EDITH COWAN UNIVERSITY

School of Exercise, Biomedical and Health Sciences

Industrial Heat Stress: Using Ice Slurry Ingestion as a Practical Approach to Reducing Heat Strain in Workers

By

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ABSTRACT

Personnel working in industry can encounter hot and humid conditions where uncompensable heat loads are experienced; an inability to dissipate stored heat increases the risk of developing a heat illness. In order to minimise the incidence of heat illnesses, several heat stress reduction interventions have been developed which aim to allow for safe repeated bouts of exposure to high thermal heat loads. These vary from modification of the working environment, wearing of personal protective equipment designed to cool, heat stress indices and/or hydration regimens. Despite these interventions, personnel still experience heat stress related illnesses. Consequently, the overall aim of the thesis was to quantify the cooling capacity of an ice slurry beverage, and to measure the physiological responses of this simple, easily implementable and cost effective cooling intervention.

Study 1 compared several commonly used heat stress indices in industry against actual physiological responses associated with work for both onshore and offshore oil workers. These indices included: ISO 7243, ISO 7933, ISO 8996, and Predicted four hour sweat rate (P_4SR). Eight onshore and offshore personnel were investigated for gastrointestinal temperature (n=8), mean skin temperature (T_{sk}) (n=3 onshore and offshore), heart rate (HR), urine specific gravity (U_{sg}) and urine colour (U_{col}). Following comparison of the heat stress indices, it was identified that the ISO standards under-predicted workloads measured in personnel, while the P_4SR most closely predicted actual measurements made for both onshore and offshore personnel. We also found that workers were hypohydrated throughout the testing period. Thus, industry standard heat stress indices under-predict heat stress, and miners are likely to be chronically hypohydrated.

The purpose of Studies 2-6 was to examine if a simple and cost effective intervention ,an ice-slurry, can help minimise heat stress and hypohydration typically experienced by personnel working in a hot environments.

Study 2 assessed the effectiveness of ice-slurry to cool men after exercising in the heat. Nine male volunteers ran until they reached a rectal temperature of 38.8°C in hot and humid conditions (30.1 ± 1.0°C, 75.4 ± 5.7 %RH and 27.3 ± 0.9°C Wet Bulb Globe Temperature (WBGT)). Participants ingested ice slurry (ICE) or a cold liquid (LIQ) to reduce body T_{re} by 1°C. HR, $\bar{T}_{sk}$ and rate of change in rectal temperature from 38.8°C to 37.8°C at 0.2°C increments were recorded. No differences ($P > 0.05$) were observed for HR, $\bar{T}_{sk}$ and ΔT_{re} between conditions at each T_{re} time point. However, a significantly less volume of ICE (0.536 ± 0.056 L) was consumed compared to LIQ (1.802 ± 0.205 L) to achieve the same rate and amount of cooling ($P < 0.05$). These findings indicate that if the priority is to cool personnel, ice slurry must be used instead of cold water.

As the previous study investigated the cooling effects of consuming ice slurry after exercise, study 3 investigated ice slurry consumption during exercise. The aim of Study 3 was to compare no fluid replacement (NF) with complete (100%) or partial (50%) fluid replacement with ICE or LIQ during exercise time to exhaustion (T_{lim}), rate of heat stored and changes in T_{re}. Volumes of consumed ICE or LIQ were determined from the volume of sweat lost during NF (trial 1). The order of trials 2 - 5 (100% ICE, 100%LIQ 50%ICE and 50%LIQ) was randomised for each subject. ICE or LIQ was administered every 20 min during exercise in aliquots equalling predicted sweat loss. T_{lim} was 84.3 ± 38.7 min for 100ICE, 79.2 ± 38.7 min for 100LIQ, 68.2 ± 38.7 min for 50ICE, 59.2 ± 28.3 min for 50LIQ and (46.5 ± 19.9 min for NF, however no differences were observed ($P > 0.05$). Changes in the rate of heat stored was 8.8 ± 2.1 $kJ \cdot min^{-1}$ during NF,

6.6 ± 2.7 kJ·min^{-1} in 50LIQ, 6.4 ± 2.6 kJ·min^{-1} in 50ICE, 5.9 ± 3.1 kJ·min^{-1} in 100LIQ and 4.5 ± 2.7 kJ·min^{-1} in 100ICE; heat storage in NF was significantly faster than 100ICE ($P < 0.001$), 50ICE ($P < 0.05$) and 100LIQ ($P < 0.05$). ΔT_{re} was 0.020 ± 0.008°C·min^{-1} for 100ICE, 0.022 ± 0.007°C·min^{-1} for 100LIQ, 0.027 ± 0.008°C·min^{-1} for 50ICE, 0.029 ± 0.008°C·min^{-1} for 50LIQ and 0.034 ± 0.007°C·min^{-1} for CON with significant differences observed between CON vs. 100ICE and 100LIQ, as well as 50LIQ vs. 100ICE and 100LIQ ($P < 0.05$). Findings from this study indicate that complete (100%) rehydration with ICE or LIQ must be encouraged to help minimise thermal stress in miners.

Study 4 investigated the effectiveness of *ad libitum* consumption of ICE to (1) estimate how much ICE miners are likely to consume voluntarily, (2) to test if *ad libitum* consumption of ICE can effectively minimise heat stress and dehydration during exercise compared to LIQ, and (3) to test if *ad libitum* consumption of ICE can increase exercise capacity compared to LIQ. Participants completed three trails during which they consumed no fluid (NF), ICE or LIQ *ad libitum* while dressed in mining attire and exercising in a hot and humid environment (28.3 ± 1.3°C, 40.3 ± 8.0 %RH). Results indicated that significantly more LIQ was ingested than ICE (1.088 ± 0.674 L vs. 0.721 ± 0.431 L; $P < 0.01$). Exercise time to T_{re} 38.0°C was 61.6 ± 27.6 min, 55.9 ± 26.3 min and 28.9 ± 15.6 min for ICE, LIQ and NF, respectively, however no differences were observed between conditions; $P > 0.05$. No differences were measured ($P > 0.05$) in T_{lim} between ICE, LIQ and NF, 108 ± 20.9 min, 104.4 ± 24.4 min and 87.6 ± 25.8 min, respectively. *Ad libitum* consumption has shown that consuming ice slurry and a cool liquid *ad libitum* during exercise lead to similar rates of rise in T_{re}, time to reach a T_{re} of 38.0°C and exhaustion while consuming 33% less ice slurry.

The results from Studies 2, 3 and 4 indicate that ingesting ICE will increase performance and reduce thermal strain in exercising persons. With these studies being performed in a controlled laboratory environment, the *in situ* applicability remained to be answered. Therefore, the purpose of Study 5 was to test the effectiveness of the ICE intervention as a practical method of cooling working personnel in liquefied natural gas (LNG) industry. Seven LNG personnel ingested ICE or LIQ on two separate occasions. Gastrointestinal temperature (T_{GI}), $\bar{T}_{sk}$ and HR were measured throughout the work day. Differences were observed for T_{GI} at times 1100 – 1200 (37.3 ± 0.2°C vs. 37.4 ± 0.0°C; $P < 0.01$) and 1400 – 1500 (37.3 ± 0.4°C vs. 37.5 ± 0.2°C; $P < 0.05$) and for HR at 900 – 1000 (85 ± 14 bpm vs. 94 ± 15 bpm; $P < 0.05$) and 1500 – 1600 (87 ± 14 bpm vs. 101 ± 15 bpm; $P < 0.05$) between ice slurry and liquid respectively. Mean T_{GI} and HR, although not significant, were lower in ICE during the entire shift. No differences were observed in $\bar{T}_{sk}$ ($P > 0.05$). Anecdotally, the volunteers enjoyed ingesting ICE and said they would use it as a cooling intervention; however, they followed by saying that they would not completely replace current drinking practices.

In conclusion, the general findings of this thesis were as follows: (1) one heat stress index (P_4SR) predicted heat strain in workers better than ISO 7243, ISO 7933, ISO 8996; (2) industry personnel typically arrive at work in a hypohydrated state and stay hypohydrated throughout the work day; (3) for a given volume, ICE has a greater cooling capacity than LIQ; (4) replacing 100% of the fluid lost during exercise can better attenuate the rate of rise in T_{re} and increase T_{lim} compared to only replacing 50%, but the ability to ingest 100% of fluid lost may be unreasonable; (5) *ad libitum* ingestion of ice slurry elicited similar physiological responses during exercise compared to consuming cold liquid, however significantly less fluid volume was required; and (6) ingesting ice slurry in the LNG industry can significantly reduce T_{re} and HR in personnel, however

complete replacement of currently implemented drink practices was not favoured. Therefore, occupational hygienists should consider administering ice slurry to personnel in conjunction with currently implemented hydration practices.

SYMBOLS AND ABBREVIATIONS

ΔBV	Change in blood volume
ΔCV	Change in cell volume
ΔHR_T	Increase in heart rate connected with the thermal strain experienced by the worker
ΔPV	Change in plasma volume
BET	Basic effective temperature
BSA	Body surface area
DB	Dry bulb
H_b	Body heat content
HR	Heart rate
HR_L	Limit of heart rate
ICE	Ice slurry
LIQ	Cool liquid
LNG	Liquefied natural gas
NF	No fluid
PO/AH	Preoptic anterior hypothalamus
P_{osm}	Plasma osmolality
PPE	Personal protective equipment
PSI	Physiological strain index
P_4SR	Predicted four hour sweat rate
p_a	Partial vapour pressure
RPE	Rate of perceived exertion
$\bar{T}_b$	Mean body temperature
T_c	Core temperature

T_{GI}	Gastrointestinal temperature
Tl_{im}	Time to exhaustion
T_{re}	Rectal temperature
$\bar{T}_{sk}$	Mean skin temperature
TWL	Thermal work limit
t_a	Air temperature (dry bulb temperature)
t_g	Globe temperature
t_{nb}	Natural wet bulb temperature
t_r	Mean radiant temperature
v_a	Air velocity
WB	Wet bulb
WBGT	Wet bulb globe temperature
Work	Definition: physical activity. Can be used interchangeably as exercise or labour

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CHAPTER ONE

INTRODUCTION

1.1 Overview

The expansion of Western Australia's mining industry has brought with it an increased number of personnel required on site (Ye 2008). As these mining sites tend to be located in remote areas exposed to hot and sometimes humid conditions (31.5°C) (Donoghue and Bates 2000) and 30.9°C wet bulb globe temperature (WBGT) (Brake and Bates 2002), the exposure of more mining personnel to extreme environmental conditions is inevitable. Thus, it is important for occupational hygienists and managers to be aware of the detrimental consequences of heat-related injuries along with strategies that could be employed to lower their incidence in industry.

1.1.1 Thermoregulation in the Heat

Mean body temperature ($\bar{T}_b$) is continually in a state of adjustment as a result of metabolic processes and interactions with the environment (Mekjavic, Sundberg et al. 1991). The regulatory centre for $\bar{T}_b$ is located in the brain; more specifically, the preoptic anterior hypothalamus (PO/AH). In response to afferent signals from thermal receptors located throughout the body, the PO/AH integrates these signals and effector responses are initiated (sweating and/or increased skin blood perfusion during warm conditions) to restore $\bar{T}_b$ or body heat content (H_b). These thermolytic mechanisms will continue until a thermal homeostasis is restored, as seen by an absence of a rising $\bar{T}_b$ or core temperature (T_c).

Under conditions of thermal neutrality, the net change in H_b approximates zero. During conditions of uncompensable heat loads (conditions where heat gain is greater

than heat loss), a rise in T_c is observed. Ultimately, it is the thermal gradient between the T_c and skin, and the skin and environment which determines the rate and direction of net heat gain or loss; this relationship is illustrated in Figure 1. This thermal heat exchange can be expressed by the following heat balance equation as adapted from (Buskirk 1977):

$$S = M \pm (R + C) \pm W - E \tag{1.1}$$

Where S = rate of net heat storage (either positive or negative)
M = metabolic heat production (always positive)
E = evaporative heat loss (always negative)
R = radiative heat exchange,
C = conductive heat exchange
W = mechanical work

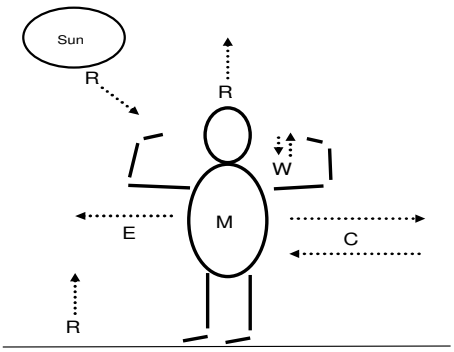

Figure 1.1 Schematic representation of heat transfer where R = radiation, M = metabolism, E = evaporation, C = conduction, W = mechanical work

In Germany, coal miners have experienced WBGT of 29.1°C (Kalkowsky and Kampmann 2006), and miners in an Australian metalliferous mine have recorded ambient temperatures of 31.5°C (Donoghue and Bates 2000) and 30.9°C WBGT (Brake and Bates 2002). In a UK coal mine, Weller (1981) measured a Basic Effective Temperature (BET) between 26.6°C and 27.0°C, whereas Chilton and Laird (1982) measured a BET of 29.4°C. These reports illustrate the high ambient temperature conditions typically experienced by mining personnel.

In addition to the heat gained by underground mining personnel in these hot environments, high metabolic heat loads associated with heavy working tasks have also been reported (Mate et al. 2007). The task of shovelling for example, has been measured

to range between 266 $W \cdot m^{-2}$ and 407 $W \cdot m^{-2}$ (Leithead 1964; Bethea 1980), while drilling has been found to range from 217 $W \cdot m^{-2}$ to 290 $W \cdot m^{-2}$ (Leithead 1964; Graves, Leamon et al. 1981). Shovelling at 266 $W \cdot m^{-2}$ for a 75 kg individual without the capacity to cool would increase T_c by ~0.1°C·min^{-1}. According to the International Standards Organization 7243, such work intensities correspond to high and very high metabolic rates (ISO 1989). If those work intensities are performed under the environmental conditions previously described, the onset of a heat-related illness can occur (Donoghue, Sinclair et al. 2000), causing symptoms ranging from central and/or peripheral fatigue (Nybo and Nielsen 2001; Todd, Butler et al. 2005; Saldanha, Nordlund Ekblom et al. 2007; Nybo 2008), decreased focus/concentration, oedema of the periphery (Coris, Ramirez et al. 2004), up to a more serious and sometimes fatal heat stroke (Coris, Ramirez et al. 2004).

The upper limit of T_c deemed safe by industrial governing bodies is a 1°C increase above resting T_c values (ISO 2004), a maximum T_c of 38.0°C (ISO 2004), and a T_c of 38.5°C if workers have been medically screened (ISO 2004). Despite these conservative limits, the incidence of heat stress related illnesses remains high, particularly during the summer months (43/million-man hours on average throughout the year versus 147/million-man hours during February) (Donoghue, Sinclair et al. 2000). This indicates that current heat stress indices are failing and that alternative heat stress interventions are required to reduce the incidences of heat related illnesses.

Currently used interventions involve, establishing maximal exposure durations to stressful environments through heat stress indices (McArdle, Dunham et al. 1947; Belding 1955; Yaglou 1957; ACGIH 2005), educating workers on hydration (Brake and Bates 2003), and although very costly, modification of the ambient working environment (Hardcastle and Kocsis 2004; Mate 2007). Anecdotal use of salt supplementation to

offset salt loss through sweating in the mining industry has also been reported, but the effects of such an intervention on work performance and heat strain of mining personnel is not known. Personal protective equipment (PPE) such as cooling garments has been used as a means to reduce thermal strain, but success of using this method to attenuate the rise of T_c has yielded conflicting results (Hasegawa, Takatori et al. 2005; Johnson BM, Somarriba GA et al. 2005). Continual replacements of melted ice (Heled, Epstein et al. 2004) may be cumbersome, as refrigeration facilities are typically not readily available in remote parts of the mine. In addition, it has been reported by workers that cooling vests are uncomfortable to wear (Corcoran 2002), thus increasing the likelihood that workers will elect not to wear the vests, particularly when unsupervised.

Environmental conditions in mines, as previously described, can place high and sometimes uncompensatable heat loads on workers. In order to help protect workers from experiencing heat stress related illnesses, heat stress indices have been created (i.e. WBGT, BET). Overall, the purpose of heat stress indices is to provide a one-measure system which will predict safe, tolerable, and repeated bouts of exposure for workers to work in the heat that integrates all relative aspects of climate. These indices are based on mathematically derived equations which encompass various environmental, physiological, and time variables. The validity of these indices have been scrutinised by various authors (Parsons 1995; McNeill and Parsons 1999; Srivastava, Kumar et al. 2000) and as a result, there is not one index that is universally accepted throughout industry. Despite the existence of multiple indices, however, typically one index is used in all mining occupations within a particular mine irrespective of clothing or PPE worn.

Statistically, under a normal distribution curve, typically 95% of the population is protected. The outliers from this 95% confidence interval will be either over or under protected. Those individuals who are over protected may not be working at optimal

productivity, whereas those who are under-protected are at an increased risk for developing a heat stress related illness and could even die. Therefore, to optimally protect workers, specific heat stress indices should be validated under field conditions to accommodate the uniqueness of each industrial environment; including the metabolic demands of the job, clothing and environmental factors.

External heat loads experienced by mining personnel have been reported to range from 29.1°C to 30.9°C WBGT (Chilton and Laird 1982; Brake and Bates 2002; Kalkowsky and Kampmann 2006) and 26.6°C to 29.4°C BET (Weller 1981; Chilton and Laird 1982). However it is uncertain which occupation(s) within a specific industry typically experience the most extreme working conditions. Moreover, whether the use of heat stress indices protects workers adequately throughout the array of industrial occupations is not known. The creation of a new heat stress index and related guidelines could assist in providing additional protection for workers. This would however, require validation of the index, which is a time consuming process. By identifying occupations which experience the highest heat loads, occupational hygienists and managers will be more aware of where specific heat stress interventions should be focussed.

1.1.2 Physiological responses to exercise under different states of hydration

Maintaining total body water has been shown to provide thermoregulatory benefits by reducing the rise of T_c in exercising individuals (Gisolfi and Copping 1974). For example, Greenleaf and Castle (1971) showed that hypohydration (-5.2% body mass) was associated with the greatest increase in $\bar{T}_b$ (0.94°C) compared with hyperhydrated (+1.2% body mass) (0.39°C), and *ad libitum* (-1.6% body mass) (0.57°C) fluid consumption trials during 70 min of cycling at 49% $\dot{V}O_2max$ in warm conditions (23.6°C, 51% relative humidity (%RH), windspeed 0.41 $m \cdot sec^{-1}$). In a study by Brake and Bates

(2003) which examined the hydration status of mining personnel, they observed that workers started their shifts in a mildly hypohydrated state (urine specific gravity (U_{sg}) exceeding 1.0220). However, despite extreme ambient conditions, U_{sg} measurements taken before, during and after the work shift revealed that workers were able to maintain their hydration status throughout the work shift. Therefore, educating workers on the importance of attaining and maintaining euhydration would appear to be the simplest and most practical option for workers to manage heat loads.

1.1.3 Physiological Response to the Thermodynamic Properties of Water

The consumption of cold liquid water ($H_2O_{(aq)}$) results in an expansion of the body's natural heat sink. As the body warms the cooler consumed $H_2O_{(aq)}$, heat energy is exchanged between the body and the $H_2O_{(aq)}$ until a thermal gradient no longer exists. Therefore, the heat energy that would have been otherwise stored in the body is now transferred into $H_2O_{(aq)}$. The consumption of cooler volumes of $H_2O_{(aq)}$ will theoretically allow even larger quantities of heat energy to be exchanged away from the body. If left undisturbed, $H_2O_{(aq)}$ begins to change physical states from liquid to solid at a temperature of approximately 0°C. However, if $H_2O_{(aq)}$ is continuously stirred, the liquid forms small ice crystals and changes into a slurry $H_2O_{(is)}$. By maintaining both physical states (solid and liquid), the $H_2O_{(is)}$ drink may provide a subtle, but significant advantage to reducing heat strain in thermally challenging conditions. This advantage is due to the phase changing feature of the $H_2O_{(is)}$; solid ice ($H_2O_{(s)}$) changes phase into $H_2O_{(aq)}$.

Although the thermodynamic effect of $H_2O_{(is)}$ consumption in humans is unknown, the influence of $H_2O_{(is)}$ infusion has been investigated in animals. Vanden Hoek et al. (2004) infused a 50 $ml \cdot kg^{-1}$ solution of either saline slurry or saline water of equal temperature in 11 swine over a 1 hr period. Brain temperature was reduced by 5.3 ± 0.7°C with saline slurry compared with 3.4 ± 0.4°C using saline water. Furthermore a

study by Merrick and co-workers (2003) showed how phase changing cryotherapy modalities were able to produce colder superficial skin temperatures (ice bag; from 35.6 ± 0.9 to 27.8 ± 3.5°C at 1 cm, 36.3 ± 0.7 to 31.8 ± 2.2°C at 2 cm, wet-ice; from 35.7 ± 0.8 to 27.2 ± 3.4°C at 1 cm, 36.2 ± 0.7 to 30.6 ± 3.0°C, and gel pack; from 35.49 ± 0.8 to 29.5 ± 2.4°C at 1 cm, 36.1 ± 0.9 to 32.1 ± 1.5°C at 2 cm) at a depth of 1 and 2 cm compared with non-phase changing cryotherapies. Finally, Kennet and colleagues (2007) investigated the cooling efficiency of four different cryotherapeutic agents and showed that crushed ice reduced skin temperatures (19.6 ± 3.8°C) more than a gel pack (13.2 ± 5.1°C), frozen peas (14.6 ± 4.2°C), and ice-water immersion (17.0 ± 2.8°C). While a thermodynamic cooling advantage should theoretically be gained through the phase change properties of solid versus liquid water, the physiological effects have yet to be reported.

From the thermodynamic cooling ability of water, topical cooling trials in humans (Kennet, Hardaker et al. 2007) and intravenous infusion cooling in animals (Vanden Hoek, Kasza et al. 2004), investigation into the effects of an $H_2O_{(is)}$ beverage seems warranted. Such a cooling method could provide industrial workers with a simple means of attenuating the rise in T_c whilst concomitantly achieving a reduction in cardiovascular strain.

1.2 Purpose of Research

The overall purpose of this thesis was to investigate the effectiveness of a non-invasive and cost effective heat stress management intervention for personnel working in the resource industry. Five studies were performed to achieve this objective. The purpose of Study 1 was to evaluate the environmental conditions associated with working in the oil and gas industry and attempt to identify the most accurate heat stress index for general use in this work environment. Study 2 measured the cooling capacity, *in vivo*, of the ice

slurry and compared it to the consumption of a liquid. Study 3 compared the effects of replacing 100% and 50% of fluid lost by drinking ice slurry and liquid solutions on core temperature during simulated mining conditions. Study 4 aimed to compare *ad libitum* drinking of liquid versus drinking of ice slurry solutions on core temperature during simulated mining tasks in a hot environment. Finally, Study 5 aimed to compare *ad libitum* drinking of liquid versus drinking ice slurry solutions on core temperature in industrial workers on an offshore liquefied natural gas (LNG) oil platform in North Western region of Western Australia during the summer of 2010.

1.3 Significance of Research

Creating a non-invasive and cost-effective method to manage heat stress *in situ* will help reduce the incidence of heat stress related illnesses in the mining industry and other heat stressful industries (i.e., military, smelters, fire service).

1.4 Research questions

1. Which current single heat stress index most accurately predicts heat strain among personnel working in both the on- and offshore liquefied natural gas industry? (Study 1)
2. Does drinking ice slurry after exercise in a hot and humid environment provide a similar cooling capacity as consuming a cold liquid? (Study 2)
3. Will complete and half replacement of sweat loss with ice slurry minimise heat stress and prolong exercise performance as compared to the consumption of cold liquid during work in a hot and humid environment? (Study 3)
4. Does drinking ice slurry *ad libitum* during exercise minimise heat stress and prolong exercise performance compared to performance associated with the consumption of liquid? (Study 4)

5. Does the ingestion of ice slurry by LNG personnel better attenuate the rise in T_c than a cool liquid during work *in situ*? (Study 5)

1.5 Hypotheses

1. The P_4SR heat stress index can more accurately predict heat strain in both on- and off shore liquefied natural gas workers;
2. Consuming ice slurry after exercise will provide a greater cooling capacity than drinking a cold liquid;
3. Completely offsetting sweat losses with the ingestion of an ice slurry will best attenuate rise in T_{re} and prolong the capacity for exercise the best, followed by liquid, half ice slurry and half liquid consumption;
4. Greater exercise duration and better attenuated rise in T_{re} will be attained by *ad libitum* ingestion of ice slurry compared to liquid solution;
5. Better attenuated rise in T_c will be attained by workers consuming ice slurry beverage during their shift compared with current industry practice (drinking cool liquids).

1.6 Limitations

Measurements recorded in Studies 1 and 5 were collected over several days and are not a comprehensive representation of the environmental conditions experienced throughout a weather season.

Study 3 replaced 100% and 50% of fluid losses. As individual sweat rates do vary, the volumes of fluid ingested will also vary; subsequently, the quantity of cooling due to slurry consumption would be different for each individual. In addition, the rate of heat gain differs between individuals.

In Study 4, the quantity of fluid ingested varied according to individual perceptions of thirst and therefore the cooling capacity administered by the fluids also differed.

Study 5 was a field experiment, and despite best efforts, it cannot be assumed that industrial personnel maintained normal working and drinking habits during the investigation.

1.7 Delimitations

There are numerous industries experiencing different levels of mechanisation, work requirements and environmental conditions throughout Western Australia. As a result, the transfer of experimental findings from these proposed field studies to other industries within Western Australia and throughout the world might not be entirely accurate. The findings from Study 1 and 2 are delimited to healthy male adults aged 18 to 45.

CHAPTER TWO

REVIEW OF LITERATURE

2.1 Overview

The expansion of Western Australia's resource industry has brought with it an increased number of personnel required on site (Ye 2008). As these industrial sites tend to be located in remote areas exposed to hot and sometimes humid conditions, the exposure of more personnel to extreme environmental conditions is inevitable. For example, miners have experienced WBGT exposures of 29.1°C to 31.5°C (Brake and Bates 2002; Kalkowsky and Kampmann 2006) and a Basic Effective Temperature ranging between 26.6°C and 29.4°C (Weller 1981). Within the mining industry, particularly underground mining, the geothermal gradient contributes to ambient heat. With current mining trends, mines are becoming increasingly deeper, and as a result, so too are the thermal gradients. For example, in a South African mine, a geothermal gradient of 10 – 22°C·km^{-1} has been recorded (Marx 1998). As such, a significant thermal environment is present thus requiring attention to improving the environmental strain experienced by personnel.

In addition to the heat gained by personnel in these hot environments, high metabolic heat loads associated with heavy working tasks have also been reported (Mate et al. 2007). For example, the task of shovelling has been measured to range from between 266 W·m^{-2} and 407 W·m^{-2} (Leithead 1964; Bethea 1980), while drilling has been found to range from 217 W·m^{-2} to 290 W·m^{-2} (Leithead 1964; Graves, Leamon et al. 1981). Shovelling at 266 W·m^{-2} for a 75 kg individual without the capacity to cool could increase T_c by ~0.1°C·min^{-1}. According to the International Standards Organization 7243, such work intensities correspond to high and very high metabolic rates (ISO 1989).

If heavy work intensities are performed during environmental conditions previously described, the onset of a heat-related illness can occur (Donoghue, Sinclair et al. 2000), causing symptoms ranging from central and/or peripheral fatigue (Nybo and Nielsen 2001; Todd, Butler et al. 2005; Saldanha, Nordlund Ekblom et al. 2007; Nybo 2008), decreased focus/concentration, oedema of the periphery (Coris, Ramirez et al. 2004), up to a more serious and sometimes fatal heat stroke (Coris, Ramirez et al. 2004).

Work-related injuries related to fatigue may be caused by dehydration (Gopinathan, Pichan et al. 1988), physical exertion and/or an elevated body temperature (Nybo 2008). The deleterious effect of dehydration on running memory and perceptual motor coordination functions was found to occur beyond 2% dehydration (Sharma, Sridharan et al. 1986). When observing the effects of 2% body dehydration on word recognition, serial addition and trail marking tests, performance was found to decrease with increases in dehydration (Gopinathan, Pichan et al. 1988). Performing prolonged activities in the heat can result in altered brain activity. During prolonged exercise (such as during a 12 h work shift), fatigue is thought to occur in the synapses due to excessive use, decreased spinal excitability to inputs and reductions in motoneural output from the spine resulting in a reduction in peripheral feedback (Saldanha, Nordlund Ekblom et al. 2007). Associated with elevated body temperatures are alterations in the central nervous system to drive working muscles (Saboisky, Marino et al. 2003; Martin, Marino et al. 2005; Thomas, Cheung et al. 2006). With a reduction in working musculature, the ability to perform tasks may increase the risk of injury. Additionally, visual acuity is impaired during elevated body temperatures (Hohnsbein, Piekarski et al. 1984) while a reduction in mental and simple tasks occurs between a temperature of 30 – 33°C WBGT (Ramsey 1995). It was also identified by Nielsen et al. (2001) through alterations in electroencephalogram measurements in the frontal cortex during hyperthermia, that the

ability to exercise was reduced. These findings indicate that there are some neurological perturbations occurring while body temperatures are elevated, which could explain the commonly observed reduction in work and coordination.

International Standards Organization (ISO), World Health Organization (WHO), National Institute for Occupational Safety and Health (NIOSH), and the American Conference of Governmental Industrial Hygienists (ACGIH) are some of the governing bodies that have developed/implemented heat stress guidelines and/or indices to allow for safe repeated bouts of heat exposure by industrial personnel. There are several criteria deemed as a safe upper limit of T_c. These limits which have been developed by industrial governing bodies are: (1) a 1°C increase above resting T_c values (ISO 2004), (2) a maximum T_c of 38.0°C (ISO 2004), and (3) a T_c of 38.5°C if workers have been medically screened (ISO 2004). Despite these conservative limits, the incidence of heat stress related illnesses remains high, particularly in an Australian mine during the summer months (43/million-man hours on average throughout the year versus 147/million-man hours during February) (Donoghue, Sinclair et al. 2000). Higher cases of heat illness during the summer months (May and September (88%)) were also observed among marine corps (Kark, Burr et al. 1996). With higher cases being reported during hotter months, one could suggest that workers and their managers are violating these imposed thermal limits and that improved heat stress interventions are required.

Thus, it seems important for occupational hygienists and managers to be aware of the severe consequences of a hot working environment and the potential risk for heat-related injuries. Some of the currently implemented interventions involve, establishing maximal exposure durations to stressful environments through heat stress indices (McArdle, Dunham et al. 1947; Belding 1955; Yaglou 1957; ACGIH 2005), educating workers on hydration (Brake and Bates 2003), and modification of the ambient working

environment (Hardcastle and Kocsis 2004; Mate 2007). By complementing these heat stress strategies with newer approaches, the incidence of heat related injuries in industry may be reducedTherefore, the purpose of this review was to identify some approaches already taken to reduce heat stress in industry-highlighting some restrictions these interventions may have, and to provide an alternative solution which may compliment currently implemented heat stress interventions.

