Identification of Heat Stress and Associated Heat Strain Caused by Temperature Related Working Conditions.

Suzanne Rice

School of Biomedical and Chemical Science

CEED Partner: Pilbara Iron

Abstract

All industrial operations introduce potential risks which may affect health and safety if adequate precautions are not taken. Heat stress is a well known contributing factor in underground mining primarily due to the high work activity demand under hot/wet environmental conditions. Surface mines in hot/dry conditions are also potentially at high risk, however there have been relatively few investigations into the occurrence and assessment of heat stress here. This study therefore aimed to assess a populace identified by Rio Tinto's surface mine operation in the hot/dry Pilbara region of Western Australia where general working conditions present high risk to heat stress. As a direct result, Occupational Health and Safety standards were determined to have adequate physiological limits set for individuals working in this unique work environment. In particular, that individual scheduled drinking routines and allowance for self-paced work were sufficient to offset the adverse effects of heat strain and associated dehydration, irrespective of the additional insulating effects of wearing personal protective equipment. Interestingly, the comparison period in winter highlighted the importance of continued rehydration and good sleep quality on ones risk to dehydrate and perception of fatigue, respectively.

1.0 Background

Heat is a naturally occuring stressor. Humans, as homeotherms, have a highly developed thermoregulatory system, which deals efficiently with heat stress. Humans can tolerate a wide range of environmental conditions, while maintaining a relatively stable deep body core temperature, ~37°C. It is maintained by the passive transfer of dry heat through conductive, convective and radiative processes that are dependent on thermal gradients from the skin, and wet heat loss, via the evaportaion of sweat. In hot climates above 34°C, the loss of dry heat becomes negligable, and often the thermal gradient becomes reversed so that heat balance becomes increasingly reliant on evaporation. Subsequently, factors affecting evaporative loss, such as dehydration, clothing, relative humidity, etc, also ultimately affect heat balance. Uncompensated heat stress results in heat storage and the associated degree of heat strain is generally marked by increases in core body temperature, heart rate and sweating, and if not adequately addressed can end in serious heat illness. Heat illness, particularly heat exhaustion and associated dehydration are common in the mining industry. It has been recently documented that the occurrence of heat exhaustion in US surface mining is approximately $0.168/10^6$ person-hours (1) and in a one-year prospective of an Australian underground mine it has been reported as $43.0/10^6$ person-hours(2). Interestingly, the majority (79.4%) of heat illness are reported during the summer months (1), highlighting the impact of high environmental heat stress on man's ability to work and survive in the heat. Furthermore, heat stress has been associated with higher accident rates and reduced work efficiency in mining. Pilbara Iron believe that all injuries and occupational illnesses are preventable and therefore its vision is to achieve and maintain zero injuries. With this in mind, Pilbara Iron identified employees of the Heavy Equipment Workshop (HEWS) at their Tom Price open pit mine site as at high risk to heat stress, primarily attributed to high environmental working temperatures exacerbated by additional occupational heat loading (HEWS, Job Demand Evaluation Role Profile) and therefore a relevant populace for review.

2.0 Objectives

To characterise and evaluate the occurrence and severity of heat stress and heat strain on workers, particularly Boilermakers, in the Pilbara. To characterise and assess environmental and physiological indices to ascertain whether current ergonomic safety standards and workplace protocols are effective in minimising heat strain. To characterise behavioural adaptations exhibited by this selected populace and evaluate the effectiveness of relevant heat stress modifying behaviour. To determine and evaluate the added heat stress effects of varying ensembles of Personal Protective Equipment (PPE) utilized by the selected populace. To achieve these objects the research was performed in two parts, Observational field studies and a control PPE climatic chamber study.

3.0 Methods

3.1 Participants

All participants gave their written informed consent to a series of field studies that were either authorised and/or supervised by Pilbara Iron's Occupational Health and Safety Officer and the Physiology Department of the University of Western Australia under approval from the University Of Western Australia's Human Ethics committee on human experimentation.

