THE EFFECT OF FLOOR INSULATION AND CLOTHING WETNESS ON THERMAL RESPONSE OF LIFE RAFT OCCUPANTS EXPOSED TO COLD

by

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Abstract

Introduction: Inflatable life rafts are the primary evacuation units used by the majority of vessels at sea. In the event of an emergency evacuation from a vessel, all passengers don the provided survival equipment and enter the life raft from the vessel or water. If the passengers do not have additional thermal protection (such is the case of many passenger vessels) they are largely dependent on the thermal protection of the life raft to prevent or minimize heat loss to the environment. Although current life raft standards require every life raft to provide sufficient insulation against cold (IMO, 1996), the standard lacks performance standards. The aim of this study was to determine the thermal response of life raft occupants with no additional thermal protection in cold conditions.

Methods: Five male and three female participants (26.3 ± 6.1 yrs, 84.4 ± 18.5 kg, 175.7 ± 9.6 cm, 23.7 ± 9.1 BF%) were exposed to four randomly assigned life raft conditions: wet clothing with uninflated floor (WU), wet clothing with inflated floor (WI), dry clothing with uninflated floor (DU), and dry clothing with inflated floor (DI). Trials were terminated based on any one of the following criteria: core temperature (both T_{re} and T_{ty}) dropped to 35^{o}C, the scheduled trial end time was reached (max 8.25 hrs), or the participant refused to continue. For all trials the ambient conditions were: 5^{o}C air and water temperature, 5m·s^{-1} wind speed, and 0.5m·s^{-1} towing speed. During each trial two participants and one researcher occupied a 16 person life raft. Participants wore a full zip cotton coverall, cotton t-shirt, cotton briefs, and a safety of life at sea (SOLAS) approved lifejacket. The extremities were protected against non-freezing cold injuries with wool lined leather mittens, wool socks and 5 mm neoprene boots. Measures of rectal and tympanic temperatures (T_{re} and T_{ty}), skin temperature (T_{sk}) and heat flow (HF) at 13 sites, and metabolic rate (MR) were recorded continuously during each trial. All trials were conducted at the National Research Council – Institute for Ocean Technology's indoor ice tank.

Results: Baseline measurements were similar across all four conditions (T_{re}: 36.85±0.04^{o}C; T_{ty}: 36.39±0.01^{o}C; T_{sk}: 33.02±0.03^{o}C; HF: 60.31±2.47W·m^{-2}; MR:

106.30±49.44W). The duration of exposure for DI (7.76±0.52h) was significantly longer compared to DU (6.49±1.07h) and WI (6.10±1.29h), with the exception of WU (6.37±2.15h). At the end of the exposures, T_{re} and T_{ty} had decreased from the baseline measurements for all condition. T_{re} decreased more significantly for the un-inflated conditions, WU (34.95±0.73^{o}C) and DU (34.76±0.69^{o}C), compared to the inflated conditions, WI (35.65±0.50^{o}C) and DI (35.72±0.49^{o}C). However, the clothing wetness had no significant effect on the T_{re} cooling. T_{ty} decreased similar amounts across all four conditions indicating that neither the clothing wetness nor floor insulation had a significant effect on T_{ty} cooling: WU (35.63±0.47^{o}C), WI (35.12±0.82^{o}C), DU (35.34±0.58^{o}C), and DI (35.30±0.41^{o}C). T_{sk} decreased across all conditions but significantly more during the wet conditions, WU (23.48±2.44^{o}C) and WI (24.01±1.91^{o}C), compared to the dry conditions, DU (26.84±1.61^{o}C) and DI (27.72±1.52^{o}C). The difference between the baseline and exposure average HF was significantly greater for the wet conditions, WU (183.20±29.27W·m^{-2}) and WI (171.95±29.63W·m^{-2}), compared to the dry conditions, DU (124.59±32.53W·m^{-2}) and DI (120.67±23.03W·m^{-2}). The floor had no significant effect on T_{sk} or HF. The average MR was greater during the exposures than baseline for all conditions with a more significant increase during the wet conditions, WU (65.17±27.12W) and WI (69.48±44.39W), compared to the dry conditions, DU (37.90±28.89W) and DI (5.44±39.00W). Similar to T_{sk} and HF, the floor had no significant effect on the change in average MR.

Conclusion: This study demonstrated that both clothing wetness and floor insulation have an effect on the thermal response of life raft occupants wearing minimal protective clothing. Clothing wetness had the biggest effect on T_{sk}, HF, and MR, with floor insulation having the biggest effect on T_{re}.

Key words: life raft, thermal protection, thermoregulation, cold

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List of abbreviations

ANOVA - Analysis of variance
CESM - Cold Exposure Survival Model
CO_2 - Carbon dioxide
DI - Dry clothing – inflated floor
DU - Dry clothing – un-inflated floor
HF - Mean heat flow
HFT - Heat flow transducers
Ht - Height
IMO - International Maritime Organization
MR - Metabolic rate
NRC-IOT - National Research Council Canada – Institute for Ocean Technology
O_2 - Oxygen
RER - Respiratory exchange ratio
SA - Body surface area
SD - Standard deviation
SOLAS - Safety of Life at Sea
T_B - Mean body temperature
T_{re} - Rectal temperature
T_{sk} - Mean skin temperature
T_{ty} - Tympanic temperature
$\dot{V}CO_2$ - Carbon dioxide output
$\dot{V}O_2$ - Oxygen consumption
WU - Wet clothing – un-inflated floor
WI - Wet clothing – inflated floor
Wt - Weight

Chapter 1 Introduction

1.1 Introduction

People began using seagoing vessels as a means of transportation thousands of years ago. Today seafaring vessels travel worldwide to transport people and goods, harvest fish, and explore for petroleum. The increase in activity at sea has raised concern for the safety of lives at sea. In 1912, following the sinking of the RMS Titanic, the need for standards concerning safety at sea was recognized, leading to a regulation requiring ships to provide lifeboats for all passengers on board (Heinz, 2005). However, an adequate number of the grossly sized lifeboats could not be stored on the war ships to accommodate the larger crew sizes during World War I and II (Heinz, 2005). Consequently the maritime world began using the more compact inflatable life rafts during World War II. Since then, inflatable life rafts have played an important role in saving lives at sea (Morall, 1983).

At present day inflatable life rafts have been adopted as the primary evacuation units used worldwide by the majority of vessels at sea, from smaller fishing vessels to larger oil installations and passenger vessels (Mak et al, 2005). In the event of a vessel evacuation, all passengers don the provided survival equipment and enter the life raft from the distressed vessel or water. If the passengers do not have additional thermal protection, they are largely dependent on the thermal protection of the life raft to prevent or minimize body heat loss to the environment.

To ensure that life rafts provide the essential thermal protection against often extreme environmental conditions, the International Maritime Organization (IMO) standard for thermal protection in life rafts states that Safety of Life at Sea (SOLAS) life rafts are required to provide sufficient insulation against cold (IMO, 1996). Even though improvements have been made to the thermal properties of life rafts to meet these standards, reports still indicate that when survivors of ship abandonment are rescued the majority of the life raft occupants inadequately clothed for the conditions suffer from hypothermia (Golden and Tipton, 2002). These reports of hypothermia are an indication of shortcomings in the construction of life rafts.

The high incidence of hypothermia cases reported during life raft rescues is not unanticipated considering the same models of life rafts are used in all geographical climates worldwide, from the warmer Caribbean waters to the colder Canadian Arctic waters. With a recent increase of passenger vessels and discussions of increased activity in petroleum exploration in the Arctic region, also comes an increase in the probability of maritime disasters occurring in these cold regions. This rise in Arctic activity has increased the attention directed towards thermal protection in the maritime world.

In the event of a maritime disaster in cold water there are many environmental factors that affect a life raft occupant's heat loss. A primary cause of heat loss from the environment is increased wind speed. As cooler air moves across the surface of the body, heat is transferred from the body to warm the surrounding air. Greater wind speeds cause a continuous push of cooler air across the body, resulting in a continuous transfer of heat from the body to the air. Heat loss is further increased when the difference between the ambient air temperature and body temperature is significant, with the ambient air temperature being lower (Danielsson, 1996; Noakes, 2000). Without wind the heat generated by the body warms the immediate surroundings, providing an additional thermal protective boundary against the cooler air, reducing the rate of heat loss.

The temperature and motion of the water play a role in heat loss by cooling the floor of the life raft and increasing air movement. Wave and current speeds can cause a continuous movement of cooler water below the floor not allowing the temperature of the floor to increase. The floor of the life raft provides a thermal protective layer between the occupant and the cold ocean water. The IMO (1996) standard for thermal requirements of a life raft specifies a need for insulated floors. Currently most life rafts are manufactured to provide extra thermal protection in the floor with a layer of air (inflatable) or closed cell foam.

To compensate for this heat loss the body must rely upon physiological responses such as shivering and vasoconstriction to increase heat production and decrease heat loss, respectively. Furthermore, the behaviour of the occupant can affect heat loss (Jessen, 2000). Different body positions and positions in relation to other occupants can affect heat loss as well. The body position will determine the contact area between the life raft and occupant. The greater the contact area the greater the amount of heat transferred from the occupant to the life raft (Golden & Tipton, 2002). Some researchers suggest that proximity of occupants can cause an increase in heat transfer among each other (Giesbrecht et al, 1987). In a survival situation, it is more likely that body to body contact decreases the rate of heat loss because the bodies act as insulation.

Each layer of clothing donned by the occupant is a layer of thermal protection between the occupant and elements of the environment. If the occupant must enter the life raft from the water or is splashed, the wet clothing can increase heat loss (Noakes, 2000). Furthermore, if the life raft is flooded and the occupant is immersed in water, heat can be transferred away from the body four times faster compared to a dry environment at the same ambient temperature because the thermal conductivity of water is 25 times greater than air (Brooks, 2003).

Improving the survival rate at sea as one of the driving forces, life raft manufactures have made many changes to the design of life rafts over the year, from open concept wooden rafts to inflatable life rafts with insulated floors and closed canopies. Today's life raft designs provide the occupants with more thermal protection against the harsh environmental conditions then previous open concept models. The improvements in the thermal properties of the life raft design have been driven by tests on the individual components of the life raft, while no previous testing has been performed on the entire life raft – occupant system. The aim of this experiment is to test the thermal properties of the life raft – occupant system to determine the effects of floor insulation and clothing wetness on the occupant's thermal response.

1.2 Purpose

The aim of this study was to determine the effect of clothing wetness and floor insulation on the thermal response and comfort of life raft occupants with no additional thermal protection in cold conditions.

1.3 Hypotheses

The following null hypotheses were tested:

H1: Physiological thermal response of life raft occupants exposed to cold conditions will remain unchanged due to clothing wetness.

H2: Physiological thermal response of life raft occupants exposed to cold conditions will remain unchanged due to floor insulation.

H3: Thermal comfort level of life raft occupants exposed to cold conditions will remain unchanged due to clothing wetness.

H4: Thermal comfort level of life raft occupants exposed to cold conditions will remain unchanged due to floor insulation.

(H_0: $\mu_1 = \mu_2 = \mu_3 = \mu_4$ where: μ_1 = WU, μ_2 = WI, μ_3 = DU, and μ_4 = DI)

Where WU is wet clothing – uninflated floor; WI is wet clothing – inflated floor; DU is dry clothing – uninflated floor; and DI is dry clothing – inflated floor.