Environmental conditions in industry, as previously described, can place high and sometimes uncompensatable heat loads on workers. In order to help protect workers from heat stress related illnesses, heat stress indices or measurements have been created. These indices can be classed into three general categories; direct, rational and empirical indices. Direct indices involve the use of standard ambient measuring equipment. The more popular direct index used in industry is the ISO 7243 – WBGT (ISO 1989). Rational indices are measurements based more on physiological parameters such as sweating, T_c, heart rate, and metabolic work. Examples of rational indices include but are not limited to: predicted heat strain (ISO 2004), heat stress index (Belding 1955), and ISO 7933. Empirically based indices are those measurements which are based on meteorological parameters such as temperature, humidity and wind speed. Examples of empirically based indices are: effective temperature (Houghton 1923), corrected effective temperature and the predicted four hour sweat rate (P_4SR) (McArdle, Dunham et al. 1947).

Some approaches in addressing the issue of heat stress range from monitoring and manipulation of the ambient working environment (heat stress indices and ventilation practices), altering work practices and work schedules (mechanical equipment and rest to work ratios), primary care (acclimation of workers), implementation of safety equipment (cooling garments), to education of workers (hydration practices). Some challenges in creating a universal heat stress index are the multitude of variables which exist in the

working environment. Such variability includes the identification of metabolic demands for tasks between workers, phenotype of workers, health status of the worker, tolerance to heat, heat sources (natural and artificial), mechanisation of occupation, interference of thermolytic mechanisms, level of intermittent work, and the ambient environment. Accounting for each variable in a single heat stress index may not be not feasible for industrial applications. As a result, several indices have been developed to assist with protecting the worker and predicting heat loads. Regardless of its type, as summarized by Epstein and Moran (2006), an index should: (1) be feasible and accurate through a range of conditions, (2) integrate important variables, (3) represent the workers exposure and (4) reflect increased physiological and psychological safety and health.

Described below are several heat stress indices and other heat stress interventions used in industry with a brief review of their function and in some cases, the variables measured and limitations.

2.2 Heat stress interventions

2.2.1 Thermal Work Limit (TWL) – This index is defined as the limiting or maximal sustainable metabolic rate that a euhydrated, acclimatized individual can maintain in a specific thermal environment within safe limits of both deep body core temperature (38.2°C) and sweat rate (< 1.2 $kg \cdot hr^{-1}$) (Brake and Bates 2002). This index has been reported to be more appropriate and realistic than the WBGT during a field study performed by Miller and Bates (2007). The index incorporates various physiological limits in thermolysis to define its scale. From these physiological limits and environmental variables (WB, DB, barometric pressure and wind speed), a portable electronic device then determines a limit value. This value is compared to a table which then determines a safe sustainable metabolic level. Although this index may provide

better accuracy in determining a safe working limit, the use of this index is difficult without the use of the calculating device.

2.2.2 ISO 7243 - Wet Bulb Glob Temperature (WBGT) – An empirical index which is a compromise between an easy to use measure of ambient conditions and a reduced precision index for industrial environments. It is regarded as an exploratory method (ISO 1989) to determine heat stress through the calculation of radiative, dry bulb, and wet bulb values.

The WBGT has been generally accepted amongst governing bodies upon which their recommendations and standards are founded (Parsons 1995). This index allows for a maximal rectal temperature (T_{re}) of 38.0°C. The WBGT is calculated and then referenced against a table for tolerable exposure times, metabolic intensities and work ratios. Weighting for spatial variation in temperature accounts for the temperature at the head (having a weighting factor of two), abdomen and ankles divided by four. Also, there is a time weighting factor which is based on the work to rest ratio. The measurement is averaged over each work period. The simplicity of this index makes it an easy field assessment tool as it requires minimal equipment and training.In addition to the averaging of body segments and time, this index has two variations; the inclusion of radiative or solar heat loads. Typically they are used indoors or outdoors:

Indoors:

$$WBGT = 0.7\ t_{nw} + 0.3\ t_g \qquad (2.1)$$

Outdoors:

$$WBGT = 0.7\ t_{nw} + 0.2\ t_g + 0.1\ t_a \qquad (2.2)$$

Where t_{nw} = natural wet bulb
t_g = globe temperature
t_a = air temperature (dry bulb temperature)

In conjunction with WBGT values, estimated metabolic rates are given in five broad categories. This index also provides work/rest ratios adjusting for ambient conditions. The reference values provided are for a normally clothed individual (0.6 Clo), physically fit for the activity being considered and in good health and both acclimated and non-acclimated individuals (ISO 1989).

While the usability of this index is easy, dry bulb measurements towards the top end of the scale may be over emphasised (Taylor 2006). Further, the index may not adequately consider air flow during hot and humid conditions, and is insensitive to air flows above 1.5 $m \cdot s^{-1}$ (Taylor 2006). This index is unable to accommodate for differences in metabolic rates; however, concomitantly using another ISO standard can correct for this shortcoming. The insulative component of clothing is not accounted for during the calculation of this index; although, another ISO standard can be used to correct for insulation. Despite the correction factors available from other indices, constantly referring to other indices may make this index cumbersome to use.

2.2.3 ISO 7933 – Ergonomics of the thermal environment – Analytical determination and interpretation of heat stress using calculation of the predicted heat strain - Predicting sweat rates and T_c are described by ISO 7933. The objectives of ISO 7933 are twofold; (1) to evaluate the working environment where rises in T_c or excessive water loss typically occur, and (2) determine exposure times where physiological strain is acceptable.

As the ISO 7933 index estimates strain in Western populations, this specificity may discriminate against other ethnicities based on phenotype. McNeill and Parsons (1999) investigated the accuracy of this heat stress index during a simulated tea leaf picking task in conditions similar to those found in India. They used Western participants in the study and observed differences in the accuracy of measured sweat rates, metabolic rates and insulative properties of clothing. The appropriateness of the index was found to be mainly directed towards Western countries as opposed to those regions where anthropometrically different people habituate. ISO 7933 states within its introduction that it is not applicable to cases where special protective clothing is worn (ISO 2004), which include reflective clothing, active cooling and ventilation clothing, impermeable clothing and PPE.

2.2.4 ISO 8996 – Ergonomics of the thermal environment – Determination of metabolic rate – Here, the ISO 8996 specifies different methods for determining metabolic rates in assessment of working practices, jobs and activities. These estimates are based on an individual of 30 years of age, weighing 70 kg and standing 1.75 m tall (BSA 1.8 m^2) for men, and weighing 60 kg and standing 1.70 m tall (BSA of 1.6 m^2) for women (ISO 2004).

The index is divided into four different assessment levels for metabolic estimates with each level having different levels of accuracy. Level 1; screening - this assessment quickly characterizes the mean workload of the occupation, but contains a high risk of error in estimation. Level 2; observation - a time motion analysis is performed for the occupation which includes workload estimates for body segments and postures. The accuracy of this level is ± 20%. Level 3; analysis - the estimation of metabolic rate is determined through heart rate. The accuracy of this level is ± 10%. Lastly, level 4;

expertise - indirect calorimetry. Accuracy of this method is ± 5%, however it is limited by the measurement, duration or motion being evaluated.

Observer experience in the interpretation of task intensity, as defined by ISO 8996, plays a key role. Additionally, the grading of an activity can vary with the appraiser's level of fitness, age, experience and training level (Kahkonen, Nykyri et al. 1992). It was found that the difference between two groups of appraisers before visual training ranged between 18-60%. After training, the largest difference in a measurement was found to be 24%. These findings highlight the importance of intra-observer experience to accurately assess metabolic demands for heat stress purposes.

2.2.5 ISO 9886 – Ergonomics – Evaluation of thermal strain by physiological measurements – several methods are provided to measure physiological parameters which are to be used in conjunction with other ISO standards. The parameters included in this standard are: body temperature, skin temperature, heart rate and body mass loss. The index provides several methods to measure each parameter with an emphasis on body temperature. ISO 9886 provides limit values for the various physiological parameters.

Using heart rate as an indicator of thermal strain may be subjective as heart rate increases with work and heat. Physiological responses to heat may vary between individuals and setting an upper limit of an increase in HR of 33 bpm may be conservative. Nielsen and Meyer (1987) attempted to calculate $\dot{V}O_2$ from measuring HR and observed both over and underestimation in $\dot{V}O_2$ due to differences in temperature, posture, and whether there were static or dynamic movements and non-steady state types of activities performed. Using HR as a factor to limit work may require further investigation.

2.2.6 Predicted 4 hour Sweat Rate (P_4SR) – developed by McArdle and colleagues (1947), with the aim to create a simple index or method of assessing the physiological effects of any combination of temperature, humidity, radiation and air movement on personnel wearing different clothing types and working at various intensities. A nomograph encompasses these variables for ease of use. As with all indices, some limits were implemented in its derivation. This includes the dry bulb or globe temperature range, wet bulb, air movement speeds, metabolic rates and an upper sweat rate limit of 4.5 L in a four hour period. Once environmental variables have been obtained, lines are drawn on the nomograph and the required sweat rate can be determined along with the predicted rise in T_{re} at the end of a 4 hour period.

The inherent limitations are described within the index itself, however, the application of this index to acclimated individuals can be challenging since such individuals can easily achieve a sweat rate of 4.5 L in a period of four hours (1.125 $L \cdot hr^{-1}$), and in fact, Wyndham et al. (1973) showed acclimated individuals had a P_4SR range between 4.95 and 5.35 L. Therefore, a sweat rate of 4.5 L could be an overly conservative estimate. In as much as the investigators provide a nomograph for calculating sweat rates and rise in T_{re}, deciphering the graph provides a further challenge to the field use of the index. Furthermore, this index accounts for partial clothing to be worn by personnel, and therefore does not consider fully encapsulating garments, which could be problematic.

2.2.7 Physiological Strain Index (PSI) –an 11 point scale (0 to 10) is used to indicate the level of stress which is based on two physiological parameters; heart rate and T_{re} (Moran, Shitzer et al. 1998). The PSI is simple to use and it does not discriminate between environmental conditions, nor the clothing worn by individuals; hence the functionality of the index. The evaluation of heat strain can be preformed instantaneously

by a supervisor or the workers themselves at any time, which is advantageous; however, the social acceptance of T_{re} monitoring and its invasiveness are questionable.

$$PSI = 5(T_{re\,t} - T_{re0}) \cdot (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \cdot (180 - HR_0)^{-1} \quad (2.3)$$

Where; $T_{re\,t}$ and HR_t are simultaneous measurements of rectal and heart rate
T_{re0} and HR_0 are the initial rectal and heart rate measurements

Conversely, the PSI could be considered a reactive rather than a proactive index. It is reactive in that, the workers would already have been or are currently being exposed to high heat loads. It is only when they stop work that their physiological responses are measured. These measurements could be a misrepresentation as a critical core temperature could have already been reached. It has been previously shown that modifications to work practices begin to occur as ambient conditions increase (Brake and Bates 2002), reducing the effectiveness of this index.

2.2.8 Heart rate – ISO 9886 (ISO 2004) - includes equations to estimate heat strain in workers based on heart rate. These equations include a limit of heart rate (HR_L) that should not be exceeded:

$$HR_L = 185 - 0.65 \cdot \text{age} \quad (2.4)$$

or a sustained heart rate;

$$HR_{L,\,sustained} = 180 - \text{age} \quad (2.5)$$

which should not be exceeded. It is suggested to set the upper limit for a change in heart rate of 33 bpm which is associated to a thermal strain being experienced by the worker (ΔHR_T). Despite these suggested limits, as with T_c, there are circumstances in which this limit can be exceeded, provided there is medical supervision. During these circumstances, the upper limit for HR would be 60 bpm.

2.3 Ventilation practices

Increasing the rate of air movement over the body will typically result in an increased rate of heat loss (evaporative heat loss). By increasing air flow, ventilatory engineers facilitate evaporative heat loss; pending the partial pressure of water vapour. Reducing heat loads in underground miners via evaporative heat loss is a method currently practiced; however, in factories or open cut mines this method of heat dissipation may not be practical. Generally, in underground mines there are two basic types of ventilatory cooling methods: forced and sectional, usually used in conjunction with each other. Forced ventilation consists of cooling units, typically on the surface, forcing conditioned surface air down into the mine. To increase the efficiency of this method, sections of the mine are blocked off in an attempt to re-direct the flow of conditioned air throughout various tunnels. The importance of wind speed rather than decreasing temperature was identified by Mitchell (1972) who observed that increasing wind speeds in low wind speed regions can increase the ambient cooling power quicker than maintaining the same wind speed but reducing wet bulb (Mtichell and Whiller 1972). In an underground mine investigated by Donoghue and colleagues (2000), they concluded that if ventilation and refrigeration practices achieved a cooling power of >250 W, then heat exhaustion would be unlikely (Donoghue, Sinclair et al. 2000). As mines are becoming deeper in order to reach richer ores, the demand for ventilation increases. Accompanying the increasing ventilatory demands are larger economic investments by the company (Hardcastle and Kocsis 2004). Therefore, cooling of the working environment is limited by the willingness of the mine to invest monetarily.

2.4 Individual cooling interventions

Types of cooling interventions vary from preventative to reactive methods. Cooling the body during work in hot environments can either attenuate or prevent the

excessive rise in T_c. Some of the preventative methods include pre-cooling and wearing of ice vests or jackets. Pre-cooling individuals is typically used in sporting events prior to the commencement of the event. This intervention usually consists of an athlete immerged in a water bath for a desired time or until a certain temperature is reached. The general aim of this technique is to delay or offset the time it takes to reach a critical T_c (Quod, Martin et al. 2006). Ice vests or jackets have several pockets with ice or some cryogenic material located inside. The ice is situated close to the skin and acts as a heat sink by conduction.

Irrespective of an ice vest's ability to cool a person, limitations associated with their use include the excess weight, frequent changing of the cooling cartridges, the comfort of the vest and the limited cooling duration (Varley 2004). It has also been reported that PPE are viewed as a hindrance rather than a protector by most personnel (Meyer and Rapp 1995).

Hand and forearm cooling is a newer cooling protocol which is gaining popularity amongst the fire fighting sector. While still semi dressed, fire fighting personnel can immerse their forearms in a cold water bath in an attempt to transfer heat energy away from the core and into the bath via conduction and convection (Barr, et al 2009). The benefit to hand immersion was described by Livingstone, Nolan and Cattroll (1989) where they immersed the hands of test volunteers in water baths of 10, 15, 20, 25 and 30°C for 20 min following 20 min of exercise. This protocol was performed at two different exercise intensities and also at rest. The largest quantity of heat was observed to be removed at the coldest water temperature. These findings are supported by other authors as well (House, Holmes et al. 1997; Giesbrecht, Jamieson et al. 2007). Intuitively these results are justifiable because submersion of the hands in colder water temperatures creates a larger thermal gradient between the bath and skin. A larger thermal gradient

would enable larger quantities of heat to be exchanged between the two systems. Performance benefits have been measured using hand cooling during a 30 km cycling time trial, where the hand cooling trial (60.9 ± 2.0 min) was faster than the no cooling trial (64.9 ± 2.6 min; $P < 0.01$) (Hsu, Hagobian et al. 2005). The difference in tympanic temperature from resting values were 1.6 ± 0.1°C and 1.2 ± 0.2°C ($P < 0.05$) for no cooling and cooling respectively.

While hand and forearm cooling has been demonstrated to be an effective cooling modality in laboratory-based situations, field access to fresh water may not necessarily be possible. In other instances where heat exhaustion had already occurred, reducing body temperature as quickly as possible is necessary. Under such conditions, forearm cooling may not be the most practical approach.

2.5 Acclimation practices

Usual physiological adaptations during heat acclimation, that occur irrespective of the acclimation modality, include: a reduction in resting heart rate in the heat (Yamazaki and Hamasaki 2003), decreased resting core temperature (Buono, Heaney et al. 1998), increase in plasma volume (Senay, Mitchell et al. 1976), decrease in rectal and skin temperature (Shvartz, Magazanik et al. 1974), change in sweat composition (Taylor 2006), reduction in the sweating threshold (Nadel, Pandolf et al. 1974) and an increase in sweating efficiency (Shvartz, Magazanik et al. 1974).

The process of acclimation is dependent upon several variables such as duration and frequency of acclimating sessions, temperature, humidity and exercise intensity. For example, Yamazaki (2003) used a 6 day acclimation protocol with participants exercising at 50% $\dot{V}O_{2max}$ in ambient conditions of 36°C and 50% RH. Buono et al. (1998) had a protocol which required their participants to exercise for 7 consecutive days for four

bouts of 25 min with a 5 min rest while treadmill walking (1.34 $m \cdot s^{-1}$ at a 3% grade) and cycling (75 W at 35°C at 75% RH). Shvartz and colleagues (1974) used a bench step protocol which equated to a load equal to 85% $\dot{V}O_{2max}$ during ambient conditions of 21.5°C DB, 17.5°C WB, for 12 days. Two hour treadmill walks for 9 days in humid heat (37°C, 74% RH) was used by Garden et al. (1966) for their acclimation protocol. Although there are many different acclimation protocols, there is a general consensus within literature that the greater the intensity of exercise during acclimation, the quicker observable responses will be elicited.

The effectiveness of acclimation is dependent upon the acclimating conditions. Ideally, individuals should be acclimated in environmental conditions and workloads similar to those they would typically experience (Yousef, Sagawa et al. 1986). For example, individuals who work in desert type conditions should be acclimated in hot and dry conditions whereas those who work in tropical conditions should be acclimated in hot and humid conditions (Garden, Wilson et al. 1966; Shvartz, Saar et al. 1973). A study on working capacity under dry and humid heat loads was performed by Nag et al. (1996). One group of subjects were acclimated to dry and hot conditions (41.3 ± 0.6°C and 40 – 50% RH) while another group was acclimated to humid and hot conditions (39.2 ± 0.6°C and 70 – 80% RH) for 9 days. It was found that those individuals who were acclimated in humid conditions were able to perform more work in similar conditions than those who were acclimated in dry acclimated condition. Regardless of the acclimation protocol, both groups increased their work performance compared to the unacclimated state.

The benefits of acclimation were eloquently demonstrated by Wyndham and colleagues (1970) when they calculated the quantity of work that could be performed between acclimated and unacclimated men in a laboratory setting. It was concluded that

unacclimated individuals would reach a critical body temperature (a $\bar{T}_b$ where voluntary cessation of exercise occurs) quicker (600 min) than acclimated individuals (750 min) at the same ambient T_{wb}, particularly when initial core temperature was already elevated. These changes in sensitivity by the various thermolytic responses facilitate a reduction in the net rate of net heat gain.

The process of acclimating requires several days to weeks of continual exposure to specific environmental and working conditions. Resources such as heat chambers may not necessarily be available on work sites which may make the process difficult. Consideration must also be made for the decay in heat acclimation status, which can range from between 6 days to 4 weeks (Wyndham and Jacobs 1957; Yousef, Sagawa et al. 1986).

Despite the physiological advantage of a lower resting T_{re}, increased sweat rate, reduced sweating threshold, reduction in resting heart rate, and increased blood volume, the commitment to induce these physiological responses in acclimation is both time and labour intensive. Even though miners have a good level of acclimatization, as previously described, heat stress related illnesses are still experienced despite currently implemented heat stress interventions. This supports the need for further cooling methods in heat stressful occupations.

2.6 Work to rest ratios

ISO 7243 has incorporated into its standard several work to rest ratios. These ratios are determined on measured WBGT temperatures and estimated metabolic activity. As temperatures increase, the ratio of rest to work also increases. Additionally, if metabolic activity increases, so too does the work-to-rest ratio. These ratios are based on estimations made for an individual to work for one hour and for them not to reach a

critical core temperature level. However, work to rest ratios identified by Donoghue and Bates (2000) are typically found to be selectively self paced during episodes of increased heat stress. This finding is supported by the works of Kalkowsky and Kampmann (2006) who suggested that workers self paced as a result of the absence of a rise in T_{re} and heart rate with increased climactic load (Kalkowsky and Kampmann 2006). Workers typically reduce work output with increasing temperatures (Donoghue and Bates 2000), and conscientious effort and strict monitoring would be required to adhere to the work to rest ratios set out by the index. Stringent monitoring of these ratios would be resource dependent, and they may therefore not be available or viable.

For occupations where self pacing is not an option and where working conditions and job requirements are comparable, Lind (1970) suggests that workers may be pushed to heat illness. Reasons include less pressure from worker unions (South Africa vs. Europe) and lack of worker supervision (particularly in South Africa). This work practice could account for the differences in the rate of occurrence in heat stress related injuries between international regions with obvious socioeconomic differences.

Numerous indices are available which incorporates many different variables. This may make it difficult for occupational hygienists to implement only one in their industry. Therefore, the most appropriate heat stress index should be investigated for each specific industry and for each occupation within that industry.

Establishing and adhering to heat stress interventions can be relatively easy compared to following heat stress indices and may require minimal infrastructure. Educating workers on maintaining hydration is a proactive approach to managing heat stress. Self pacing is an additional heat stress strategy which can be tailored to individual worker requirements.

There have been general recommendations made to improve ambient working conditions by a number of authors. Piekarski (1995) suggests increasing fresh air flow in mines to a maximal rate of 6 $m \cdot s^{-1}$, gradually acclimating workers and wearing heat protective clothing or ice cooled jackets. Donoghue (2004) suggests that more preventative measures should be targeted during the summer months, while Meyer and Rapp (1995) suggest implementing easy to use standardized heat stress indices for short exposures to very hot conditions. Finally, Minard et al. (1971) suggest mechanizing more tasks to reduce the metabolic demands on workers.

Despite these recommendations, not one heat stress intervention has been agreed upon by industry. Due to the unique working conditions experienced, one general intervention may not be adequate. Therefore, incorporating several approaches to reducing heat stress in industry could hold promise.

2.7 Limitations to current heat stress interventions

Heat stress interventions typically do not consider individual variability. As such, individuals will respond differently to the same condition. Therefore, the accuracy of the index will vary. The development of a heat stress index is based on the statistical probability that most of the population will be protected and this probability will then either over protect or not protect at all. Those individuals who are considered to be at either one of the tail ends of the probability curve may not be adequately protected. Over the past century, there have been many indices developed that are aimed at protecting workers; however, the one major shortcoming of all indices is that they do not consider the unique characteristics of each individual during its prediction. In addition to the limitation of accuracy, a new index can be difficult to implement or regulate.

Creation of a new heat stress index could take years to accurately develop and trial. Manipulating the working environment can prove to be too costly and implementing cooling PPE would provide benefits when adhered to. As all workers are required to drink at rest breaks or during work, therefore supplying personnel with a specific type of drink could be an effective cooling intervention to implement. Drinking a solution which changes physical states, solid to liquid, has the potential to provide additional cooling to the worker during work.

2.8 Drinking a cold liquid as a heat stress intervention

The consumption of cold liquid water ($H_2O_{(aq)}$) results in an expansion of the body's natural heat sink. As the body warms the cooler consumed $H_2O_{(aq)}$, heat energy is exchanged between the body and the $H_2O_{(aq)}$ until a thermal gradient no longer exists. Therefore, the heat energy that would have been otherwise stored in the body is transferred to the $H_2O_{(aq)}$. The consumption of cooler quantities of $H_2O_{(aq)}$ will theoretically allow even larger quantities of heat energy to be transferred from the body to the solution. In order to increase the temperature of $H_2O_{(aq)}$ by 1°C, approximately 4210 $J \cdot g^{-1} \cdot K^{-1}$ of heat energy is required to be transferred into the liquid. Thus, the specific heat equation 2 is used to calculate the quantity of heat transferred to 500 g (assuming the density of water is 1.000 ($kg \cdot m^{-3}$)) of 0°C $H_2O_{(aq)}$ consumed by an individual (body temperature of 37°C).

$$Q = m \cdot C_p \cdot \Delta T \tag{2.6}$$

Where: Q is the quantity of heat gained or lost (kJ)
m is the mass of the substance (kg)
C_p is the specific heat capacity of the substance ($kJ \cdot kg^{-1} \cdot K^{-1}$)
ΔT is the change in temperature (°K)

Using this equation, it can be determined that approximately 77.9 kJ of energy is required to equilibrate the water to body temperature. In other words, by consuming 500 g of 0°C water, 77.9 kJ of cooling capacity is administered to the individual.

An ice slurry (combination of both solid ($H_2O_{(s)}$) and $H_2O_{(aq)}$ water; $H_2O_{(is)}$) results in an even greater thermodynamic potential for heat energy to be exchanged with the body. If left undisturbed, $H_2O_{(aq)}$ begins to change physical states from liquid to solid at a temperature of approximately 0°C. However, if $H_2O_{(aq)}$ is continuously stirred, the liquid forms small ice crystals and changes into an $H_2O_{(is)}$. By maintaining both physical states (solid and liquid), the $H_2O_{(is)}$ drink may provide a subtle, but significant advantage to reducing heat strain in thermally challenging conditions This advantage is due to the phase changing feature of the $H_2O_{(is)}$ when $H_2O_{(s)}$ is converted to $H_2O_{(aq)}$. $H_2O_{(s)}$ has a different specific heat capacity (C_p) (2108 $J \cdot g^{-1} \cdot K^{-1}$) to that of $H_2O_{(aq)}$. Comparing $H_2O_{(aq)}$ and $H_2O_{(is)}$, the $H_2O_{(is)}$ would have a greater C_p as a result of having both phases of water in its solution; this ultimately increases the solution's heat sink capacity. Therefore, if the C_p of $H_2O_{(s)}$ is used as a conservative approximation for $H_2O_{(is)}$ at temperatures below 0°C, and the C_p of $H_2O_{(aq)}$ is used for temperatures above 0°C, $H_2O_{(is)}$ results in a greater heat sink capacity than $H_2O_{(aq)}$ alone.

An additional factor which contributes to the larger $H_2O_{(is)}$ heat sink capacity is the energy required to change the physical state of a solid to a liquid. That is, the energy required to change the physical state of $H_2O_{(s)}$ to $H_2O_{(aq)}$ without a change in temperature. This is termed the latent heat of melting or 'enthalpy of transformation'. For water, the energy required is 334 $kJ \cdot kg^{-1}$. To estimate the cooling capacity of $H_2O_{(is)}$ from equation 5 while incorporating both the enthalpy of transformation and the C_p of $H_2O_{(s)}$, the cooling capacity for 500 g of $H_2O_{(is)}$ at -1°C becomes 245.9 kJ. Again, using equation 5

to determine the change in T_c for a 75 kg individual drinking 500 ml of $H_2O_{(aq)}$ or $H_2O_{(is)}$, a change of 0.299°C and 0.945°C would occur, respectively.

While the thermodynamic effect of $H_2O_{(is)}$ consumption has been investigated in animals. Vanden Hoek et al. (2004) infused a 50 ml·kg^{-1} solution of either saline slurry or saline water of equal temperature in 11 swine over a 1 hr period. Brain temperature was reduced by 5.3 ± 0.7°C with saline slurry compared with 3.4 ± 0.4°C using saline water. Another study by Merrick and co-workers (2003) showed how phase changing cryotherapy modalities were able to produce colder superficial skin temperatures (ice bag; from 35.6 ± 0.9 to 27.8 ± 3.5°C at 1 cm, 36.3 ± 0.7 to 31.8 ± 2.2°C at 2 cm, wet-ice; from 35.7 ± 0.8 to 27.2 ± 3.4°C at 1 cm, 36.2 ± 0.7 to 30.6 ± 3.0°C, and gel pack; from 35.49 ± 0.8 to 29.5 ± 2.4°C at 1 cm, 36.1 ± 0.9 to 32.1 ± 1.5°C at 2 cm) at a depth of 1 and 2 cm compared with non-phase changing cryotherapies. Kennet and colleagues (2007) investigated the cooling efficiency of four different cryotherapeutic agents and showed that crushed ice (19.6 ± 3.8°C) reduced skin temperatures more than a gel pack (13.2 ± 5.1°C), frozen peas (14.6 ± 4.2°C), and ice-water immersion (17.0 ± 2.8°C). Lee et al. (2008), demonstrated that cold (4°C) versus warm (37°C) drinks administered prior to and during cycling exercise lowered mean T_{re} during exercise (37.3 ± 0.4°C versus 38.0 ± 0.4°C) and extended time to exhaustion (63.8 ± 4.3 vs. 52.0 ± 4.1 min; cold versus warm drink, respectively). More recently, Siegel et al. (2010) showed that consuming 7.5 ml·kg^{-1} ice slurry resulted in a lower pre-exercise T_c, which remained lower for the first 30 min of treadmill running compared with ingesting cool liquid of the same composition. This supports the notion of ice slurry having a greater cooling capacity than cool liquids of equal volumes. Additionally, time to exhaustion was significantly ($P = 0.001$) increased in the ice slurry (50.2 ± 8.5 min) versus cold liquid (40.7 ± 7.2 min). While a thermodynamic advantage should theoretically be gained through the phase change

properties of solid versus liquid water, the physiological effects of consuming such a mixed solution during exercise have yet to be reported.

With a greater theoretical cooling capacity of an ice slurry over a liquid, ingesting this as an additional cooling source should aid in regulating heat during work. In addition to the cooling potential of an ice slurry, the capacity to hydrate also increases as the ice slurry provides a source of fluid replacement. Replacing fluids, as described below, with an ice slurry could theoretically better attenuate the rate of rise in body temperature and increase exercise performance compared to water alone.

2.9 Hydration and thermoregulation

Maintaining total body water level has been demonstrated to provide thermoregulatory benefits by reducing the rate of rise in T_c for exercising individuals (Gisolfi and Copping 1974). Greenleaf and Castle (1971) showed that hypohydration (-5.2% body mass) was associated with the greatest increase in $\bar{T}_b$ (0.94°C) compared with hyperhydrated (+1.2% body mass) (0.39°C), and *ad libitum* (-1.6% body mass) (0.57°C) fluid consumption trials during 70 min of cycling at 49% $\dot{V}O_{2max}$ in warm conditions (23.6°C, 51% RH), windspeed 0.41 $m \cdot sec^{-1}$).

Brake and Bates (2003) investigated the hydration status of mining personnel through several time points in a work shift. They observed workers starting their shifts in a mildly hypohydrated state (urine specific gravity (U_{sg}) exceeding 1.0220). Despite commencing work in a hypohydrated state, U_{sg} measurements taken pre, mid and post shift revealed that workers were able to maintain their hydration status throughout the work shift. The importance of this study was that it identified the ability of workers to maintain hydration status despite experiencing extreme ambient conditions. Therefore, educating workers on the importance of attaining and maintaining euhydration would

appear to be the simplest and most practical option for workers to manage their heat stress.

Individuals typically delay replenishing body fluids and this phenomena has been termed 'voluntary dehydration' (Morimoto and Itoh 1998). Despite workers typically arriving hypohydrated at the beginning of a work shift, mining personnel were able to maintain the same level of hypohydration at the end of a work shift (Brake and Bates 2003). To promote drinking, ingesting palatable fluids (preferred flavour and/or temperature) has been shown to increase the volumes of fluid consumed by subjects (Bergeron, Waller et al. 2006). Maintaining adequate body water levels, delays the onset of fatigue (Sawka 1992), reduces heart rate during exercise (Barr, Costill et al. 1991) and provides an increased source of cooling (Wimer, Lamb et al. 1997).