The Observational study participants were all employees of the HEWS, at Pilbara Iron Tom Price mine site, and were all considered well informed with respect to working in the heat and in particular, adequately versed in the importance of self-pacing and the need for fluid replacement. The targeted workers were typical of industrial workers at this operation. The control group were working in the same operation in sedentry work spending the majority of time in thermoneutral conditions. All participants for the PPE Study were recruited from the general metropolitan population and advised on hazards before participation. Each PPE recruit acted as their own control.

3.2 Observational Study

The project was broken into seasonal observational studies for direct group and individual seasonal comparison. Acclimatised participants were monitored for the duration of their shift with various physiological, subjective and environmental indices measured and recorded.

Environmental indices of dry bulb temperature (DB) and relative humidity (RH) were recorded from the main workshop floor and air-conditioned crib and office spaces. Determination of the water vapour pressure of air gave an estimate of the evaporative capacity air during shift hours. Actual work locations were subject to considerable variation, for example, differing radiant heat loads from individual tasks. Therefore due to the intermittent nature of the tasks the general central values were considered reasonable estimates.

Physiological heat strain is typically assessed during exposure to heat stress, according to elevation in the physiological responses of core body temperature, heart rate and sweating, according to International Standard 9886. In this study, deep core body temperatures were obtained by using ingestible Jonah telemetry capsules. These were activated and ingested a minimum of eight hours prior to recording periods to ensure placement within the digestive tract.

Mean skin temperatures were determined by measuring the temperature of a number of external body sites by attaching wireless, miniaturized dermal patch sensors. Sensors were logged continuously by personal monitors for the duration of the shift. Heart rates were concurrently measured using Actiheart wireless heart monitors attached to electrodes placed on the torso for a lead I electrode site measure. Personal strain index (PSI), on a universal scale of 1-10, was determined as follows (3):

$$PSI = \left[5 \times \frac{(T_n - T_{rest})}{(39.5 - T_{rest})}\right] + \left[5 \times \frac{(HR_n - HR_{rest})}{(180 - HR_{rest})}\right]$$

T_n = Core temperature at time n
T_{rest} = Core temperture at rest
HR_n = Heart rate at time n
HR_{rest} = Resting Heart Rate

Hydration status: Sweat rate and total body water loss, the sum of sweat and insensible water loss, were determined by obtaining crude measurements of the change in nude body mass, and adjusted for liquid and solid matter ingestion/excretion during the shift period. Urinary specific gravity (USG) was measured using an electronic digital refractometer, model ATAGO USG-1, and a hand-held refractometer, model RHC-200ATC, each calibrated for the specific use of urine. Urine was collected in specimen containers pre-, mid- and post-shift, corresponding to 06:00, 12:00 and 16:00 hours respectively.

Fatigue: Blood glucose levels were obtained using single use lancets on the fingers for blood samples subsequently collected on test strips and analysed by an Accu-Chek advantage glucometer. Samples were taken post 60 minute fast periods at 06:00, 12:00 and 16:00 hours on test days. Additonally, participants were also asked to complete abbreviated mood disturbance score, POMS, pre- and post-shift period, a sleep 10-scale score pre-shift and a fatigue 10-scale score pre-, post-shift and at alloted tea break times.

3.3 Personal Protective Equipment Study

The study was completed under controlled conditions in a climatic chamber at the University of Western Australia's School of Human Movement and Exercise Science. Each participant performed an identical work/rest routine in hot (40°C), dry (<30%RH) conditions, whilst clothed in one of three PPE ensembles; 1. Standard PPE (long sleeved shirt and pants, safety glases and boots), 2. Standard PPE plus leather welding jacket, reflective welding gloves and welding helmet, and 3. Standard PPE plus leather welding jacket, reflective welding gloves, ventilated welding helmet and belt air pump. The work/rest routine undertaken consisted of two 20min rest periods pre- and post- entry into the climatic chamber and once in the chamber, three sets of 15 min light work intensity periods each followed by 5mins of rest. Heat strain and hydration status were all assessed as per the observational study, hydration status being measured only pre- and post-work/rest routine. Additionally, fatigue was assessed pre- and post-work/rest routine and a thermal comfort analogue score was completed at the beginning and end of each work or rest period.