1.4 Limitations

1. There was only one clothing ensemble tested. However, on a passenger vessel there would be many variations of clothing worn, including synthetics which is known for minimizing the effect of wetness on thermal response (Hooper et al, 2015).
2. Due to the complexity of the experiment a decision was made to have a test population of 8 participants with longer duration trials.
3. The findings of this study are intended to represent passengers of vessels such as ferries and cruise ships. The participants in this study were young healthy individuals and may not reflect the demographic of the passenger ship passengers.

Chapter 2 Literature Review

2.1 Introduction

Inflatable life rafts are currently used worldwide as a means of evacuation and survival from almost all seagoing vessels, regardless of their size and purpose. This ranges from fishing and other commercial vessels with small crew sizes to offshore oil installations and passenger ships with thousands of persons onboard (Hahne, 1983; Mak et al, 2005). In the event of an emergency vessel evacuation all passengers don the provided survival equipment and enter the life raft from the vessel or water. If the passengers do not have additional thermal protection they are largely dependent on the thermal protection of the life raft to prevent or minimize heat loss.

Currently the same models of life rafts are used in both cold Northern Canadian waters and warmer Caribbean waters. Although the IMO standard for thermal protection in life rafts states that SOLAS life rafts are required to provide sufficient insulation against cold (IMO, 1996), this standard is not specific to the different geographical climates of the world. This is of a concerning nature because when survivors of ship abandonment are rescued the majority of the life raft occupants suffer from hypothermia, confirming that thermal protection remains the predominant problem of survival at sea (Golden & Tipton, 2002).

There are many factors that can affect a life raft occupant's heat loss in a survival situation. These factors are grouped into environmental factors, physiological and psychological factors, behavioural factors, and life raft characteristics. This literature review will discuss the factors that contribute to occupant heat loss during cold exposure in a life raft.

2.2 Cold environmental factors that affect thermoregulation

Convection, evaporation, conduction and radiation are the four principle ways the human body exchanges heat with the environment (Colin & Houdas, 1967; Makinen et al, 2000).

The primary cause of convective heat loss from the body to the environment is wind. As cooler air moves across the surface of the body, heat is transferred from the body to warm the surrounding air. Convective heat loss is further increased when the ambient air temperature is less than the average skin temperature of 33°C (Danielsson, 1996; Noakes, 2000). The magnitude of heat lost is dependent on the wind speed (Makinen et al, 2000). In fact, higher ambient temperatures combined with increased winds speed can result in the same risk of tissue cooling as very low ambient temperatures (Danielsson, 1996).

Much research has been carried out on how wind speed in cold environments contributes to heat loss. Siple and Passel (1945) studied the combined effect of wind speeds and cold ambient temperatures on the cooling rate of a plastic water container in the Antarctic. The results led to the development of the wind-chill index (WCI). The WCI was used to determine the wind chill temperatures (WCTs), defined as the perceived ambient temperature felt by the exposed skin. Later research found that the WCTs calculated from Siple and Passel's (1945) research were not reliable (Kessler, 1993; Molnar, 1960; Osczevski, 1995, 2000; Steadman, 1971). Research conducted by Ducharme and Brajkovic (2005) determined that the WCI defined by Siple and Passel were based on conditions that were too sever and suggested a new WCI to include more mild conditions. Similarly, Osczevski and Bluestein (2005) developed a chart of wind chill equivalent temperatures (WCETs).

When humidity is introduced to a cold environment, convective heat loss increases because water has a higher conductivity than air (Brooks, 2003; Golden & Tipton, 2002). Similarly, wet clothing will also increase heat loss (Noakes, 2000). Since the thermal conductivity of water is 25 times greater than air, individuals immersed in cold water will lose heat approximately four times faster than in air at the same temperature (Brooks, 2003). Evaporative heat loss also increases when the clothing is wet. Heat required to transform the water into vapors is removed from the surface of the skin, further cooling the skin (Brooks, 2003).

Conductive heat loss occurs when heat is transferred from the body's surface area to the surrounding environment by direct contact (Brooks, 2003). Three factors that impact the amount of heat loss by conduction are: temperature gradient between the body surface and object, size of the contact area, and thermal conductivity of the object (Golden & Tipton, 2002). In a life raft environment, heat loss by conduction primarily occurs between the occupant and the floor. Waves or current can cause a continuous movement of cooler water below the floor not allowing the temperature of the floor to increase (Mak et al, 2008).

All living humans emit thermal radiation from exposed body surface area (Brooks, 2003). At the same time, radiant heat generated by the sun can be absorbed by the human body. The amount of radiant heat lost is dependent on the effective radiating body surface areas, temperature gradient between the environment and the body surface area, and emissivity and reflectivity of the body surface area in relation to the emissivity and average radiant temperature of the environment (Golden & Tipton, 2002). Body position and layered clothing can reduce the amount of radiant heat loss (Golden & Tipton, 2002).

2.3 Physiological and psychological factors that affect thermoregulation

Heat loss is also affected by the physiological response and condition of the occupant. Without proper clothing or shelter, the human body has a high capacity for heat loss during cold exposure. To compensate for this heat loss the body must rely upon physiological responses such as shivering and vasoconstriction to increase heat production and decrease the rate of heat loss, respectively. This section will also discuss the psychological factors that may affect thermoregulation.

2.3.1 Hypothermia

When the body detects a decrease in the core body temperature, thermoregulatory responses are activated in an attempt to maintain thermal homeostasis (Satinoff, 1978). Humans are most comfortable with a core body temperature of approximately $36.9^{o}C \pm 1.0^{o}C$ (Gagge & Herrington, 1947). A core body temperature between 32 to $35^{o}C$ is defined as mild hypothermia, 28 to 32^{o}C is defined as moderate, and below 28^{o}C is defined as severe (Biem et al, 2003). A decrease in core body temperature of approximately 10^{o}C can result in death (Golden & Hervey, 1972; Stocks et al, 2004).

During cold exposure the human body’s primary objective is to maintain core body temperature for cardiac functioning (Giesbrecht, 2000; Golden & Tipton, 2002). However, if the rate of cooling is faster than heat produced by the thermoregulatory responses, the core temperature will decrease and the body will begin to experience symptoms of hypothermia. A decrease in core body temperature causes an increase in the viscosity of the blood and a decrease in the transmission of electrical activity throughout the heart (Giesbrecht, 2000). This results in a decreased heart rate and cardiac output to the rest of body. A decrease in blood flow triggers the brain to gradually shut down cerebral areas, reducing metabolism in the brain (Golden & Tipton, 2002). The reduced metabolism decreases the amount of damage to the dormant areas of the brain (Giesbrecht, 2000). If core temperature continues to decrease, more areas of the brain will shut down leading to impaired cognition during moderate hypothermia and unconsciousness during severe hypothermia (Golden & Tipton, 2002).

2.3.2 Vasoconstriction

In response to cold exposure the sympathetic nervous system reduces blood flow to the periphery in an attempt to maintain warm blood flow to the major organs (Biem et al, 2003; Wyss et al, 1974). Constricting the blood flow to the peripheral areas results in an overall reduction in heat loss by decreasing the thermal conductivity between the skin surface and surrounding environment (Golden & Tipton, 2002). Vasoconstriction begins when the environmental temperature is lower than the skin temperature, causing warm thermal receptors to decrease firing rate and cold thermal receptors to increase firing rate (Golden & Tipton, 2002; Graham, 1988; Tipton, 1989). The cold thermal receptors send the information to the thermal control centers of the brain. The thermal control centers of the brain are thought to be located in the pre-optic area and anterior hypothalamus (Boulant & Dean, 1986), however the precise location of the thermal control centers remains unclear (Blight, 1998). The thermal control centers process the information triggering vasoconstriction and other physiological responses, such as change in breathing rate (Boulant & Dean, 1986).

The intensity of vasoconstriction depends on the temperature gradient between the environment and skin, the rate of change in environmental temperature, and size and location of the exposed skin region (Hensel, 1981; Jessen, 2000). During prolonged exposure to cold temperatures active vasoconstriction is maintained by the sympathetic noradrenergic nervous pathway. The noradrenaline released by the vasoconstrictor fibres stimulates α-adrenergic fibres to constrict and β-adrenergic fibres to relax the walls of the blood vessels. Since β-adrenergic fibres are outnumbered by α-adrenergic fibres in the blood vessels, vasoconstriction is the predominate response (Schmidt & Thews, 1989). Some research has measured vasoconstriction to cause greater than 99% decrease in blood flow to the periphery (Golden & Tipton, 2002).

2.3.3 Metabolic response (Shivering)

If vasoconstriction is not sufficient to prevent a decrease in core body temperature during cold exposure, a change in muscle metabolism occurs to increase heat production (Benzinger, 1970). To prepare the body for an increase in muscle metabolism the thermal control centers trigger changes in breathing and heart rate (Budd, 1962; Golden & Tipton, 2002; Tipton, 1989). The initial exposure to cold air and water triggers an increase in respiratory rate (Cooper et al, 1976; Keatinge & Nadel, 1965; Keatinge & Evans, 1961), and heart rate (Graham, 1988; Hayward & Eckerson, 1984; Wagner & Horvath, 1985).

The increase in muscle metabolism is the result of shivering which is characterized by involuntary, synchronous and rhythmic muscle contractions (Golden & Tipton, 2002). Generating metabolic heat is the solitary purpose of shivering (Golden & Tipton, 2002). Shivering intensity peaks between skin temperatures of 17^{o}C and 20^{o}C (Eyolfson et al, 1998; Tikuisis & Giesbrecht, 1999; Tikuisis, 2003; Tikuisis et al, 2002). If heat loss continues to be greater than heat production, shivering intensity will increase (Stocks et al, 2004). However, shivering can disappear below core temperature of 30^{o}C (Bristow & Giesbrecht, 1988). Maximum survival time during cold exposure is related to the duration of shivering (Eyolfson et al, 1998). Individuals with greater subcutaneous fat show slower cooling rates and maintain shivering for longer, and individuals with higher aerobic capacity are capable of more intense shivering resulting in greater heat production (Eyolfson et al, 1998; Tikuisis et al, 1999). Shivering intensity and duration can also be influenced by the available energy substrate (Tikuisis et al, 1999).

Shivering is fuelled by the breakdown of lipids, carbohydrates and proteins (Weber & Haman, 2005). Muscular shivering can increase metabolic rate to be approximately five times greater than the average basal metabolic rate of 110 W (Eyolfson et al, 1998; Jansky, 1998; Rintamaki, 2007). The rate of heat production from lipids, carbohydrates and proteins have been quantified for low intensity shivering (2.3 x resting metabolic rate (RMR) and high intensity shivering (3.5 x RMR) (Haman et al, 2002; 2005). Therefore, there is an increased demand on the energy stores. During low intensity shivering the main energy sources utilized are fats while higher intensity shivering is fuelled by carbohydrates (Rintamaki, 2007; Weber, 2010; Weber & Haman, 2005). Proteins normally contribute 10% to heat production during shivering (Weber, 2010). However, if one energy source becomes depleted, the body will utilize another substrate to fuel the involuntary contractions of shivering (Haman et al, 2004b; Weber, 2010; Weber & Haman, 2005). Two mechanisms used by shivering humans to determine fuel selection are the recruitment of different pathways within the same fibres and the recruitment of different fibres within the same muscles (Haman et al, 2004a). This suggests that muscle fibre composition could impact shivering endurance and survival. The amount of substrate reserve may also impact shivering endurance, which suggests that diet could play a role in survival time, however it remains unknown. There is some indication that specific fatty acids could provide a survival advantage (Weber & Haman, 2005).

