At^2 \qquad [2]$$

where $t_C$ is the maximum (final) body core temperature, °C; $t_{ci}$ is the initial body temperature, °C; A and B are constants varying with heat accumulation rate and t is time in minutes.

As constant A and B are varying with the levels of heat accumulated in the body, S, it is possible to correlate these two constants to the heat accumulation rate. Based on the polynomial equations described in Figure 3, the correlation between constants A and B and heat accumulation rate can be calculated and expressed in the following equations:

$$A = 1.777\ 10^{-5} + 3.015\ 10^{-7}\ S + 4.104\ 10^{-9}\ S^2 + 3.027\ 10^{-11}\ S^3 \qquad (R^2 = 0.996)$$
[3]

$$B = -7.775\ 10^{-5} - 1.441\ 10^{-5}\ S + 7.435\ 10^{-7}\ S^2 - 1.414\ 10^{-8}\ S^3 + 7.687\ 10^{-11}\ S^4 - 1.191\ 10^{-13}\ S^5 \qquad (R^2 = 0.991)$$
[4]

where S is as defined earlier and $R^2$ is the coefficient of determination (the square of correlation coefficient).

Stewart and Van Rensburg (1975) suggested that an initial rectal temperature of 36.8°C is generally accepted and referred to as the so-called "normal" body temperature of resting men provided the environment is neither too hot nor too cold. However, in this study, an initial body core temperature of 37.5°C was used as this was the average initial body temperature of the subjects measured using the Cortemp instrument. This difference, no doubt, reflects the rectal temperature measurement technique and external atmospheric influence on this measurement.

If a limiting maximum safe body temperature of 39.0°C is used, the maximum safe working time under various heat accumulation conditions can be calculated. Equation [2] may be rewritten as:

$$At^2 + Bt + (t_{ci} - t_{cl}) = 0$$
[5]

where $t_{cl}$ is the limiting body temperature. If $(t_{ci} - t_{cl})$ equals constant C, equation [5] may be rewritten as:

$$At_{max}^2 + Bt_{max} + C = 0$$
[6]

Solving this equation, the maximum safe working time allowed under the given heat stress environment can be calculated from the following:

$$t_{max} = (-B \pm (B^2\text{-}4AC)^{0.5})/2A$$
[7]

As $(-B - (B^2\text{-}4AC)^{0.5})/2A$ always gives a negative value, the meaningful values for t can be calculated from:

$$t_{max} = (-B + (B^2\text{-}4AC)^{0.5})/2A$$
[8]

where absolute values of $B^2$-4AC should be used for meaningful solutions. Figure 4 illustrates the predicted maximum safe working time under heat accumulations based on an initial body temperatures of 37.5°C with a limiting body temperature of 39.0°C.

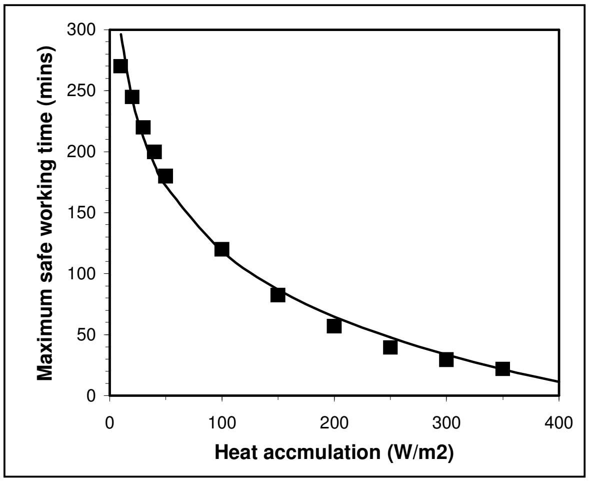



Figure 4 The predicted maximum safe working time at various heat accumulation conditions.

A physiological heat strain model has been developed. It determines the maximum body temperature expected and the maximum safe working time allowed for any input combination of psychrometric conditions, air velocity, physical activity and type of clothing. The program structure is depicted in Figure 5.