3.4 Statistics

Observational group assessment were analysed via two-sample, non-equal variance student t-tests, p level < 0.05. For available seasonal measures a two-way (season x time) repeated measures ANOVA was used for appropriate participants to analyze variables for the two observations. Where differences were found, post-hoc analysis was performed with Newman-Keuls test, p level=0.05. Similarly, a two-way (suit x time) repeated measures ANOVA was used for the PPE study and post-hoc anlysis was performed with Newman-Keuls test, p level=0.05. All data are expressed as means ±SE.

4.0 Results

4.1 Environmental Conditions

Table 1, details the environmental parameters of average, maximum and minimum dry bulb temperatures (DB), Relative Humidity (RH), Wet Bulb Globe Temperature (WBGT), and Water Vapour pressure recorded for each test day (N = number) in the HEWS.

Error! Not a valid link.

Crib DB were not significantly different ($p = 0.688$), between the seasons, whilst Workshop DB were more than 15°C higher in summer than winter, ($p = 3.23E^{-6}$). Additonally, DB exceeeded 34°C 58.1% of the hours worked in summer in comparison to 0% during winter. At no time during observed hours was DB recorded above 40.0°C. Daily averages for RH were not statisticaly different for Crib and Workshop between the seasons. Water vapour pressure values in all conditions were low.

Climatic chamber study environmental conditions were maintained at 40.0 ±4.6°C and 25.8 ±4.1% for DB temperature and RH respectively. DB and RH were not different between ensemble treatments.

	SUMMER	WINTER	CHAMBER
N	11	9	8
SEX	10male:1female	8male:1female	8 male
AGE	45.1 ± 7.8yrs	41.2 ± 8.9yrs	30.8 ± 9.0yrs
BMI	28.3 ± 3.7kgm^{-2}	27.6±4.3kgm^{-2}	24.6 ±2.9kgm^{-2}
BSA	2.01 ± 0.18m^{-2}	2.07 ± 0.18m^{-2}	2.01 ± 0.19m^{-2}
Fitness	Variable	Variable	Variable
Acclimatized	Yes	Yes	No
Diet	Normal	Normal	Normal

Figure 2:
Anthropometric characteristics of test populaces; Body mass index (BMI), Body surface area (BSA), number of participants (N).

4.2 Individual Characteristics

The physical characteristics from each study populace are provided in Table 2. The number of men and women are given followed by the means and standard deviations for age, BMI, BSA, and one word descriptions for fitness, acclimatisation status and typical diet. During the observed timeframe there were no major health issues or occurences of heat illness reported from either test populace.

4.3 Heat strain as determined by core body temperatures and heart rate

In the HEWS none of the five-minute averaged body core temperatures exceeded 38°C and heart rates rarely exceeded 110bpm for any observed period. Daily core temperatures and heart rates were 37.33±0.17°C: 88±7bpm and 37.30±0.13°C: 88±9bpm for controls and workers respectively in winter, and 37.26±0.06°C: 81±7bpm and 37.34±0.19°C: 88±9bpm for controls and workers respectively in summer. All p values > 0.05 illustrates no statistical significance between controls and workers as well as within and/or between seasons. Daily mean skin temperature averages were 32.79±0.19°C and 32.08±0.66°C for controls and workers respectively in winter, and 33.19±0.35°C and 34.14±0.48°C for controls and workers in summer respectively. P levels < 0.05 demonstrated significant differences between controls and workers for both seasons and for workers between seasons only. Figures 1 and 2 illustrate the concurrent changes in PSI and mean skin temperature over an eight hour period for a control, a worker and a worker-boilermaker, in summer and winter. PSI at no time reached high heat strain values with all values consistently under 3. Additionally, no statistical differences were noted between the groups during and between seasons.