Remaining hydrated during hot conditions and heavy metabolic workloads will enable better thermolytic responses compared to being hypohydrated. When Greenleaf and Castle (1971) compared hypohyrated, *ad libitum* and hyperhydrated subjects during a 1 h cycling session, a significant elevation in T_{re} and mean body temperature was observed between the hypohydrated and hyperhydrated conditions. Even though the hypohydrated trial was not significantly different to *ad libitum* fluid consumption, T_{re} and mean body temperature were higher while hypohydrated.

Delivery of fluid into cells is limited by the rate of intestinal absorption. Initially, a person's voluntary fluid consumption rate depends on fluid palatability (Bergeron, Waller et al. 2006). If palatability of a fluid is dismissed then the major influence on gastric emptying is the volume of the contents in the stomach (Maughan and Leiper 1999). The rate at which a fluid is emptied from the stomach is dependent on the volume

consumed (Mitchell and Voss 1991), the energy density and the intensity level of physical activity (Brouns 1998).

In humans, when larger volumes of liquids are consumed, more quantities are able to pass through the stomach and into the small intestine. This was demonstrated by Mitchell and Voss (1991) who had subjects consume three different volumes of fluids relative to body weight. They aspirated the contents of the stomach at the end of exercise and found that the greater the volume ingested, the greater that was emptied. When carbohydrates (CHO) are introduced into the fluid being consumed, concentrations of up to 8% will have little effect on the rate of gastric emptying (Coyle and Montain 1992). Even though CHO concentrations of up to 8% have little effect on gastric emptying rate, water will still empty faster than a glucose containing solution (Maughan and Leiper 1999). Therefore, lowering the osmolarity of a CHO solution will help to promote gastric emptying and eventually the rate of water absorption.

As exercise intensity increases above 80% $\dot{V}O_{2max}$, the rate of gastric emptying has been shown to slow (Convertino, Armstrong et al. 1996). During intense bouts of physical activity, the shunting of blood away from the abdominal region and concomitant lowered gastrointestinal motility could explain this decreased rate of stomach emptying. These studies suggest that the availability of fluids is not limited by volume but rather by CHO concentration and exercise intensity. This indicates that industrial personnel have the capacity to remain hydrated while working as exercise intensity and fluid compositions are such that they would at best minimally interfere with fluid absorption.

Drink temperature has also been suggested to influence the rate of gastric emptying. A study by Ritschel and Erni (1977) investigated the effects of various drink temperatures (5°C, 20-25°C and 45°C) on stomach emptying of solid material. Of the

three drink temperatures, it was observed that solid material was emptied into the duodenum quickest at 5°C (15.91 ± 10.04 min) followed by 20 - 25°C (48.18 ± 28.97 min) then 45°C (71.42 ± 37.08 min).

As with the stomach, the osmolarity of a solution in the intestine will influence the rate of absorption. The osmolarity in the small intestine ranges between 270 and 290 mosmol·kg^{-1} (Leiper 1998). Consumption of drinks greater than 290 mosmol·kg^{-1} are hypertonic and thus draw fluid away from the lumen. Conversely, consuming solutions less than 200 mosmol·kg^{-1} slows the absorption of fluids. Therefore, manipulating CHO concentration to the isotonic range of the intestine could enhance intestinal absorption of water (Convertino, Armstrong et al. 1996). Attention to the type of CHO used to promote water uptake should however be made. It has been suggested that sucrose or glucose polymers can be substituted for glucose, however fructose can promote less water uptake and in excess, can cause gastrointestinal issues (Maughan and Leiper 1999).

2.10 Cold drinks and ice slurry as a cooling aid

Using fluids as a method of internal cooling during exercise has not been extensively investigated. Mundel and colleagues (2006) administered two drink temperatures (19°C and 4°C) to subjects during a submaximal work trial (65% $\dot{V}O_{2max}$ until exhaustion. They observed an increase in performance, a reduced heart rate and T_{re} and greater volume of fluid being ingested in the cold drink condition. Gisolfi and Copping (1974) investigated ingestion of cold (10°C) versus body temperature fluid ingestion during exercise in the heat (34°C). They observed a lower T_{re} and a smaller percentage of weight loss in the cold fluid condition. In a more recent study by Lee et al. (2008), the serial drinking of different fluid temperatures (10°C, 37°C and 50°C) during cycling at 50% $\dot{V}O_{2max}$, showed a lower T_{re} during 10°C fluid ingestion.

Drinking cooler liquids has unequivocally been shown to increase performance and attenuate the rate of rise in T_{re} during exercise Lee et al. (2008). By ingesting fluids of a lower temperature, the capacity to create a larger heat sink greatly increases. A phase changing drink could yield such a heat sink. Infusion of a saline ice slurry bolus (-1 to 0°C) into swine was conducted by Vanden Hoek et al. (2004). The authors showed a greater reduction in brain temperature 5.3 ± 0.7°C versus infusion of a 0 to 1°C liquid saline solution (3.4 ± 0.4°C reduction). Thus, the phase changing ability of an ice slurry solution could provide a better cooling ability then typically used hydration practices. Therefore, using a phase changing drink could serve the dual purpose of both hydrating and cooling personnel working in hot environments.

While the ice slurry appears to be a novel method for cooling and rehydrating a worker during exercise, the optimal quantity of ice slurry to administer is currently unknown. Additionally, it is not known whether the ingestion of an ice slurry would provide the greatest benefits during or after exercise. Due to the dynamic nature of the workplace, laboratory findings may however not adequately describe industry. Therefore, confirmation of laboratory results in the field is also needed.

2.11 Summary

Heat stress standards are continually being developed, validated and revised within industry. A single heat index has not yet been universally accepted in industry and may not be possible due to the economic investment required for the development of new indices which encompass the diversity and uniqueness of occupations exposed to heat. Thus, heat stress illnesses are still being experienced by personnel despite current strategies to reduce heat stress. Consequently, to protect workers from heat illness, other heat reduction strategies must be implemented along with currently practiced methods. The predicted thermodynamic cooling estimates presented, along with published data

collected in humans (Kennet, Hardaker et al. 2007; Siegel, Mate et al. 2010) and animals (Vanden Hoek, Kasza et al. 2004), supports further investigation into the effectiveness of ice slurry ingestion as a practical means of controlling rises in body temperature during work in hot environments. Such a cooling method could provide workers in the hot industries with a simple means of attenuating the rise in T_c whilst concomitantly maintaining their hydration needs. Such an intervention has the potential to increase the workers tolerance of heat stressful conditions, ensure safe exits from dangerous situations, and lower the risk of developing a heat stress related injury.

CHAPTER THREE

APPROPRIATNESS OF HEAT STRESS INDICES USED IN THE ON- AND OFFSHORE LIQUID NATURAL GAS INDUSTRY

3.1 ABSTRACT

Background: Heat loads and exposure levels can vary between occupational groups due to location, geography and terrain. Typically, one environmental heat stress index is implemented on a work site and this could potentially over- or under-protect workers. **Purpose:** The applicability of several heat stress indices was investigated in order to identify an index that can best predict heat stress in onshore and offshore workers in the liquid natural gas (LNG) industry. **Methods:** Environmental conditions and physiological variables (HR, T_{pill}, T_{sk}, and hydration) were measured while personnel worked so that the accuracy of each prediction could be assessed against the true (measured) heat stress. The indices were ISO 7243, ISO 7933, ISO 8996, and predicted four hour sweat rate (P_4SR). **Results:** ISO 7243 and ISO 7933 underestimated heat stress for both onshore and offshore personnel, and personnel worked longer in high wet bulb globe temperatures than these standards dictate they should. ISO 8996 did not accurately predict metabolic rate for offshore personnel ($R^2 = 0.061$; $P = 0.718$) and was only moderately correlated with the observed metabolic rate experienced by onshore personnel ($R^2 = 0.339$; $P = 0.043$). P_4SR showed a higher correlation between measured and predicted for offshore personnel ($R^2 = 0.756$; $P = 0.013$) with onshore personnel observing a significant negative correlation ($R^2 = -0.777$; $P = 0.014$). **Conclusion:** P_4SR was the most accurate heat stress index for use in both onshore and offshore LNG

workers. Occupational hygienists should educate workers appropriately and implement the P_4SR as a heat stress management tool.

3.2 INTRODUCTION

Many heat stress indices have been developed, all of which aim to safely allow the worker to be exposed to repeated bouts of heat-related work. Initially, the WBGT was developed by Yaglou and Minard (1957) for desert military purposes. This index measures wet bulb, dry bulb and globe temperatures. These variables are then entered into an equation and the resultant value determines the intensity/duration of work that can be performed. As this index is simple to use, it has gained popularity in industry and has been adopted globally however, there are shortfalls with this index. Environmental variables are measured but physiological responses to work are not considered. Since individuals do not all respond similarly to thermal stressors and workloads, this index may not be appropriate for continuous monitoring or intermittent work during warm or hot conditions. Other indices which have been developed and/or tested in laboratories, such as predicted sweat rates, may be able to predict levels of heat stress in workers. However, they may not be the most practical tools for use in industrial settings due to the requirements to perform several calculations, decipher complex histograms and purchase and maintain expensive monitoring equipment.

If a heat stress index is able to accurately predict heat loads experienced by personnel, it may not necessarily be the most appropriate strategy to apply across all work environments. For example, in the case of open cut and underground mining, both groups of workers may experience similar total heat loads; however, the open cut miners are exposed to high radiative loads from the sun. Similarly, not all land-based personnel are exposed to similar heat loads due to geography, terrain, and bodies of water. It could therefore be assumed that land-based occupations have the potential to experience different ambient working conditions than offshore personnel.

Working in the liquefied natural gas (LNG) industry can expose workers to a spectrum of environmental conditions. For the purposes of this investigation, the industry has been divided into two distinct groups, onshore and offshore. Onshore personnel must contend with ambient conditions typically experienced by geographic location; which is region dependent. Offshore personnel must also contend with oceanic geography and working on a platform in open waters introduces additional thermal challenges such as reflection of solar loads and working proximity to hot machinery.

Both onshore and offshore groups can encounter different work and thermal challenges, which questions the appropriateness of using a single index to protect workers. Therefore, the purpose of this investigation was to identify the most appropriate heat stress index for the onshore and offshore LNG industry in Western Australia.

3.3 METHODOLOGY

Subjects

After completing a general health questionnaire, eight personnel who worked both onshore and offshore gave their written informed consent to participate in the study. All workers were given an information session by the medical staff and questions were answered by the investigator. Clearance from management, union representatives, supervisors and the human research ethics committee of Edith Cowan University was obtained prior to testing.

Experimental Procedure

Onshore Protocol

The same eight participants volunteered on two consecutive days. Between 06h30 and 07h00, participants presented themselves to the medical suite and were asked to provide a mid-stream urine sample. Anthropometric measurements were recorded, followed by body mass in underwear. Participants were then appropriately instrumented with dermal patches (skin thermistors) and a data logger (n = 3) and a heart rate monitor (n = 8). Volunteers were then requested to ingest a telemetric pill with tap water. The telemetric pill is a thermistor which measures T_{GI} and is indicative of T_c. Participants took mandatory rest breaks at ~09h00 to 09h930, then ~16h00 to 16h30 with lunch at ~12h00 to 12h30.

In order to estimate the metabolic demands associated with the most physically demanding job, as determined by workers, one participant (Wharf Logistical Operator) was visually monitored by the researcher throughout the work day to record activities performed. Metabolic demands were classified and estimated according to the ISO 7933

(ISO 2004) method. At the end of the work shift participants were de-instrumented and body mass was then reassessed.

Offshore Protocol

In the medical suite, body composition was determined prior to the investigation. Participants presented themselves between 05h15 to 05h45 to ingest the telemetric pill before breakfast. Participants consumed a non-standardized breakfast then proceeded to their pre-shift meeting.

Between 06h00 and 07h00, participants were asked to provide a pre-shift mid-stream urine sample. They were then weighed in their underwear and appropriately instrumented with dermal patches and data logger (n = 3) and a heart rate monitor (n = 7). In order to estimate the metabolic demands associated with the jobs being investigated, two participants were visually monitored by the investigator from the start to the end of their work shift to record activities performed. These metabolic demands were classified and estimated according to ISO 7933 (ISO 2004). Each hour throughout the work shift, thermal sensation and T_{GI} was collected. These measurements commenced at 08h00.

Mid-stream urine samples were collected again at lunch and at the end of the work shift, when participants were de-instrumented and their body mass reassessed.

Anthropometric Measurements

Heights were given by participants while pre and post work shift body mass was measured using a standard bathroom scale (Glass Bathroom Scale, China). Body composition was assessed using skin fold callipers (Model HSK-BI-3; Baty International, West Sussex, UK) from seven different locations; chest, tricep, axilla, subscapular, abdominal, suprailiac and mid thigh. These values were then entered into seven equations (Sloan 1967; Wilmore JH 1969; Forsyth HL 1973; Katch 1973; Jackson 1976;

Thorland WG 1984; Withers RT 1987a) where the mean body density was calculated for each participant. From the mean body density, the body fat percentage was averaged and estimated from the equations of Siri (1961) and Brozek (1963). Body Surface Area (A_D) was determined according to the equation of DuBois and DuBois (1916) $A_D = 0.202m^{0.425} \times height^{0.725}$, expressed as m^2.

Clothing and Personal Protective Equipment (PPE)

Onshore workers donned safety boots, cotton pants, and a long-sleeved cotton shirt. While working on the wharf, safety glasses, helmet and gloves were worn. While ships were docking, life vests were worn. Once the ship was tied to the dock, the vests were removed. Upon exiting their living quarters, offshore personnel donned safety boots, one piece coveralls, working gloves, safety glasses and helmets. Safety equipment was only removed in designated break rooms or living quarters.

Urine Analysis

Start of shift, pre lunch break, and end of shift assessments of urine specific gravity was determined with an electronic refractometer (Atago, UG-α, Japan).

Heart Rate

Heart rate measurements (RS800 Polar Heart Rate Monitor, Finland) were collected continuously throughout the work shift. Data was collected every 15 seconds and then averaged into 1 minute intervals.

Environmental Measurements

Data collection took place in during the first week of March 2010; later half of Australian summer. Ambient working conditions were measured using a portable WBGT thermometer (Quest temps, USA). As the jobs evaluated require walking to several locations, ambient conditions were measured in the area where workers spent the majority

of their work shift. Daily values recorded for both groups are displayed in Figures 3.1A – 3.1D. On shore wind data was provided by the Australian Bureau of Meteorology from measurements taken from the local air port located approximately 10 km away; while off shore wind measurements were taken from the onsite weather station located 3 m above the platform.

Core Temperature Measurements

Gastrointestinal temperature was measured using a single use ingestible telemetric pill (Mini mitter, USA). The telemetric pill was ingested after the workers pre-shift meeting, approximately 2 hours before the start of shift and measurements. Mean skin temperature was assessed by adhering thermistor patches (Mini mitter, USA) to four different sites on the body; namely, the chest, bicep, quadriceps and calf. Both T_{GI}, and T_{sk} were recorded approximately every 10 seconds. Mean temperature was calculated using a modified Ramanathan's (Ramanathan 1964) equation. The remaining five participants had their pill temperature assessed at their work stations at approximately 15 min intervals. Time between ingesting the telemetric pill and breakfast is a limitation to this investigation.

Heat storage was estimated for participants wearing dermal patches. Mean body temperature ($\bar{T}_b$) was calculated using the formulae of Colin et al. (1971): $\bar{T}_b = 0.66\ (T_{re}) + 0.34\ (T_{sk})$ for the initial 20 min of data collection, and $\bar{T}_b = 0.79\ (T_{re}) + 0.21\ (T_{sk})$ for the remainder of the work shift; with the exception of mandatory rest breaks ("smoke-o") and lunch. Heat storage was calculated at 5 min increments using the formula of Adams et al. (1992): heat storage = $0.965 \times m \times \Delta\bar{T}_b/A_D$, where 0.965 is the specific heat storage capacity of the body ($W \cdot kg^{-1}{}^{\circ}C$), m the mean body mass (kg) over the duration of the trial, and A_D (previously defined).

Heat Stress Indices

Many heat stress indices have been developed which are in use throughout industry. This study focused on: ISO 7243 (ISO 1989), ISO 7933 (ISO 2004), ISO 8996 (ISO 2004) and P_4SR. Detailed descriptions of these indices are presented in section 2.2 of this thesis. For ISO 8996, metabolic rates ($W \cdot m^{-2}$) were estimated through the use of heart rate, age and weight. Using the mean age and weights for both groups, the following equation was taken from the ISO 8996 (ISO 2004) table to determine metabolic rates:

$$\text{Metabolic Rate} = 5.4 \cdot HR - 326 \tag{3.1}$$

The P_4SR was estimated from the environmental measurements recorded, and then the required sweat rate was determined from the P_4SR normograph.

Statistical Analysis

A Pearson's correlation coefficient test was performed to examine relationships between observed and predicted T_c for each heat stress index. A Student's t-test was used to decipher differences between interventions at the same time point of the work shift. Significance was set at $P < 0.05$ and all data are presented as means ± standard deviations. Data analyses were performed using a statistical software program (SPSS 17.0 for windows, SPSS, Inc., Chicago, IL, USA).

3.4 RESULTS

Table 3.1 lists the mean and ± standard deviation (SD) values of the anthropometric measurements for on and off-shore groups. Environmental conditions in Figure 3.1 show the fluctuating WBGT (Figure 3.1D) values recorded throughout the day. Conditions early in the work day vary between on and off shore locations however the environmental conditions tend to be similar from 13h00 onwards.

Urine specific gravity measurements (Figure 3.2) between the groups were the same at start and end of work shift, but mid shift samples were higher in offshore workers ($P = 0.001$). U_{sg} values were observed to range between 1.019 ± 0.006 to 1.0283 ± 0.0026.

ISO 7243 - Hot environments - Estimation of the heat stress on working man, based on the WBGT- index (wet bulb globe temperature) and ISO 7933 - Ergonomics – evaluation of the thermal strain by physiological measurements. In Table 3.2, the estimated time spent at each of the ISO metabolic workloads and reference WBGT are displayed for both onshore and offshore workers. Duration of the work shift spent at each metabolic zone was determined according to ISO 7933 Annex C (ISO 2004). Approximately 27.9% of onshore and 33.1% offshore time was spent at resting levels while the majority of time (38.7% for onshore and 35.6% for offshore) was spent at metabolic rates of $130 \leq M \leq 200$ $W \cdot m^2$. Measured WBGT ranges as identified by ISO, revealed that approximately 60% of onshore time was spent at a WBGT range of 30.0 to 33.0°C while offshore workers were exposed to similar temperatures for 35.8% of the time. Comparing the time spent at specific metabolic intensities and WBGT values, it appears that personnel are working at a higher intensity than what is recommended by ISO.

ISO 8996 - Ergonomics of the thermal environment — Determination of metabolic rate. A correlation between estimated (ISO 8996) and observed metabolic rates for offshore personnel (R^2 = 0.061; P = 0.718) was not significant; however, onshore workers were observed to have a significant relationship when comparing ISO 8996 and observer measurements (R^2 = 0.339; 0.043). The work rate for offshore personnel as identified in Figure 3.3A is more variable than for onshore workers (Figure 3.3B). Most of the work shift was spent at a metabolic rate class of 2.

Predicted Four Hour Sweat Rate (P_4SR)

Based on the P_4SR results in Figure 3.4, sweat rates of between 0.5 L to 2.5 L for offshore workers and 0.5 L to 3.5 L for onshore workers were required for the current ambient working conditions and intensities. Offshore workers had a fairly consistent required sweat rate throughout most of the workday, which then gradually increased towards the end of the shift. An inverse trend was observed for onshore personnel where the largest required sweat rate occurred during the initial three hours of work. Afterwards, a slight reduction in sweating was required for the environmental conditions and work intensities.

Figure 3.5 compares the measured and P_4SR predicted T_{re} values of offshore and onshore workers respectively. A significant correlation between measured and the predicted P_4SR for offshore workers (R^2 = 0.756; P = 0.013) is shown in Figure 3.5A, while a significant negative correlation between measured and predicted is shown in Figure 3.5B for onshore workers (R^2 = -0.777; P = 0.014).

Table 3. 1 Anthropometric characteristics for on (n=9) and off shore (n=7) personnel

	Height (m)	Age (yrs)	BSA (m^2)	Weight (kg)	Body Fat (%)
Onshore	1.77 ± 0.10	32 ± 8	2.06 ± 0.23	88.8 ± 16.1	24.5 ± 7.0
Offshore	1.75 ± 0.03	40 ± 7	2.11 ± 0.13	96.0 ± 13.0	29.0 ± 8.6

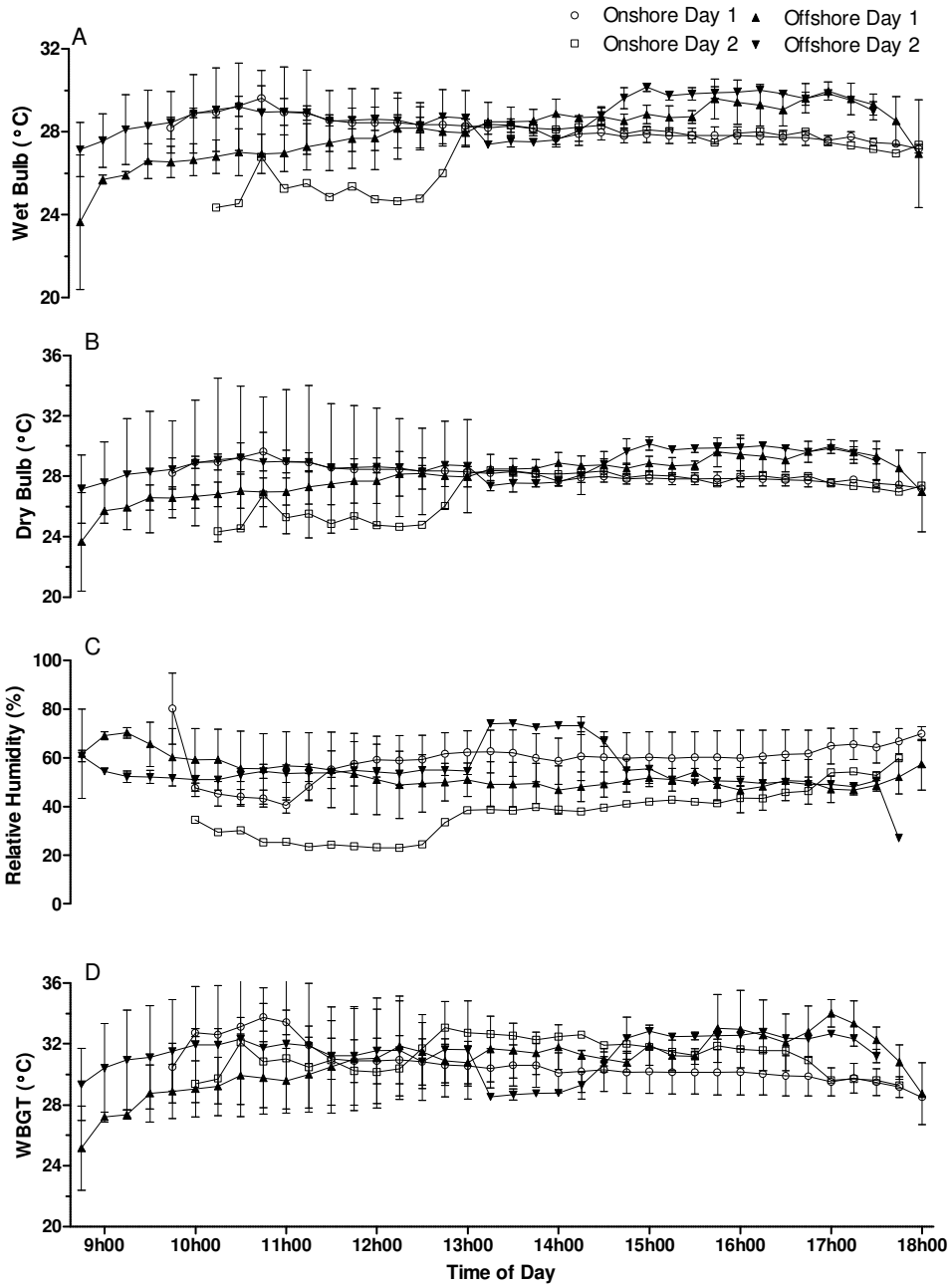

Figure 3. 1 Environmental measures of dry bulb, wet bulb, relative humidity and WBGT for offshore and onshore workers.

Note: On shore day 2 data represent values obtain from one instrument

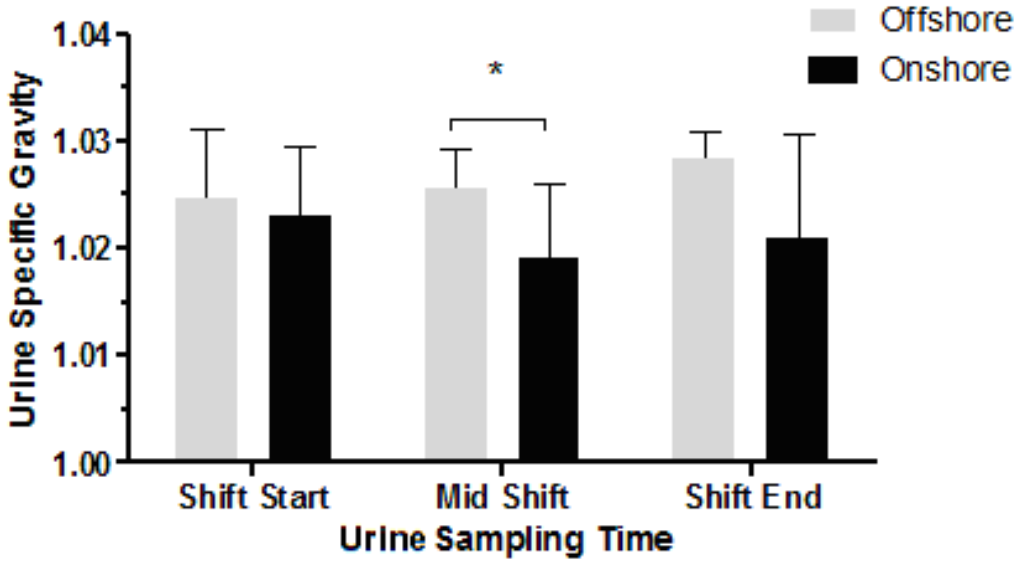

Figure 3. 2 Urine specific gravity measurements conducted in offshore (n = 7) and onshore (n=9) workers for the start, mid and end of work shift**.**

Note: * signifies a difference (P = 0.001)

Table 3. 2 Estimated time spent in each ISO 7933 metabolic range ($W \cdot m^2$) and duration of work shift in ISO 7933 reference WBGT zones for onshore (n=2) and offshore (n=2) workers.

Metabolic Range		M ≤ 65	65 ≤ M ≤ 130	130 ≤ M ≤ 200	200 ≤ M ≤ 260	M ≥ 260
Reference Value WBGT (℃)	>33	30 - 33	28 - 30	26 - 28	25 - 26	<25.0
Time in Metabolic Range (%)						
Onshore		27.9	28.8	38.7	4.5	0.0
Offshore		33.1	13.8	35.6	11.0	4.9
Duration in Reference WBGT (%)						
Onshore	0.0	60.0	35.0	0.0	0.0	0.0
Offshore	25.6	35.8	18.2	18.2	0.0	2.2

Note: Metabolic range (M) modified from ISO 7933(ISO 2004).

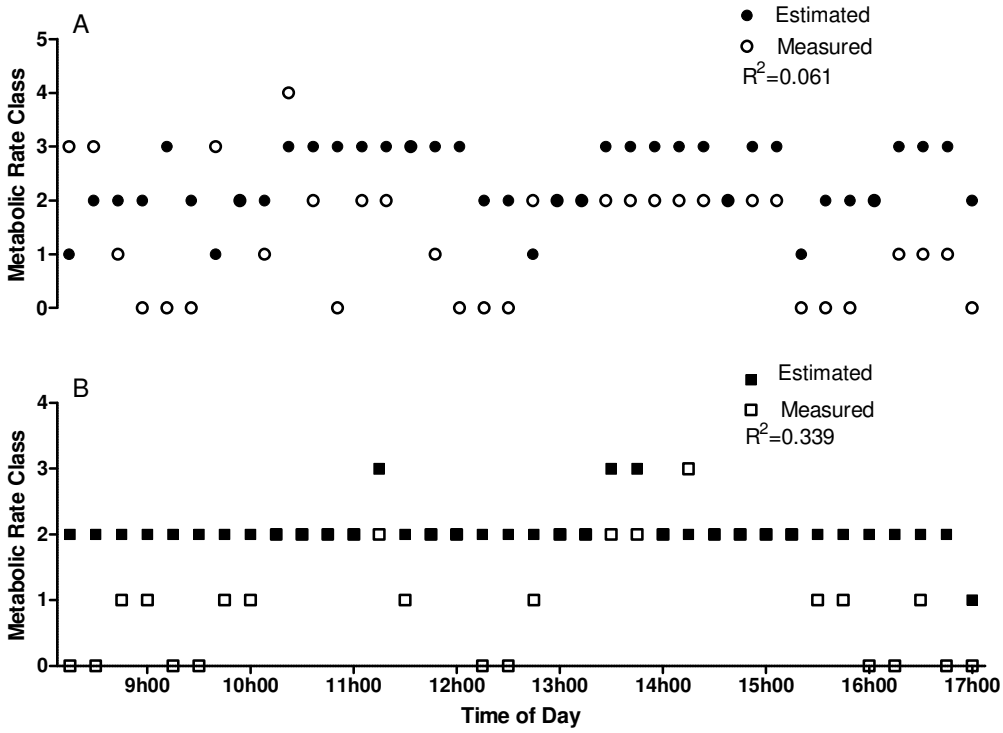

Figure 3. 3 Metabolic rate class of the estimated ISO 8996 and measured observations made for offshore (n=2) (A) and onshore (n=2) (B) personnel.

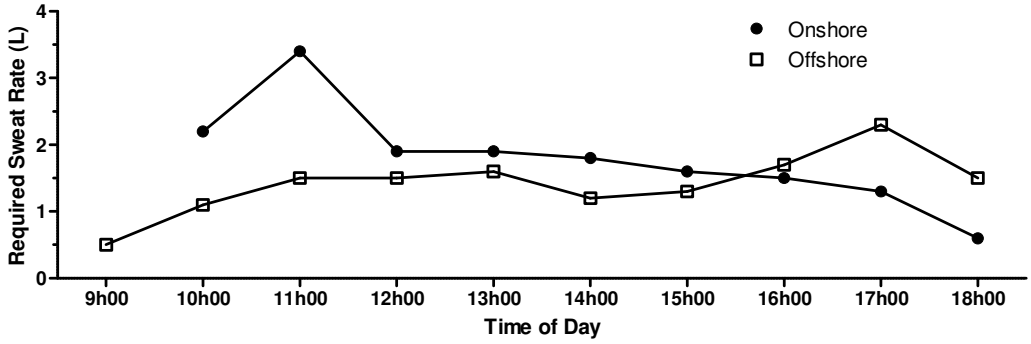

Figure 3. 4 Required sweat rate for offshore and onshore personnel throughout a work shift.