2.3.4 Psychological and cognitive response

Thermal comfort has been defined as the condition of the mind which expresses satisfaction with the thermal environment (Fanger, 1967). Air temperature, humidity, mean radiant temperature, relative air velocity, activity level and insulation value of clothing are all factors that affect the thermal comfort level of a human (Olesen & Rosendahl, 1990).

While much research has been conducted to determine the impact of environmental conditions on thermal comfort levels and heat loss, little research has been carried out to assess the impact of perceived thermal comfort on heat loss. However, the perceived discomfort of the environmental temperature may distract an individual and indirectly affect heat loss by altered decision making. Perception, assessment and decision-making can be impaired if assessed in both cold and noise polluted environments (Pellerin & Candas, 2003, 2004). Twenty-two studies reported an average decrease of 14% in cognitive performance during exposures to temperatures below 10^{o}C (Pilcher et al, 2002). Exposure to extreme cold temperatures resulted in larger performance decrements despite shorter exposure times (Pilcher et al, 2002; Thomas et al, 1989).

2.4 Behavioural factors that affect occupant thermoregulation

The thermal neutral ambient temperature for a naked and resting human is 27^{o}C in air and 30^{o}C in water (Rintamaki, 2007). Since the ambient temperatures of our environment can be much lower, humans have adapted to life in a cold environment primarily through behaviour (Jessen, 2000). Each layer of clothing donned by the occupant is a thermal protection layer, which decreases the rate of heat loss. If the occupant must enter the life raft from the water or is splashed, the wet clothing can increase heat loss. Different body positions and position in relation to other occupants can affect heat loss as well. The body position will determine the contact area between the life raft and occupant. The greater the contact area the greater the amount of heat transferred between the occupant and the life raft. Proximity of occupants can cause an increase in heat transfer among each other decreasing the rate of heat loss.

2.4.1 Clothing

A change in skin temperature will often trigger thermal behaviour and motivate humans to seek shelter or adapt clothing so that deviations of core temperature are reduced or mitigated (Hensel, 1982). Clothing can reduce the rate of cold related mortality

(Donaldson et al, 1998; Donaldson et al, 2001). Clothing provides a protective barrier between the surface of the skin and environment. Properly fitted clothing will trap a layer of air between outer layer of clothing and skin surface (Golden & Tipton, 2002). The layer of trapped air is warmed by the skin increasing the level of insulation between the skin and environment. The layer of air trapped between the skin and clothing contributes to the overall clothing insulation level (Golden & Tipton, 2002).

Clothing insulation is measured in clo units. A clothing ensemble with an insulation value of 1.0 clo will allow a loss of $0.155^oC*m^2\bullet W^{-1}$, where W is total body heat (Golden & Tipton, 2002). A long sleeve shirt and dress pants with undergarments is equal to 1 clo. An individual wearing this clothing ensemble would remain comfortable at an ambient temperature of 21^oC with normal humidity and low wind speeds (Golden & Tipton, 2002; Noakes, 2000). The addition of humidity and wind increases the amount of clothing required. Humidity and wet clothing increases the amount of heat transfer in the air and reduces clo value compared to the dry clothing ensemble (Noakes, 2000). Increased wind speeds compress the clothing against the skin, decreasing the amount of trapped air between the skin and clothing (Golden & Tipton, 2002; Havenith & Nilsson, 2004). Pugh (1966) showed that wetting reduces the insulation of clothing by 50%, wind speeds of $14.5\ km\bullet h^{-1}$ reduces insulation by 30%, and a combination of wetting, wind and movement reduces insulation by 85%.

When exposed to marine environments individuals can benefit from the extra thermal protection provided by immersion suits or other thermal protective aids (TPAs). Insulation of the limbs and torso can prolong survival time during cold water immersion (Tipton & Golden, 1987). While immersion suits prevent the underlying clothing from becoming wet, the clo values of immersion suits are lower when in water because of hydrostatic compression of the suits (Golden & Tipton, 2002). A fully insulated dry suit immersed in water has a clo value of approximately 0.7, allowing for a survival time up to 15 hours of immersion in 12^oC water (Golden & Tipton, 2002). In a life raft environment a TPA can be worn to reduce heat loss. In addition to reducing heat loss, a TPA can reduce the energy expenditure. An individual wearing wet clothing will expend

675 W to evaporate one liter of water in one hour, and only 35 W to warm one liter of water from 4^oC to 33^oC in one hour if a TPA is worn (Golden & Tipton, 2002).

2.4.2 Posture and orientation

A simple change in posture or orientation towards a heat source can reduce the impact of heat loss. Studies have shown that a change in posture from standing to supine, and vice versa, can cause a shift in rectal and mean skin temperature (Tikuisis et al, 1991; Ducharme & Tikuisis, 1991). Assuming a fetal position with legs together and arms to the side, or folded across the chest can prolong survival time during exposure to cold (Allan, 1983; Golden & Hervey, 1972; Hayward et al., 1977; Keatinge, 1961; Nunnely & Wissler, 1980). This position can reduce the amount of body surface area emitting radiant heat. In a life raft environment it can also reduce the amount of surface area in contact with the cold life raft floor, reducing heat loss through conduction.

Body-to-body heat transfer can be used as a re-warming technique for hypothermic victims (Giesbrecht et al, 1987). The method of body-to-body re-warming does not impact the rate of re-warming in a healthy mild hypothermic victim because the shivering intensity decreases (Giesbrecht et al, 1994). However, in a life raft survival situation where heat loss is greater than the heat produced by shivering, the heat gained by body-to-body contact may reduce the rate of heat loss.

2.5 Life raft characteristics that affect thermoregulation

Since the thermal conductivity of water is approximately 25 greater than air (Brooks, 2003), an immersion suit alone would not provide sufficient thermal protection to survive for extended durations in cold water. A life raft can remove people from the water and provide additional protection from the cold environment. The construction of the life raft will impact how much additional protection is provided. All SOLAS approved inflatable life rafts are constructed of a durable canopy, an inflatable collar, and an insulated or inflatable floor.

The canopy shelters the occupant from the harsh elements of the environment, and reduces the convective, evaporative, and radiant heat loss compared to that experienced in an open boat. A closed canopy will allow the environment within the life raft to warm up by the heat radiating from the occupants (Golden & Tipton, 2002). Mak et al. (2008) measured a 4.4^{o}C increase in air temperature within a 16-person life raft at 69% capacity in less than two hours. The decrease in temperature gradient between the surface of the skin and the ambient air reduces convective heat loss. Convective heat loss is further reduced because the canopy provides protection from the wind. However, if there is no active ventilation the air quality can become uncomfortable. In a study where no active ventilation was present in a 16-person life raft at 69% capacity the CO_2 concentrations reached an uncomfortable level (> 5000 ppm) in less than an hour (Mak et al, 2008). Some ventilation would occur when the occupants perform survival tasks such as, looking out for help, excreting bodily fluids, and bailing. If this ventilation is not sufficient to maintain the air quality inside the life raft, active ventilation is recommended.

The insulated and inflatable floor can have different thermal properties. The thermal properties of the inflatable floor can be significantly different when inflated compared to not inflated. The thermal properties of the floor are further compromised if they are wet. Golden & Tipton (2002) describe the challenges that are faced when trying to manually inflate a life raft floor. Since it is impossible to exert sufficient pressure with the manual pump to overcome the weight of the seated bodies, sitting on a life jacket may be an alternative option to reduce the conductive heat loss to the life raft floor (Golden & Tipton, 2002).

2.6 Gaps in the Literature

Much research has been undertaken to explore the impact of cold exposure on thermal response and survival. However, no formal research has been carried out to specifically look at the thermal response of life raft occupants exposed to cold temperatures. This research better quantifies the thermal responses of life raft occupants exposed to cold temperatures.

Chapter 3 Methods

3.1 Design of experiment

A Phase 1 pilot experiment was conducted in a mild cold (19^{o}C air temperature and 16^{o}C water temperature) environment to determine which environmental variables had the most effects on heat loss (Mak et al, 2009c). The Phase 2 experiment was conducted in a mild cold (19^{o}C air temperature and 16^{o}C water temperature) environment to further explore three variables: floor insulation (uninflated (0.2 cm), inflated (15 cm)), clothing wetness (dry, wet), and occupancy level (12.5%, 37.5%) (Mak et al, 2009b). Phase 2 experiment identified floor insulation and clothing wetness to have a significant effect on occupant heat loss. These results were used to inform the test protocol for the experiment reported herewith.

Phase 3 experiment was conducted to explore the effects of floor insulation and clothing wetness upon human life raft occupants in a cold (5^{o}C air temperature and 5^{o}C water temperature) environment. The experiment was a 2 x 2 within-subjects factorial design with independent variables being the floor insulation (uninflated or inflated) and clothing wetness (wet or dry) (Table 3.1). The four conditions, wet - uninflated (WU), wet - inflated (WI), dry - uninflated (DU), and dry - inflated (DI), had system insulation values of 0.116 ± 0.006 (m$^{2}\cdot{}^{o}$C)/W, 0.145 ± 0.017 (m$^{2}\cdot{}^{o}$C)/W, 0.185 ± 0.022 (m$^{2}\cdot{}^{o}$C)/W, and 0.224 ± 0.023 (m$^{2}\cdot{}^{o}$C)/W, respectively. The system insulation values were measured using a thermal manikin (NEMO; Measurement Technologies Northwest, Seattle, WA).

Table 3.1 Design of Experiment.

	Wet	Dry
Uninflated	WU	DU
Inflated	WI	DI

Mak et al (2009a) compiled a final report on all three phases.

3.2 Participants

Eight healthy volunteers with no previous cold related injuries or illnesses were recruited with a recruitment poster (Chapter 6Appendix A) and gave their informed written consent to participate in this study (Chapter 6Appendix B). Approval for this study was obtained from the Memorial University of Newfoundland, Human Investigation Committee (MUN-HIC) and the National Research Council Canada, Ottawa Research Ethics Board (NRC-OREB). All participants were cleared for participation in this study upon completion of a medical history questionnaire (Chapter 6Appendix C). Participants were instructed to refrain from consumption of food two hours, caffeine and hot beverages six hours, and exercise and alcohol 24 hours prior to the start of each data collection period. Physical characteristics of the participants are presented in Table 3.2.

Table 3.2 Physical characteristics of participants.

Participant	Age	Gender	Mass (kg)	Stature (cm)	Body Fat (%)	Surface Area (m^2)
1	26	M	107.6	188	28.5	2.38
2	35	M	105.6	180	31.2	2.32
3	21	F	82.2	171	32.8	1.99
4	24	M	89.2	185	16.3	2.15
5	26	F	62.8	168	24.6	1.72
6	36	F	57.5	159	20.1	1.61
7	22	M	94.9	174	29.9	2.16
8	20	M	75.8	182	6.1	1.96
Mean	26.3	-	84.4	176	23.7	2.04
SD	6.1	-	18.5	9.7	9.1	0.27

3.3 Facility characteristics

Experimental data were collected in the Ice Tank (Figure 3.1) at the National Research Council Canada, Institute for Ocean Technology (NRC-IOT) (St. John's, Newfoundland

and Labrador, Canada). The 90m long, 12m wide, and 3m deep Ice Tank is equipped with a towing carriage and water and air temperature cooling systems.