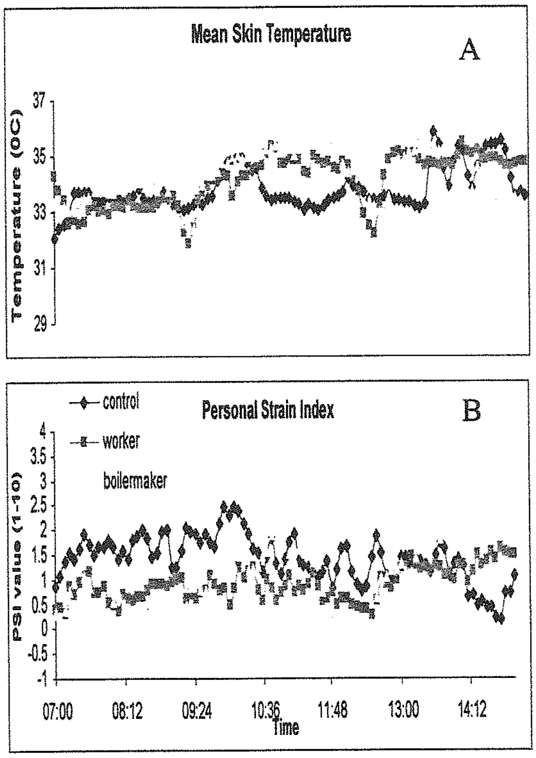

Figure 1: A: Mean skin temperature and B: Personal Strain Index for three individuals in summer.

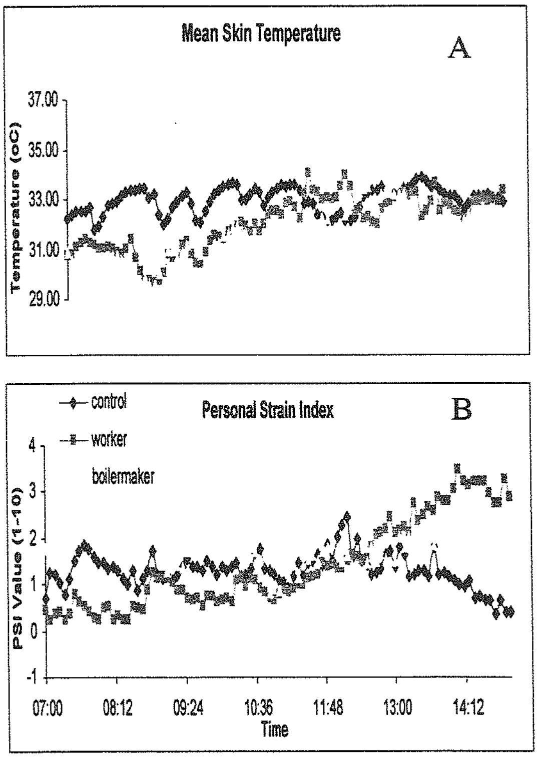

Figure 2: A: Mean skin temperature and Personal Strain Index for three individuals in winter.

For PPE chamber trials, core temperatures, heart rates and mean skin temperatures increased upon entry and continued, with variable significance, to rise for the duration spent in the chamber. Heart rates were statistically higher for work periods 2 and 3, and the last two rest periods of the routine for ensemble 2 in comparison to ensemble 1. No statistical differences in heart rates were noted between ensemble 2 and ensemble 3, and ensemble 1 and ensemble 3. Core temperatures were only statistically higher in the first work period for ensemble 2 over ensemble 1, ($p=0.045$), and only higher for the second work and rest period for ensemble 2 over ensemble 1, ($p<0.001$). Core temperatures for the first rest period in the chamber onwards were significantly lower in ensemble 3 over ensemble 2, ($p<0.009$). Mean skin temperatures were statistically higher for ensembles 2 and 3 during the initial rest period, ($p<0.028$), over ensemble 1. Mean skin temperatures within ensembles increased significantly upon entry to chamber for ensemble 1 and 3, and upon first rest period for ensemble 2, (all $p<0.05$).

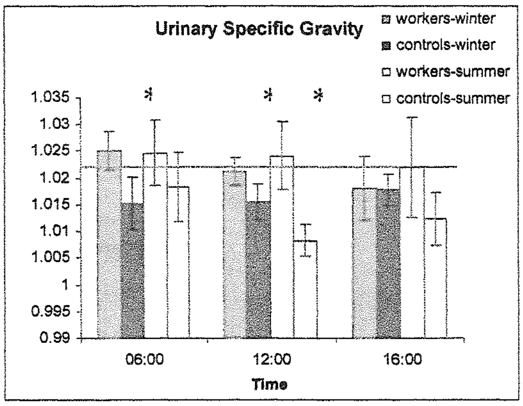

Figure 3: Urinary specific gravity values of populations during summer and winter. Red line expresses cut-off considered for moderate risk to dehydration. (* = significance)