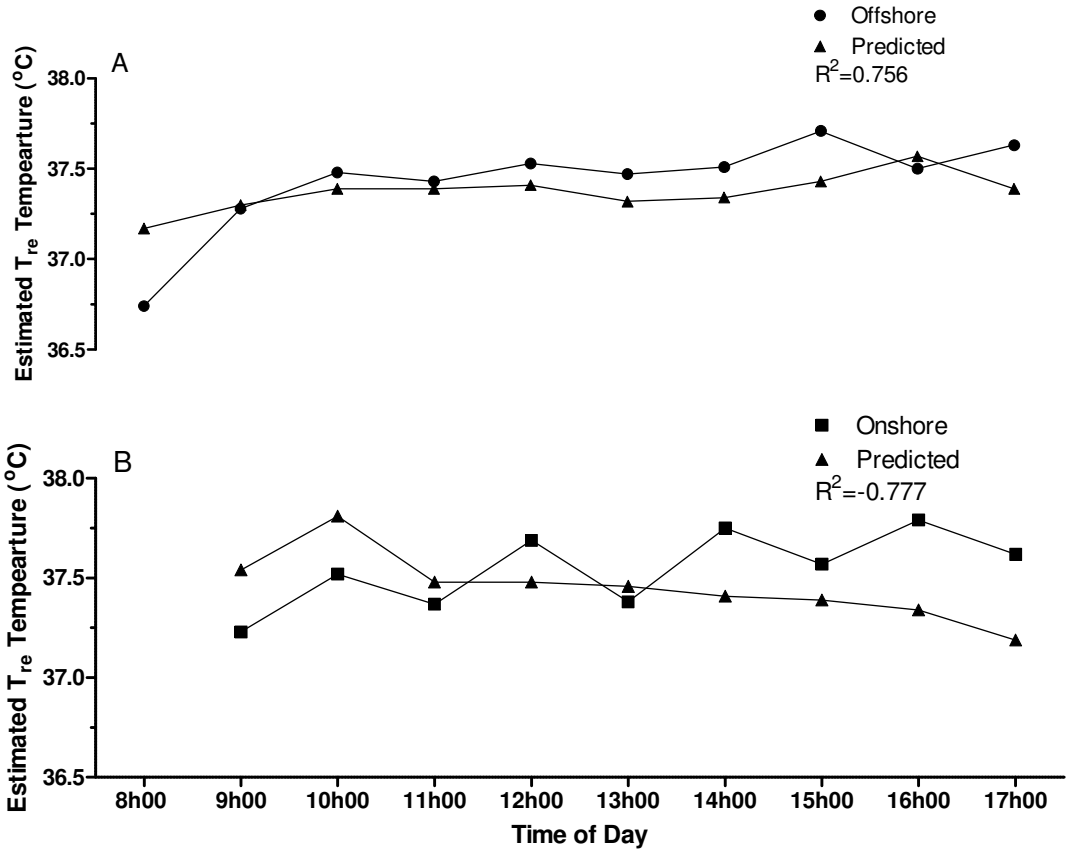

Figure 3.5 Comparison of the actual and four hour sweat rate predicted core temperature for offshore (n=14) (A) and onshore (n=18) (B) LNG workers.

3.5 DISCUSSION

The aim of this study was to determine the most appropriate heat stress index to be used in both the on and offshore LNG industry. While several heat stress indices are available, this study focused on ISO 7243, ISO 7933, ISO 8996, and P_4SR. It was identified that P_4SR was best able to predict heat strain in both onshore and offshore workers for the days investigated.

This investigation monitored workers who were self-paced; however ISO 7243 was found to be inaccurate in protecting workers from heat stressful conditions. Table 3.2, shows that workers spent almost a third of their work shift in WBGT values where a work to rest ratio of 25:75 was recommended, however workers were still able to maintain production without any injury. This indicates that ISO 7243 is overly conservative in predicting heat stress in workers. With relative humidity ranging between 40 and 80%, ISO 7243 could possibly not adequately discriminate between dry and humid heat. The lack of discrepancy could be the result of the simplicity and ease of use of the index; both factors which makes this index so widely applied (Parsons 2006).

In support, Pulket et al. (1980) compared several empirical and rational heat stress indices under several temperatures, vapour pressures and air velocities. They concluded that the wet globe temperature and corrected effective temperature indices are both better predictors of heat strain than the WBGT. The authors suggested that separate heat stress indices should be considered for hot-dry and hot-humid conditions when controlling for heat stress.

To compliment ISO 7243, ISO 7933 attempts to adjust for these environmental insensitivities. Laboratory testing revealed that the ISO 7933 is an inaccurate index during conditions of high radiant heat loads (Forsthoff, Mehnert et al. 2001). Forsthoff

and colleagues (2001) developed a correction factor to the index; however they attributed the overestimation of radiant heat exchange to be the result of an incorrect sensible heat exchange value. Although a corrected and more accurate equation was developed, the mathematical manipulations required make this a cumbersome measure for field application. Sakoi et al. (2006) also developed a correction factor for this index but again, there are many correction factors that make the adjustments difficult to determine which correction will adequately protect the worker.

Mairiaux and Malchaire (1995) collated the results from a data base of several studies and compared the physiological responses to several heat stress indices. They identified the P_4SR to have a better relationship than ISO 7933 and WBGT between observed sweating rate and indices and that a good agreement between observed and predicted sweat losses may not necessarily be appropriate during transient phases. The reason for this lack of appropriateness could be due to the intermittent type of work performed by personnel throughout a work shift. This would in turn influence the sweat rate required for effective heat loss.

The P_4SR and ISO 7933 indices attempt to predict sustained required sweat rates over a four hour period, it could then be inferred that the hydration status of a worker is an important variable to consider if these indices are to be accurate. In Figure 3.2, U_{sg} data indicate that both offshore and onshore personnel were possibly dehydrated at the start and end of their work shift. Remaining in a state of hypohydration may reduce sweat loss, which could reduce the appropriateness of the P_4SR and ISO 7933 indices. If workers remain dehydrated, as was evident in a study by Brake and Bates (2003), then an alternative heat stress intervention may be required. Hydration status of workers could have played an important role in the accuracy of each of the investigated heat stress indices as the level of hydration has been shown to influence thermoregulation.

Using heart rate as a method of monitoring heat strain (ISO 8996) may not be a suitable approach to managing heat stress, as evidenced by the low R^2 measured in this study. Static or dynamic muscular contractions (Nielsen and Meyer 1987), changes in orthostatic pressures (Yamazaki and Hamasaki 2003), heat acclimation (Yamazaki and Hamasaki 2003) and psychological state have all been known to influence heart rate. Although this index is easily implementable, applying it in isolation to manage heat stress is not always appropriate.

This investigation identified the P_4SR as the index which can better predict heat strain in onshore and offshore LNG industry, however additional indices should be considered to compliment this index. Reason being, seasonal changes in weather can present different sources of heat strain on personnel. Lifestyle factors such as diet, smoking and exercise have also been known to influence the ability of the body to regulate its temperature. Therefore, the implemented index should consider these changing parameters. Additionally, the hydration status of personnel when presenting themselves for work is concerning. Hydration status can assist with thermoregulation, and therefore may be an additional consideration when selecting the appropriateness of a heat stress index.

In conclusion, this investigation has observed several key findings. First, the predicted four-hour sweat rate was better able to approximate body temperatures in both offshore and onshore workers. Second, heart rate as a heat stress index may not be appropriate due non-thermal influences affecting heart rate. Finally, workers were hypohydrated before the start of their shift and throughout. This level of hypohydration may interfere with thermoregulatory processes and could indirectly influence the applicability of an applied heat stress index. Therefore, other methods of managing heat stress should be considered.

CHAPTER FOUR

COMPARING ICE SLURRY AND LIQUID AS A COOLING MODALITY

4.1 ABSTRACT

Background: Decreasing an elevated body temperature post exercise in hot and humid conditions can be difficult. Some methods can be cumbersome for field application. Ingestion of ice slurry may be an alternative method but its effectiveness at reducing body temperature is unknown. **Purpose**: To quantify the cooling capacity of ice slurry as a post exercise cooling intervention. **Methods**: On two separate occasions, nine males volunteered to run at approximately 65% of $\dot{V}O_{2max}$ until a T_{re} of 38.8°C. During recovery, participants drank a pre-calculated volume of either an orange flavoured drink (LIQ; 1.802 ± 0.205 L, drink temperature of 4°C) or ice slurry (ICE; 0.536 ± 0.056 L, drink temperature of -1°C) equivalent to the heat energy required to decrease body temperature by 1.0°C. While seated in an environmental heat chamber (30.1 ± 1.0°C, 75.4 ± 5.7% relative humidity and 27.3 ± 0.9°C Wet Bulb Globe Temperature), heart rate (HR), mean skin temperature (T_{sk}) and rate of change in T_{re} (ΔT_{re}) were measured at 38.8°C and every 0.2°C until a T_{re} of 37.8°C was achieved. **Results**: No differences were observed in the rate of change in T_{re} between LIQ and ICE (0.042 ± 0.021°C·min^{-1} vs. 0.039 ± 0.010°C·min^{-1}; $P > 0.05$, respectively). Time to cool was also similar between LIQ and ICE (27:48 ± 9:11 min vs. 27:33 ± 6:57 min; $P > 0.05$). No differences in the cooling rate of HR, T_{sk} and ΔT_{re}, measured at each T_{re} time point, were found between conditions ($P < 0.05$). **Conclusion**: It appears that ICE is a more practical method for cooling than water because the same cooling can be achieved with one third the volume,

and (2) the results indicate that a significantly larger, but still tolerable volume of ICE (~1.5 L) could cool hyperthermic individuals at a rate of $0.1^{o}C \cdot min^{-1}$. Consequently, consumption of ice slurry can be considered as an alternative method to cool hyperthermic individuals.

4.2 INTRODUCTION

The consumption of cold liquid water ($H_2O_{(aq)}$) results in an expansion of the body's natural heat sink. As the body warms the $H_2O_{(aq)}$, heat energy is exchanged between the body and the $H_2O_{(aq)}$ until a thermal gradient no longer exists. The consumption of even cooler volumes of $H_2O_{(aq)}$ would theoretically allow for an even larger heat sink. If left undisturbed, $H_2O_{(aq)}$ begins to change physical states from liquid to solid at a temperature of approximately 0°C. However, if $H_2O_{(aq)}$ is continuously stirred, the liquid forms small ice crystals and changes into a slurry $H_2O_{(is)}$. By maintaining both physical states (solid and liquid), the $H_2O_{(is)}$ drink may provide a subtle, but significant advantage to reducing heat strain in thermally challenging conditions. This advantage is due to the phase changing feature of the $H_2O_{(is)}$; solid ice ($H_2O_{(s)}$) changes phase into $H_2O_{(aq)}$.

While the thermodynamic effect of $H_2O_{(is)}$ consumption in humans during or post-exercise is unknown, the influence of $H_2O_{(is)}$ as a precooling intervention has been investigated. Seigel et al. (2010) showed that consuming 7.5 $ml \cdot kg^{-1}$ ice slurry resulted in a lower pre-exercise T_c, which remained lower for the first 30 min of treadmill running compared with ingesting cool liquid of the same composition and volume. Intravenous infusion of $H_2O_{(is)}$ in animals has also been investigated. Vanden Hoek et al. (2004) infused a 50 $ml \cdot kg^{-1}$ solution of either saline slurry or saline water of equal temperature in 11 swine over a 1 hr period. Brain temperature was reduced by 5.3 ± 0.7°C with saline slurry compared with 3.4 ± 0.4°C using saline water. Furthermore a study by Merrick and co-workers (2003) showed how phase changing cryotherapy modalities were able to produce colder superficial skin temperatures (ice bag; from 35.6 ± 0.9 to 27.8 ± 3.5°C at 1 cm, 36.3 ± 0.7 to 31.8 ± 2.2°C at 2 cm, wet-ice; from 35.7 ± 0.8 to 27.2 ± 3.4°C at 1 cm,

36.2 ± 0.7 to 30.6 ± 3.0°C, and gel pack; from 35.49 ± 0.8 to 29.5 ± 2.4°C at 1 cm, 36.1 ± 0.9 to 32.1 ± 1.5°C at 2 cm) at a depth of 1 and 2 cm compared with non-phase changing cryotherapies. Finally, Kennet and colleagues (2007) investigated the cooling efficiency of four different cryotherapeutic agents and showed that crushed ice reduced skin temperatures (19.6 ± 3.8°C) more than a gel pack (13.2 ± 5.1°C), frozen peas (14.6 ± 4.2°C), and ice-water immersion (17.0 ± 2.8°C).

The effects of drink temperature (19°C or 4°C) on exercise performance was studied by Mundel and colleagues (2006) in subjects exercising at 65% $\dot{V}O_{2max}$ until exhaustion. They observed an 11.6% increase in time to exhaustion, a reduced heart rate of approximately 5 beats and reduced T_{re} (0.25ºC) when subjects drank the 4ºC drink compared to the 19ºC drink. Gisolfi and Coping (1974) investigated the effects of serial ingestion of 10°C fluid versus a fluid at (body temperature) during exercise in the heat (34°C). They observed that the cooler fluid resulted in a lower T_{re} of approximately 0.2ºC. More recently, Lee et al. (2008) investigated serial drinking of different temperature fluids (10°C, 37°C and 50°C) on thermoregulatory responses during cycling at 50% $\dot{V}O_{2max}$. The T_{re} responses were not significant different between drink temperatures; however, T_{re} was lower at the end of 90 min of riding during 10°C and 37°C (38.11 and 38.10°C respectively) fluid ingestion compared to 50°C (38.21°C). These results illustrate the effects of ingesting colder drink temperatures on T_{re}.

From the thermodynamic cooling ability of water, topical cooling trials in humans (Kennet, Hardaker et al. 2007) and intravenous infusion cooling in animals (Vanden Hoek, Kasza et al. 2004), investigation into the effects of an $H_2O_{(is)}$ drink seems warranted. Such a cooling method could be used to reduce risk of injury or death by hyperthermia. While a thermodynamic cooling advantage should theoretically be gained

through the phase change properties of solid versus liquid water, the physiological effects have yet to be reported. Therefore, the purpose of this study is to measure and compare the cooling capacity of ice slurry and a cool liquid as post exercise cooling interventions.

4.3 METHODOLOGY

Participants

Nine healthy, non-acclimated males (age; 27 ± 1 y, height; 176 ± 5 cm, body mass; 75.4 ± 6.6 kg, 15.9 ± 2.8% body fat, body surface area of 1.91 ± 0.10 m^2, and $\dot{V}O_{2max}$ 48.3 ± 4.3 $mlO_2 \cdot kg^{-1} \cdot min^{-1}$) gave written consent and successfully completed the *PAR-Q and You* questionnaire prior to participating in this study. The study was approved by the Edith Cowan University Human Research Ethics Committee.

Preliminary Measurements

On their first visit to the laboratory, body mass and height were measured using an electronic floor scale (Model ID1; Mettler Toledo, Columbus OH, USA) and stadiometer (Seca, Brooklyn N.Y, USA), respectively. Body fat percentage was determined through Dual Energy X-ray Absorptiometry (Hologic, Hong Kong). Under ambient room conditions (23.8 ± 1.3°C at 40.4 ± 8.0 %RH) (Microtherm; Casella Measurement Ltd., Bedford, UK), a modified Bruce treadmill protocol was used to determine $\dot{V}O_{2max}$. Participants began running at 0° incline at 8 $km \cdot h^{-1}$ with increases of 2 $km \cdot h^{-1}$ every two minutes until 16 $km \cdot h^{-1}$, after which the incline was increased 2° every two minutes until volitional fatigue occurred. Expired gasses were continuously analysed (ParvoMedics TrueOne 2400 diagnostic system, Sandy, UT) throughout the test.

Experimental Design

Participants visited the laboratory euhydrated on two separate occasions at approximately the same time of the day with a minimum of three days and a maximum of ten days separating each visit. Mid stream urine was collected and analysed to ensure that subjects were euhydrated, and after instruction, and a rectal thermistor (Monatherm Thermistor, 400 Series; Mallinckrodt Medical, St. Louis, MO, USA) was self-inserted

approximately 10 cm past their anal sphincter. Nude body mass was recorded after the insertion of the thermometer. Participants were then prepared with skin thermistors and a heart rate monitor (Model S610i; Polar Electro Oy, Kempele, Finland). Participants donned running shoes, swimming trunks, track pants, and a t-shirt during exercise. Skin temperature was determined by skin thermistors fixed to the mid belly of the left gastrocnemius, quadriceps, biceps, and chest and the Ramanathan's equation was used to calculate mean skin temperature ($\bar{T}_{sk}$) (Ramanathan 1964). Heat storage was estimated by using the participants body mass, specific heat capacity of the body (3.47 $kJ \cdot kg^{-1} \cdot °K^{-1}$) and the equation presented by Colin's et al. (1971).

Once instrumented, participants entered the environmental heat chamber (30.1 ± 1.0°C, 75.4 ± 5.7 %RH and 27.3 ± 0.9°C WBGT) and were seated upright for 15 min before exercising. Thermal sensation measurements were then taken. Participants then ran on a treadmill at approximately 65% of $\dot{V}O_{2max}$ until rectal temperature reached 38.8°C. Once the designated temperature was achieved, participants disrobed into their swimming trunks and sat upright in a chair for the duration of recovery. In a randomised order, they were then asked to ingest either a liquid drink (LIQ) or ice slurry (ICE) as quickly as possible. From pilot testing, 45 min into recovery during a no drink intervention, T_{re} above 37.8^{0}C was still being observed. Therefore, using no drink as a control method was deemed not necessary as such an extended recovery time was observed. The quantity of beverage ingested to reduce T_{re} by 1.0°C was determined based on pre-exercise body mass. Calculations for determining volumes are described below. Post exercise nude body mass was then reassessed. Metabolic and respiratory water losses were not calculated.

Urine Analysis

Confirmation of euhydration was determined by measuring urine osmolarity (U_{osm}) < 286 mOsm·kgH_2O^{-1} (Latzka, Sawka et al. 1998) by freezing point depression (Advanced Instruments Inc, Massachusetts, USA), and urine specific gravity (U_{sg}) between 1.006 and 1.020 (Popowski, Oppliger et al. 2001) by refraction (Refractometer, Nippon Optical Works, Tokyo, Japan). All urine analysis was performed in duplicate with mean values expressed.

Rectal and Skin Temperature and Heart Rate and Thermal Sensation

T_{re} and T_{sk} was recorded at 1 Hz via a data-logger (Grant Instruments, Shepreth Cambridgshire UK) then calculated into 5 min averages. Heart rate was sampled every 5 s via telemetry (RS800 Polar Heart Rate Monitor, Finland) and 5 min average values were calculated. Thermal sensation was recorded by asking the participant their thermal sensation on an eight point scale (0 = extremely cold; 8 = extremely hot) (Young, Sawka et al. 1987). Thermal sensation was measured before and at the end of exercise, and every 0.2°C decrease in T_{re} during recovery until a T_{re} of 37.8°C was achieved.

Ice Slurry and Liquid Composition and Quantity

The temperature of the ice slurry was approximately -1°C while the temperature of the liquid was approximately 4°C with both being composed of a commercially available orange flavoured cordial (Cottee's Foods, NSW, Australia) which contained water and 5% carbohydrate. Ice slurries were made using a slushy machine (Essential Slush Co., QLD, Australia).

1.802 ± 0.205 L of LIQ and 0.537 ± 0.056 L of ICE were administered to participants for cooling. The differences in these volumes were found to be significant ($P < 0.001$) upon analysis. Determining the quantity of beverage to administer were

computed as follows. Calculating the quantity of ice slurry ingested was based on the required amount of heat energy to be lost which resulted in a decrease of 1.0°C in T_{re}. This calculation was a function of each participant's pre-exercise body mass. To calculate the quantity of heat to be removed for each participant, the following equation was used:

$$Q = m \cdot C_{sp} \cdot \Delta T \tag{4.1}$$

Where Q is the quantity of energy required to be removed (kJ), m is the body mass of the individual (kg), C_{sp} is the estimated specific heat capacity of the body 3.47 $kJ \cdot kg^{-1} \cdot °K^{-1}$ and ΔT is the required change in temperature (°K).

The specific heat capacity (C_{sp}) of the ice slurry is dependent upon its temperature and can be dissected into three different components. First, when the temperature is ≤ 0°C, it is assumed to have a C_{sp} of 2.108 $kJ \cdot kg^{-1} \cdot °K^{-1}$. Conversely, when the temperature is ≥ 0°C, it is assumed to have a C_{sp} of 4.187 $kJ \cdot kg^{-1} \cdot °K^{-1}$. Finally, during the change of physical states, solid to liquid, the enthalpy of fusion is also incorporated in the C_{sp}, and this was assumed to be 334 $kJ \cdot kg^{-1} \cdot °K^{-1}$. As these C_{sp} values are that of water, it is an estimation of the C_{sp} of the ice slurry.

While the C_{sp} of the various components of the ice slurry are dependent on volume, a linear equation was developed to calculate volume. Volumes ingested were based on the energy required to remove heat from the participant. This was calculated from equation 2:

$$y = 499.401x + 0.001 \tag{4.2}$$

Where y is the quantity of energy to be removed (determined from equation 4.1), x is the volume to be administered. To apply this equation, several assumptions must be met.

These were as follows: (1) the thermodynamic characteristics of the ice slurry are equal to water, (2) the ice slurry has a uniform ingestion temperature of -1°C, (3) the end temperature of the solution is 38.8°C (equal to end of exercise T_{re}) once ingested into the stomach, (4) errors in rounding C_{sp} are negligible and (5) environmental changes (ice slurry machine to thermal chamber) do not influence the thermodynamics of the ice slurry. To determine the volume of liquid to administer, equation 1 was used with the 'm' variable being the unknown. It was assumed that the mass of the liquid was equal to water and thus the volume of liquid was determined.

Data Analysis

A Students t-test was performed between conditions (LIQ and ICE) at rest, 38.8°C and every 0.2°C until T_{re} of 37.8°C to identify any changes in thermal sensation. When differences were found, a Tukey's post hoc analysis was performed. Significance was set at $P < 0.05$. All values are presented as means ± SD. Data analyses was performed using a statistical software program (SPSS 17.0 for windows, SPSS, Inc., Chicago, IL, USA)

4.4 RESULTS

Both U_{osm} and U_{sg} measurements identified all participants as euhydrated upon commencement of testing. No hydration differences were observed between conditions ($P > 0.05$); Table 4. 1.

Subjects exercised for the same duration to reach a T_{re} of 38.8°C in LIQ and ICE (46.1 ± 17.1 min and 41.4 ± 10.5 min, respectively; $P > 0.05$), and the transition time between exercise and recovery was also the same ($P > 0.05$) between LIQ and ICE (2.0 ± 1.0 min and 2.2 ± 0.9 min, respectively). As shown in Figure 4.1, the cooling rate of LIQ and ICE was similar ($P > 0.05$); consequently time to reduce T_{re} by $1^{o}C$ in the cooling phase was also similar between LIQ and ICE (27:48 ± 9:11 min vs. 27:33 ± 6:57 min; $P > 0.05$).

Rest and cooling phase heart rate values for ICE and LIQ were not significantly different ($P > 0.05$) at each time point (Figure 4.2A). Figure 4.2C shows thermal sensation was not significantly different ($P > 0.05$) between conditions at each time point and was highest immediately after exercise, then gradually decreased to resting values as T_{re} fell. The volume of drink administered to participants between conditions to achieve the same $1.0^{0}C$ decrease in T_{re} was significantly different between ICE and LIQ (0.536 ± 0.056 L and 1.802 ± 0.205 L; $P < 0.05$, respectively).

In Table 4.2, minute changes in T_{re} and percent change in body mass were not significantly different between conditions.

Table 4. 1 Pre-exercise urine osmolarity (U_{osm}) and urine specific gravity (U_{sg}) of participants.

	U_{osm}	U_{sg}
LIQ	301 ± 170	1.007 ± 1.005
ICE	364 ± 227	1.010 ± 1.007

Table 4. 2 Changes in rectal temperature and percent change in body mass from rest.

	Liquid	Ice Slurry
Rectal Temperature at rest (°C)	37.08 ± 0.31	37.18 ± 0.26
ΔRectal Temperature ($°C \cdot min^{-1}$)	0.042 ± 0.021	0.039 ± 0.010
Body mass loss (%)	1.97 ± 0.68	1.76 ± 0.44

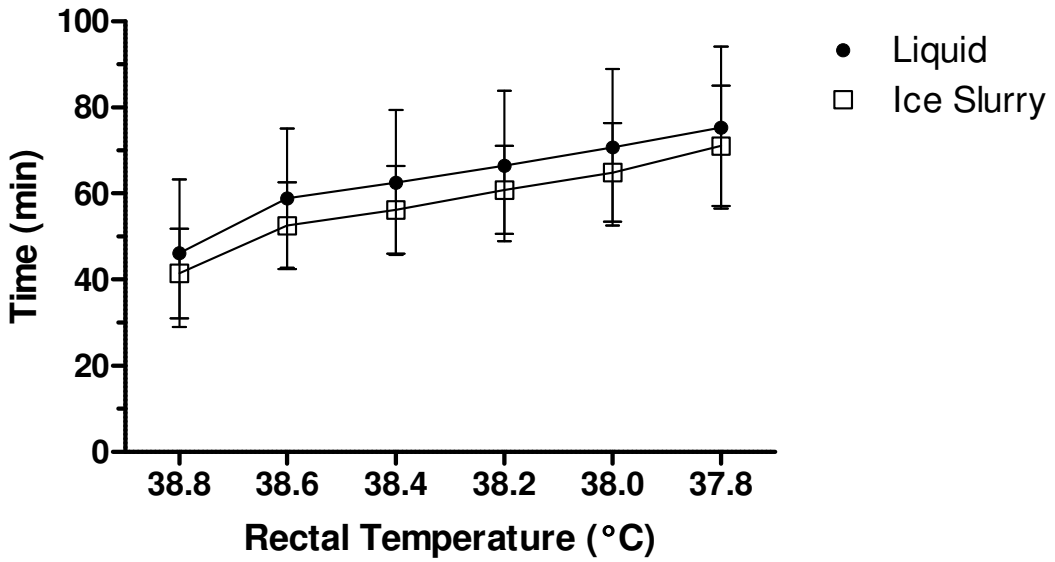

Figure 4.1 Time comparison between LIQ and ICE at 0.2°C rectal temperature intervals.

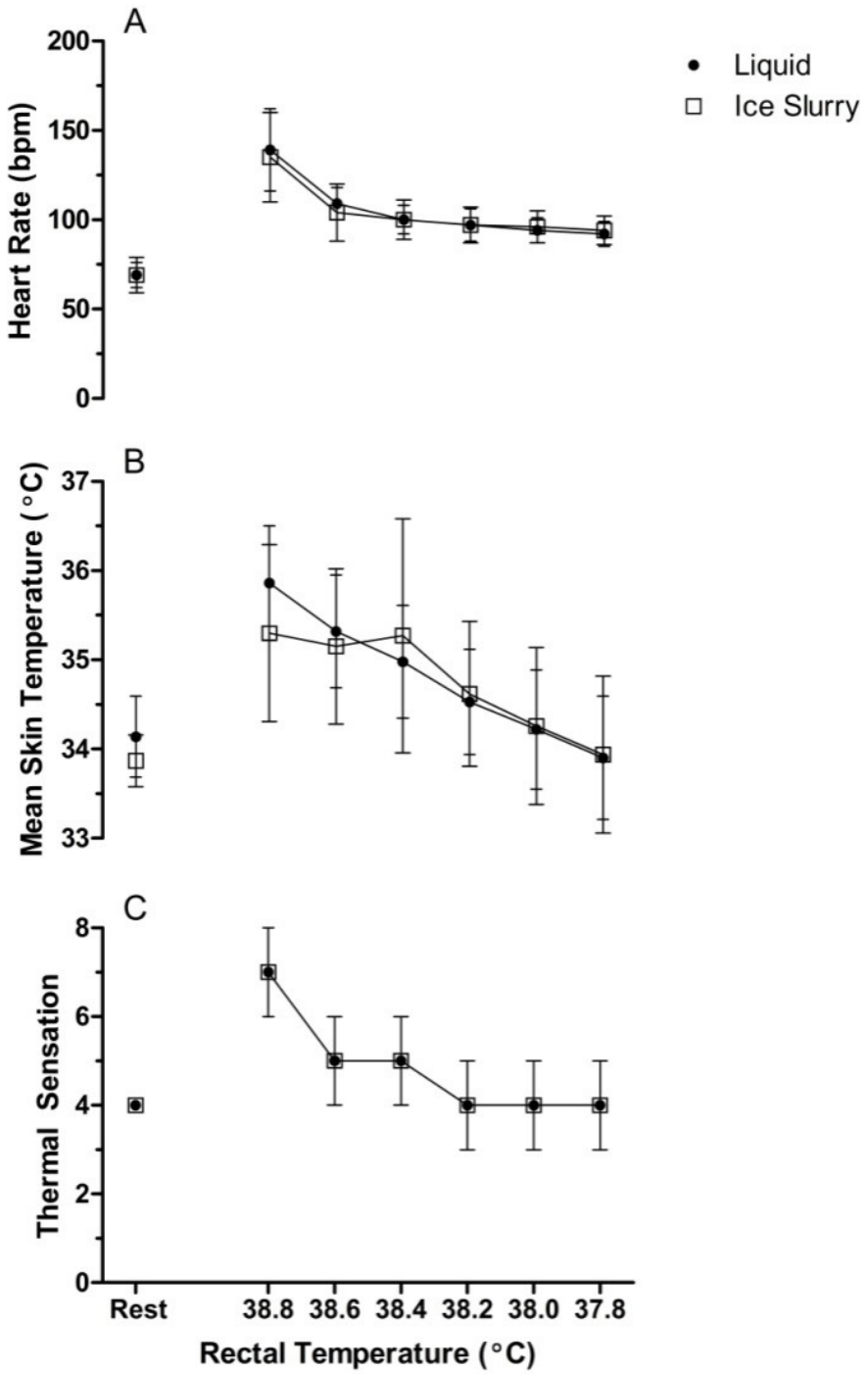

Figure 4.2 The mean ± SD for heart rate (A), mean skin temperature (B) and thermal sensation (C) at rest before exercise, and after exercise in relation to T_{re}.

4.5 DISCUSSION

The purpose of this investigation was to quantify the cooling capacity of ice slurry versus liquid consumption and compare them as a post exercise cooling intervention. The results show that significantly less volume of ICE (0.536 ± 0.056 L) elicited the same physiological responses as LIQ (1.802 ± 0.205 L). Importantly this included cooling rate, which was 0.042 ± 0.021°C·min^{-1} and 0.039 ± 0.010°C·min^{-1} for LIQ and ICE, respectively. This illustrates the potential magnitude of cooling a phase changing solution possesses.