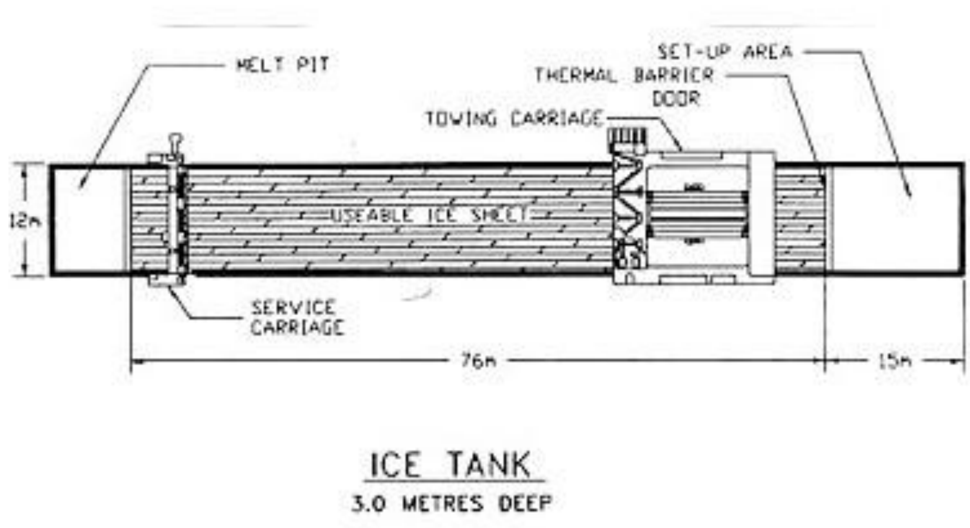


Figure 3.1 Ice Tank dimensions.

The towing carriage is a single manned carriage with a 4-wheel synchronous motor drive that can generate speeds of 0.0002 m/s (0.00039 knots) to 4.0 m/s (7.78 knots). The computer equipment for the drive control is housed in a thermally insulated carriage control room (Hill, 2008).

The ice tank water is initially cooled by re-circulating water through a chilling system at flow rates of 110 litres/second. The desired water temperature is then maintained by cooling the air temperature to an equivalent temperature. The water is stirred to ensure uniform water temperature throughout the tank. An ammonia-based cooling system with 26 evaporators and computerized temperature control can regulate the ambient air temperature between -30°C to +15°C (Hill, 2008).

3.4 Life raft characteristics

A 16 person SOLAS approved inflatable life raft (DBC Marine Safety Systems, Richmond, BC) was utilized during this study (Figure 3.2). The octagonal life raft had an overall diameter of 3.31 m and height of 1.56 m. The life raft was constructed of eight inflatable sides, an inflatable floor and an inflatable arch to support a canopy. The sides were constructed of two cylindrical chambers stacked for a total vertical height of 0.63 m. The inflatable floor was constructed of two layers of butyl rubber that were attached at multiple points with round fasteners. When the floor was fully inflated, the points of attachment caused a dimple effect. The sides and arch were inflated with CO_2 and the floor was inflated with air. The internal pressures of the inflated components were continuously monitored with a Druck 800 series pressure transducer (model PDCR 830) and adjusted for consistency. The two canopy openings were double closures with ties and were closed for the duration of each test.

Figure 3.2 Life raft structure.

3.5 *Clothing ensemble and SOLAS lifejacket*

The participant wore a full length, non-insulated 100% cotton coverall with zip front closure (model Big Bill 414; Codet inc., Magog, QC), 100% cotton short sleeve t-shirt, 100% cotton briefs, and a SOLAS approved lifejacket (model MD8000; Mustang Survival, Richmond, BC). This cotton clothing ensemble was selected to resemble a “worst case” scenario of a passenger by maximizing the effect of wetness. The extremities were protected against non-freezing cold injuries with wool lined leather mittens, wool socks and 5mm neoprene boots with zipper (model BT500; XS Scuba, Santa Ana, CA).

3.6 Experimental set up

The towing carriage and a service carriage were set up to move as one unit. The life raft was positioned between the towing carriage and service carriage. A modified towing patch was mounted to the side chamber of the life raft below each opening. Two mooring lines were extended from each towing patch to two towing posts on the towing carriage and service carriage. This allowed continuous towing in both carriage directions. This set up ensured that one canopy opening was directly exposed to the wind produced by the fans mounted under the towing carriage. (Figure 3.3)

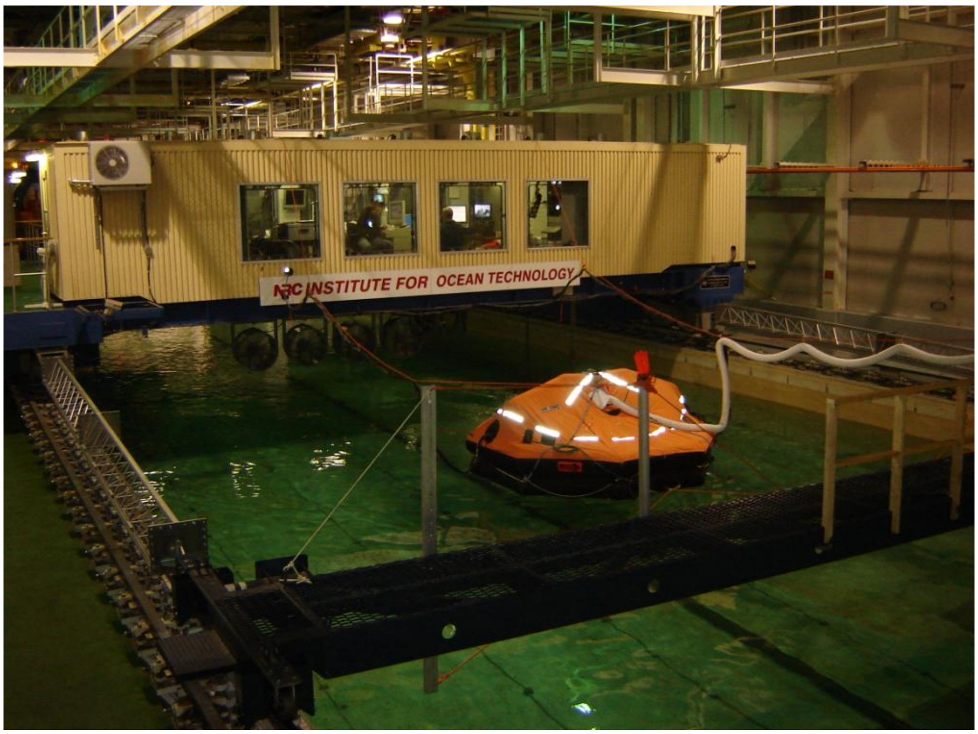


Figure 3.3 Life raft set up.

Participants sat on opposite sides of the life raft in RT4 and LF3 positions. A thermal manikin was situated in the RT1 position, and a researcher sat at the exit (see Figure 3.4).

This seating arrangement minimized or eliminated body heat transfer between occupants and evenly ballasted the life raft. The manikin was not turned on during the trails with the human participants. Additional trails were conducted to collect manikin data (Mak et al, 2009a).

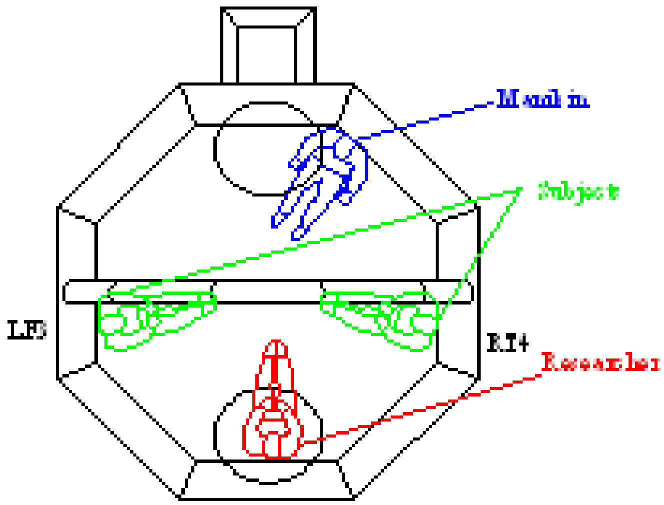


Figure 3.4 Seating arrangement.

3.7 Environmental measurements and instrumentation

3.7.1 Data acquisition system

Three data acquisition systems (developed by NRC-IOT, St. John’s, NL) were used to acquire analog signals from the sensors monitoring the internal and external life raft environment and the human participants. Isolation amplifiers were integrated into the data acquisition systems to eliminate the potential shock hazards to the human participants. The analog signals were amplified and conditioned, then sent to an A/D converter (DaqBook/2000 Series; IOtech Inc.; Norton, MA) and converted to digital data. The digital data were logged by a GDAC (GEDAP Data Acquisition and Control) client server acquisition system (developed by NRC-IOT, St. John’s, NL).

3.7.2 Ambient temperatures

The ambient air and water temperatures of the testing environment were measured with 400 series thermistors (model ON-401-PP; OMEGA Engineering, inc., Stamford, CT). The air temperature was measured in four locations on the interior and exterior of the life raft. The water temperature of the ice tank was measured in two locations near the towing carriage, approximately 1 meter below the water surface (Figure 3.5 and Figure 3.6). The seating configuration in the following figures depicts the setup in Phase 2. Figure 3.4 illustrates the seating arrangement for Phase 3 testing.

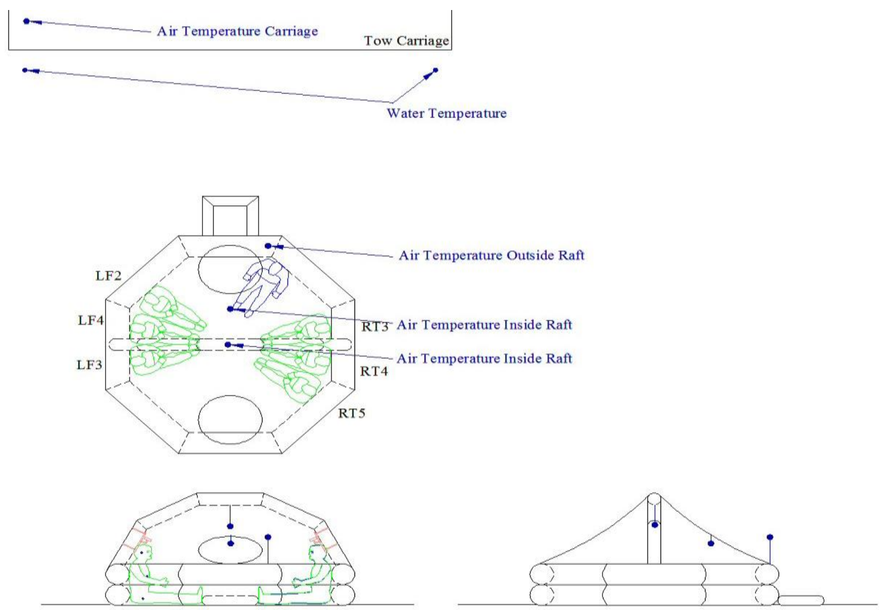


Figure 3.5 Location of air and water temperature sensors.