The physiological heat strain prediction model involves employing the thermoregulation model developed by McPherson (1992) to calculate the inequality between the computed net heat transfer and a known or estimated metabolic rate. The behaviour of the model emulates that of an individual who changes metabolic rate or moves into a different climatic environment. A transient period will occur when the body temporarily accumulates or loses heat at a rate S, given by equation [8].

$$S = M - (R + C + Br + E) \quad W/m^2 \qquad [9]$$

where R = radiant heat transfer, $W/m^2$,
C = convective/conductive heat transfer, $W/m^2$,
Br = the respiratory heat transfer, $W/m^2$ and
E = the evaporative heat transfer, $W/m^2$

If the value of S is positive, then the reaction of the individual may be to rest, reduce the rate of work or discard clothing (behavioural response). However, the physiological heat strain prediction model assumes that the metabolic rate is maintained and the body temperature is increased as a function of S over time.

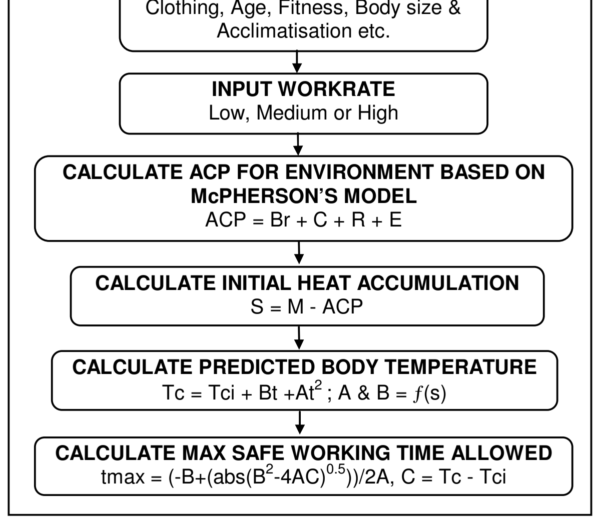



Figure 5 Program structure of the physiological heat strain prediction model.

*Example*

A person works in a narrow mine opening. Given the following information, it is possible to determine the values of the maximum body temperature after four hours and the maximum safe working time allowed, if the work rate is 130 $W/m^2$.

Clothing: Thick trousers, long-sleeved shirt, hard hat and boots
Airflow: Wet bulb temperature = 28°C
Dry bulb temperature = 33°C
Barometric pressure = 100kPa
Air velocity = 1 m/s
Rock surface (radiant) temperature = 33°C

*Solution*

From the thermoregulation model, an initial base skin temperature of 34.63°C was established using the equation proposed by Gagge et al (1969) and taking clothing and the convective heat transfer coefficient into account. Detailed description of this calculation has been well documented (McPherson, 1992).

The heat transfers between the human body and the environment have been found to be:

| | | | |
|---|---|---|---|
| respiration, | Br = | 9 | $W/m^2$ |
| convection, | C = | 7 | $W/m^2$ |
| radiation, | R = | 3 | $W/m^2$ |
| evaporation, | E = | 88.3 | $W/m^2$ |
| Total (net) cooling | ACP = | 107.3 | $W/m^2$ |

The human metabolic rate is, however, M = 130 $W/m^2$. Hence, the initial rate of heat accumulation (S) is

$$S = 130 - 107.3 = 22.7 \ W/m^2$$

In this example, if an initial body temperature of 37.5°C is used, the maximum body temperature expected after four hours can be calculated as follows. From equation [2] and [3], the values of constants A and B can be obtained.

$$A = 1.777\ 10^{-5} + 3.015\ 10^{-7}\ (22.3) + 4.104\ 10^{-9}\ (22.3)^2 + 3.027\ 10^{-11}\ (22.3)^3 \quad = \quad 2.687\ 10^{-5}$$

$$B = -7.775\ 10^{-5} - 1.441\ 10^{-5}\ (22.3) + 7.435\ 10^{-7}\ (22.3)^2 - 1.414\ 10^{-8}\ (22.3)^3 + 7.687\ 10^{-11}\ (22.3)^4 - 1.191\ 10^{-13}\ (22.3)^5 = \ -1.678\ 10^{-4}$$