Administration of cooling and how quickly body temperature is decreased is paramount for treatment of persons who suffer from exertional heat stroke (EHS) as this condition can result in death or injury (Coris, Ramirez et al. 2004). Consequently, it has been recommended by authors that persons who experience EHS should be cooled at a rate of no less than 0.078 to 1.0°C·min^{-1} to limit exposure to hyperthermia to within an hour after diagnosis (McDermott, Casa et al. 2009). For example, cooling at a rate of 0.078°C·min^{-1} would take approximately 40 min to cool an individual from 42.20°C to 38.89°C.

In the present study, the cooling rates of ICE and LIQ indicate that a very large, likely intolerable volume of LIQ must be consumed to achieve the recommended cooling rate of 0.078 to 0.1^{o}C·min^{-1}. In contrast however, theoretically a cooling rate of 0.1^{o}C·min^{-1} could have been achieved if our participants had consumed three times the volume of ICE, which roughly equates to 1.5 L. Importantly, this volume (1.5 L) could be tolerable as it is well within the capacity of most adult stomachs.

An interesting trend was recorded for $\overline{T}_{sk}$ (Figure 2B) during the ingestion of ICE. Temperatures remained relatively constant to temperatures at the end of exercise. As

body temperature increases, skin temperature increases and in turn an increase in peripheral blood flow can be seen (Brengelmann, Wyss et al. 1973). When exercise stops, heat production ceases however, temperatures still continues to rise. This lag between the cessation of heat application and continual rise in temperature was noted by Webb (1986) during cooling of a leg of beef. This delay could possibly explain the slightly longer, although not significantly different, time to achieve the first T_{re} time point (Figure 1) from 38.8^{0}C to 38.6^{0}C and then 36.6^{0}C to the other time points. With respect to the ingestion of ICE on $\overline{T}_{sk}$, ICE as identified earlier, has a greater cooling capacity than LIQ per unit volume. As such, the delayed change in temperature which was observed by Webb (Webb 1985) could have been better attenuated by ingesting ICE than LIQ. Hence the marginal difference between $\overline{T}_{sk}$ for the initial time points immediately following exercise.

Cardiac responses between the cooling modalities as indicted in figure 2a were not different which confirms the equal overall cooling capacity administered to participants. With equal cooling capacities being administered, this is not an unexpected finding. Should different cooling capacities have been delivered to participants (different volumes of drink) then different heart rate values would have been observed. A decrease in heart rate was observed by Lee et al. (Lee, Shirreffs et al. 2008) when the same volume of drink but different temperature drinks were administered to exercising participants. This difference can be attributed to the different cooling capacities of fluid. Extending from his work, if participants in this study would have consumed equal volumes of drink, it is probable that a decrease in heart rate would also be observed.

Although the observations made in this study are founded on the ingestion of ICE and LIQ, a comparison of these drinks could have been better illustrated with a no fluid

ingestion to serve as a control. From pilot work, it was observed following the aforementioned protocol, the recovery times lasted more than 45 min. The participants used for piloting were smaller individuals with low body fat, high relative fitness levels and large body mass to surface area ratio. These phenotypical characteristics are favourable during thermally stressful conditions as thermolysis is more efficient compared to the reciprocal (Faber and Garby 1995; Havenith, Luttikholt et al. 1995; Marino, Mbambo et al. 2000).

In conclusion, it appears that ICE is a more practical method for cooling than water because (1) the same cooling can be achieved with one fourth the volume, and (2) ICE can potentially cool at a rate of $0.1^{o}C \cdot min^{-1}$. Consequently, consumption of ice slurry can be considered as an alternative method to cool hyperthermic individuals.

CHAPTER FIVE

EFFECT OF LIQUID VERSUS ICE SLURRY INGESTION ON CORE TEMPERATURE DURING SIMULATED MINING CONDITIONS

5.1 ABSTRACT

Purpose: To compare the effects of replacing 100% and 50% sweat losses with a 5% carbohydrate liquid or ice slurry solution on core temperature during exercise in the heat. **Methods**: Ten euhydrated male volunteers participated in five randomized conditions: no fluid (NF) with no fluid replacement, 100% (100ICE) and 50% (50ICE) sweat loss replaced with ice slurry (~ -1°C) solution and 100% (100LIQ) and 50% (50LIQ) sweat loss replaced with liquid (~ +4°C) solution. Participants walked on a treadmill (3.0 $km \cdot hr^{-1}$, 15° gradient at 28.3 ± 0.4°C, 74.1 ± 3.6 % RH (25.9 ± 0.4°C WBGT)) until volitional fatigue. While walking, solutions were administered every 20 min during exercise. . **Results**: T_{lim}, from longest to shortest, was 100ICE (84.3 ± 38.7 min) followed by 100LIQ (79.2 ± 38.7 min), 50ICE (68.2 ± 38.7 min), 50LIQ (59.2 ± 28.3 min) and NF (46.5 ± 19.9 min) with NF being significantly different from 100ICE, 50ICE and 100LIQ ($P < 0.05$). Rate of heat stored during exercise occurred in the opposite order, from 8.8 ± 2.1 $kJ \cdot min^{-1}$ during NF, followed by 50LIQ (6.6 ± 2.7 $kJ \cdot min^{-1}$), 50ICE (6.4 ± 2.6 $kJ \cdot min^{-1}$), 100LIQ (5.9 ± 3.1 $kJ \cdot min^{-1}$) and 100ICE (4.5 ± 2.7 $kJ \cdot min^{-1}$) with NF being significantly faster than 100ICE ($P < 0.001$), 50ICE ($P < 0.05$) and 100LIQ ($P < 0.05$). ΔT_{re} was 0.020 ± 0.008°$C \cdot min^{-1}$ for 100ICE followed by 100LIQ (0.022 ± 0.007°$C \cdot min^{-1}$), 50ICE (0.027 ± 0.008°$C \cdot min^{-1}$), 50LIQ (0.029 ± 0.008°$C \cdot min^{-1}$) and NF (0.034 ± 0.007°$C \cdot min^{-1}$) with differences shown between NF vs. 100ICE and 100LIQ, as well as 50LIQ vs. 100ICE and 100LIQ (all $P < 0.05$). **Conclusion**: Comparatively,

ingestion of ice slurry resulted in longer T_{lim}, slower rates of ΔT_{re}, and a lower rate of heat storage then liquid conditions of equal fluid volume replacement. Consequently, it is recommend that occupational hygienists should consider administering ice slurry to personnel to lower heat strain during hot working conditions.

5.2 INRODUCTION

Miners perform physically demanding work in hot ambient working conditions, often with minimally exposed skin surface area to dissipate their body heat. For example, the task of shovelling has been measured to range from between 266 $W \cdot m^{-2}$ and 407 $W \cdot m^{-2}$ (Leithead 1964 Bethea 1980) with sitting at ease being approximately 65 $W \cdot m^{-2}$. Ambient temperatures in the work environment can range from 29.1°C to 31.5°C WBGT (Brake and Bates 2002; Donoghue and Bates 2000; Kalkowsky and Kampmann 2006) or 26.6°C to 29.4°C BET (Chilton and Laird 1982; Weller 1981). Miners must also occasionally wear personal protective equipment that encapsulates them and reduces their ability to dissipate heat through evaporative sweat (McLellan, Cheung et al. 1999). Consequently, heat-related illnesses are a regular occurrence in the mining industry (Donoghue, Sinclair et al. 2000).

Current interventions used to reduce the development of a heat stress related illness in miners include: setting the upper limit on body temperature during work to 38.5°C (ISO 2004), limiting the work time in hot ambient conditions according to various different heat stress indices (McArdle, Dunham et al. 1947; Belding 1955; ISO 1989; ISO 2004; ACGIH 2005), improving ventilation practices to cool the working environment (Hardcastle and Kocsis 2004; Mate 2007), wearing cooling garments (Corcoran 2002) and educating workers on the importance of fluid replacement (Brake and Bates 2003). However, despite these interventions, the incidence of heat stress related illnesses in the industrial setting remains high, particularly during the summer months (Donoghue, Sinclair et al. 2000). Therefore, there is a need to examine alternative cooling methods.

A potential alternative intervention that is economically viable, easily implementable, and could be used in conjunction with those currently in use, are

modification of drinking practices so that workers stay euhydrated by drinking ice-slurry beverages. Research has shown that dehydration caused by sweating can impair physical and cognitive performance (Cian, Barraud et al. 2001), reduce maximum voluntary contraction (Hayes and Morse 2010), and that staying euhydrated by drinking enough fluid to offset sweat losses can attenuate the rise in rectal temperature (McConell, Burge et al. 1997; Pitts G. C., Johnson R. E. et al. 1944), cardiovascular strain and perceived exertion (Murray, Michael et al. 1995) during physical activity in the heat. Likewise, research has also shown that ingestion of cool versus warm fluids during exercise attenuates the rate of rise in rectal temperature (T_{re}) (Gisolfi and Copping 1974). I speculate that ingestion of ice-slurry solutions during exercise may therefore be more effective at cooling than liquid solutions because they offer a larger heat sink due to the additional heat required to change phase from solid (ice) to liquid water, known as the 'enthalpy of fusion'. The potential effectiveness of consuming an ice-slurry solution during exercise was demonstrated in the previous study and also by Siegel et al. (2010) who observed a lower T_{re} for the first 30 min of exercise when subjects consumed ice slurry versus a liquid of equal volume and composition prior to exercise. The physiological effects of completely or partially replacing fluid loss during exercise with an ice slurry is unknown.

Thus, the purpose of this investigation was to compare the effects of ingesting ice slurry versus liquid beverages on core temperature during simulated mining conditions. I hypothesised that offsetting sweat losses and remaining euhydrated by drinking an ice-slurry beverage would attenuate rises in rectal temperature, cardiovascular strain, and perceived exertion, to a greater extent than drinking a cold liquid beverage.

5.3 METHODOLOGY

Participants

Ten healthy non-acclimated males (height 1.75 ± 0.05 m; age 29 ± 5 y; body mass 81.8 ± 9.0 kg; 19.2 ± 3.1 % body fat; $\dot{V}O_{2max}$ 46.37 ± 5.99 $ml \cdot kg^{-1} \cdot min^{-1}$) gave written consent and completed a pre-screening questionnaire, *PAR-Q and You,* prior to participating in this study. The study was approved by the Edith Cowan University Human Research Ethics Committee.

Preliminary Measurements

On their first visit to the laboratory, each subject's body mass and height were measured using a weight scale (Model ID1; Mettler Toledo, Columbus OH, USA) and stadiometer (Seca, Brooklyn N.Y, USA), respectively. Adiposity was determined through Dual Energy X-ray Absorptiometry (Hologic, Hong Kong). Under ambient room conditions (25.8 ± 2.0°C at 44.1 ± 8.1 %RH) (Microtherm; Casella Measurement Ltd., Bedford, UK), a modified Bruce treadmill protocol was used to determine $\dot{V}O_{2max}$ (ParvoMedics TrueOne 2400 diagnostic system, Sandy, UT). Calibration of the metabolic cart occurred prior to each $\dot{V}O_{2max}$ testing session. Participants began running at 0° incline at 8 $km \cdot h^{-1}$ with increases of 2 $km \cdot h^{-1}$ every two minutes until 16 $km \cdot h^{-1}$, after which the incline was increased 2° every two minutes until volitional fatigue occurred.

Experimental Design

Participants visited the laboratory on five separate occasions at approximately the same time of day with a minimum of 7 days separating each visit. All participants performed their first session, considered the control condition (NF), without any drink ingestion. The difference between pre and post exercise nude body mass was used to estimate sweat rate and drink volume to be consumed in the remaining trials. The

remaining four sessions, which were completed in a randomized order, included 100% replacement of estimated sweat losses with ice slurry solution (100ICE), 50% replacement of estimated sweat losses with ice slurry solution (50ICE), 100% replacement of estimated sweat losses with liquid solution (100LIQ) and 50% replacement of estimated sweat losses with liquid solution (50LIQ). As the solution to be drunk will be revealed to the participant upon delivery, blinding the participant to the drink is not possible and therefore a limitation to this study.

Experimental Protocol

On arrival at the laboratory, urine and blood samples were collected and, following instruction, a rectal thermistor (Monatherm Thermistor, 400 Series; Mallinckrodt Medical, St. Louis, MO, USA) was self-inserted by subjects, approximately 10 cm past their external anal sphincter. Nude body mass was measured before participants were instrumented with skin thermistors and a heart rate monitor (Model S610i; Polar Electro Oy, Kempele, Finland). Participants then donned running shoes, cotton pants, t-shirt and a mining helmet. Skin temperature (Fixomull, Smith and Nephew Ltd., Auckland, New Zealand) was determined by skin thermistors fixed to the mid belly of the left gastrocnemius, quadriceps, biceps, and chest; Ramanathan's equation was used to calculate mean skin temperature (Ramanathan 1964). Heat storage was estimated by using the participants body mass, specific heat capacity of the body (3.47 $kJ \cdot kg^{-1} \cdot {}^{\circ}K^{-1}$) and the equation presented by Colin's et al. (1971).

Upon entering the climate chamber, participants were seated in an upright chair for 15 min prior to exercise. Exercise then commenced and consisted of walking on a treadmill at a constant workload of ~290 $W \cdot m^{-2}$ (3.0 $km \cdot hr^{-1}$ at an inclination of 15°) (ISO 7243). Ambient conditions were 28.3 ± 0.5°C, 74.2 ± 4.6% RH (25.9 ± 0.4°C WBGT) and wind speed less than 0.1 $m \cdot s^{-}$. This work intensity and ambient condition does not

require an altered rest to work ratio (work 100% without rest) for industrial standards (ISO).

During exercise, drinks were administered to participants after 20 min of exercise and every 20 min thereafter; participants were asked to ingest each solution as quickly as possible. Subjects continued walking until either voluntary exhaustion, achieving a T_{re} of 39.0°C, or after 120 min of exercise. In situations where participants completed 120 min of exercise, no drink was administered at that time point. Participants were allowed to wipe sweat from their face only. Immediately after the protocol was completed, nude body mass, blood and urine, were reassessed in that order. Metabolic and respiratory water loss was thought to be similar between trials and was therefore not accounted for.

Urine Analysis

Confirmation of euhydration was determined by one or all of the following criteria: urine osmolarity through freezing point depression (Advanced Instruments Inc, Massachusetts, USA) $U_{osm} < 286$ mOsm·kgH_2O^{-1} (Latzka, Sawka et al. 1998), urine specific gravity (U_{sg}) (Refractometer, Nippon Optical Works, Tokyo, Japan) between 1.006 and 1.020 (Popowski, Oppliger et al. 2001). All urine analysis was performed in duplicates pre and post exercise.

Blood Analysis

Participants sat upright in a chair for approximately 3 min prior to blood being drawn from the antecubital vein. Plasma osmolality (S_{osm}), through freezing point depression (Advanced Instruments Inc, Massachusetts, USA), was determined by collecting 8.5 ml of blood into an SST heprinized tube and centrifuging (Heraeus Multifuge 3 S-R, Australia) for 15 min at 3,000 rev·min^{-1} at 4°C. For measuring changes in plasma volume (ΔPV), 8.5 ml of blood was collected into a plain clot tube before

immediately separating into 2 aliquots (30 µL each) in non-heparinized capillary tubes. Capillary tubes were then spun (MED Instruments, MPW-212, Poland) at 12000 rev·min^{-1} for 5 min at ambient room temperature. Haemoglobin concentration was measured (Hemocue, Hb 201, Sweden) using a sample of blood (10µL each) from the same plain clot tube. If sample values differed, then a third analysis was taken. ΔPV was calculated based on the method of Dill and Costil (1974). All blood analyses were preformed in duplicate, unless otherwise stated, with mean data presented.

Rectal and Skin Temperature and Heart Rate (HR)

T_{re} and $\bar{T}_{sk}$ was recorded at 1 Hz via a data-logger (Grant Instruments, Shepreth Cambridgshire UK); 5 min averages were then calculated. Heart rate (RS800 Polar Heart Rate Monitor, Finland) was sampled every 5 s via telemetry and 5 min average values were calculated.

Ice Slurry and Liquid Composition

Both ice slurry (~ -1°C) and liquid drinks (~ +4°C) were composed of a commercially available orange flavoured cordial (Cottee's Foods, NSW, Australia) with a 5% carbohydrate concentration. Ice slurries were made using a commercial slushy machine (Essential Slush Co., QLD, Australia). Volumes of drink administered to participants were determined from individual sweat loss. Participants consumed approximately 1.30 ± 0.31 L for 100ICE and 100LIQ conditions while 0.650 ± 0.160 L was administered during 50ICE and 50LIQ. The temperature chosen for the liquid solution was based on typical household refrigeration temperature while the warmest temperature was used for the ice slurry in an attempt to maintain a low thermal gradient between both drinks.

Data Analysis

A condition (NF, 100ICE, 50ICE, 100LIQ and 50LIQ) x time repeated measures analysis of variance (ANOVA) was performed to identify any changes in T_{re}, $\bar{T}_{sk}$, and HR. A 1-way ANOVA was used to examine differences in time-to-exhaustion (T_{lim}) between conditions. A urine x condition repeated measures ANOVA was performed to identify any changes in U_{osm}, U_{sg}, body mass, sweat rate, and PV. When differences were found, a Tukey's post hoc analysis was performed. Significance was set at $P < 0.05$ for all comparisons. All analyses was performed using a statistical software program (SPSS 15.0 for windows, SPSS, Inc., Chicago, IL, USA), with values presented as means ± SD.

5.4 RESULTS

Hydration status and serum volume

Table 5.1 shows the environmental conditions between each condition. No differences were observed. Hydration markers, U_{sg}, U_{osm} and S_{osm}, are given in Table 5.2. Change in U_{sg} was significant only in the 50LIQ ($P < 0.05$) condition. Changes in blood volume for 100ICE were less than in NF ($P < 0.05$). The reduction in cell volume was greater in NF versus 50ICE ($P < 0.001$) and NF versus 50LIQ ($P < 0.05$). No differences were observed for %ΔPV between drink interventions.

Rate of heat storage and change in rectal temperature (ΔT_{re})

Significant differences in rate of heat storage (Figure 5.1A) occurred between NF versus 100ICE ($P < 0.05$), NF versus 50ICE ($P < 0.05$) and NF versus 100LIQ ($P < 0.05$). The minute rate of change in T_{re} (ΔT_{re}) are shown in Figure 5.1B there were significant differences being observed for 100ICE and NF ($P < 0.05$), 100LIQ and NF ($P < 0.05$), 100ICE and 50LIQ ($P < 0.05$) and between 100LIQ and 50LIQ ($P < 0.05$).

Time to exhaustion

As shown in Figure 5.1C, differences in time to exhaustion were observed between NF versus 100ICE ($P < 0.05$) and 50ICE versus 100LIQ ($P < 0.05$). T_{lim} increased by approximately 6% when consuming 100ICE versus 100LIQ, 15% between 50ICE and 50LIQ and 28% between 100% fluid replacement and 50% fluid replacement.

Table 5. 1 Environmental dry bulb and relative humidity during each drink intervention

	Dry Bulb (℃)	Relative Humidity (%)
No Fluid	28.3 ± 0.5	75.5 ± 4.6
100% Ice Slurry	28.2 ± 0.4	72.9 ± 4.6
50% Ice Slurry	28.2 ± 0.4	74.9 ± 4.2
100% Liquid	28.5 ± 0.5	73.4 ± 5.0
50% Liquid	28.6 ± 0.5	73.5 ± 3.9

Table 5.2 Urine osmolality (U_{osm}), specific gravity (U_{sg}), plasma osmolality (S_{osm}), changes in blood volume (%Δ BV), cell volume (%Δ CV), plasma volume (%Δ PV), and changes in body mass for each drink intervention.

		Uosm	Usg	Posm (n=9)	% Δ BV	% Δ CV	% Δ PV	Δ Body Mass (kg)
No Fluid	**pre**	163 ± 97	1.011 ± 0.009	296 ± 7				
	post	302 ± 178	1.010 ± 0.008	294 ± 6	-4.10 ± 2.83	-6.44 ± 1.78	-2.81 ± 5.73	1.04 ± 0.53
100% Ice Slurry	**pre**	169 ± 75	1.006 ± 0.004	291 ± 5				
	post	239 ± 117	1.007 ± 0.004	290 ± 5	-0.11 ± 2.68(b)	-0.53 ± 4.02	0.38 ± 4.68	0.11 ± 0.32(b)
50% Ice Slurry	**pre**	120 ± 58(a)	1.005 ± 0.005	295 ± 5				
	post	243 ± 156	1.007 ± 0.005	294 ± 5	-1.58 ± 4.14	-1.35 ± 2.62(b)	-0.58 ± 6.88	0.71 ± 0.39(c)
100% Liquid	**pre**	156 ± 71	1.005 ± 0.003	293 ± 3				
	post	255 ± 194	1.007 ± 0.006	292 ± 4	-2.97 ± 3.77	-3.07 ± 1.75	-2.30 ± 6.11	0.13 ± 0.47(b)
50% Liquid	**pre**	98 ± 64(a)	1.005 ± 0.005 (a)	293 ± 6				
	post	358 ± 300	1.011 ± 0.010	294 ± 6	-1.89 ± 2.45	-1.43 ± 3.50(b)	-1.89 ± 4.62	0.64 ± 0.35(b)

(a) difference between pre and post values ($p < 0.05$)
(b) different to No Fluid ($p < 0.05$)
(c) different to 100% Ice Slurry ($p < 0.05$)

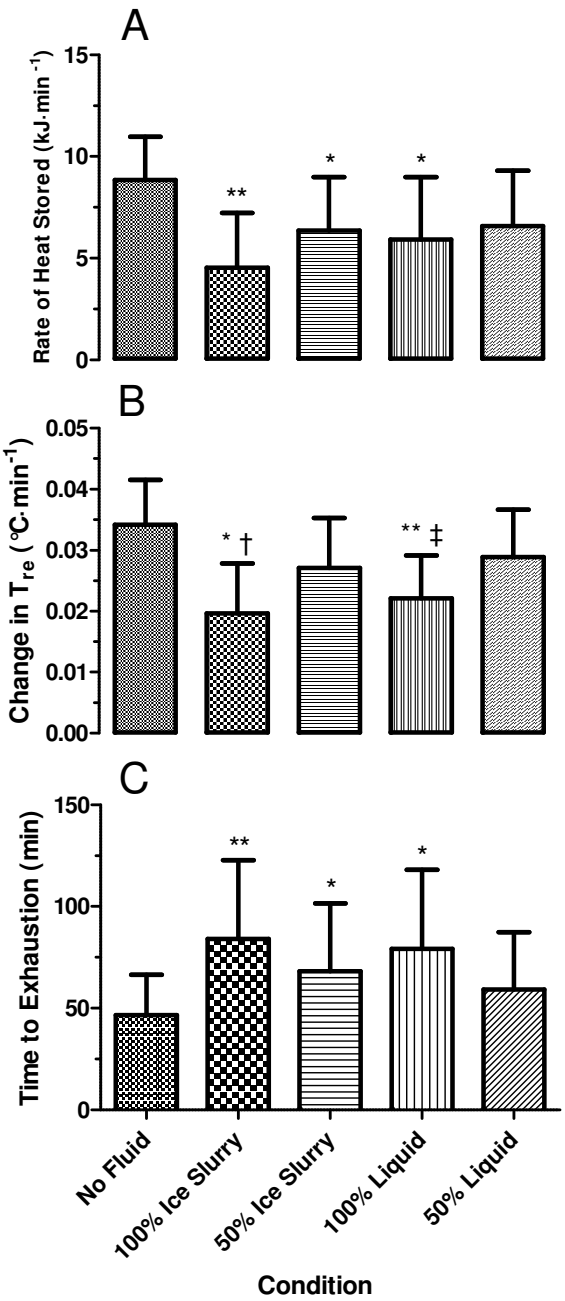

Figure 5.1A Estimated rate of heat stored during each drink intervention. * denotes a difference of P < 0.05 from NF while ** denotes a difference of P < 0.051 from NF. **Figure 5.1B** Estimated minute changes in rectal temperature during each of the five drink interventions. * Denotes a difference P < 0.05 to NF, ** Denotes a difference P < 0.05 to NF, † Denotes a difference P < 0.05 to 50LIQ and ‡ Denotes a difference P < 0.05 to 50LIQ. **Figure 5.1C** Mean (± SD) time to exhaustion for each drink intervention with * denoting a difference of P < 0.05 from NF while ** denotes a difference of P < 0.05 from NF.

Termination Criteria

Ratings of perceived exertion at the end of exercise were 18 ± 2 (100ICE), 19 ± 2 (100LIQ), 18 ± 1 (50ICE), 18 ± 2 (50LIQ) and 19 ± 2 NF. Across all interventions (50 trials), subjects completed 120 min of exercise in 7 trials; 27 trials were stopped before 120 min because subjects were exhausted; and 16 trials were stopped before 120 min because subjects reached our highest allowable T_{re} 39.0°C. No trials were stopped because heart rate was too high. Sixteen individuals reached a critical T_{re}, with 1 of the 16 trials (6.3%) occurring for 100ICE, followed by 3 of 16 (18.7%) during 100LIQ and 4 of 16 (25%) for the remaining conditions of NF, 50ICE and 50LIQ.

In total, 50 trials were completed by participants with 43 of those finishing due to physical exhaustion. 10 of the 10 (100%) trials were stopped during NF and 50LIQ, 9 of 10 (90%) were stopped for 50ICE, 8 of 10 (80%) during 100LIQ and 6 of 10 (60%) during 100ICE.

Table 5.3 outlines the time to achieve a T_{re} of 38.0ºC of each participant. Of the 50 trials completed, three participants were exhausted before their T_{re} reached 38.0ºC. All mean times between conditions were similar ($P > 0.05$) except for 100LIQ and 50LIQ ($P < 0.05$) conditions.

Table 5.4 identifies individual participant time to achieve a T_{re} of 38.5ºC between conditions. In this table, 14 participants were exhausted before achieving T_{re} of 38.0ºC. Participant 8 during 100ICE was able to complete the entire 2 hour protocol without achieving a T_{re} of 38.0ºC. Therefore, a value of 120 was allocated. No differences were observed ($P > 0.05$) between mean end times.

Sweat Rate

Estimated minute sweat rates for each drink condition are shown in Figure 5.2. Sweat rates were similar ($P > 0.05$) between conditions and ranged from 18.8 ± 4.3 $ml \cdot min^{-1}$ for 50ICE up to 21.7 ± 5.1 $ml \cdot min^{-1}$ for NF.

Heart Rate

No differences were observed between conditions for heart rates. 100ICE produced a mean heart rate value of 163 ± 12 bpm followed by 50LIQ (167 ± 11 bpm), 100LIQ (169 ± 9 bpm), NF (169 ± 15 bpm) and 50ICE (172 ± 6 bpm).

Table 5.3 Individual time to reach T_{re} of 38.0ºC

	NF	100ICE	50ICE	100LIQ*	50LIQ
Subject					
1	**29.0**	**31.0**	**29.0**	**43.0**	**28.0**
2	**33.0**	**41.0**	**35.0**	**37.0**	**35.0**
3	**18.0**	**30.0**	**21.0**	**-**	**-**
4	**14.0**	**20.0**	**21.0**	**22.0**	**14.0**
5	**19.0**	**31.0**	**24.0**	**35.0**	**23.0**
6	**21.0**	**26.0**	**23.0**	**37.0**	**31.0**
7	**32.0**	**29.0**	**35.0**	**33.0**	**29.0**
8	**45.0**	**70.0**	**41.0**	**48.0**	**37.0**
9	**35.0**	**21.0**	**24.0**	**35.0**	**17.0**
10	**27.0**	**42.0**	**35.0**	**34.0**	
Mean	**27.3**	**34.1**	**28.8**	**36.0**	**26.8**
SD	**9.4**	**14.5**	**7.2**	**7.1**	**8.2**

*difference from 50LIQ ($P < 0.05$)

Table 5.4 Individual time to reach T_{re} of 38.5ºC

	NF	100ICE	50ICE	100LIQ	50LIQ
Subject					
1	**39.0**	**59.0**	**42.0**	**103.0**	**-**
2	**50.0**	**119.0**	**107.0**	**88.0**	**55.0**
3	**-**	**-**	**-**	**-**	**-**
4	**23.0**	**32.0**	**-**	**-**	**27.0**
5	**30.0**	**63.0**	**39.0**	**70.0**	**40.0**
6	**32.0**	**46.0**	**40.0**	**62.0**	**46.0**
7	**48.0**	**69.0**	**73.0**	**64.0**	**50.0**
8	**-**	**-**	**66.0**	**83.0**	**-**
9	**-**	**40.0**	**-**	**-**	**34.0**
10	**-**	**-**	**54.0**	**-**	**-**
Mean	**37.0**	**61.1**	**60.1**	**78.3**	**42.0**
SD	**10.6**	**28.7**	**24.5**	**15.9**	**10.4**

No significant differences

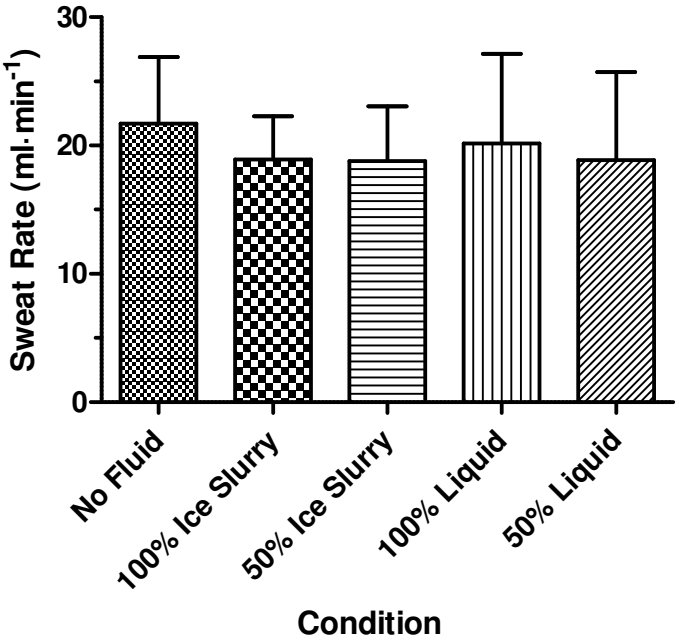

Figure 5.2 Estimated sweat rates for the five drink conditions.

5.5 DISCUSSION

It was hypothesised that 100ICE would have the most cooling capacity during exercise between conditions because of the large cooling capacity associated with the larger enthalpy of fusion. However, contrary to our hypothesis, both 100ICE and 100LIQ provided similar physiological responses in participants. Complete replacement of sweat loss increased T_{lim}, reduced the rate of ΔT_{re} and reduced the rate of heat stored when comparing to replacement of half sweat loss during simulated mining conditions.