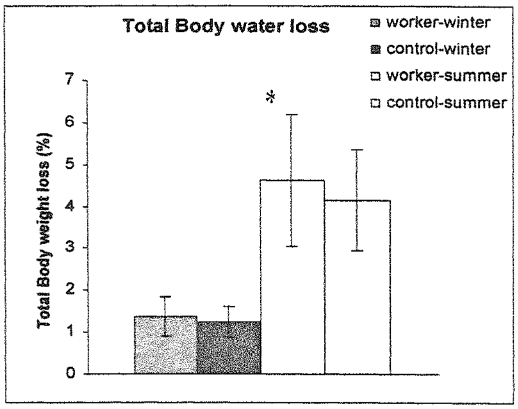

Figure 4: Total body water loss, expressed as a percentage of total body weight loss during summer and winter for controls and workers.

4.4 Hydration status

Figure 3, details the average USG for controls and workers during the observational summer and winter studies. It was observed that workers generally presented at the start of their shifts with USG values of 1.024±0.006 and 1.025±0.003 for summer and winter respectively, these were significantly higher than controls for summer, p=0.019. Worker's midday USG values were also significantly higher irrespective of season, p=0.0006 and p=0.032. End shift values were not significantly different for groups or seasons with the majority of USG values less than 1.022. Control midday USG values were significantly lower in summer than winter, p=0.035. Total body water loss, as expressed as a percentage of total body weight is illustrated in Figure 4, with loss in summer higher for controls and workers, (p=0.063, p=0.002 respectively). Mean sweat rate averages were calculated as 0.37±0.16lhr^{-1} and 0.36±0.12lhr^{-1} in summer compared to rates of 0.12±0.05lhr^{-1} and 0.12±0.03lhr^{-1} in winter for workers and controls respectively. Sweat rates were not statistically different between workers and controls, (p>0.05), seasonal comparison demonstrated sweat rates for workers in summer were significantly higher, (p=0.0239) but controls did not reach significance, (p=0.0636). The percentage of total water loss replaced by fluid intake rates were 81.9±23.8%,0.29±0.12lhr^{-1} and 61.9±3.9%,0.31±0.08lhr^{-1} in summer and 73.8±27.3%,0.13±0.07lhr^{-1} and 60.4±17.9%,0.12±0.01lhr^{-1} in winter for workers and controls respectively. Workers replaced a greater percentage of total water loss than controls in summer, (p=0.051).

PPE chamber trials tended to result in higher USG values post routine for all ensembles, but not significantly, (p>0.05), and 58% pre-USG were above 1.022. Averaged percentage body water losses were 0.43±0.18%, 0.67±0.14% and 0.61±0.16% for suits 1, 2 and 3 respectively for the observed two hours. Total water loss was statistically higher for ensembles 2 and 3 than ensemble 1, (p=0.0106 and p=0.0282 respectively). No statistical differences was reported for fluid intake.

4.5 Fatigue

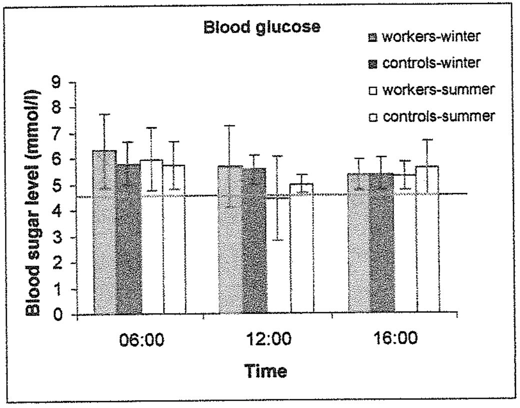

Figure 5: Physiological fatigue expressed as blood sugar levels in mmoll^{-1} of glucose. Red line at 4.5mmoll^{-1} represents quantitative physiological fatigue.