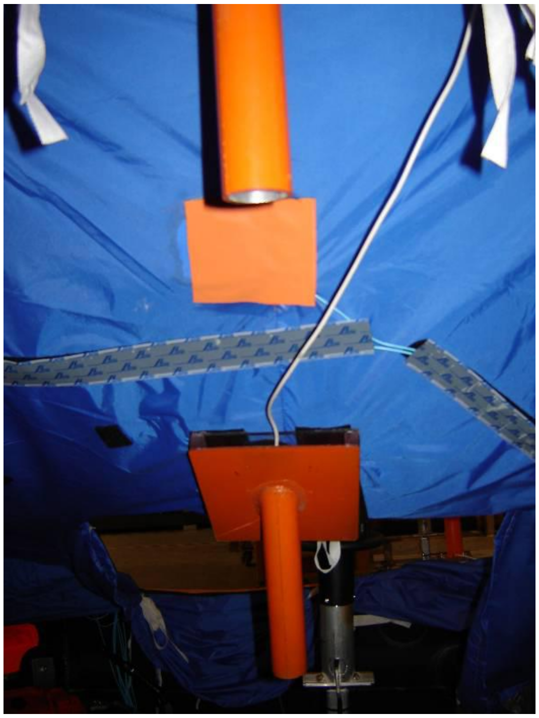
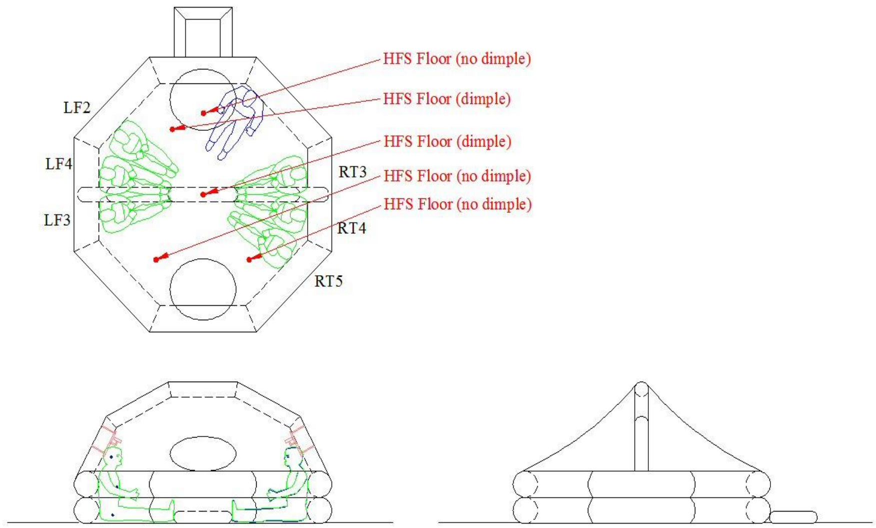


Figure 3.6 Air temperature sensor with fibreglass shield.

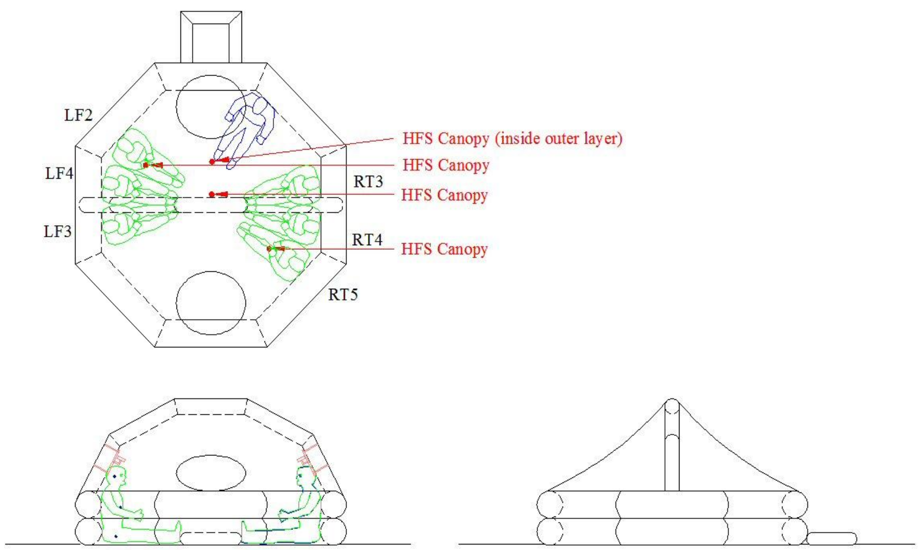
3.7.3 Life raft temperatures

The temperature and heat loss of the life rafts interior floor, canopy, and side chambers were measured using 13 heat flow transducers (HFT) with integrated thermistors (model FR-025-TH44033-F10 and F-002-4-TH44033-F20; Concept Engineering, Old Saybrook, CT) (Figure 3.7 and Figure 3.8).



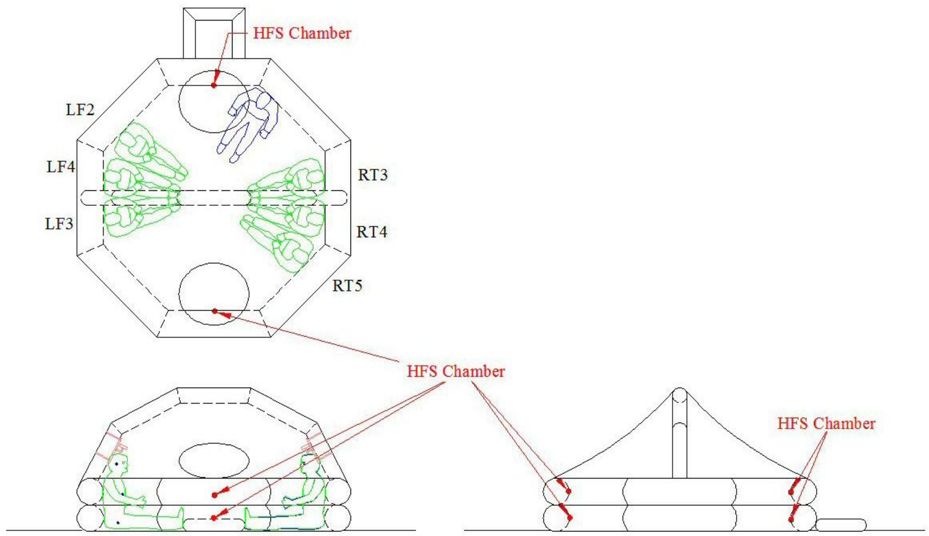
HFS Floor (no dimple)
HFS Floor (dimple)
HFS Floor (dimple)
HFS Floor (no dimple)
HFS Floor (no dimple)
LF2
LF4
LF3
RT3
RT4
RT5

(a)



HFS Canopy (inside outer layer)
HFS Canopy
HFS Canopy
HFS Canopy
LF2
LF4
LF3
RT3
RT4
RT5

(b)



(c)

Figure 3.7 Location of heat flow transducers on life raft: (a) floor, (b) canopy, and (c) side chambers.

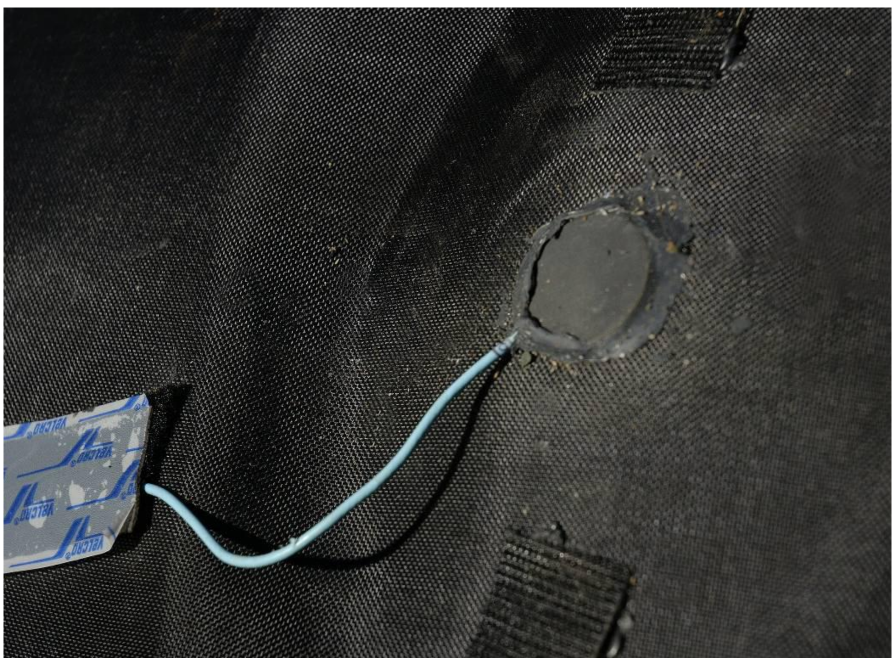


Figure 3.8 Heat flow sensor mounted on life raft.

3.7.4 Wind speed

Four industrial fans were mounted to the towing carriage and used to produce 5 m·s^{-1} wind speeds. Three Windsonic anemometers (model 1405-PK-040; Gill Instruments Ltd., Lymington, Hampshire) were used to measure the wind speeds in different locations: outside the life raft on the windward side, inside the life raft on the windward side, and inside the life raft near the participant (Figure 3.9 and Figure 3.10).

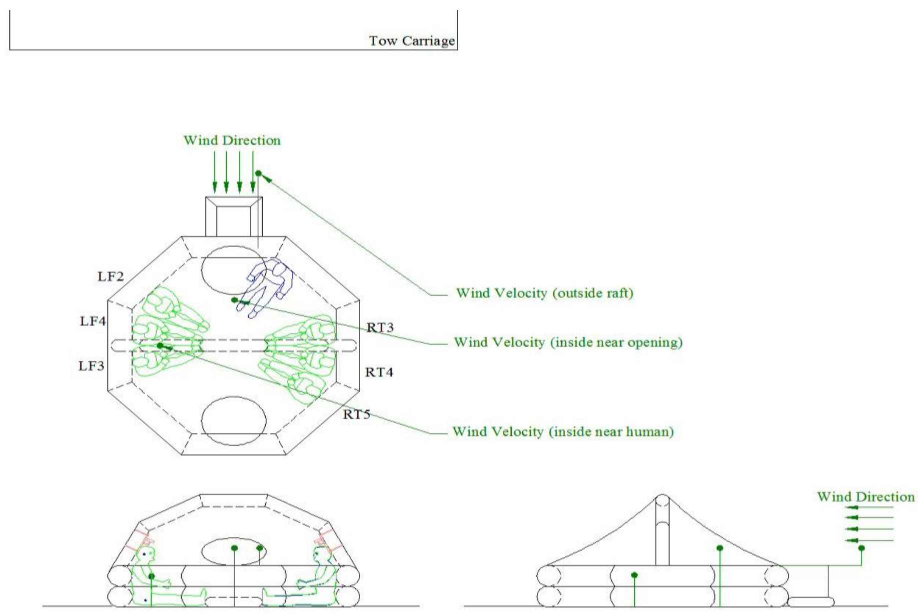


Figure 3.9 Location of wind anemometers.

Figure 3.10 Wind anemometer.

3.7.5 Leeway

Leeway is the motion of the life raft over water due to the wind. To simulate this, the towing carriage and a service carriage were utilized to continuously tow the life raft over the water, back and forth the length of the ice tank, at a speed of 0.5 m/s (0.972 knots) for the duration of each test.

3.8 Physiological measurements and instrumentation

3.8.1 Anthropometric measurements

Mass (kg) and stature (cm) were measured with a portable scale and tape, respectively. Skinfolds were measured using a Harpenden skinfold calliper (British Indicators Ltd, London, UK). Measurements were recorded to the nearest 0.2 mm at the triceps, subscapular, pectoralis, midaxillary, suprailiac, abdomen, and quadriceps (Table 3.3). All skinfold measurements were made on the right side of the body. A minimum of two measurements was performed at each site. A third measurement was recorded if the first two measurements were not within 0.4 mm of each other.

Table 3.3 Description of the seven skinfold sites.