Although there was an increase in T_{lim} and an attenuated rise in T_{re} during exercise for both 100% sweat replacement conditions, this is in disagreement with the theoretical cooling capacities of the solutions. The theoretical cooling capacity was calculated from sweat rates of each participant during NF. For each condition, the order of greatest cooling capacity was as follows: 100ICE (594.2 ± 104.7 kJ), 50ICE (320 ± 76.2 kJ), 100LIQ (179.8 ± 42.8 kJ), 50LIQ (89.9 ± 21.4 kJ) and NF (0 kJ). Therefore, it is hypothesized that T_{lim} and the attenuated rise in T_{re} would follow the same order as the drink's cooling capacities. This was contrary to what was observed. Possible explanations could be due to the thermal inertia within the body. As 50ICE has half the volume as 100LIQ, the inertial heat energy contained in the body was enough such that the additive effect of the enthalpy of heat did not reduce the rate of heat production. If a large enough heat sink was ingested (i.e., 100ICE), then this energy could affect the heat stored within the body. Webb, (1985) observed a similar thermal inertial phenomenon while measuring in several locations the cooling and warming gradient in a leg of beef submerged in a cold (16°C) and warm water (42°C) bath. He observed quicker temperature changes from the outside of the leg and slower changes within. Upon rewarming, an after-drop was noticed from the inner layers until a point where the deeper

thermometers began to warm. This would suggest that a specific quantity of heat must be removed before a temperature change is observed. As the participants in the present study were not static, such as the leg of beef, the total quantity of solution provided (100% versus 50%) may not have been sufficient to overcome the gradient.

Our findings extend upon the work of Lee et al. (2008), who demonstrated that cold (4°C) drinks administered prior to and during cycling exercise lowered mean T_{re} during exercise (37.3 ± 0.4°C versus 38.0 ± 0.4°C) and extended time to exhaustion (63.8 ± 4.3 versus 52.0 ± 4.1 min; cold versus warm drink, respectively) compared to warm drinks (37°C). The most likely explanation for the slower rate of rise in T_{re} seen in our participants during the 100 percent fluid replacement conditions is the greater heat sink associated with the larger volumes of fluid ingested. The rate of rise in T_{re} was lowest and T_{lim} was longest for 100ICE and 100LIQ conditions. It could be assumed that hydration status of the participants could account for our results however, upon closer examination of hydration status post exercise; differences were only observed in the 50 percent fluid replacement conditions. Both NF and 100 percent fluid replacement conditions identified participants as not differing in hydration status; rather, they differ only in heat sink quantity administered. This would then suggest that the results observed are due solely to the heat sink ingested. This heat sink increased the total capacity of heat to be stored, hence the observable slower rise in T_{re} and greater T_{lim} in 100ICE and 100LIQ compared to 50ICE and 50LIQ. A reduction in work rate is often observed with an elevated body temperature (Caputa, Feistkorn et al. 1986; Thomas, Cheung et al. 2006; Tucker, Marle et al. 2006) and could possibly explain the differences observed in T_{lim} between 100 and 50 percent fluid replacement conditions. Therefore, the reduced rate of rise in T_{re} can be attributed to the cooling capacity of the larger fluid volumes. This does not however explain the similarities observed between 100ICE and 100LIQ. The

approximate cooling capacities were 639.4 ± 147.5 kJ for 100ICE and 180.6 ± 41.7 kJ for 100LIQ. This equates to an approximate 3.5 fold increase in cooling capacity for 100ICE. This provides evidence that the additional cooling provided by the 100 % fluid replacement was delivered to other regions of the body compared to 50 percent fluid replacement.

Siegel et al. (2010) showed that consuming 7.5 $ml \cdot kg^{-1}$ ice slurry resulted in a lower pre-exercise T_c, which remained lower for the first 30 min of exercise compared with ingesting cool liquid (4ºC) of the same composition. Although their study had participants ingest the solutions before exercise in a thermoneutral environment, the study confirms that drinking ice slurry has a greater cooling capacity then cool liquids of equal volumes. Additionally, time to exhaustion was significantly ($P = 0.001$) increased during ice slurry (50.2 ± 8.5 min) versus cold liquid (40.7 ± 7.2 min) condition. The findings from Seigel et al. (2010) are not congruent withour observations possibly due to the fact that our participants ingested the ice slurry while exercising and their participants ingested the ice slurry pre-exercise. Mundel and colleagues (2006) administered two drink temperatures (19°C and 4°C) *ad libitum* to subjects cycling at 65% of their peak maximal aerobic power until exhaustion. They observed an increase in performance from 55 ± 4 min to 62 ± 4 min, a reduction in heart rate of approximately 5 bpm and a reduction in T_{re} of approximately 0.25°C during the second half of exercise when consuming the colder drink. Furthermore, there was a greater volume of fluid consumed during the cold drink condition (1.3 ± 0.3 $L \cdot h^{-1}$ vs. 1.0 ± 0.2 $L \cdot h^{-1}$; $P < 0.05$). Consuming a cooler beverage resulted in an increased time to exhaustion and lowered cardiovascular strain; a finding, although not statistically significant, mirrors that of the present study.

The deleterious effects of dehydration can potentially be offset by increasing evaporative heat loss (Saunders, Dugas et al. 2005). However, due to low air flow

conditions in an underground mine (Donoghue, Sinclair et al. 2000), this thermolytic avenue can become limited. While comparing 100% and 50% fluid replacement on performance and hydration status in the current study, 100% sweat loss replacement resulted in increased performance. Both 100% fluid replacement conditions resulted in a slower rate of rise in T_{re}, heat storage, increased T_{lim}, and produced higher sweating rates, compared to 50% and NF. As the fluid replacement volumes were equivalent, the thermolytic and performance based responses could be attributed to the greater availability of fluids, for increased rates of sweating between 100% and 50% conditions, while the slight increase in performance could be attributed to the ice slurry.

Heart rate increases under increasing thermal stress (Gonzalez-Alonso, Teller et al. 1999). In the present study, although not significant, 100ICE had the smallest increase in heart rate during exercise. A smaller increase in heart rate could be attributed to the larger heat sink provided by the ingestion of the cooler ice slurry (Mundel, King et al. 2006). Reducing thermal strain could decrease sweat rates and in turn preserve blood volume. As seen in Table 5.2, 100ICE produced the smallest change in blood volume. Further support to blood volume sparing is given by similar before and after U_{sg} and U_{osm} values seen in Table 5.2. As blood volume remained close to pre-exercise values (Table 5.2), cardiac output may therefore have been preserved. This conclusion is indirectly supported with similar heart rate data values recorded between all conditions. .

Industrial best practices are focused on maintaining a core temperature below that of approximately 38.0°C; however there are circumstances where T_c can be 38.5°C (ISO 2004). Should T_c rise above set upper limits, production is halted and the worker must rest until T_c returns to a safer temperature. As we have shown, replacing 100% sweat loss can prolong time to achieve both 38.0°C and 38.5°C better than replacing 50% sweat loss while working in the heat. Although greater thermal relief can be observed by drinking

100ICE than 50ICE, participants complained of bloating while consuming the larger bolus drinks. Such stomach discomfort may hinder production. Additionally, 100% fluid replacement is not usually practiced in industry. Therefore future investigations should examine the effect of a more practical *ad libitum* drinking protocol on exercise time and T_{re}.

In summary, this investigation has demonstrated that the ingestion of 100ICE or 100LIQ during exercise at rates equivalent to sweat rate can increase the time to exhaustion, reduce the rate of heat stored, and in turn attenuate the rate of rise in rectal temperature in hot and humid conditions when compared to ingesting 50ICE and 50LIQ. Therefore, replacing 100% of lost fluids will provide greater thermal relief during work in hot and humid conditions, which may be a practical and effective cooling strategy which Occupational Hygienists may wish to consider.

CHAPTER SIX

COMPARISON OF *AD LIBITUM* DRINKING OF LIQUID VERSUS ICE SLURRY SOLUTIONS ON CORE TEMPERATURE DURING SIMULATED MINING CONDITIONS

6.1 ABSTRACT

Purpose: To quantify and compare the effects of *ad libitum* consumption of ice slurry and liquid on core temperature (T_{re}) and time to exhaustion (T_{lim}) during exercise in the heat. **Methodology:** Eight males consumed either no fluid (NF), *ad libitum* ice slurry (ICE) or *ad libitum* liquid (LIQ) on three different occasions while walking on a treadmill at approximately 50% of $\dot{V}O_{2max}$ until exhaustion. Volume of fluid ingested, time for $T_{re,}$ to reach 38°C and T_{lim} were measured for each condition. **Results:** More LIQ was ingested than ICE (1.088 ± 0.674 L vs. 0.721 ± 0.431 L; P<0.01). No differences (P > 0.05) in exercise time to 38.0°C were seen between ICE (61.6 ± 27.6 min) LIQ (55.9 ± 26.3 min) and NF (28.9 ± 15.6 min). T_{lim} was ICE; 108 ± 20.9 min, LIQ; 104.4 ± 24.4 min and NF; 87.6 ± 25.8 min (P > 0.05). **Conclusion:** *Ad libitum* consumption of ICE elicited similar changes in T_{re} and T_{lim} per unit volume compared to LIQ despite ingesting 33% less volume of ICE compared to LIQ. Occupational hygienists should encourage personnel to add ICE to their current drink practices to help cool while working in order to help manage heat loads in hot environments.

6.2 INTRODUCTION

Industrial personnel can experience high thermal heat loads, particularly in the summer months (Donoghue and Bates 2000). Heat loads can be further exacerbated by wearing personal protective equipment such as nuclear, biological and chemical protective clothing or by being in a hypohydrated state. By removing the ability to dissipate heat, there will be a tendency for it to be stored in the body. Several interventions have been developed (i.e. heat stress indices, personal and environmental cooling devices, education) to reduce heat loads experienced by industrial personnel however, many of these cooling interventions are complex, expensive to implement or require continual monitoring.

Maintaining euhydrated during hot conditions and heavy metabolic workloads will enable efficient thermolytic responses during strenuous conditions. This was demonstrated by Greenleaf and Castle (1971) when they compared hypohyrated, *ad libitum* and hyperhydrated subjects during a 1 hr cycling session. They observed a significant elevation in T_{re} and mean body temperature between the hypohydrated and hyperhydrated conditions. Despite the lack of significance, T_{re} and mean body temperature were higher in the hypohydrated trial than in the *ad libitum* condition.

Typically, drinking to achieve hyperhydration is not practiced (Brake and Bates 2007); rather, *ad libitum* is representative of drink practices. Although individuals tend to drink fluids, typically not all lost fluid is replaced. This is termed 'voluntary dehydration' (Morimoto and Itoh 1998). Therefore, the benefits of ingesting will vary according to the volume consumed by individuals.

Research into the thermoregulatory benefits of using fluids as a method of cooling during exercise is increasing. Mundel and colleagues (2006) administered two drink

temperatures (19°C and 4°C) to subjects while cycling at 65% of peak power until exhaustion. They observed an increase in performance, a reduced heart rate and T_{re} and a greater volume of fluid being ingested for the colder drink condition. Gisolfi and Coping (1974) investigated serial ingestion of fluids (10°C versus body temperature) during exercise in the heat (34°C). They found that the cold fluid elicited a lower T_{re} and a smaller percentage of weight loss. In a more recent study, Lee et al. (2008) investigated serial drinking of fluids at different temperature (10°C, 37°C and 50°C) on thermoregulatory responses during cycling at 50% $\dot{V}O_{2max}$. Although the results were not significant, T_{re} tended to be lowest during 10°C (38.11ºC) followed by 37ºC (38.10ºC) and 50 ºC (38.21ºC) fluid ingestion while heart rate was significantly higher ($P < 0.05$) in the 50°C fluid condition.

When ingesting a cold fluid compared to a very cold fluid, a larger heat sink is created. A phase changing drink could therefore provide a greater cooling capacity over non-phase changing therapies. Using a phase changing cryotherapy has been demonstrated by several authors to provide greater cooling capacity over non-phase changing therapies. Kennet et al. (2007) compared four different therapies, gel pack (-14.5ºC), frozen peas (-10ºC), crushed ice (0ºC) and water immersion of the ankle (10ºC) directly on skin temperature of the right ankle. They observed the greatest reduction in skin temperatures with the phase changing therapy. More recently, Siegel et al. (2010) observed an increased time to exhaustion when drinking ice slurry (-1ºC) versus a cold liquid (4ºC) before exercising in the heat. Exercise times increased from 40.7 ± 7.2 min to 50.2 ± 8.5 min when drinking 7.5 $g \cdot kg^{-1}$ of ice slurry versus cold water. These observations were attributed to the phase changing ability of the ice slurry to lower T_{re} more than cold water. Therefore, using a phase changing drink during exercise could provide a greater cooling capacity than traditional liquid drink replacement practices.

Extending from the previous study in this thesis, and in light of the fact that workers would typically not follow a prescribed fluid ingestion, the aim of this study was two-fold. Firstly, to measure the volume of *ad libitum* fluid ingested and secondly, to compare *ad libitum* ingestion of liquid versus ice slurry solutions on core temperature during simulated mining tasks in a hot environment.

6.3 METHODOLOGY

Participants

Eight healthy, non-acclimated males (age 26 ± 1 y; height 176 ± 5 cm, body mass 70.0 ± 10.9 kg, body fat 17.5 ± 2.1%) gave written consent and completed a pre-screening questionnaire, *PAR-Q and You,* prior to participating in this study. The study was approved by the Edith Cowan University Human Research Ethics Committee.

Preliminary measurements

On their first visit to the laboratory, the participant's body mass and height were measured using a floor scale (Model ID1; Mettler Toledo, Columbus OH, USA) and stadiometer (Seca, Brooklyn N.Y, USA), respectively. Adiposity was determined through Dual Energy X-ray Absorptiometry (Hologic, Hong Kong). Under ambient room conditions (23.8 ± 1.3°C and 40.4 ± 8.0 %RH) (Microtherm; Casella Measurement Ltd., Bedford, UK), a modified Bruce treadmill protocol was used to determine participants $\dot{V}O_{2max}$. Participants began running at 0° incline at 8 $km \cdot h^{-1}$ with increases of 2 $km \cdot h^{-1}$ every two minutes until 16 $km \cdot h^{-1}$, after which the incline was increased 2° every two minutes until volitional fatigue occurred. The participants expired gasses were continuously analysed (ParvoMedics TrueOne 2400 diagnostic system, Sandy, UT) throughout the test with calibration of the metabolic cart occurring approximately one hour before each testing session.

Experimental design and protocol

Participants visited the laboratory on three separate occasions at approximately the same time of the day with four or five days separating each visit. All participants completed three sessions in random order. These sessions included: no drink which

served as a control (NF), *ad libitum* ice slurry ingestion (ICE) and *ad libitum* liquid ingestion (LIQ).

On arrival at the laboratory, the participant's urine and blood samples were collected and after instruction, a rectal thermistor (Monatherm Thermistor, 400 Series; Mallinckrodt Medical, St. Louis, MO, USA) was self inserted approximately 10 cm past the external anal sphincter. Nude mass was then recorded before participants were instrumented with skin thermistors and a heart rate monitor (Model S610i; Polar Electro Oy, Kempele, Finland). The participants donned running shoes, cotton pants, t-shirt and a helmet. Skin temperature was determined by skin thermistors fixed to the mid belly of the participant's left gastrocnemius, quadriceps, biceps, and chest and the Ramanathan's equation was applied to calculate mean skin temperature ($\bar{T}_{sk}$) (Ramanathan 1964). Heat storage was estimated by using the participants body mass, specific heat capacity of the body (3.47 $kJ \cdot kg^{-1} \cdot °K^{-1}$) and the equation presented by Colin et al. (1971).

Upon entering the climatic chamber, participants were seated upright in a chair for 15 min prior to exercise. Exercise consisted of walking on a treadmill at approximately 50% of $\dot{V}O_{2max}$. Ambient conditions were 28.6 ± 0.5°C and 74.2 ± 4.8 %RH (26.2 ± 0.5°C WBGT).

During exercise, drinks were administered in approximately 125 ml aliquots. Participants were encouraged to drink as much of the aliquot and as frequently as they wanted. Participants continued walking until either voluntary exhaustion, achieving a T_{re} of 39.0°C, or after 120 min of exercise. Participants were allowed to wipe sweat from their face only. Once the participants stopped walking, they towel dried themselves and nude body mass was measured; urine and blood measurements were then reassessed.

Urine analysis

Confirmation of euhydration was determined by one or all criteria: urine osmolarity through freeze point depression (Advanced Instruments Inc, Massachusetts, USA) $U_{osm} < 286$ mOsm·kgH_2O^{-1} (Latzka, Sawka et al. 1998) and urine specific gravity (U_{sg}) (Refractometer, Nippon Optical Works, Tokyo, Japan) between 1.006 and 1.020 (Popowski, Oppliger et al. 2001). All urine analysis was performed in duplicate before and after exercise.

Blood analysis

Before and after exercise, blood was drawn from an antecubital vein after the participants had sat upright in a chair for approximately 3 min. 8.5 ml of blood was collected in an SST heparinised tube, immediately centrifuged (Heraeus Multifuge 3 S-R, Australia) after collection for 15 min at 3,000 rev·min^{-1} at 4°C. serum osmolality (S_{osm}) was determined through freezing point depression (Advanced Instruments Inc, Massachusetts, USA). 8.5 ml of blood was also collected into a plain clot tube where 2 aliquots (30 µL each) were extracted into non-heparinized capillary tubes and an additional 2 aliquots (10 µL each) were collected into microcruvettes. The capillary tubes were spun (MED Instruments, MPW-212, Poland) at 12000 rev·min^{-1} for 5 min at ambient room temperature to measure changes in plasma volume (ΔPV) while the microcruvette samples were analysed immediately (Hemocue, Hb 201, Sweden) for haemoglobin concentration. ΔPV, changes in blood volume (ΔBV) and changes in cell volume (ΔCV) were calculated based on the methods of Dill and Costil (Dill and Costill 1974). All blood analyses were preformed in duplicate.

Core Temperature, Skin Temperature and Heart rate

T_{re} and $\bar{T}_{sk}$ were recorded at 1 Hz via a data-logger (Grant Instruments, Shepreth Cambridgshire UK); from which 5 min averages were calculated. Heart rate was measured via telemetry (RS800 Polar Heart Rate Monitor, Finland) and was sampled every 5 s from which 5 min average values were calculated.

Ice slurry and liquid temperature and composition

The temperature of the ice slurry was ~ -1°C and the liquid was ~ +4°C; both ice slurry and liquid drinks were composed of a commercially available orange flavoured cordial (Cottee's Foods, NSW, Australia) with a 5% carbohydrate concentration. Ice slurries were made using a commercial slushy machine (Essential Slush Co., QLD, Australia). The temperature selected for the liquid solution was based on typical household refrigeration temperature while the warmest temperature possible was used for the ice slurry in an attempt to reduce temperature discrepancies between both drinks.

Data analysis

A condition (NF, ICE and LIQ) x time repeated measures analysis of variance (ANOVA) was performed to identify differences in the change of T_{re}, T_{sk} and HR to LIQ or ICE. A 1-way ANOVA was performed to assess differences in T_{lim} over the different conditions. A Students t-test was used to determine any differences between pre and post exercise measurements in U_{osm}, U_{sg}, body mass, sweat rate, and PV. Significance was set at $P < 0.05$ for all comparisons. All analyses were performed using a statistical software program (SPSS 15.0 for windows, SPSS, Inc., Chicago, IL, USA), with values presented as means ± SD.

6.4 RESULTS

Rate of Change in T_{re} during Exercise

As shown in Figure 6.1, the rate of ΔT_{re} between conditions was not different ($P > 0.05$) despite observing a rate of $0.018 \pm 0.007°C \cdot min^{-1}$ in NF compared to ICE ($0.012 \pm 0.004°C \cdot min^{-1}$) and LIQ ($0.012 \pm 0.004°C \cdot min^{-1}$).

Hydration Status and Blood Analysis

Results for U_{osm}, U_{sg}, and S_{osm} are shown in Table 6.1. Several differences were measured in pre/post U_{osm} U_{sg} , and S_{osm}, however no differences were measured between conditions. All participants were hydrated upon presentation to the laboratory as illustrated in table 6.1.

Sweat rates and fluid consumed

As shown in Table 6.2, no differences in sweat rates were shown between conditions. However, significantly less fluid consumed during ICE compared with LIQ ($P < 0.05$). Consequently, subjects lost more mass in NF than both ICE and LIQ, and lost more mass in ICE than LIQ ($P < 0.01$). Participants replaced 75.1 ± 36.3 % of fluid lost in LIQ, and 48.4 ± 25.1 % in ICE; $P < 0.01$.

Exercise duration and heart rate at T_{re} of 38.0°C and at exhaustion

Exercise duration and heart rate at a T_{re} of 38.0°C were not different between conditions ($P > 0.05$). Likewise, time to exhaustion and T_{re} were not different between conditions ($P > 0.05$). T_{re} at exhaustion was 38.4 ± 0.4°C in NF, 38.3 ± 0.3°C in ICE, and 38.3 ± 0.4°C in LIQ. Exercise duration and heart rate at T_{re} of 38.0°C and at exhaustion are illustrated in Table 6.3.

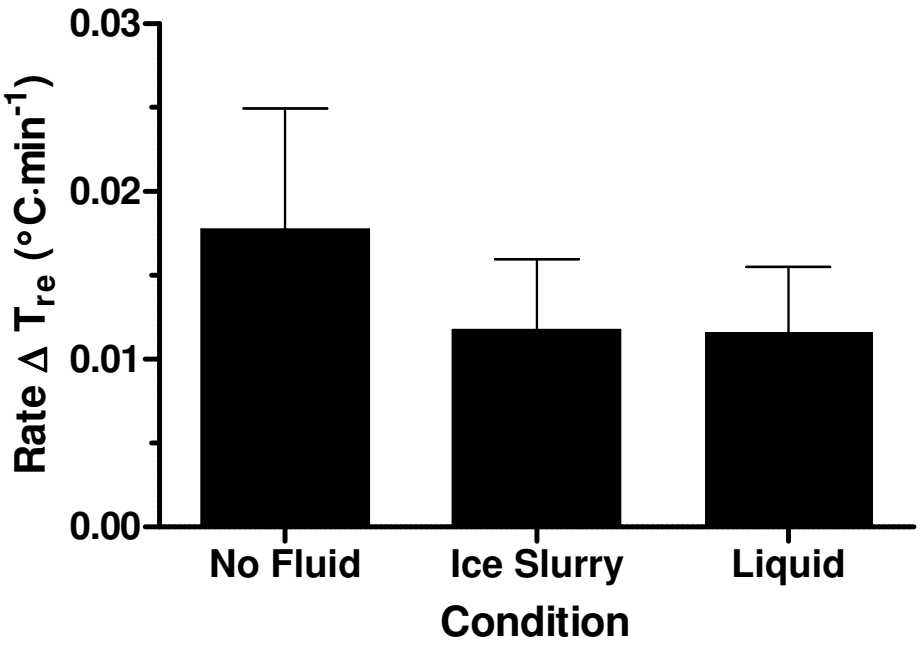

Figure 6.1 Rate of change in rectal temperature (ΔT_{re}°C·min^{-1}) no fluid, ice slurry and liquid interventions.

Table 6. 1 Pre and post exercise urine osmolarity (U_{osm}), specific gravity (U_{sg}) and plasma osmolality (S_{osm}) measurements.

		U_{osm} (mmol·kg^{-1})	U_{sg}	S_{osm} (mmol·kg^{-1})
Control	**pre**	188 ± 49	1.002 ± 0.002(a)	293 ± 4(a)
	post	434 ± 249	1.014 ± 0.007	296 ± 4
Ice Slurry	**pre**	131 ± 40(b)	1.004 ± 0.001(b)	295 ± 4
	post	384 ± 188	1.012 ± 0.006	293 ± 6
Liquid	**pre**	196 ± 64(a)	1.007 ± 0.004	292 ± 6
	post	384 ± 139	1.012 ± 0.004	290 ± 4

(a) difference between pre and post values ($p < 0.05$)

(b) difference between pre and post values ($p < 0.01$)

Table 6. 2 Sweat rates (SR), volume consumed, percent body mass lost (%BML) and percentage of fluid replaced (%FR).

	SR (L·h^{-1})	Volume Consumed (L)	%BML	%FR
No Fluid	0.731 ± 0.171	0.00 ± 0.00	1.4 ± 0.6	0.0 ± 0.0
Ice Slurry	0.681 ± 0.148	0.721 ± 0.431(a)	0.7 ± 0.6(a)	48.4 ± 25.1
Liquid	0.721 ± 0.136	1.088 ± 0.674(a,b)	0.2 ± 0.9(a,b)	75.1 ± 36.3(c)

(a) different from Control ($p < 0.01$)

(b) different from Ice Slurry ($p < 0.05$)

(c) different from Ice Slurry ($p < 0.01$)

Table 6.3 Exercise duration and heart rate at T_{re} of 38.0°C and at exhaustion and T_{re} at start and end of exercise.

	Exercise Time (min)		Heart Rate (bpm)		Rectal Temperature (°C)	
	38.0°C	Exhaustion	38.0°C	Exhaustion	Start	End
Control	48.9 ± 15.6	87.6 ± 25.8	147 ± 17	155 ± 24	37.0 ± 0.2	38.4 ± 0.4
Ice Slurry	61.6 ± 27.6	108.0 ± 20.9	145 ± 15	152 ± 22	37.0 ± 0.4	38.3 ± 0.3
Liquid	55.9 ± 26.3	104.4 ± 24.4	142 ± 20	146 ± 23	37.1 ± 0.2	38.3 ± 0.4

Note: no differences were observed between conditions

6.5 DISCUSSION

The purpose of the study was to compare the effects of *ad libitum* drinking of ice slurry and liquid solutions on T_c during exercise. There were three main findings in this study: (1) the ingestion of ice slurry during exercise to achieve a T_{re} of 38.0°C was ICE (61.6 ± 27.6 min), LIQ (55.9 ± 26.3 min) and NF (48.9 ± 15.6 min) and time to exhaustion was ICE (108 ± 20.9 min), LIQ (104.4 ± 24.4 min) and NF (87.6 ± 25.8 min); (2) percent of fluid replaced between conditions was greatest for LIQ compared to ICE (75.1 ± 36.3% versus 48.4 ± 25.1%, respectively); (3) sweat rates were statistically significantly not lower while consuming ICE (0.681 ± 0.148 $L \cdot hr^{-1}$) followed by LIQ (0.721 ± 0.136 $L \cdot hr^{-1}$) and NF (0.731 ± 0.171 $L \cdot hr^{-1}$).

In our previous study, completely replacing fluid losses with ICE caused gastric distress in some of our participants. During this investigation, no gastric distress was reported from any of the volunteers. Despite a greater cooling capacity with ICE compared to LIQ, similar end physiological responses were observed. Conversely, in this study, less ICE was consumed and similar physiological responses were measured with no distress being reported. Based on the results from the previous study, theoretically, ICE per unit volume cools more efficiently than LIQ. Consequently if personnel can be trained to drink more ICE to offset sweat loss, they would then experience less thermal and cardiovascular strain and which in turn would delay the onset of fatigue.

Complete fluid replacement was not observed in any of the trials of this investigation. There are a number of possible explanations for this. Firstly, participants were ingesting fluids *ad libitum* and the ice slurry contains a larger volume per unit of drink. It is assumed that for 1 ml of water, the equivalent volume is 1 mm^3. When 1.088 ± 0.674 L of liquid was consumed, the volume was 1.088 ± 0.674 dm^3, conversely when

0.721 ± 0.431 L of ice slurry was consumed, the volume was 0.813 ± 0.486 dm^3. This represents an approximate 12.8 % increase in volume. Therefore, stretch receptors in the participant's stomach may have partially signalled for fullness (Villanova, Azpiroz et al. 1997) and stopped participants from drinking more.

Secondly, thermal receptors located at the posterior aspect of the tongue could have possibly influenced the perception of body temperature as this region is innervated by the ninth cranial nerve. Cold efferent signals from this region, due to the ingestion of the ice slurry, may have altered the brain's perception of heat (Benzinger, 1964). The authors theorise that that it is this afferent signal could then alter the behavioural response to the rate of heat being stored.

Finally, so called 'voluntary dehydration' is a common occurrence (Morimoto and Itoh 1998). While plasma osmolality and total body water were not measured in this study, it is possible that these markers remained within a normal range throughout the exercise trials. Indeed, as heart rate and rate of change in rectal temperature were not different between either *ad libitum* trials, despite differences in fluid consumption, there is little evidence to suggest that hydration status had any major influence on fatigue in this study. Had hydration status played a more dominant role over body temperature (or brain temperature); a trend towards a longer time to exhaustion during the *ad libitum* fluid trial would have been expected.

Alterations in the central nervous system to drive working muscles (Martin, Marino et al. 2005; Saboisky, Marino et al. 2003; Thomas, Cheung et al. 2006) are associated with elevations in body temperature. Additionally, dehydration beyond 2% has been shown to affect running memory and perceptual motor coordination (Sharma, Sridharan et al. 1986). To combat the effects of dehydration and indirectly an elevated

body temperature, it has been suggested that workers should consume approximately 250 ml of fluids every 20 min during a work shift (Kenefick and Sawka 2007). As most industries have *ad libitum* practice which are insufficient to replace total fluid lost, workers should therefore drink prescribed volumes or monitor intake and increase intake accordingly to avoid dehydration. The *ad libitum* practices of mining personnel consuming ice slurry *in situ* is unknown and requires further investigation; however, current evidence suggests that *ad libitum* ICE ingestion may better attenuate heat strain associated with working in a hot and humid environment.

Attenuation of the increase in body temperatures in various industries is of particular importance for the maintenance of a worker's health. Several criteria have been developed by governing bodies which take into account 'safe upper limits' for core temperature (T_c). These limits are: (1) a 1°C increase above resting T_c values (ISO 2004); (2) a maximum T_c of 38.0°C; and (3) a T_c of 38.5°C if workers have been medically screened (ISO 2004). The results of this study show, although not statically significant, that the time to reach 38.0°C and 38.5°C (if participants could achieve that temperature) was greatest while consuming ICE followed by LIQ. This increased time can be attributed to the greater cooling capacity of ICE (361.6 ± 216.2 kJ) versus LIQ (154.9 ± 96.0 kJ) and a reduced rate of heat gained, despite less ice slurry being consumed. Blood perfusion to the stomach, small intestine and local regions may have been conductively cooled more by ICE than LIQ. It is thought that colder temperatures increase rates of gastric emptying, which could assist to cool the small intestines and other deep tissues. Ritschel and Erni (1977) investigated the effects of various drink temperatures (5°C, 20 - 25°C and 45°C) on stomach emptying of solid material. Of the three drink temperatures, it was observed that solid material was emptied into the duodenum significantly quicker at a drink temperature of 5°C (15.91 ± 10.04 min), followed by 20 - 25°C (48.18 ± 28.97

min) then 45°C (71.42 ± 37.08 min). As the temperature of the ice slurry was ~-1.0°C compared to liquid at ~4.0°C, the ice slurry may have entered the small intestine at a rate quicker than liquid. The implications of an increased time to achieve a safe upper core temperature include increased productivity and less down time.

In conclusion the present investigation has shown that consuming ice slurry is a more efficient method (per unit volume) to the gain the same physiological responses than a cool liquid during *ad libitum* drinking while exercising. Similar rates of rise in T_{re}, time to reach a T_{re} of 38.0°C and exhaustion while consuming 33% less ice slurry was recorded. As workers in industry often do not drink to levels that replace lost fluids, it is recommended that Occupational Hygienists substitute ice slurry for liquid in order to facilitate the thermolytic responses for personnel working during heat stressful conditions.