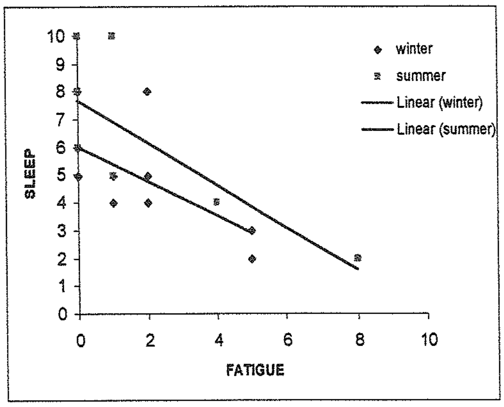

Figure 6: Direct comparison of sleep quality and subjective fatigue each expressed as 1-10 scores, linear best fit lines included.

Physiological fatigue expressed as mean blood glucose levels (BSL) were not recorded below 4.5moll^{-1}, irrespective of season, group or time of day, ($p>0.05$), with the execption of workers at midday in summer. A trend of decreasing BSL levels were observed across the shift with lowest levels at the end of shift in winter, whilst controls and workers were observed to have lowest levels at midday during summer, as detailed in Figure 5. Subjective fatigue and scored contribution to POMS were not significantly different across the shift irrespective of season, group or time of day, with the large variation of subjective fatigue occurring at the beginning of the shift. Sleep quality and beginning shift subjective fatigue as expressed in figure 6 show a negative correlation, with poorest quality sleep corresponding to highest levels of fatigue.

5.0 Discussion

Setting Occupational Health and Safety limits for work in hot environments is usually approached in two ways, setting limits for physiological indices and setting limits for the environment itself. Given the broad range of occupationally derived heat stressors in the HEWS, physiological indices were assessed according to ISO 9886(4). Individual and group thermal strain indices were reported at levels well below the prescribed limit of 38°C or a 1.4°C/hr rise in core body temperature, below the maximum local skin temperature of 45°C and below daily averaged heart rates of 110bpm at all times observed, irrespective of recorded environmental indice. In fact, core body temperatures did not exceed a 1°C variation, which is equivalent to and could solely reflect the natural diurnal temperature amplitude. Combining concurrent measures of core body temperature and heart rate, low PSI values were observed, here primarily attributed to the low level of work activity self -reported by each participant and confirmed physiologically by consistently low heart rates recorded across the shift for controls and workers alike. In other words, low levels of internally generated heat, by metabolic work, substantially lessens the strain on the cardiovascular system. This in conjunction with the high evaporative capacity of dry air, (RH<35%), suggests that responses to environmental heat stressors were mediated locally from the skin by efficent evaporation of sweat and for that reason reduced additional strain on the cardiovascular system. This line of reasoning is supported by the reported low daily heart rate averages, higher sweat rates and mean skin temperatures observed in summer. Consequently we could conclude that under the unique conditions observed the populace of workers and controls in the HEWS were adequately managing for heat stress as purported by the reported low PSI levels. The rise and fall in PSI values demonstrates that behavioural regulation of habitual self-pacing, and additional behavioural heat avoidance in seeking thermal refuge, clearing observed here by the drop in mean skin temperature at scheduled breaks exhibited in figure 1 at approximately 09:00 and 12:00, is an important contributing factor to reducing heat strain. Additionally, the replicated self pacing at similar work intensities in the PPE study also demonstrated lower heat strain levels irrespective of ensemble, thereby adding credence to behavioural regulation as an effective means of reducing thermal strain. A potential bias in the study was that ambient temperature was lower than the the more typical 40°C days generally endured. But given that work under the shelter of the HEWS greatly reduced radiant environmental heat loading and that low levels of activity all contributed to lower levels of heat stress observed during the observed period, any heat loading changes in these few areas might result in increased heat stress and associated heat strain. However, behavioural self pacing and appropriate clothing would offset this additional heat stress and allow employees to maintain their physiological and subjective responses at safe and sustainable levels, a confidence held by other investigators, (5).