Therefore,

$$t_c = 37.5 - 0.0001678\ (240) + 0.000026872\ (240)^2$$
$$= 37.5 + 1.52 = 39.02^{o}C \text{ (fourth hour)}$$

and the maximum safe working time allowed for the body core temperature not to exceed 39°C, $t_{max}$, can be calculated using equation [6]:

$$t_{max} = (-B + (B^2\text{-}4AC)^{0.5})/2A$$
$$= ((0.00016781 + (abs((-0.00016781)^2 - 4(0.000026872)(39.0 - 37.5)))^{0.5})/2(0.000026872)$$
$$= 238 \text{ minutes}$$

McPherson (1992) reported that under the same thermal condition for heavily clothed personnel, the limiting rates of continuous work (fourth hour body temperature less or equal to 39.0°C) is 127 W/m$^2$. This indicates that the result from the model agrees well with McPherson's prediction. A comparison of the results from the body temperature prediction model and the observed values published by past researchers is illustrated in Table 5.

The table suggests that the observed values and predicted values for the first hour correlate well (38.8 and 38.8°C for S=223 W/m$^2$; 37.5 and 37.7°C for S=135 W/m$^2$). However, the predicted body temperatures are much higher than the observed values for the second hour. This may be because the values measured by Strydom et al (1975) were based on an acclimatisation exercise program which included some resting periods during exercise. This allowed the body temperatures of the subjects to cool down. This indicates that a series of Cortemp thermometer tests are required, as proposed by Gillies (1991), to validate the concept and establish a faithful and reliable model that also includes the resting periods during normal working shifts.

Table 5 Comparison of predicted (by the body temperature prediction model) and observed (Strydom et al, 1975) body temperatures under various heat stress conditions.

| S (W/m$^2$) | Observed Body Temperature °C | | | Predicted Body Temperature °C | | |
|---|---|---|---|---|---|---|
| | 0 mins | 60 mins | 120 mins | 0 mins | 60 mins | 120 mins |
| 223 | 36.5 | 38.8 | 39.9 | 36.5 | 38.8 | 45.6 |
| 135 | 36.9 | 37.7 | 38.4 | 36.9 | 37.5 | 39.5 |

$t_w/t_d$ = 33.8/35.6°C; V = 0.4 m/s; Clothing type: Nude

Stewart (1982) has proposed that heat accumulation (storage) of the persons under heat stress may be calculated from the following equation:

$$S = m_t\, c_{pt}\ (0.2\Delta t_s + 0.8\Delta t_{re})/\Delta t \qquad W/m^2 \qquad [10]$$

where $m_t$ is the mass of the human body, kg; $c_{pt}$ is the average specific heat of the human body, J/kg°C; $t_s$ is the mean skin temperature, °C; $t_{re}$ is the rectal temperature, °C and t is time, s. Equation [9] indicates that an average person accumulating heat at a rate of 67W would experience a 1.0°C rise in rectal temperature over a period of one hour. The skin surface area, $A_{skin}$, can be calculated from a knowledge of body mass and height using the following equation suggested by Stewart (1982).

$$A_{skin} = 0.217 m_t^{0.425}\ H_t^{0.725} \quad m^2 \qquad [11]$$

where $m_t$ is the body mass of the human body, kg, and $H_t$ is the height, m. Assuming that an average person has a body mass of 70kg and a height of 1.75m, the skin surface area will be approximately 2 m$^2$. With heat accumulating at a rate of 22.7 W/m$^2$, the total heat accumulated would be 45.4W for a person with a skin area of 2 m$^2$.

Equation [10] indicates a 2.72°C rise in both body and skin temperature. This is nearly twice (2.7°C compared with 1.52°C) the value predicted by the model. This suggests that equation [10] overestimates the body temperature rise as the physiological conductance could be increased due to increase in peripheral blood circulation. Measurements from the Cortemp thermometer, however, have taken the changes of physiological heat strain into account as it measures the body core temperature directly and continuously.