CHAPTER SEVEN

FIELD INVESTIGATION OF A LABORATORY TESTED HEAT STRESS INTERVENTION USING AN ICE SLURRY DRINK

7.1 ABSTRACT

Background: Australian offshore LNG workers in the North West Shelf are frequently exposed to heat stressful conditions. Consuming ice slurries during exercise has been shown to attenuate heat loads in laboratory trials, but field studies are currently lacking. **Purpose:** To validate a laboratory tested ice slurry intervention in the LNG industry *in vivo* as a practical cooing modality. **Methods:** Seven workers (age 40 ± 7 yrs; height 1.75 ± 0.03 m; body mass 96.0 ± 13 kg; body fat 29.0 ± 8.6%) performed *ad libitum* drinking practices on two separate days with either an ice slurry (ICE) or liquid (LIQ). Heart rate (HR), deep tissue temperature (T_{GI}) via an ingestible pill and skin temperature (T_{sk}) via dermal patch were all measured telemetrically throughout the work shift. **Results:** Mean T_{GI} were different between ICE and LIQ (37.2 ± 0.4°C versus 37.4 ± 0.3°C; $P < 0.001$). Mean HR was also different ($P < 0.001$) between ICE (91 ± 18 bpm) and LIQ (95 ± 15 bpm). **Conclusion:** ICE appears to lower T_{GI} and reduce HR compared to LIQ, therefore it is recommended that workers compliment current drink practices with ICE in order to reduce the chances of experiencing a heat-related injury.

7.2 INTRODUCTION

Australian offshore LNG workers in the North West Shelf are frequently exposed to high ambient temperatures, humidity and solar loads. With limited space on an oil platform, LNG personnel must also work in close proximity to heat generating machinery. In addition to these high thermal heat loads, personal PPE must be worn while working. The combination of both hot ambient conditions and PPE in conjunction with work activities facilitates a high endogenous heat load for personnel. To assist in reducing exposure to these conditions, heat stress indices are used on the oil platform. Typically, the WBGT is utilised. Although this heat stress index may provide adequate protection for personnel onshore, its appropriateness for offshore use is questionable. Due to the possible hydrocarbon environment on an oil platform, traditional onshore devices used to facilitate heat loss (fans or misters) may not be possible; therefore alternative methods to cool personnel should be considered.

Performance benefits associated with the consumption of cold compared to thermoneutral or warm beverages during exercise have been observed (Gisolfi and Copping 1974; Lee, Shirreffs et al. 2008; Mundel, King et al. 2006), and may be explained by the larger heat sink generated. In a recent laboratory study, Siegel et al. (2010) showed that time to exhaustion and the rate of rise in rectal temperature were attenuated when ice slurry compared to drinking cold fluids was ingested prior to exercise in the heat; however, this study provides evidence to indicate that ice slurries could be used as an alternative heat stress intervention, whether or not ice slurries would be of benefit in a field setting is unknown.

With fluids readily available for LNG workers and literature identifying the thermodynamic benefits of ice slurry consumption during work, ingesting ice slurries

could be an easily implementable heat stress intervention for workers. Therefore, the purpose of this investigation was to validate the effectiveness of ice slurry ingestion in the LNG industry *in vivo* as a practical cooing modality.

7.3 METHODOLOGY

Subjects

Seven subjects (age 40 ± 7 yrs; height 1.75 ± 0.03 m; body mass 96.0 ± 13 kg; body fat 29.0 ± 8.6%) gave their written informed consent prior to participating in the study. All workers were given an information session by the medical staff and an additional information session was delivered to the participants with any/all questions being answered by the investigator. Clearance from management, union representatives, supervisors and the human research ethics committee of Edith Cowan University was obtained prior to testing.

Experimental Procedure

Participants presented themselves to the medical suite on two consecutive days between 05h15 to 05h45 to ingest a telemetric pill before breakfast. Participants consumed a non-standardized breakfast then proceeded to their pre-shift meeting.

Between 06h00 and 07h00, participants were asked to provide a pre-shift urine sample. They were then weighed in their underwear and appropriately instrumented with dermal patches and data logger (n = 3), and a heart rate monitor (n = 7). At this point participants were randomised and instructed to drink either *ad libitum* ice slurry (ICE) or liquid (LIQ) drink throughout the work shift. During mandatory rest breaks (~09h00 to 09h930, and ~16h00 to 16h30) "smoke-o" and lunch periods (~12h00 to 12h30), participants were not required to drink the control or intervention drink. This was done to 'normalise' work conditions. Typical fluids consumed with meals were, water, carbonated drinks, coffee or cordial. Volumes of drink consumed by personnel throughout the work day were not measured, along with the time between ingestion of the telemetric pill and initial T_{GI} measurements; as such, these are potential sources of limitations to this investigation.

During each hour throughout the work shift, both thermal sensation (Young, Sawka et al. 1987) and T_{GI} values were measured.

Urine samples were collected again at lunch and at the end of the work shift. At the end of the work shift, participants were then de-instrumented and body mass was reassessed. A schematic timeline is presented in Figure 7.1.

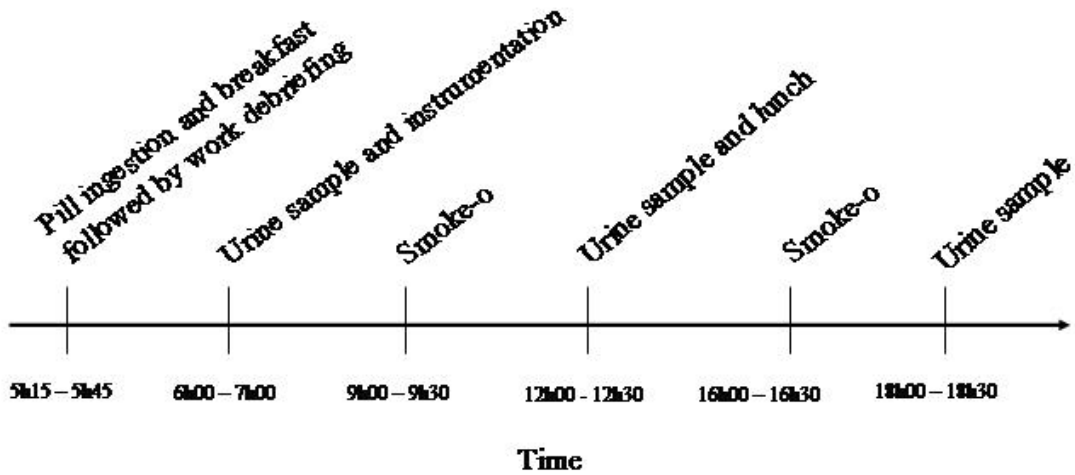

Figure 7. 1 Experimental timeline for offshore personnel

Anthropometric Measurements

Body composition was assessed from seven different locations using skinfold callipers (Model HSK-BI-3; Baty International, UK). These sites included: chest, tricep, axilla, subscapular, abdominal, suprailiac and mid thigh the day before testing commenced. Values were then entered into seven different equations (Sloan 1967; Wilmore JH 1969; Forsyth HL 1973; Katch 1973; Jackson 1976; Thorland WG 1984; Withers RT 1987a) to calculate mean body density which was used to estimate body fat percentage from the equations of Siri (1961) and Brozek (1963). Body Surface Area (A_D) was determined by the equation of DuBois and DuBois (1916) $A_D = 0.202m^{0.425} \times height^{0.725}$, expressed as m^2.

Urine Analysis

Start of shift, lunch break, and end of shift assessments of urine specific gravity were determined by using an electronic refractometer (Atago, UG-α, Japan).

Ratings of Thermal Sensation and Heart Rate

Participants were familiarised on how to use the thermal sensation scale before the start of the work shift. They were then presented at their work location with the scale and were asked to rate their thermal sensation for each working hour of their shift. Heart rate measurements via telemetry (RS800 Polar Heart Rate Monitor, Finland) were collected continuously throughout the work shift. Data was collected every 15 seconds and then averaged into 1 hour intervals.

Environmental Measurements

Ambient conditions were measured in the area where workers spent the majority of their shift using a portable WBGT thermometer (Quest temps 34, USA). Measurements were recorded every minute throughout the work shift.

Temperature Measurements

Gastrointestinal temperature (T_{GI}) was measured using a onetime use ingestible telemetric pill (Mini mitter, USA). The pill was ingested between 15 – 45 min before breakfast. $\bar{T}_{sk}$ was assessed by adhering skin thermistors to four different sites on the body, including chest, bicep, quadriceps and calf and was used to determine changes in the rate of heat stored. $\bar{T}_{sk}$ was calculated using a modified Ramanathan's (1964) equation. Both pill and patch transmissions were received by a data logger that was worn by three participants throughout the work shift. The signal was continually collected and then converted into 1 hour averages which included rest periods. The remaining four

participants had their T_{GI} measured by having the researcher measure them at their work location approximately every 30 min.

Heat storage was estimated only for three participants wearing skin thermistors. $\bar{T}_b$ was then calculated using the formula of Colin et al. (1971): $\bar{T}_b = 0.66\ (T_{re}) + 0.34\ (\bar{T}_{sk})$ for the initial 20 min of data collection, and $\bar{T}_b = 0.79\ (T_{re}) + 0.21\ (\bar{T}_{sk})$ for the remaining of the work shift, with the exception of mandatory rest breaks ("smoke-o") and lunch. Heat storage was calculated at 1 min increments using the formula of Adams et al. (1992): heat storage = $0.965 \times m \times \Delta\bar{T}_b/A_D$, where 0.965 is the specific heat storage capacity of the body ($W \cdot kg^{-1}{}^{\circ}C$), *m* the mean body mass (kg) over the duration of the trial, and A_D was determined by the equation of DuBois and DuBois (1916) $A_D = 0.202m^{0.425} \times height^{0.725}$, expressed as m^2. Heat storage was then averaged into 1 hour intervals which included rest periods.

Statistical Analysis

A Student's t-test was performed on mean environmental conditions, and hourly time points for HR, T_{GI}, and thermal sensation between ice slurry and liquid conditions. As the sample size was small for T_{sk}, all values are expressed as means and standard deviation. A one-wayway repeated measured ANOVA was used to determine differences between urine measures. If differences were found, a Tukey's post-hoc analysis was performed. Significance was set at $P < 0.05$ and all data are presented as means ± standard deviations. Data analyses were performed using a statistical software program (SPSS 17.0 for windows, SPSS, Inc., Chicago, IL, USA).

7.4 RESULTS

No differences ($P > 0.05$) were observed between mean dry bulb, relative humidity or WBGT between testing days. Mean values are presented in Table 7. 1.

$\bar{T}_{sk}$ (Figure 7.2A) at time points 10h00-11h00 and 14h00-15h00, both conditions showed decreases in temperature. Generally, the physiological responses appeared to be similar between both interventions. As expected, T_{GI} and HR were lowest at the beginning of the shift, and then progressively increased for both conditions.

Daily mean T_c was significantly lower during ice slurry ingestion compared to liquid (37.2 ± 0.4°C versus 37.4 ± 0.3°C; $P < 0.001$ respectively). A post-hoc testing revealed T_c was different between trials at 11h00 – 12h00 ($P = 0.01$) and 14h00 – 15h00 ($P = 0.021$; Figure 7.2B). Daily mean heart rate values were also significantly lower ($P < 0.001$) during the ICE trial. Mean heart rate for ICE was 91 ± 18 bpm while LIQ was 95 ± 15 bpm. Changes in HR did not appear to coincide with changes in T_{GI} or $\bar{T}_{sk}$. Rather, Figure 7.2C identifies differences near the beginning of the work shift (9h00 – 10h00; $P = 0.021$) and 15h00 – 16h00 ($P = 0.042$).

Table 7.1 Mean ± (SD) ambient environmental conditions in the area where workers spent most of their time during each trial.

Testing Day	Dry Bulb (°C)	Relative Humidity (%)	WBGT (°C)
1	28.0 ± 0.7	54 ± 11	30.7 ± 1.8
2	28.8 ± 1.2	50 ± 23	31.9 ± 3.2

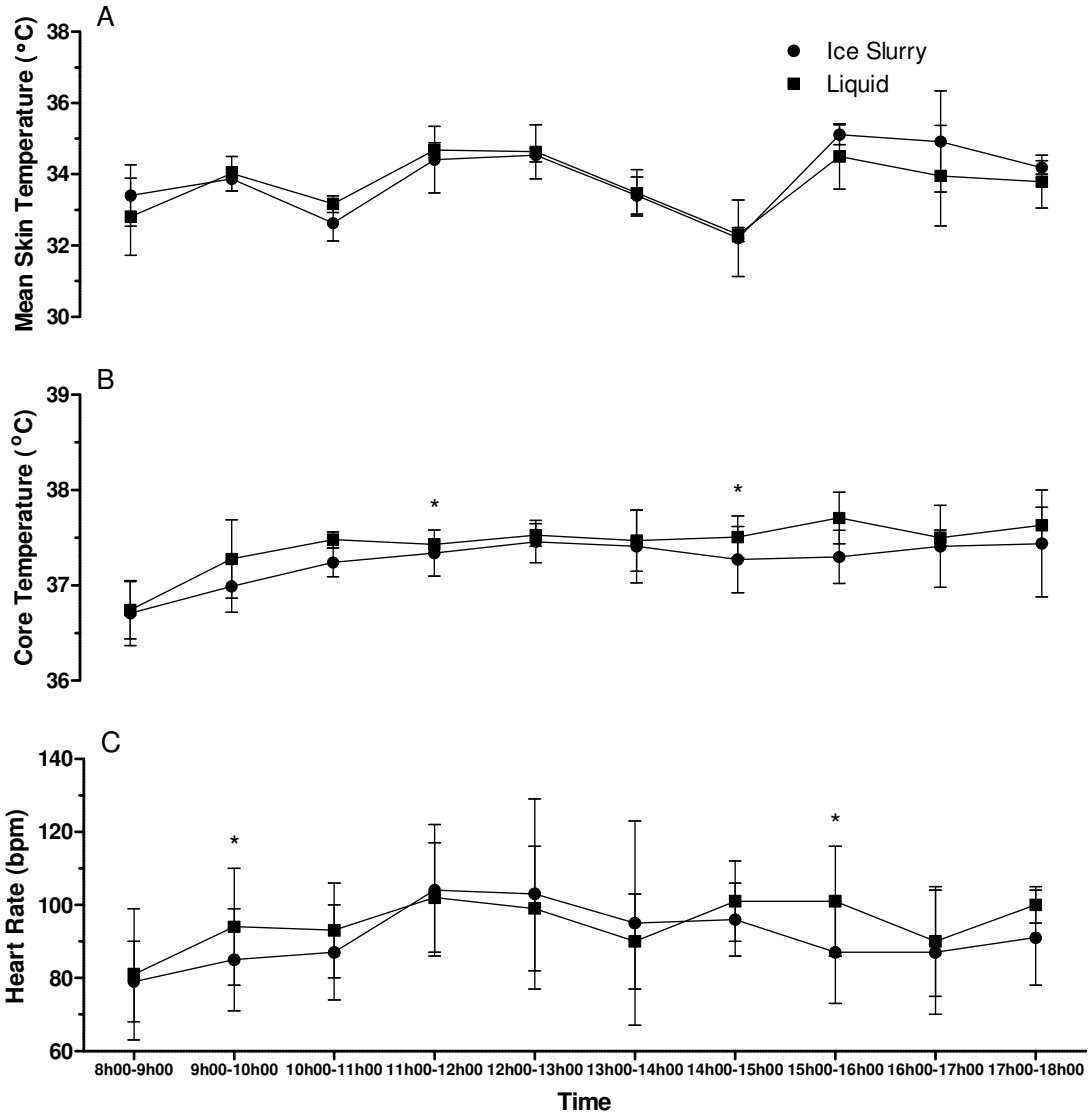

Figure 7. 2 Mean skin temperature (n=3) (A) core temperature (n=7) (B) and heart rate (n=7) (C) between Ice Slurry and Liquid conditions in one hour segments throughout the work shift.

*denotes a difference ($P < 0.05$)

No differences were measured in thermal sensation between conditions any time point. Values ranged from 4 ± 1 to 6 ± 0 in ICE 3 ±1 to 6 ± 1 in LIQ. Peak thermal sensation values were measured at 9h00 (4 ± 1) and 18h00 (6 ± 0) for ICE and 12h00 (3 ± 1) and at 14h00 (6 ± 1) and 18h00 (6 ± 0) for LIQ.

Figure 7.3 shows the U_{sg} for both cooling interventions. In both Figures, the mode of samples were found to be between 1.0251 – 1.0300 category. One participant presented himself to work (pre-shift urine sample) with a U_{sg} in the range of 1.0101 – 1.0150 for both interventions. Mean U_{sg} values for pre-shift, lunch and post-shift are presented in Table 7.2.

Table 7.2 Mean ± SD pre-shift, lunch and post shift measures of urine specific gravity (U_{sg}) between conditions (n=7).

	Preshift	Lunch	Postshift
Ice Slurry	1.0251 ± 0.008	1.0249 ± 0.0036	1.0278 ± 0.0036
Liquid	1.0244 ± 0.005	1.0263 ± 0.0037	1.0287 ± 0.0022

Note: no differences ($P > 0.05$) were observed in urine measures

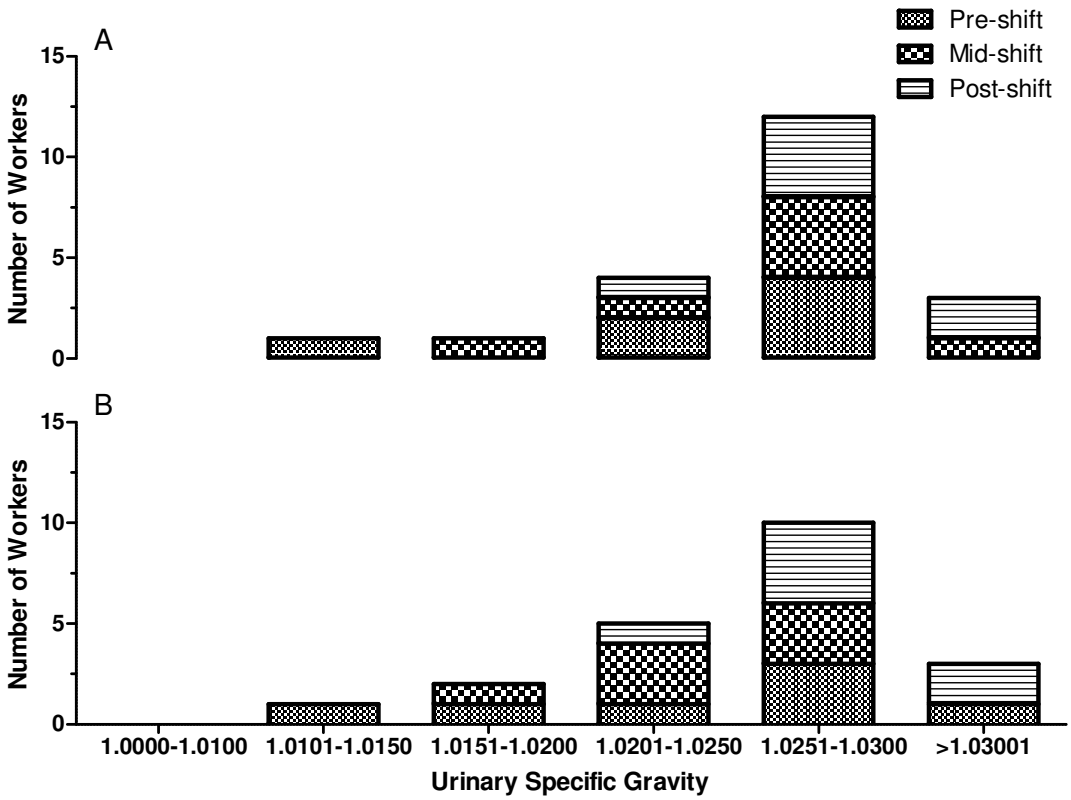

Figure 7. 3 Frequency distribution of urine specific gravity for offshore workers who consumed liquid (A) and ice slurry (B) during their shift. Samples were collected pre-shift, mid-shift and post-shift (n=7).

Note: The U_{sg} categories created are grouped in 0.005 unit increments with no bias towards classification or results

7.5 DISCUSSION

The overall purpose of this investigation was to test a laboratory validated heat stress intervention (an ice slurry beverage) in LNG workers working on an offshore oil platform. It was found, although not statistically significant, that *ad libitum* consumption of ICE resulted in a lower body temperature, heat storage and heart rate in those personnel during their work shift compared to when they consumed cold liquid (LIQ). Overall, workers were dehydrated from the beginning and throughout the work shift on each days tested.

The phase changing ability of ICE provided a greater thermal heat sink which was then reflected in differences in T_c. Although the total volume of fluid ingested by participants may have varied, it was shown previously in this thesis that a smaller volume of ingested ice slurry can provide similar thermolytic abilities. This could be explained by the phse changing ability of ICE compared to LIQ. When comparing 1 L of ICE (-1°C) to LIQ (4°C) and raising drink temperature to 37.0°C, ICE requires approximately 484 kJ whereas LIQ requires 138 kJ. This difference in cooling capacity is predominately due to the enthalpy of fusion which is the additional energy required to change physical states of solid to liquid. Assuming ICE has similar characteristics to water (2.108 $kJ \cdot kg \cdot K^{-1}$ for ice and 4.187 $kJ \cdot kg \cdot K^{-1}$ for liquid); an additional 334 kJ of energy is required to change the drink from solid to liquid. In a study by Lovell et al. (2004), no thermal benefits associated with the consumption of drinks at different temperatures (4°C and 50°C) during exercise at 60% VO_2 at 24°C and 37% relative humidity were observed. Even though there is a large thermal gradient between drinks, unlike in this study, no differences were seen.

Typically, increasing blood skin perfusion is associated with greater cardiac demand which could then be indirectly interpreted as an increased HR (Brengelmann, and

Johnson, et al. 1977; Roberts and Wenger, 1979). As the mean HR measurements were significantly lower while ingesting ice slurry during the investigation, this could suggest that the cooling capacity of ICE is better at decreasing cardiac strain than a cool liquid. With a small sample size used in this study, further investigations are warranted to confirm these findings.

A lower mean T_{GI} and HR could provide an explanation for the elevated $\bar{T}_{sk}$ observed in Figure 7.2A during the later portion of the work shift. With warmer blood being redirected to the periphery for heat loss, the concomitant result would be a reduced T_c. With metabolic tasks assumed to be similar during both conditions, an observed increased $\bar{T}_{sk}$ could be associated with the ice slurry providing greater internal cooling than liquid. This cooling capacity then redirects blood to the skin to facilitate thermolysis.

An interesting finding of the study was the dehydration level in workers. Two of the seven participants arrived to work euhydrated but three workers presented themselves in a hypohydrated with a U_{sg} of 1.0251 – 1.0300. The remaining two workers were slightly hypohydrated with a U_{sg} (1.0201 – 1.0250). During any point in the work day, only two workers were in a euhydrated state. It is important to note that the first urine samples were collected before work. This finding is concerning because hypohydration can impair performance (Sawka 1992) increase heart rate (Barr, Costill et al. 1991) and T_c during exercise. Thus, increasing the likelihood of reducing productivity and increasing the risk of a heat stress related illness. Even though these findings are concerning, they are comparable to observations made by Brake and Bates (2003) who identified that over half of the workers they studied, arrived to work hypohydrated. Additionally, we

observed that hypohydrated workers stayed hypohydrated throughout the shift with some incurring additional dehydration.

It is therefore important for workers to ingest adequate volumes of fluid throughout the work shift. Anecdotally, the workers enjoyed the ice slurry intervention; however, they were not supportive of having ice slurry completely substitute their normal fluid replacement practices. By having a palatable drink available, more fluids tend to be ingested. Bergeon et al. (2006) observed 1736.5 ± 543.3 ml and 1896.6 ± 644.8 ml of water versus carbohydrate drink, respectively, being consumed during a 120 min training session. This may be one approach occupational hygienists may take to encourage fluid replacement in workers.

This investigation has confirmed that a laboratory tested heat stress intervention of consuming ice slurry can provide similar *in situ* physiological responses among LNG workers. However, fully substituting an already implemented drink practice with ice slurries may not be palatable for all workers and is therefore not recommended. Alternatively, using ice slurry to compliment current cooling strategies is a heat stress intervention should be considered by occupational hygienists.

CHAPTER EIGHT

8.1 General Discussion

Working in extreme environments, in particular during uncompensable conditions, the body's ability to regulate its temperature becomes compromised. Fatigue and dehydration are some of the effects of a continuously elevated body temperature, which indirectly result in a heat stress illness. Industry has developed methods to help workers manage heat while working, however, these methods can sometimes be impractical or economically non-viable to implement. It is therefore necessary to develop an alternative method to help workers manage heat loads experienced during work in hot and humid environments. As drinking cool beverages during exercise has been observed to attenuate the rate of rise and absolute increase in T_{re} in individuals, it was hypothesized that drinking an even cooler beverage could further reduce heat loads experienced in persons exercising. Thus, the purpose of this thesis was to quantify the cooling capacity of an ice slurry post exercise and then to measure the cooling effects while working both *in vivo* and *in situ*. Through the *in vivo* and *in situ* quantification of the ice slurry, it was aimed to validate the ice slurry as a practical and economically viable alternative to cool personnel working in a hot and humid environment. The major findings from this thesis were: (1) current preventative methods, ie. heat stress indices, did not adequately predict thermal stress in workers; (2) personnel arrived to work hypohydrated and remained in that state throughout the work shift; (3) personnel were working at greater than acceptable ambient conditions as determined by currently implemented heat stress indices; (4) to administer the same cooling capacity between an ice slurry (-1°C) and liquid (4°C), the volume required is significantly less ($P < 0.001$) for an ice slurry; (5) replacing 100% fluid loss with either liquid or ice slurry will increase time to exhaustion when compared to replacing 50% or 0%; (6) during *ad libitum* consumption of liquid or ice slurry, more

liquid was consumed ($P < 0.01$) compared to ice slurry, however the rate of heat stored was similar; and (7) *in situ* comparison of liquid and ice slurry ingestion resulted significantly lower ($P < 0.05$) T_c and HR during the work shift when ice slurry was consumed compared to liquid with anecdotal evidence supporting greater perceptual relief of thermal strain while consuming ice slurry.

Working in hot and humid environments can challenge the body's thermolytic processes. Physiologically, the metabolic heat created by work and the ability to dissipate this generated heat is dependent on the thermal and partial pressure gradients between the body and the environment. In order to protect personnel working under such extreme conditions, heat stress indices have been developed. Invariably, some of these indices account for metabolic activity, ambient conditions, clothing, and/or the physiological responses associated with these changes (Brake and Bates 2002; ISO 2004; ISO 2004; ISO 1989; McArdle, Dunham et al. 1947; Moran, Shitzer et al. 1998). Despite the development of several heat stress indices, the WBGT has generally been accepted by industry and is widely used, even though the shortcomings of the index have been well documented (McNeill and Parsons 1999; Mutchler, Malzahn et al. 1976; Taylor 2006). Acknowledging these criticisms, Study 1 of this thesis aimed at identifying a single heat stress index which could best predict the heat load experienced by personnel working in the LNG industry both on-and offshore. The results from that study revealed that the WBGT was in fact not the best index to predict heat strain among LNG workers and that the P_4SR is the preferred index. A significant correlation between measured responses and the P_4SR for off and onshore was observed. Although this index provides recommended sweat rates during specific ambient conditions for both acclimated and non-acclimated individuals, this index has also received criticism (Wyndham, Strydom et al. 1973). The LNG personnel investigated in this thesis were acclimated and wore lose

fitting clothing; both aspects of which aided in evaporative heat loss. Additionally, work was self-paced which allowed personnel to self-manage heat loads. These aspects of the working environment should be incorporated when considering a heat stress index to be implemented. Attention should be directed towards the hydration status of personnel as water loss has been known to influence performance (Sawka 1992). This study reaffirms the predictive inaccuracies and the variability of using a single heat stress index or index that isn't site specific for all types of industry. Therefore, it is recommended that each industry or occupational group should be evaluated in order to ensure that the most appropriate index for that population is being applied. It is acknowledged that this recommendation is resource intensive; hence alternative methods to manage heat stress have been developed and have been evaluated and are presented in this thesis.

Understanding the various shortcomings of heat stress indices along with alternative methods to reduce heat strain in personnel that are both economically viable and easily implementable were developed and investigated. It has been shown that the ingestion of a cool liquid can attenuate the rate of rise of body temperature (Gisolfi and Copping 1974; Lee, Shirreffs et al. 2008; Mundel, King et al. 2006). During cryotherapy, the greatest reduction in skin temperature was achieved by using a phase changing material (Kennet, Hardaker et al. 2007; Merrick, Jutte et al. 2003). When a phase changing material (ice slurry) was infused into swine, the results indicated that the ice slurry cooled the brain more effectively than liquid of equal temperature (Vanden Hoek, Kasza et al. 2004). More recently, when an ice slurry was ingested by humans as a pre-cooling method at ambient room temperature, the ice slurry reduced body temperature by 0.66°C ± 0.14°C as compared with cold liquid 0.25°C ± 0.09°C ($P = 0.001$) (Siegel, Mate et al. 2010). These findings suggest that drinking an ice slurry to reduce rectal temperature (T_{re}) would be greater than ingestion of a cold liquid. Therefore, the purpose

of Study 2 was to quantify the cooling capacity of ice slurry as a post exercise cooling intervention. Using the ingestion of an ice slurry and cold liquid as a heat sink, a specific quantity of heat to be removed was predetermined for each participant, thus accounting for the different cooling capacities of ice slurry and the cold liquid lead to different volumes of drink being consumed. As expected, the physiological responses to the rate of change in T_{re}, heart rate and thermal sensation were not different ($P > 0.05$) between conditions, however, the volumes administered were (ice slurry 0.536 ± 0.056 L and liquid 1.802 ± 0.205 L; $P < 0.001$). The ice slurry is composed of both liquid ($H_2O_{(aq)}$) and solid ($H_2O_{(s)}$) phases. To increase the temperature of 1 g of $H_2O_{(s)}$ requires approximately 2108 $J \cdot g^{-1} \cdot K^{-1}$, while to increase 1 g of $H_2O_{(aq)}$ requires approximately 4210 $J \cdot g^{-1} \cdot K^{-1}$. The greater heat sink capacity of the ice slurry is attributed to the energy required to change physical states from $H_2O_{(s)}$ to $H_2O_{(aq)}$. This is termed enthalpy of fusion. The energy required to melt $H_2O_{(s)}$ into $H_2O_{(aq)}$ is approximately 334000 $J \cdot g^{-1}$. It then becomes evident that the volume required to remove heat is significantly less for the ingestion of ice slurry compared to a cold liquid. From this study, it is now understood that ingesting ice slurry is useful as a post-exercise cooling modality compared to other cooling methods.

All work sites provide drinking water *ad libitum* for personnel; therefore using an ice slurry to assist in the cooling of workers seems warranted. Study 2 investigated the cooling capacity of the ice slurry as a post exercise cooling intervention and identified that consuming a significantly smaller volume of ice slurry will result in similar physiological responses as drinking a cool liquid; however, these same physiological responses to ice slurry compared to cold liquid occur during simulated mining conditions are unknown.