Exercise- and heat-induced deydration is responsible for almost all the deleterious effects of working in the heat. A 1% loss of total body water compared with hydrated individuals has been documented to cause an increase in core temperature during exercise in warm environments. It was observed here as has been observed in other Australian mines that workers generally presented with degrees of dehydration, (6), expressed here as USG values above 1.022. Workers were therefore considered at moderate risk of dehydration if sweat rates were not adequately matched by fluid intake rates throughout the day. This study confirmed that the workforce that habitually worked in the heat replaced 81% of total water loss through routine drinking, whilst controls who also undertook routine drinking replaced only 61%, a point of concern given the equivalent sweat rates. The subsequent percentage body weight loss corresponded to degrees of dehydration, though changing USG values demontrated rehydration for workers. Dehydration in controls could be attributed to their already replete hydration status on presentation to shift and the enforced drinking routine, factors that inhibit Antidiuretic hormone release and thereby increasing urinary water loss. This was confirmed by the midday USG values of 1.008±0.003 which fall within the specific gravity range of the glomerular filtrate of the kidney, demonstrating inhibition of water reabsorption from the end filtrate process. The argument for water dumping by the kidneys is further supported by the lower percentage of total water replaced (61%) given the sweat rates were equivalent to workers who replaced 81% of total body water loss. Therefore we could conclude that the workforce that habitually works in the heat are resonably well educated about the affects of dehydration and actively pursue drinking routines to maintain hydration levels throughout the day, and in these particular circumstances were shown to help facilitate rehydration. On the other hand, pursuit of drinking routines in controls who are already presenting well hydrated are dehydrating through increased urinary water loss stimulated from the water loading effect of routine drinking. Although dehyration is occurrring in this population the fact that they are continually presenting to work in well hydrated states means the degree of dehydration is of short term concern given their predominately thermoneutral work space.

Fatigue, a sensation of diminishing willingness to work that reduces work capacity and resistance, prompts the decision to stop work and thereby protects the body from stress. It has been demonstrated that workers exposed to hot environments are inclined to subjective fatigue and their fatigue symptoms increase with heat exposure levels, (7). In these observed conditions no significant change in fatigue was observed during the shift. However sleep quality was shown to negatively influence perception of fatigue on presentation to work, this phenomenon having been reported also in other mining operations,(8). This highlights the need for educating employees on other external factors that contribute to work performance at the beginning of shifts.

6.0 Conclusions

1. This reviewing process has checked that Occupational Health and Safety standards are being adhered to and that this particular location is currently adequately managed for HEWS employees.
2. That the physiological data collected accurately provided an objective measure of adequate heat tolerance on a good sample of individuals working in the HEWS.
3. That hydrated individuals in thermoneutral environments can dehydrate where fluid intake mismatches fluid requirement and that pursuit of scheduled hydration is more important for the workforce that is habitually exposed to the heat.
4. That sleep quality is a major influencing factor on fatigue, and therefore could lead to lower productivity and higher risks of accidents during periods when heavy task activities are generally scheduled particularly in summer where environmental heat stress and heat strain levels are considered to be lower. This highlights the need for further education with respect to recognizing and preventing fatigue.

7.0 References

1. Donoghue, A.M. 2004. Heat Illness in the U.S. Mining Industry. American Journal of Industrial Medicine. 45:351-356
2. Donoghue, A.M, Sinclair, M.J., and Bates, G.P. 2000. Heat Exhaustion in a deep underground meatlliferous mine. Occup Environ Med. 75:165-174
3. Moran, D.S., Shitzer, A. and Pandolf, K.B., 1998. A physiological strain index to evaluate heat stress. Am. J. Physiol. 275 (Regulatory intergrative Comp. Phsyiol. 44): R129-R134.
4. International Standard 9886, 1992. Evaluation of thermal strain by physiological measurements. International Organization for Standardization, Geneve, Switzerland.
5. Brotherhood, J.R., Budd, G.M., and Schutten, M., 2001. Occupational Acclimatisation to Hot Heavy Work in Australian Bushfire Fighters. Proceedings of the Australian Physiological and Pharmacological Society. 32(2)Suppl 1.
6. Brake, R.D and Bates, G.P, 2002. Deep Body Core Temperatures in Industrial Workers Under Thermal Stress. JOEM 44(2)125-135.
7. Chen, M., Chen, C-J, Yeh, W-Y, Huang, J-W, and Mao, I-F. 2003. Heat Stress Evaluation and Worker Fatigue in a Steel Plant. AIHA Journal, 64:352:359