Skinfold Site	Location Description
Tricep	Vertical fold on the posterior midline of the upper arm, midway between the acromion and olecranon process.
Subscapular	Diagonal fold 1 cm below the inferior angle of the scapula.
Pectoralis	Diagonal fold between the anterior axillary line of the underarm and nipple.
Midaxillary	Vertical fold on the midaxillary line at the level of the xiphoid process.
Suprailiac	Diagonal fold 3 cm above the iliac crest, on the midaxillary line.
Abdominal	Vertical fold 2 cm to the right of the umbilicus.
Quadriceps	Vertical fold on the anterior midline of the thigh, midway between the proximal border of the patella and the inguinal fold.

3.8.2 Rectal and tympanic temperature

Rectal temperature (T_{re}) was measured using a Philips 400 series thermistor (model 21090A, Philips Medical Systems; Andover, MA) that was participant-inserted 15cm into the rectum. To minimize movement of the rectal temperature sensor, a t-bandage was used to secure the sensor once inserted (Figure 3.11). Tympanic temperature (T_{ty}) was measured with a Mon-a-therm 400 series thermistor (model 90058, Mallinckrodt Medical, inc., St. Louis, MO) inserted into the external ear, positioned as close to the tympanic membrane as possible (Figure 3.12). Cotton swabs and non-transporous tape were used to secure the tympanic temperature sensor in place and prevent ambient air from entering the ear canal. Both temperature probes were used to account for any possible local cooling effect due to seating position of the participant in the life raft. Esophageal temperature was not measured because of the risk of motion sickness.

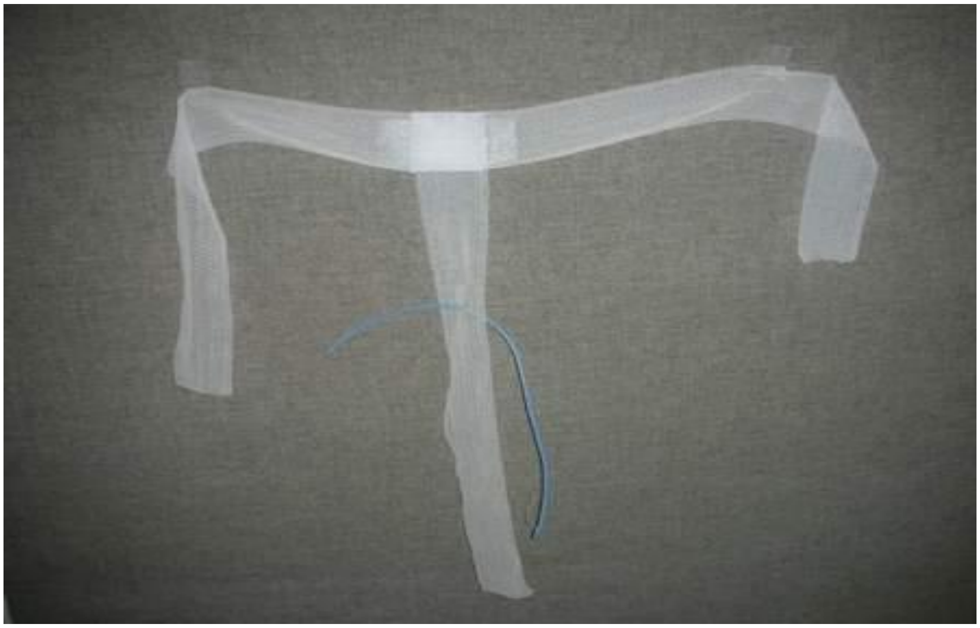


Figure 3.11 T-bandage and rectal temperature sensor.

Figure 3.12 Tympanic temperature sensor.

3.8.3 Skin temperature and heat flow

Skin temperatures and heat flow were measured using heat flow transducers (HFTs) with integrated thermistors (model R-025-TH44033-F6, Concept Engineering, Old Saybrook, CT). These HFTs are most commonly used to measure the dry component of the body heat loss. To ensure that the HFTs accurately reflect the wet component of the body heat loss a validation study was conducted to compare the sensors to direct calorimetry (Appendix D). No significant differences were reported between the heat loss measured by the HFTs and direct calorimetry for the dry and wet conditions. Thus, the HFTs are a valid method of measuring dry and wet heat loss components of the total skins heat loss.

The HFTs were located at 13 sites (Figure 3.13) similar to Hardy and Dubois 12-point system (Hardy & Dubois, 1939). The two extremity sites (hands and feet) were not considered because their ability to vasoconstrict minimizes any contribution to the heat loss of individuals exposed to cold. The two sites plus one extra were relocated to the left posterior thigh, left calf, and right buttock. Since the participants were instructed to sit semi-passively with freedom to adjust their posture and legs for comfort, these additional sites more accurately monitored heat loss into the floor compared to Hardy and DuBois 12-point system that assumes homogeneous heat loss for the right and left side of the body. Due to the non-uniform thermal environment and variation over time in seating postures, heat loss could not be assumed to be homogeneous between the right and left posterior legs. To prepare the 13 sites for HFTs, the skin was shaved and cleansed with alcohol. Two-inch transpore tape was used to secure the HFTs to the skin.

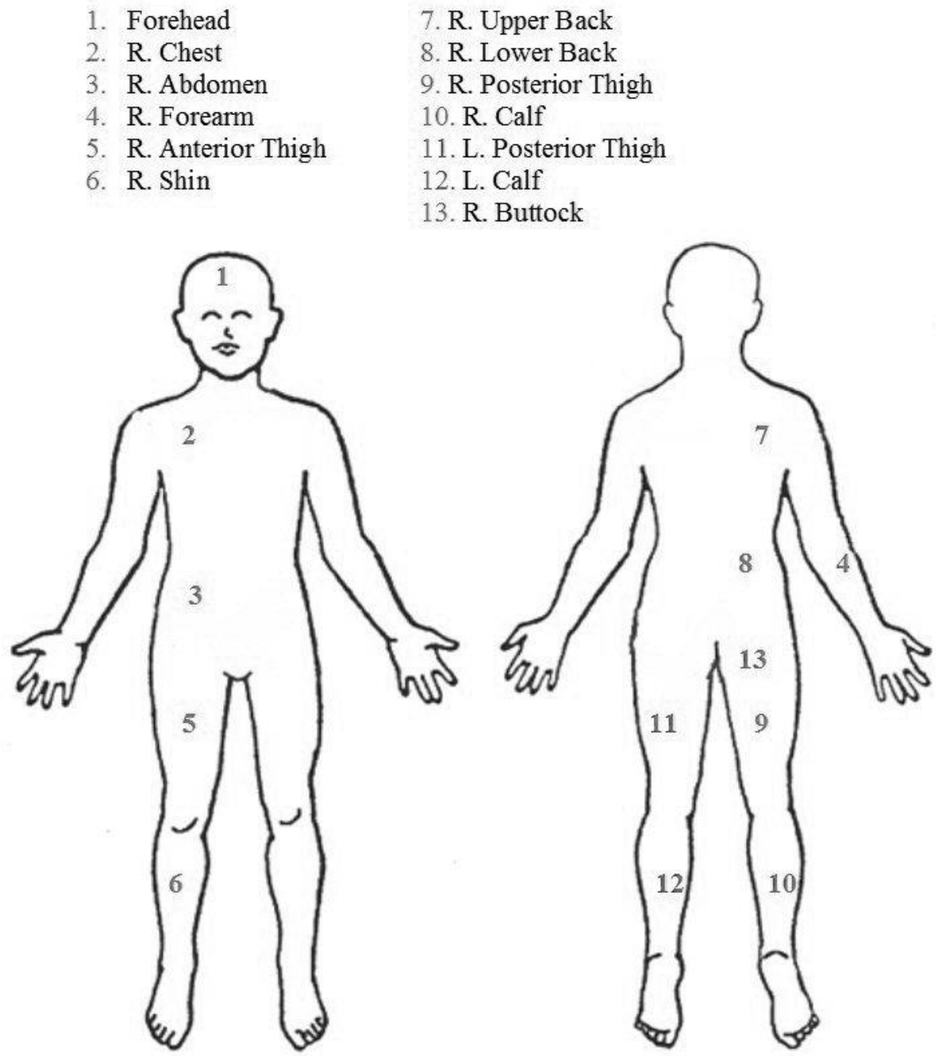


Figure 3.13 Thirteen sites for heat flux transducers.

3.8.4 Indirect calorimetry

During the test, oxygen uptake ($\dot{V}O_2$) and carbon dioxide output ($\dot{V}CO_2$) were measured using one of two portable cardiopulmonary indirect breath-by-breath calorimetry systems (MetaMax 3B ®; Cortex Biophysik, Leipzig, Germany and K4b^2; Cosmed, Rome, Italy) using a Nafion filter tube and a turbine flow meter (Opto-electric). Both systems used electrochemical cells and infrared techniques as O_2 and CO_2 sensors, respectively. Prior to baseline testing, volume and gas analyzers were calibrated with a 3-liter calibration syringe and medically certified calibration gases (14% O_2 and 5% CO_2), respectively. All calibrations were performed in a thermal neutral environment, the same location where baseline measurements from the participants were recorded. Following baseline testing, both systems were given ample time to acclimatize to the 5^{o}C testing environment to minimize chance of equipment drift due to temperature.

3.8.5 Thermal comfort level

The McGinnis Thermal Comfort 13-point Scale (Table 3.4) was used to assess the thermal comfort of the participants (Hollies & Goldman, 1977). Post baseline and during cold exposure participants were presented with a printed copy of the thermal comfort scale and asked to report his/her thermal comfort level during the baseline and cold exposure trials.

Table 3.4 The McGinnis Thermal Comfort 13-point Scale.

McGinnis Thermal Comfort Scale	
My body feels:	
1	So cold I am helpless
2	Numb with cold
3	Very cold
4	Cold
5	Uncomfortably cool
6	Cool but fairly comfortable
7	Comfortable
8	Warm but fairly comfortable
9	Uncomfortably warm
10	Hot
11	Very hot
12	Almost as hot as I can stand
13	So hot I am sick and nauseated

3.8.6 Postures and movements within the life raft

Two video cameras were positioned in the interior of the life raft at such angles to observe the participants from the tow carriage at all times. The captured video was further used to observe changes in participant's postures.

3.9 Protocol

Participants were recruited using posted advertisements. During the recruitment process, the participant was provided with sufficient information to assist them in their decision to participate.

3.9.1 Familiarization trial

Each participant participated in a one-hour familiarization trial a minimum of two days and a maximum of 16 days prior to testing. The participant was introduced to the equipment and was exposed to the most severe condition (wet-uninflated). This allowed the participant to make an informed decision whether to participate or not. This strategy was used to minimize the risk of participant dropout during the experimental trials.

3.9.1.1 Familiarization Set up

The familiarization trial was conducted in the large cold room at the NRC-IOT. The 5.5m by 1.3m room was equipped with a Freon gas based cooling system that could regulate the temperature between –10^{o}C and +20^{o}C. For this familiarization session the temperature was controlled at +5^{o}C.

A simulation of the life raft was constructed of a two person inflatable boat, which was modified with an inflatable pillow to simulate the two side chambers of the life raft. The floor chamber of the inflatable boat remained deflated to simulate the uninflated floor condition. A large bag was filled with water and placed under the simulated life raft. Three days prior to the first familiarization session the equipment was set up and the cooling system was activated to allow the water and equipment to acclimatize to the ambient temperature (Figure 3.14).

Figure 3.14 Familiarization set up.

3.9.1.2 Familiarization Protocol

The participant signed and completed the consent form and medical history questionnaire at which time they were given opportunity to ask questions about the experiment. After consent was obtained a researcher recorded the participant's stature, mass, and skinfold thickness measurements.