Maintaining body water levels has been shown to delay decrements in performance (Sawka 1992), reduce cardiovascular strain during exercise (Barr, Costill et al. 1991) and increase thermolytic responses compared to hypohydration. In Study 2 it was observed that the ingestion of an ice slurry could cool an individual equally compared to a cold liquid while requiring significantly less volume. Understanding the physiological benefits of hydration and the cooling capacity of the ice slurry post exercise, investigating these effects during physical activity was deemed necessary. Therefore, replacing 100%, 50% or 0% of sweat loss with either ice slurry or cool liquid was performed as Study 3. Replacing 100% sweat rate with ice slurry or liquid enabled participants to exercise the longest (T_{lim}) and attenuated the rate of rise in T_{re} compared to 50 % and 0 % sweat replacement. A reduction in work rate is often observed with an elevated body temperature (Caputa, Feistkorn et al. 1986; Thomas, Cheung et al. 2006; Tucker, Marle et al. 2006) and could possibly explain the different T_{lim} observed between 100 and 50 percent fluid replacement conditions. Hence, the reduced rate of rise in T_{re} could be attributed to the cooling capacity of the larger fluid volumes. The practicality of using an ice slurry to assist in reducing heat loads experienced by personnel is feasible as central drink stations are provided by the employer which could in turn house an ice slurry machine.

Although the volumes ingested in Study 3 were predetermined by the researchers, complete replacement of lost fluids is typically not observed *in situ*. This incomplete fluid replacement is termed 'voluntary dehydration' (Morimoto and Itoh 1998). Ingesting palatable fluids (preferred flavour and/or temperature) increases *ad libitum* fluid consumption (Bergeron, Waller et al. 2006), however it is not known if the *ad libitum* intake of ice slurry compares favourably (to delay dehydration) or unfavourably (to incur dehydration) to cold liquid. Consequently, Studies 2 and 3 necessitated Study 4 which

aimed to measure the volume of fluid ingested *ad libitum* during simulated mining tasks in a hot environment and to compare the effects of *ad libitum* ingestion of liquid versus ice slurry solutions on core temperature.

Participants ingested less ice slurry than liquid (0.721 ± 0.431 L versus 1.088 ± 0.674 L; $P < 0.01$), exercise time to 38.0°C was longest for ICE, LIQ then NF (61.6 ± 27.6 min; 55.9 ± 26.3 min and 28.9 ± 15.6 min; respectively $P > 0.05$) and rate of heat storage was similar between ICE and LIQ, 3.1 ± 1.3 $kJ \cdot min^{-1}$ and 3.0 ± 1.5 $kJ \cdot min^{-1}$; $P > 0.05$ respectively.

The results from Study 4 indicate that the cooling capacity of an ice slurry is greater than consuming a cold liquid *ad libitum*. This study supports findings from Studies 2 and 3 that ingesting an ice slurry is a practical method to cool physically active individuals. Although the laboratory studies show promise that an ice slurry cooling intervention can cool exercising individuals, the applicability of an ice slurry cooling intervention *in situ* is still questionable.

Therefore, the purpose of study 5 was to assess the practical application of using an ice slurry as a cooling intervention *in situ*, a field analysis was performed under hot and humid conditions on an LNG platform located of the coast of North Western region of Western Australia. I found that, T_c and HR were significantly lower during the work shift when ice slurry was consumed compared to when cold liquid was consumed. Thermal sensation ratings were similar between conditions, even where differences were observed in T_c and HR, however, participants suggested that they would prefer a combination of ice slurry and cold liquid to increase palatability and encourage fluid replacement.

8.2 Directions for Future Research

The general findings from the studies conducted in this thesis are as follows:

1) there is not one single heat stress index that can protect all industrial personnel;

2) in creating a heat sink, significantly less ice slurry compared to cold liquid is required;

3) *ad libitum* ingestion of ice slurry during laboratory and *in situ* investigations resulted in a reduced rate of rise of T_c in participants.

Although these findings contribute to the current body of thermophysiology, questions still remain which require further research.

The volumes administered in Study 2 indicated that replacement of 100% sweat loss better attenuated the rate of rise in T_{re} than 50 and 0%. As complete sweat loss replacement is typically not practiced in the field, optimal strategies for fluid replacement that incorporate ice slurry requires attention. Additionally, the anecdotal evidence provided by LNG workers suggests that full substitution of ingested fluid with ice slurry would like to be implemented in the foreseeable future; therefore research into the ideal ratio of ice slurry and liquid ingestion during a work shift is justified.

8.3 Conclusion

The main findings from this thesis were that:

(1) current preventative methods, heat stress indices, did not adequately predict thermal stress in workers;

(2) personnel arrived to work hypohydrated and remained in that state throughout the work shift;

(3) personnel were working at greater than acceptable ambient conditions as determined by currently implemented heat stress indices;

(4) to administer the same cooling capacity between an ice slurry (-1°C) and liquid (4°C), the volume required is significantly less ($P < 0.001$) for an ice slurry;

(5) replacing 100% fluid loss with either liquid or ice slurry will increase time to exhaustion when compared to replacing 50% or 0%;

(6) during *ad libitum* consumption of liquid or ice slurry, more liquid was consumed ($P < 0.01$) compared to ice slurry, however the rate of heat stored was similar; and

(7) *in situ* comparison of liquid and ice slurry ingestion resulted significantly lower ($P < 0.05$) T_c and HR during the work shift when ice slurry was consumed compared to liquid with anecdotal evidence supporting greater perceptual relief of thermal strain while consuming ice slurry.

Cooperatively, this thesis has demonstrated that ice slurry is effective to manage heat and must be adopted to protect workers from hyperthermia. A gap still remains in the ability to manage heat stress among personnel working in hot and humid

environments and that additional interventions are required. Further, consuming ice slurry can provide significant cooling while ingesting significantly less volume in a laboratory setting. Thus, ingesting such a solution can provide a modest heat sink for personnel. This method of cooling is both a simple and cost effective heat stress intervention. Although the results of this thesis are encouraging for individuals working in hot and humid environments, further research is required for personnel working in other extreme environments where different clothing types are donned. It is therefore recommended that workers compliment current drink practices with ice slurry in order to reduce the probability of experiencing a heat stress related injury.

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APPENDIX A

BACKGROUND INFORMATION TO THE PARTICIPANT

Field validation of a laboratory developed heat stress intervention in the Australian liquid natural gas sector

Investigators:
Mr. Joseph Mate – chief investigator
Senior Lecturer. Dr. Jacques Oosthuizen – chief investigator
Edith Cowan University, School of Exercise, Biomedical and Health Sciences

This investigation has been approved by ECU Human Research Ethics Committee

This research is being conducted for a Doctorate Degree in the School of Exercise, Biomedical and Health Sciences and is being supervised by Dr. Jacques Oosthuizen (6304 5876)

BACKGROUND

The Western Australian resource boom and its lure of financial reward have resulted in an increased number of personnel working in this State's resource industry. This industry requires personnel to perform metabolically high workloads under hot and sometimes humid conditions. However, working in such extreme environmental situations can increase the risk of heat stress related illnesses and even death.

In order to prevent workers succumbing to heat illness, several heat stress management interventions aimed at controlling or reducing the rise in core temperature (T_c) of the worker have been implemented. These include work environment modification (i.e., air conditioning), worker education, and use of heat indices. Despite these interventions, heat stress related illnesses still occur, particularly during the summer months.

Despite the enhanced predictability of heat stress indices, it is still necessary to continue to investigate ways of reducing heat strain in personnel. Educating workers on the importance of maintaining their hydration level may be the simplest and most cost-effective method to reduce heat strain, as cold ingested fluids act as a heat sink to absorb heat from the body. While ice slurry infusion has been shown to reduce brain temperatures in swine compared with an equal temperature saline, the effect of ice slurry consumption on the body temperature response in humans working in hot environments is not known. As such, a cost effective heat stress intervention may be revealed through the combined effects of an ice slurry solution's enhanced cooling capacity.

The purposes of these two studies are;
1) to measure heat strain experienced during work and
2) to compare the effect of a ice slurry drink to normal drink *in situ*.

Protocol

Study 1 – measuring heat strain during work

Participants will arrive 2 hours prior to the beginning of the work shift for pre shift measurements. Measurements will include urine (color and specific gravity, height, weight, and skin folds.

Participants dressed in their working attire will present themselves to the researcher approximately 2hr before their work shift. Body mass, height, and body composition (9 skin fold sites) will be measured. Pre shift urine will then be collected. Deep tissue temperature will be measured with a one time use disposable telemetric pill (Mini Mitter, USA). The telemetric pill will be ingested with room temperature water. Skin temperature (Mini Mitter, USA) will be measured with sensors located on the body. Heart rate (RS800 Polar Heart Rate Monitor, Finland) will be recorded throughout the work shift using a heart rate monitor strapped to the chest. Work performed throughout the work shift will be estimated using a tri-dimensional force transducer. The participant will then begin their normal work day with the researcher observing the tasks performed. Each hour during work the participant will be asked to rate their perceived level of exertion and thermal comfort on a scale provided. All fluids and food consumed during the shift will be weighed and recorded. Mid day urine samples will again be collected.
Once the work shift has finished, post body weight and urine samples will be taken.

Study 2 – Comparing the effects of an ice slurry drink to a normal drink on core temperature

Day 1 - Measuring the physiological responses to regular drink practices
Day 2 - Measuring the physiological responses to a ice slurry drink
Note: the same participants will be used for days 1 and 2

Day 1 - Heat stressful occupations will be targeted as identified by Woodside. Protocol and instrumentation will be identical as per Study 1.

Day 2 - The same participants, protocol and instrumentation will be used as in Day 1 with the exception of the drink intervention. Participants will be required to drink an ice slurry solution as a replacement to their typical drink.

Instrumentation

Deep Tissue Temperature: Using a telemetric "pill", the temperature is transmitted as the "pill" moves through the stomach and intestines. The "pill" is naturally eliminated during the bowel movement 24 – 48 hours later. The transmitter pills are disposable and not recycled. The signal is captured and recorded in the portable data logger carried in a small back pack under your outer clothing layer. No discomfort is associated to swallowing the "pill".

Skin Thermistors: Eight skin probes will be taped to the skin surface with hypoallergenic tape. These probes give an indication of skin temperature and heat loss from the skin surface. Some hair may need to be shaved in order to secure the probes adequately to the skin surface. Some discomfort may be experienced upon removing the tape. The skin thermistors will be located at: left upper chest, left upper arm, left front thigh, and left calf.

Heart Rate: Heart rate will be monitored by a strap placed around the chest (Polar S610i, Finland). No discomfort is associated from wearing a heart rate monitor.

Rating of Perceived Exertion: A 10 point scale which the participant can rate their perceived level exertion. No discomfort is associated from being asked exertion level.

Thermal Comfort: An 8 point scale which the participant can rate their thermal comfort. No discomfort is associated from being asked thermal comfort level.

Your anonymity is ensured as much as is possible during the investigation and, by the assigning of number codes to subjects by the investigators. Only pooled data will be published and you will not be identified in any written reports or publications.

Confidentiality will be ensured to the extent that raw data will be seen only by the investigators. Data will be stored on a single computer (password protected - with limited access). Hardcopy (electronic data and data sheets) data will be stored in a locked cabinet.

The hardcopy data will be kept for a period of 5 years after publication of results and then destroyed.

If you agree to participate in this project, you will be given a copy of this background information and consent form to keep for future reference.

Your participation in this research project is entirely voluntary and you may refuse to participate or withdraw from the study at any time without adverse consequence. If you have any further questions regarding this project or the nature of the protocol, at any time before, during or after your consenting to participate, please contact:

Mr. Joseph Mate School of Exercise, Biomedical and Health Sciences Faculty of Computing and Health Sciences Edith Cowan University Joondalup, Western Australia 6027, Australia Email: j.mate@ecu.edu.au Phone: +61 (08) 6304 5152	Senior Lecturer Dr Jacques Oosthuizen (COH) School of Exercise, Biomedical & Health Sciences Faculty of Computing and Health Sciences Edith Cowan University Joondalup, Western Australia 6027, Australia Email: j.oosthuizen@ecu.edu.au Phone: +61 (08) 6304 5876

Or if you would like to speak with an independent person, if you have any ethical concerns with regards to your participation this study, you may contact the Research Ethics Officer of Edith Cowan University, Kim Gifkins at 6304 2170.

APPENDIX B

INFORMED CONSENT OF THE PARTICIPANT

Edith Cowan University – School of Exercise, Biomedical and Health Sciences

Investigators:
Mr. Joseph Mate – chief investigator
Senior Lecturer. Dr. Jacques Oosthuizen – chief investigator
Edith Cowan University, School of Exercise, Biomedical and Health Sciences

This investigation has been approved by ECU Human Research Ethics Committee

This research is being conducted for a Doctorate Degree in the School of Exercise, Biomedical and Health Sciences and is being supervised by Dr. Jacques Oosthuizen (6304 5876)

Having read the background information provided to me, I understand that the purpose of this original study (title: **Field validation of a laboratory developed heat stress intervention in the Australian liquid natural gas sector**) is to enhance our understanding of practical methods to cool the body during work in hot environments. To study this, 2 different drink cooling methods will be measured during work. These drink conditions being; 1) the participants drink their own typical drink solution and 2) water ice slurry.

I have read and understood the information presented in the letter of information and I understand all the risks involved with each of the 2 test sessions and the instrumentation that will be used in the testing procedure. I understand that if I need any further explanation I can seek the advice of a qualified medical practitioner or consult the investigators before participating.

I am aware that participation in this study will involve reporting to the work site 2 hours prior to the start of a work shift on 2 separate days. Before I participate, I understand that I will be given an information session regarding the instruments and protocol. During Day 1, I will have signed and returned a completed consent form and I also understand that I will have my body composition assessed. Following this assessment, I will be equipped with 4 skin temperature probes and will ingest a telemetric "pill" to measure stomach temperature. I understand that urine samples will be taken and used solely for the purposes described in the information form. I am also aware that I will be asked to substitute my usual drinking beverage for water ice slurry for one of the two testing sessions.

I understand that my anonymity will be maintained at all times through the assignment of specific codes. Access will be restricted to only the investigators and the data will be presented in pooled form. In any written reports or publications I will not be identified. The only benefit to me in participation is gaining the knowledge of my body composition

and learning about the research process. However, the investigator may learn more about the physiological controls of the cardiovascular system and may share this information upon request.

I understand that my participation and the results obtained in this study will have no influence on my employment status.

I attest that I have never been made aware of heart pathologies (murmurs, arrhythmias, cardiac anomalies) that could put me at risk in this experiment.

I attest that I have never been made aware of blood pressure irregularities that could put me at risk in this experiment.

I am currently not taking medications for any blood pressure or heart conditions.

I attest that I had a medical evaluation in the past year and am unaware of such heart or blood pressure problems.

I have talked with Joseph Mate and/or Dr. Jacques Oosthuizen about this study and my questions have been answered. If I have any other questions I may call Joseph Mate at 6304 5152, Dr. Jacques Oosthuizen at 6304 5876 or the Research Ethics Officer, Kim Gifkins at 6304 2170

I have been given a copy of this consent form and of the background information sheet. My participation in this research is voluntary. I may decline to participate in the study at any time and may withdraw without prejudice or discrimination of any form. All raw data collected at termination of the study will be destroyed within 5 years of termination of the study.

_____	_____
Volunteering Participant	Signature of Researcher
Date _____	Date_____

APPENDIX C

BACKGROUND INFORMATION TO THE PARTICIPANT

Heat stress in the mining industry: A practical approach to reducing heat strain in miners

Investigators:
Mr. Joseph Mate – lead investigator
Assoc. Prof. Paul Laursen – co-investigator
Edith Cowan University, School of Exercise, Biomedical and Health Sciences

This investigation has been approved by ECU Human Research Ethics Committee

BACKGROUND

The Western Australian resource boom and its lure of financial reward have resulted in an increased number of personnel working in this State's mining industry. This industry requires personnel to perform metabolically high workloads under hot and sometimes humid conditions. However, working in such extreme environmental situations can increase the risk of heat stress related illnesses and even death.

In order to prevent workers succumbing to heat illness, several heat stress management interventions aimed at controlling or reducing the rise in core temperature (T_c) of the worker have been implemented. These include work environment modification (i.e., air conditioning), worker education, and use of heat indices. Despite these interventions, heat stress related illnesses still occur, particularly during the summer months.

Despite the enhanced predictability of heat stress indices, it is still necessary to continue to investigate ways of reducing heat strain in miners. Educating workers on the importance of maintaining their hydration level may be the simplest and most cost-effective method to reduce heat strain, as cold ingested fluids act as a heat sink to absorb heat from the body. While ice slurry infusion has been shown to reduce brain temperatures in swine compared with an equal temperature saline, the effect of ice slurry consumption on the body temperature response in humans working in hot environments is not known. The ergogenic benefits of salt supplementation are also known. Salt supplementation has been shown to lower cardiovascular strain by expanding plasma volume. Moreover, an aqueous solution of salt and water has a greater cooling capacity compared with water alone. As such, a cost effective heat stress intervention may be revealed through the combined effects of an ice/salt-slurry solution's enhanced cooling capacity along with its plasma volume expanding qualities.

Thus, the aim of this study is to compare the combined and interactive effects of salt supplementation and ice slurry consumption during exercise in hot conditions.

Protocol

Day 1 – Signing of consent forms and familiarization to protocol and apparatus (Approximately 1 hour)

Day 2 - 8 – Acclimation protocol (Approximately 3 hours)

Day 9 – Maximal oxygen consumption test and DEXA (Approximately 1.5 hours)

Day 10 - 14 – Experimental sessions (5 conditions; no drink, water drink, sodium with water drink, ice slurry drink, or sodium ice slurry drink) (Approximately 4 hours each)

Note: participants will perform all conditions only once in a randomized order

You may not participate in this study if you have any history of heart or blood pressure irregularities nor if you are currently taking any medication for heart or blood pressure conditions.

Day 1: The procedures will be reviewed and the experimental instruments that will be used will be described/explained. At this point you will be asked to provide written informed consent and you will be asked to partake in a short screening process. You will be required to fill out a health, fitness history questionnaire and physical activity readiness questionnaire (PAR-Q and you). If you do not meet the criteria you will be ineligible for the study.

Day 2-8: As a participant you will be asked to participate in 7 heat acclimation protocol (after the screening session) to be conducted on 7 consecutive days. For each acclimation session, it will be required that you are clothed in shorts, a t-shirt and running shoes. For all experimental sessions it will be necessary to equip you with instruments to measure heart rate and core temperature probes to ensure safety.

You will be instructed to walk on a treadmill at $1.34 m \cdot s^{-1}$ on a 3% grade for four 25min sessions separated by 5min rests. The temperature at which this will be performed will all be at 35°C, 75%RH and wind speed of $0 m \cdot s^{-1}$.

Day 9: We will assess your body composition via Dual Energy X-ray Absorptiometry (DEXA) (Hologic, Hong Kong) In this procedure you will lay face up on a table while a low dose x-ray scans the body. The dose of radiation is equivalent to spending one day out doors. Following this evaluation, you will then perform a maximal exercise test ($\dot{V}O_2max$) on a treadmill at room temperature.

An automated metabolic system (ParvoMedics TrueOne 2400 diagnostic system, USA), which will require participants to wear a nose plug and a mouth piece, will be used to measure oxygen consumption during the progressive exercise test. The mouth piece is attached to a small hose (1mm in diameter) that draws a sample of their expired air and then is analyzed by the automated system. The said automated metabolic system then analyzes the oxygen and carbon dioxide content of the expired gas sample. This information is used to determine the speed of walking for the subsequent test.

The protocol for the $\dot{V}O_2max$ will require the participant begin jogging at $8 km \cdot h^{-1}$ for 2 min at a zero percent gradient. Speed will increase by $2 km \cdot h^{-1}$ every 2min until $16 km \cdot h^{-1}$ is reached. Two minutes after the $16 km \cdot h^{-1}$ speed is reached, and if the subject is still running, the gradient will be increased by 2 % every 2 min until volitional fatigue. Participants heart rate will be recorded throughout the test

Finally, participants will be informed of the necessary pre-experimental preparations to ensure that they are in good physical health and condition to perform the experimental sessions.

They will be instructed to prepare for experimental sessions as follows:

Obtain adequate sleep (at least 8 hours) prior to each session
Avoid alcohol or the use of non-prescription medication
Maintain adequate hydration (at least 250mL/hr in the evening and morning prior to the experimental sessions)
Eat a well-balanced meal
Refrain from strenuous physical activity for 12 hours prior to the experimental sessions

Day 10 – 13: Participants will report to the laboratory no more than 3 days following any previous experimental session. Participants will be asked to present themselves in a euhydrated state by drinking approximately 250ml of water for every waking hour prior to the experimental session. Participants will don running shoes, cotton pants, and a cotton t-shirt. Pre experimental urine and blood measurements will then be taken.
After voiding their bladder, participants will be weighed and instrumented with rectal (T_{re}), tympanic (T_{ty}), skin thermometers and a heart rate monitor. Blood pressure will then be taken. Participants will then enter the climatic chamber with ambient conditions set at 31.0°C WBGT (31.0°C and 50%relative humidity). Participants will sit quietly on a chair and once steady state temperature has been achieved (T_{re} ± 0.1°C for 5min) blood pressure will again be taken followed by commencement of exercise on a treadmill at ~290W·m^{-2} (approximately 3.5km·hr^{-1} as determined from $\dot{V}O_2$max test). The inclination will be set and maintained at 15°. This energy expenditure corresponds to a heavy workload in industry which does not require an altered rest to work ratio (work 100% of shift without any stoppage except for scheduled lunch and 'coffee' breaks).
Except for the control condition, participants will consume 194mL of solution every 20min for the duration of the exercise protocol (2hr) or until T_{re} reaches 39.0°C. Sodium chloride concentration will be 9.58 g/L. Once either a T_{re} of 39.0°C has been achieved for 5 consecutive minutes, or 2hr of activity has been completed, the subject will be asked to cease exercising and commence 30min of recovery while seated in the climatic chamber. Blood pressure will be measured every 10 min during recovery.
Post recovery, the participant will exit the chamber and body mass, urine and blood samples will once again be taken.

Instrumentation:

Skin thermistors: Eight skin probes will be taped to the skin surface with hypoallergenic type. These probes give an indication of skin temperature and heat loss from the skin surface. Some hair may need to be shaved in order to secure the probes adequately to the skin surface. Some discomfort may be experienced upon removing the tape. The skin thermistors will be located at: forehead, right scapula, left upper chest, right upper arm, left lower arm, left wrist, right from thigh, and left calf.

Rectal probe: A flexible probe (2 mm in diameter) will be inserted through the anus into the rectum (~10 cm). This probe provides us with an indication of the accumulated heat storage in the core. The participant will be responsible for the insertion of this probe. Lubricating gel will also be used to insert the rectal probe in order to facilitate the insertion and minimize any risks. For all experimental sessions, rectal temperature will be used as our indices of core temperature as it relates to terminating the experimental sessions. A rectal temperature of 39.0C will be used as a cut off temperature to stop the testing session.

Tympanic probe: A probe will be inserted in the participants' ear canal by the participant. The probe will be pushed gently until such a time as it touches the tympanic membrane. At this point, the participant will sense a slight discomfort and the probe will then be retracted slightly. The probe will be secured in its position by packing the ear with cotton balls held in place with hypoallergenic surgical tape. The auditory canal temperature will be used as an index of brain and core temperature. The insertion of the tympanic probe is comparable to inserting a Q-Tip in the ear. The insertion of the probe itself poses minimal risk to the subject. The probe is inserted with the participant actively participating with the researcher to indicate any discomforts associated with the insertion. It should be noted that the tympanic probe is inserted in the aural canal and NOT the tympanic membrane. The only discomfort associated with the implant is the point of contact with the membrane that is significantly reduced by slow insertion of the probe. Once the membrane has been contacted it is withdrawn slightly such that the participant feels no discomfort.

Oxygen consumption: An automated metabolic cart (ParvoMedics TrueOne 2400 diagnostic system, USA) will be used to assess oxygen consumption. The participants will be required to wear a breathing valve connected to the metabolic cart and a nose plug for the majority of this test.

Heart rate: Heart rate will be monitored by a strap placed around the chest (Polar S610i, Finland).

Blood Sampling: A qualified person will be taking 2 (two) blood samples during each experimental session, 1 (one) pre experiment and 1 (one) post experiment. Blood samples will be taken from the antecubital vein in the arm while the participant is in a seated position. A small pricking feeling may occur while a small blood sample is taken. This sensation will quickly subside.

Blood Pressure: An automatic blood pressure cuff will inflate around the upper arm. There maybe slight discomfort during the inflation of the blood pressure cuff. This sensation will quickly subside.

There is negligible risk of physical harm while recording the different body temperatures and the oxygen consumption. There is some risk of minor irritation associated with the placement of the temperature probes on the skin and in the, rectum or ear canal. In general these risks are considered to be minimal.

There will be no direct benefit to you from these procedures or from your participation in this study outside of your $\dot{V}O_2max$ and DEXA results. However, the investigators may

learn about the energy cost of mine work and will share these results at the end of the study, upon your request.

Your anonymity is ensured as much as is possible during the investigation and, by the assigning of number codes to subjects by the investigators. Only pooled data will be published and you will not be identified in any written reports or publications.

Confidentiality will be ensured to the extent that raw data will be seen only by the investigators. Data will be stored on a single computer (password protected - with limited access). Hardcopy (electronic data and data sheets) data will be stored in a locked cabinet.

The hardcopy data will be kept for a period of 5 years after publication and then destroyed.

If you agree to participate in this project, you will be given a copy of this background information and consent form to keep for future reference.

Your participation in this research project is entirely voluntary and you may refuse to participate or withdraw from the study at any time without adverse consequence. If you have any further questions regarding this project or the nature of the protocol, at any time before, during or after your consenting to participate, please contact:

Mr. Joseph Mate School of Exercise, Biomedical and Health Sciences Faculty of Computing and Health Sciences Edith Cowan University Joondalup, Western Australia 6027, Australia Email: j.mate@ecu.edu.au Phone: 6304 5152	Assoc. Prof. Paul Laursen School of Exercise, Biomedical and Health Sciences Faculty of Computing and Health Sciences Edith Cowan University Joondalup, Western Australia 6027, Australia Email: p.laursen@ecu.edu.au Phone: 6304 5012

If you have any ethical concerns with regards to your participation this study, you may contact the Research Ethics Officer of Edith Cowan University, Kim Gifkins at 6304 2170.

APPENDIX D

INFORMED CONSENT OF THE PARTICIPANT

Edith Cowan University – School of Exercise, Biomedical and Health Sciences

Investigators:
Mr. Joseph Mate – lead investigator
Assoc. Prof. Paul Laursen – co-investigator
Edith Cowan University, School of Exercise, Biomedical and Health Sciences

This investigation has been approved by ECU Human Research Ethics Committee

This research is being conducted for a Doctorate Degree in the School of Exercise, Biomedical and Health Sciences and is being supervised by Assoc. Prof. Paul Laursen (6304 5012)

Having read the background information provided to me, I understand that the purpose of this original study (title: **Heat stress in the mining industry: A practical approach to reducing heat strain in miners)** is to enhance our understanding of practical methods to cool the body during work in hot environments. To study this, 5 different drink cooling methods will be used during exercise. These drink conditions being; 1) no drink, 2) water drink, 3) water with sodium chloride, 4) water ice slurry and 5) water ice slurry with sodium chloride.

I have read and understood the information presented in the letter of information and I understand all the risks involved with each of the 5 test sessions and the instrumentation that will be used in the testing procedure. I understand that if I need any further explanation I can seek the advice of a qualified medical practitioner or consult the investigators before participating.

I am aware that participation in this study will involves reporting to the laboratory for testing after the screening session on 14 separate days for total time ranging between 1.5 hours to 4 hours. During Day 1 I understand that I will be given an information session regarding the instruments and protocol. On Day 2, I will have signed and returned completed consent forms and will begin the acclimation protocol of four bouts of 25 min with 5 min rest periods for 7 consecutive days during which I will be instrumented with a heart rate monitor and rectal thermometer. Day 8 I understand that I will have my body composition assessed followed by instrumentation of a nose plug and a mouth piece while performing a peak oxygen consumption test. On Days 9 -14, I will be equipped with 8 skin temperature probes, heart rate monitor, rectal and a tympanic temperature probes. I will also have my blood pressure taken during the sessions. I should be aware that there is some risk associated with the insertion of the rectal probe. Perforation of the rectum could occur during insertion of the rectal probe (potentially causing inflammation and infection). However, such an incident is rare and no such incident has ever occurred in this laboratory and the researchers are unaware of any such occurrences. The risk of transmission of infectious disease is negligible as each participant has his own one time use sterile probe that will be disposed of once each test have been completed.

I also understand that I will be required to perform exercise and that there are some risks associated with physical activity. The exercise component of the study will involve exercise on a treadmill at an intensity approximate to 50% $V0_{2\ peak}$ in a thermal chamber set at an ambient wet bulb globe temperature of 31.0°C (31.0°C at 50% relative humidity). There are essentially no risks for young, active healthy people performing exercise at submaximal intensities. When performing maximal intensity exercise, there is a very minor risk of cardiovascular dysfunction. All tests will be conducted under standard exercise conditions for human exercise experiments as laid out by the Canadian Society for Exercise Physiology and the American College of Sports Medicine.

I understand that my anonymity will be maintained at all times through the assignment of specific codes. Access will be restricted to the investigators and the data will be presented in pooled form. In any written reports or publications I will not be identified. The only benefit to me in participation is gaining the knowledge of my maximal oxygen uptake and body composition and learning about the research process. However, the investigator may learn more about the physiological controls of the cardiovascular system and may share them upon request.

I attest that I have never been made aware of heart pathologies (murmurs, arrhythmias, cardiac anomalies) that could put me at risk in this experiment.

I attest that I have never been made aware of blood pressure irregularities that could put me at risk in this experiment.

I am currently not taking medications for any blood pressure or heart conditions.

I attest that I had a medical evaluation in the past year and am unaware of such heart or blood pressure problems.

I have talked with Joseph Mate and/or Assoc. Prof. Paul Laursen about this study and my questions have been answered. If I have any other questions I may call Joseph Mate at 6304 5152, Assoc. Prof. Paul Laursen at 6304 5012 or the Research Ethics Officer, Kim Gifkins at 6304 2170

I have been given a copy of this consent form and of the background information sheet. My participation in this research is voluntary. I may decline to participate in the study at any time and may withdraw without prejudice or discrimination of any form. All raw data collected at termination of the study will be destroyed within 5 years of termination of the study.

_____ _____

Volunteering Participant Signature of Researcher

Date _____

APPENDIX E
Thermal Sensation Scale

0.0 – EXTREMELY COLD

0.5

1.0 – VERY COLD

1.5

2.0 – COLD

2.5

3.0 – COOL

3.5

4.0 – COMFORTABLE

4.5

5.0 – WARM

5.5

6.0 – HOT

6.5

7.0 – VERY HOT

7.5

8.0 – EXTREMELY HOT