## THE PERSONAL HEAT STRESS METER

Based on the physiological heat strain model, the concept of a personal heat stress meter calibrated to the physiology of the range of employees within the mine workplace has been developed. The meter would be able to measure the workplace environmental parameters such as air temperature, humidity and air velocity and the user can either select or manually enter other heat stress parameters such as work rate, clothing type and subject's personal response to heat. With a built-in computer program, the meter will calculate the ACP of the workplace, the fourth hour body core temperature expected and the maximum safe working time allowed for a pre-defined limiting body temperature. Figure 6 illustrates the proposed personal response heat stress meter.

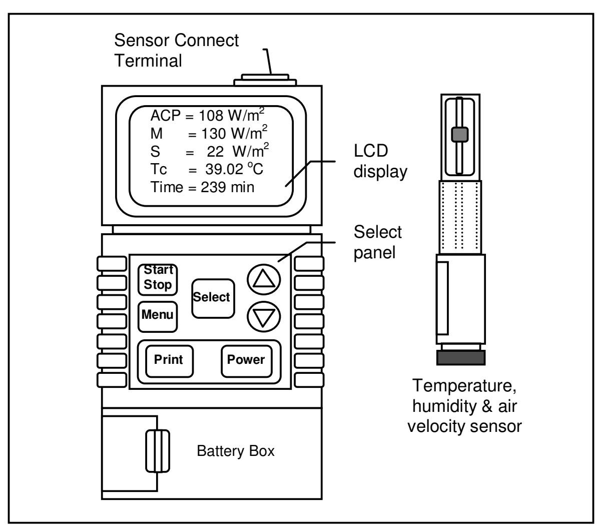


Figure 6 A conceptual diagram of the personal response heat stress meter.

The meter can be hand held and battery powered. It can operate on a standard battery which will provide long operation.

The most important part in developing the meter involves the definition of the heat strain model that completely satisfies requirements of the human body's physiological response to heat stress environments. A physiological heat strain model has been conceptually defined and described previously. However, before the physiological heat strain model can be employed with confidence, it is necessary to study the responses of a large number of subjects for a lengthy period of heat exposure at various heat accumulation rates in order to establish a tested model. These would require the following.

- A full series of body core temperature tests under controlled mine conditions. This should be carried out partly in a controlled laboratory (hot box) and partly in underground and surface mine conditions (for instance wet bulb temperatures of 25 to 35$^{o}$C, dry bulb temperatures of 30 to 45$^{o}$C) to establish body core temperature elevation under varying heat accumulation rates using a statistically valid population of subjects. Length of exposure and rest time during tests should be considered. It is important that tests are undertaken on enough individual to gain variation in response reflecting difference in employee age, gender, body size and fitness.

- Tests on the metabolic rate produced by the subjects examined for typical mine tasks. The metabolic rate can be assessed based on oxygen consumption during the designed exercise program undertaken in the Cortemp tests.

- Development of a prototype heat strain model calibrated to the physiology of the range of employee groups within the mine workplace based on the findings from work outlined above.

- Tests on the application of the meter in terms of economic and technical benefits. These tests should be undertaken on the range of employee groups; the meter should be tested in the arduous mine environment and Cortemp readings used for comparison purposes.

- Investigation on the systematic and practical use of the instrument.

## BENEFITS TO THE MINING INDUSTRY OF IMPROVED HEAT STRESS ASSESSMENT

Benefits to the mining industry from adoption of a personal response heat stress meter will include the following.

Firstly, physiologically the concept of the personal response heat stress meter involving ACP and body core temperature is most representative for employees working in a hot and humid mine environment. There is no dispute that the concept can be used to accurately reflect heat stress conditions and it is in the best interests of mine owners, employees and the relevant statutory authorities to promote its introduction and use.

Secondly, the personal heat stress meter is calibrated to the individual physiology of the employee within the workplace and is able to assess individuals within any working environment. The use of the meter will allow more efficient mine planning for refrigeration requirements and reduce lost time through six hour and stop job conditions.