The participant was given written and verbal instructions on how to self-insert the rectal temperature sensor. A researcher then assisted in the insertion of the tympanic temperature sensor. The participant donned the clothing ensemble without the SOLAS lifejacket. In a non-stressed thermal environment, baseline measures were recorded for 10 minutes. A handheld pressurized garden sprayer was then used to wet participants with temped water. It was determined that one litre of water would saturate the clothing ensemble. Subsequent to the wetting the participant donned the SOLAS lifejacket. The participant entered the cold room and was instructed to sit passively in the simulated life raft. The trial was terminated after 60 min or when both the rectal and tympanic temperatures dropped below 35^{o}C.

The participant was transported to a warm room and provided with thermal blankets, hot water bottles and warm beverages. Rectal and tympanic temperatures were monitored during the rewarming process. Once the participant's rectal and tympanic temperatures reached 36^{o}C the instrumentation was removed, tympanic temperature was checked with a handheld tympanic thermometer, and visual examination of the ear canal and tympanic membrane was performed with an otoscope to ensure no damage had been done to the ear.

3.9.2 Experimental trials

The participant was exposed to each experimental condition in pairs, with attempts made to keep the same participants paired for all four conditions, WU, WI, DU, and DI. The order of conditions was randomized for each pair of participants. Each exposure was a maximum duration of 480 min, with a minimum of two days and maximum of ten days between exposures.

3.9.2.1 Participant preparation

Mass was recorded prior to each trial to ensure no major changes over the four trials. Each participant was instrumented with a rectal temperature sensor, tympanic temperature sensor, and 13 HFTs. The participant then donned the clothing ensemble without the SOLAS lifejacket. Protected from the cold by wool blankets, the participant was assisted from the preparation area to the carriage control room to perform baseline measures. In the carriage control room blankets were removed. The participant then sat while being instrumented with a portable indirect calorimetry system.

3.9.2.2 Data collection

The participant's rectal, tympanic, and skin temperature and heat flow sensor monitoring cables were connected to a computerized data acquisition system. All the data were collected at 1Hz, with the exception of metabolic data, which were collected breath-by-breath.

3.9.2.2.1 Baseline

The participant was given a minimum of 20 minutes rest in the thermal neutral carriage control room prior to collection of baseline measures. During the 20 minutes the participant's instrumentation was connected to the data acquisition system and signal verification was performed for all channels. Following signal verification a 5-minute baseline measures was collected for each participant. Post baseline, the participant was asked to report his/her thermal comfort level during the baseline. The indirect calorimetry systems were removed from the participant and instrumentation was disconnected from the data acquisition system. The participant was wrapped in wool blankets and assisted to the preparation area.

3.9.2.2.2 Transition

In the preparation area, the participant was given one last opportunity to urinate before entering the life raft. For the dry trials, the participant would sit passively and wait for a minimum of 10 minutes. For the wet trials, two handheld pressurized garden sprayers were used to wet the participant's clothing. The same two researchers performed the wetting for the duration of the experiment to ensure consistency. The quantity of water was determined by coverall size for each participant (Table 3.5 and Table 3.6).

Table 3.5 Quantity of water for coverall size.

Coverall size	Quantity of water (L)
34	0.8
36	0.8
38	1.0
40	1.2
42	1.2
44	1.4
46	1.4

Table 3.6 Individual participant's coverall sizes.

Participant	Coverall size
1	46
2	44
3	38
4	42
5	36
6	34
7	40
8	38

The participant donned the SOLAS lifejacket and was protected from the cold with a wool blanket. For the wet trials a foil blanket was used to minimize water transfer from the participant's clothing. The participant was then moved to the ice tank area where they were instrumented with the indirect calorimetry systems.

3.9.2.2.3 Towing trials

The participant was assisted into the life raft and asked to sit semi-passively but with freedom to alter the sitting posture. Participant instrumentation was connected to the data acquisition system and signal verification was performed. The blankets were removed and the canopy entrance was closed. The life raft was moved away from the floating platform to the start point, at which time the fans were activated. When the fans were running, towing and collection of data began simultaneously.

During all trials the indirect calorimetry system mask was removed periodically to assess the participant's state of awareness. While the mask was removed any accumulated condensation was dried. During wet conditions a handheld pressurized garden sprayer was used to wet the participant with temped water. To ensure the participant remained wet during the testing they were rewetted every 60 min with 50% of the initial quantity of water, more than the rate of evaporation. The participant was sprayed on the shoulders, arms, sides of torso, lower abdomen, groin, anterior legs, posterior legs, and back. The life jacket prevented the rewetting of the chest and upper abdomen areas.

Trials were terminated based on one of the following criteria: when rectal and tympanic temperatures dropped below 35^{o}C, exposure time reached 480 min, the participant refused to continue, or a researcher deemed it was no longer safe to continue. At the end of each trial the participant was asked to report his/her thermal comfort level during the exposure.

3.9.2.3 Re-warming

The participant was assisted from the life raft and transported to the re-warming room in a horizontal position via stretcher. The participant remained in the horizontal position and was provided with insulative blankets, hot water bottles and warm beverages. Rectal and tympanic temperatures were monitored during the rewarming process. When both temperatures reached 36^{o}C and the participant and researcher agreed it was safe, the instrumentation was removed from the participant. Following removal of the experimental instrumentation, the participant continued the re-warming process in a warm shower. After re-warming, tympanic temperature was checked with a handheld tympanic thermometer, and visual examination of the ear canal and tympanic membrane was performed with an otoscope to ensure no damage had been done to the ear.

3.10 Data reduction

The breath-by-breath metabolic data were re-sampled at 1 Hz and all time series data were then synchronized. All exposure data (rectal and tympanic temperature, skin temperature and heat flow, and metabolic measures) were normalized by subtracting the mean baseline corresponding to each participant and condition.

3.10.1 Anthropometrics and body composition

An estimation of body surface area (SA in m^2) was derived using height and weight (Gehan & George, 1970) (Equation 3.1).

$$SA = 0.1644 \times WT^{0.51456} \times HT^{0.42246}$$

Equation 3.1 Body surface area.

To calculate body composition the mean of the two skinfold measures that most closely matched was calculated for each site. If three measures were recorded and all three measures were equidistant, the mean of all three measures was calculated. The sum of the seven sites was then used to calculate body density (Jackson & Pollock, 1978) (Equation 3.2).

$$\text{(a) } BD = 1.112 - 0.00043499(sum7) + 0.00000055(sum7)^2 - 0.00028826(age)$$

$$\text{(b) } BD = 1.0970 - 0.00046971(sum7) + 0.00000056(sum7)^2 - 0.00012828(age)$$

Equation 3.2 Body density (a) males (b) females.

An estimation of body fat percentage was calculated using the Jackson and Pollock's calculated body density and Siri's equation of body fat (Siri, 1956) (Equation 3.3).

$$\%Fat = 495 / BD - 450$$

Equation 3.3 Percent body fat.

3.10.2 Skin temperature and heat flow

A correction factor of 1.03 was applied to the HFTs (Firm & Ducharme, 1993). A modified Hardy and DuBois weighting system was then used to calculate the mean skin temperature (T_{sk}) and heat flow (HF) (Hardy & DuBois, 1939) (Equation 3.4).

(a)

$$\begin{aligned} T_{sk} = [&0.07(T1) + 0.088(T2) + 0.088(T3) + 0.14(T4) + 0.095(T5) + 0.065(T6) \\ &+ 0.088(T7) + 0.088(T8) + 0.02375(T9) + 0.0325(T10) \\ &+ 0.02375(T11) + 0.0325(T12) + 0.0475(T13)]/0.882 \end{aligned}$$

(b)

$$\begin{aligned} HF = [&0.07(HF1) + 0.088(HF2) + 0.088(HF3) + 0.14(HF4) + 0.095(HF5) \\ &+ 0.065(HF6) + 0.088(HF7) + 0.088(HF8) + 0.02375(HF9) \\ &+ 0.0325(HF10) + 0.02375(HF11) + 0.0325(HF12) \\ &+ 0.0475(HF13)]/0.882 \end{aligned}$$

Equation 3.4 Mean (a) skin temperature (b) heat flow.

The modifications to Hardy and DuBois' weighting system were due to the exclusion of the hand and foot measures and the addition of three posterior measurement sites. The sum of the weighting factors equalled 0.882 because the extremities were not included. To compensate, T_{sk} and HF were divided by a factor of 0.882. The left and right posterior thighs, and buttock, were treated as Hardy and DuBois' posterior thigh. The right and left posterior thighs had a combined weighting factor equal to the buttock. The right and left calf had equal weighting factors that when combined equalled Hardy and DuBois' calf. The sites and their respective weighting factors are presented in Table 3.7.

Table 3.7 Comparison of current experiment and Hardy and DuBois' weighting factors (Hardy & DuBois, 1939).

Site Number	Site Description	Weighting Factors for Current Experiment	Weighting Factors for Hardy and DuBois
1	Forehead	0.07	0.07
2	R Chest	0.088	0.088
3	R Abdomen	0.088	0.088
4	R Forearm	0.14	0.14
5	R Anterior Thigh	0.095	0.095
6	R Shin	0.065	0.065
7	R Upper Back	0.088	0.088
8	R Lower Back	0.088	0.088
9	R Posterior Thigh	0.02375	0.095
10	R Calf	0.0325	0.065
11	L Posterior Thigh	0.02375	-
12	L Calf	0.0325	-
13	R Buttock	0.0475	-
	Hand	-	0.05
	Foot	-	0.07

3.10.3 Rectal and tympanic temperature

As a result of the non-uniform thermal environment, with the coldest exposure at the buttock, there was speculation that localized cooling might occur in the rectal region of the body during this experiment. Therefore, tympanic temperature (T_{ty}) was used as the primary estimate of core temperature. Since further calculations are based on rectal temperature (T_{re}) and T_{ty} is lower by nature, the T_{ty} was adjusted up by the difference between the start points of the T_{re} and T_{ty}, specific to each participant and condition (Equation 3.5).

$$T_{adj_n} = T_{ty_n} + (T_{re_{start}} - T_{ty_{start}})$$

Equation 3.5 Adjusted tympanic temperature.

3.10.4 Mean body temperature

Mean body temperature (T_B) is the averaged temperature over the whole body and is a weighted balance between the temperatures of the core and peripheral (Parsons, 2003). In this study temperature of the core and peripheral are represented by T_{ty} and T_{sk}, respectively. The T_{sk} and adjusted tympanic temperature (T_{adj}) were used to calculate mean body temperature (T_B). The T_{adj} was weighted heavier than the T_{sk} at 0.65 and 0.35, respectively (Burton, 1935) (Equation 3.6).

$$T_B = 0.65(T_{adj}) + 0.35(T_{sk})$$

Equation 3.6 Mean body temperature.

3.10.5 Heat production

Heat production is quantified as metabolic rate (MR), which was calculated using Equation 3.7 (Peronnet & Massicotte, 1991):

$$MR = (281.65 + 80.65 \cdot RER) \cdot \frac{Vo_2}{SA}$$

Equation 3.7 Metabolic rate.

where $\dot{V}o_2$ is the oxygen consumption measured in $l \cdot min^{-1}$, SA is body surface area in m^2, and RER is the respiratory exchange ratio ($\dot{V}co_2$/ $\dot{V}o_2$). However, since $\dot{V}co_2$ values were invalid we set RER at a constant value of 0.85. This is done without large error because RER has little influence on MR.