Finally, the use of a heat stress meter which measures heat stress and heat strain directly will eliminate the need to use $P_4SR$ or ACP charts and can provide a consistent and simple method for use in the management control strategy with respect to potential heat stress conditions. It will also provide better workforce response and acceptance of six hour administration and reduce possible disagreement between supervisors and employees.

## CONCLUSIONS AND RECOMMENDATIONS

The fundamentals of heat stress have been reviewed and the application of ACP as a heat stress index evaluated. The ACP concept is one of the most highly researched heat stress indices. Work conducted by the Chamber of Mines of South Africa on the ACP concept has been based on some primary assumptions that have inhibited the wide use of the concept in the mining industries of many western countries. Previous work has concluded that there was a need for the development of a heat stress index for use in all parts of Australia.

A body temperature prediction concept based on the Cortemp thermometer tests has been developed. The concept is linked to a maximum safe body temperature at which a person will experience negligible risk of suffering heat stroke. This limit has been set at 39$^{o}$C. It follows then that persons will be able to achieve a safe equilibrium body temperature in all instances where the calculated ACP equals or exceeds the rate of metabolic heat generated by the persons in question. Body temperature will increase only as the ACP calculated is less than the metabolic rate produced. The rate of body temperature increase will depend on the rate of heat accumulation (heat storage) within the body. Different environmental conditions having the same heat accumulation rate may be assessed as having the same heat stress, in that they will all be associated with the same body temperature.

The concept of direct measurement of heat stress and possible applications of the concept have been described in this paper. As the concept is the result of a theoretical evaluation based on limited empirical data, it will require a further detailed study on the relationship between the body core temperature and the heat accumulation rate. In spite of the need for this experimentation to be extensive, both the theoretical arguments and the potential usage of the concept appear sufficiently promising to warrant further work.

## REFERENCES


Brumpton, S.K., 1993. The development of a hest stress monitoring instrument. Bachelor of Engineering Thesis, Department of Mining & Metallurgical Engineering, The University of Queensland.

Gagge, J. et al 1969. The prediction of thermal comfort when thermal equilibrium is maintained by sweating, *Trans. ASHRAE*, Vol. 75, Part 2, pp. 108-112.

Gillies, A.D.S., 1991. The problem of heat stress in the Australian mining industry, Report to AMIRA, January 1991.

Howes, M.J., 1992. Mount Isa Mines - January 1992 Ventilation and Refrigeration Review, MIM Internal Report.

McPherson, M.J., 1992. The generalisation of ACP, *Proceedings 5th Internat. Min. Vent. Cong.*, Johannesburg, 1992, pp 27-35.

Murray-Smith, A.J., 1987. The effects of clothing on heat stress in mining environment, *Journal Mine Vent. Soc. S. Afr.*, Vol 40(3), pp 37-39.

Stewart, J.M. and Van Rensburg, A.J., 1975. The link between thermal stress and physiological strain, *Proceedings 1st Internat Min Vent Cong* (Eds R Hemp and FH Lancaster), Johannesburg, pp 267-271 (Mine Vent Soc S Africa: Johnnesburg).

Stewart, J.M., 1981. Heat transfer and limiting physiological criteria as a basis for the setting of heat stress limits, *Journal of S. Afr. Inst. Min. Metall.*, Vol 81, pp 239-251.

Stewart, J.M., 1982. Fundamental of human heat stress, Ch. 20 in *Environmental Engineering in South African Mines*, Mine Vent. Soc. S. Afr., pp 495-533.

Strydom, N.B., Benade, A.J.S. and V.D. Walt, W.H., 1975. The performance of the improved microclimate suit, *J. S. Afr. Inst. Min. Metall.* Vol. 76, pp. 329-333.

Travers, I.B., 1990. Heat stress and its effects on miners, specifically in the underground environment, . Bachelor of Engineering Thesis, Department of Mining & Metallurgical Engineering, The University of Queensland.

Wu, H.W., 1994. Mine ventilation recirculation and cooling strategies in deep Australian mines, Doctor of Philosophy thesis, Department of Mining & Metallurgical Engineering, The University of Queensland.