3.11 Statistical analysis

Duration, temperature, heat flow, metabolic rate, and thermal comfort data were analyzed using a two factor ANOVA with repeated measures [2 (clothing) x 2 (floor)]. F ratios for main effects and interactions were considered significant at $p<0.05$. When significance ($p<0.05$) was found, a post hoc test was performed to locate significance among the means. As well, the Mauchly's test of sphericity was used to test if the variance of the difference between all combinations of related groups were equal. The Statistical Package for Social Sciences (SPSS) was used for all statistical analyses (SPSS Inc., Chicago, USA). Descriptive statistics include means ± SD.

Chapter 4 Results

4.1 Introduction

Measures of skin, rectal, and tympanic temperature; heat flow; oxygen consumption; and thermal comfort were collected during baseline and exposure in four different conditions. Mean body temperature and metabolic rate were calculated from tympanic and mean skin temperature; and oxygen consumption, respectively.

Due to the different durations of conditions, the difference between the first five minutes and last five minutes of exposure were calculated for T_{sk}, T_{re}, T_{ty}, and T_B. These deltas were then divided by delta time to allow for analysis of the rates of temperature change. Since HF and MR do not change in a constant direction during exposure, the moving averages were calculated. All the data presented in this chapter are in aggregate form.

4.2 Baseline

Pre-exposure measures of T_{sk}, HF, T_{re}, T_{ty}, T_B, MR, and thermal comfort were recorded for four trials, WU, WI, DU, and DI (Table 4.1). No significant differences were observed in the thermal responses between the four trials during the pre-exposure with the exception of T_B (indicated with a * in the table). Even though T_B was significantly ($p=0.003$ and $p=0.019$) greater for DI (35.64 ± 0.26 ^oC) compared to WU (35.41 ± 0.19 ^oC) and WI (35.47 ± 0.27 ^oC), the differences were slight reaching only 0.23 ^oC and 0.17 ^oC, respectively. These outcomes represent the biological variations within participants.

Table 4.1 Mean baseline measures.

	WU	**WI**	**DU**	**DI**
T_{sk} (^oC)	32.78 ± 0.55	33.08 ± 0.73	33.05 ± 0.51	33.16 ± 0.55
HF_{sk} ($W*m^{-2}$)	63.75 ± 6.83	57.59 ± 6.68	61.43 ± 4.61	58.49 ± 5.98
T_r (^oC)	36.82 ± 0.13	36.76 ± 0.22	36.84 ± 0.17	36.98 ± 0.17
T_{ty} (^oC)	36.38 ± 0.10	36.31 ± 0.19	36.42 ± 0.30	36.44 ± 0.23
T_B (^oC)	35.41 ± 0.19*	35.47 ± 0.27	35.52 ± 0.19*	35.64 ± 0.26*
MR ($W*m^{-2}$)	88.15 ± 30.93	99.31± 35.80	100.88 ± 37.30	95.17 ± 40.52
Comfort	6.81 ± 0.53	6.88 ± 0.83	7 ± 0.00	7.13 ± 0.64

4.3 Duration of Conditions

A core temperature (T_{re} and T_{ty}) drop to 35^{o}C was achieved in seven participants during exposure to three conditions (4-DU, 2-WU, and 1-DI). Six trials were terminated early upon participants request because of intolerable discomfort (painful numbing and/or cramping and/or need to urinate). Termination by participant's request occurred more often during wet exposures (3-WI and 2-WU) then dry exposures (1-DI). Participant 2 (WI) and participant 4 (DU) were terminated early because a shift in equipment which resulted in a lower reading of core temperature. The remainder 17 trials continued for the full duration of 6.75h to 8.25h. Full duration varied due to delays in start time and fixed end time. Participants were exposed to the dry trials, DU (6.49 ± 1.07 hr) and DI (7.76 ± 0.52 hr), for longer durations of conditions than the wet trials, WU (6.37 ± 2.15 hr) and WI (6.10 ± 1.29 hr). While there was a significant difference (p=0.050) in the duration of the conditions for the clothing wetness, there was no significant difference (p=0.480) in the duration of the conditions for the floor insulation (Figure 4.1).

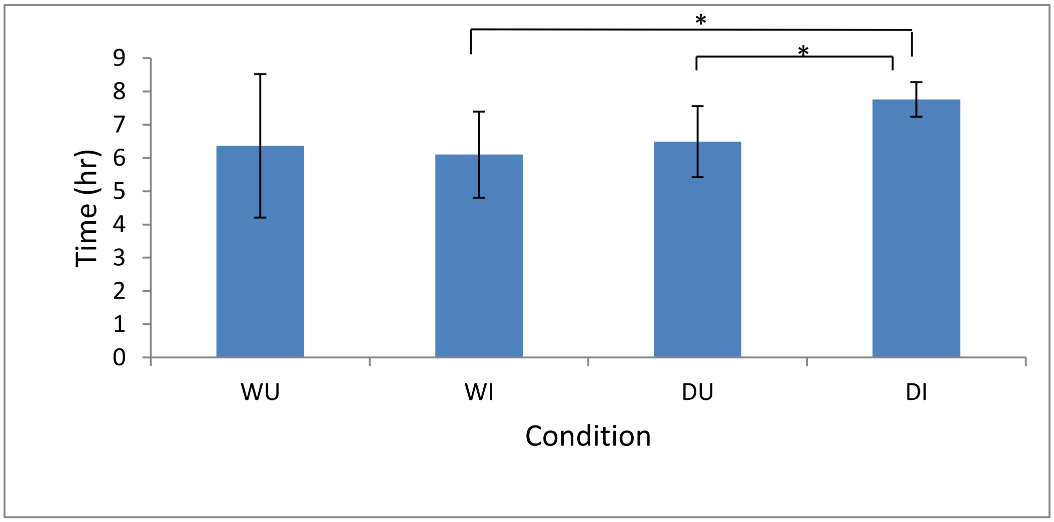


Figure 4.1 Mean duration of conditions in hours.

4.4 Mean skin temperature and heat flow

In the wet conditions ΔTsk/Δt was (-0.78 ± 0.17 ^{o}C/hr) and (-0.78 ± 0.24 ^{o}C/hr), for WU and WI respectively. In the dry conditions ΔTsk/Δt was (-0.57 ± 0.11 ^{o}C/hr) and (-0.41 ± 0.11 ^{o}C/hr), for DU and DI respectively. A repeated measure ANOVA showed no significant difference (p=0.091) for the floor insulation. There was a significant difference (p<0.0001) for the clothing wetness (Figure 4.2).

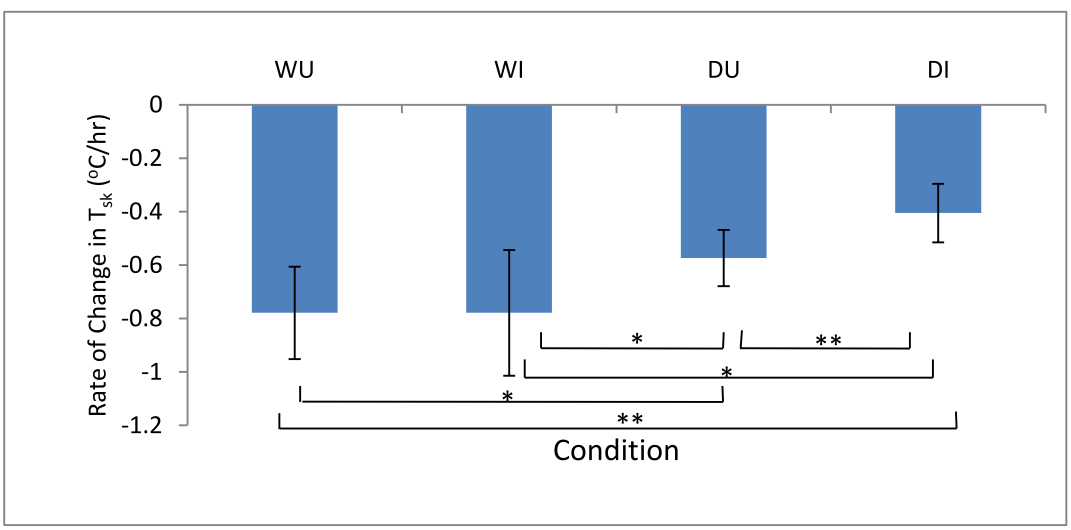


Figure 4.2 Mean rate of change in mean skin temperature for each condition.

Similar to the rate of change in T_{sk}, the floor had no significant ($p=0.135$) effect on the mean HF, however clothing wetness did have a significant ($p<0.0001$) effect on the mean HF. The mean HF was significantly greater for the wet conditions, WU (183.21 ± 29.27 $W \cdot m^{-2}$) and WI (171.95 ± 29.64 $W \cdot m^{-2}$), compared to the dry conditions, DU (124.59 ± 32.53 $W \cdot m^{-2}$) and DI (120.67 ± 23.03 $W \cdot m^{-2}$) (Figure 4.3).

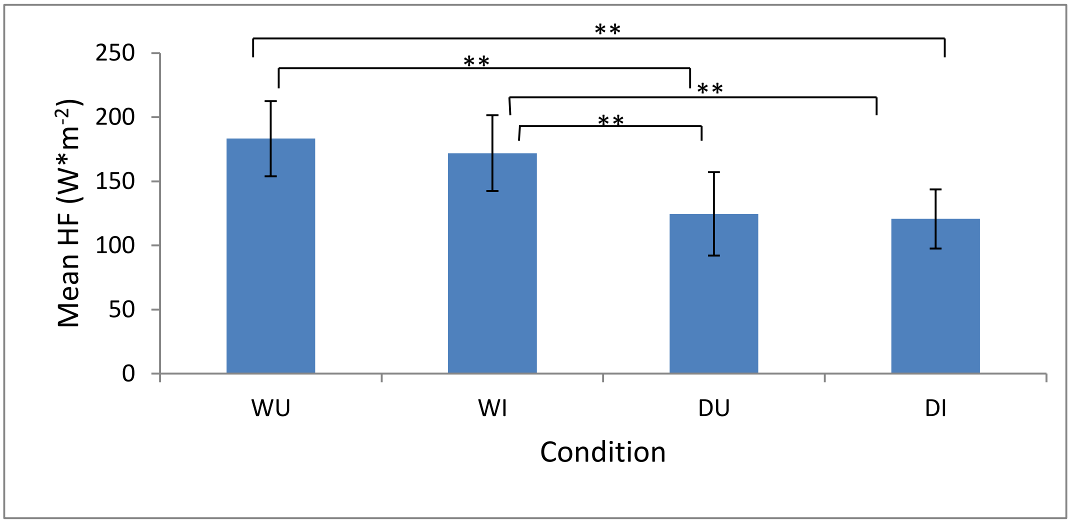


Figure 4.3 Mean heat flow for each condition.

4.5 Rectal and tympanic temperature

At the end of the exposure, T_{re} and T_{ty} had decreased from the baseline measurements for all conditions. T_{re} had decreased to a lower temperature for the uninflated conditions, WU (34.95 ± 0.73 ^oC) and DU (34.76 ± 0.69 ^oC), compared to the inflated conditions, WI (35.65 ± 0.50 ^oC) and DI (35.72 ± 0.49 ^oC). As a result, the rate of decrease for T_{re} was greater ($p=0.079$) for the uninflated conditions, WU (-0.44 ± 0.43 ^oC/hr) and DU (-0.34 ± 0.12 ^oC/hr), compared to the inflated conditions, WI (-0.24 ± 0.09 ^oC/hr) and DI (-0.17 ± 0.06 ^oC/hr) (Figure 4.4).

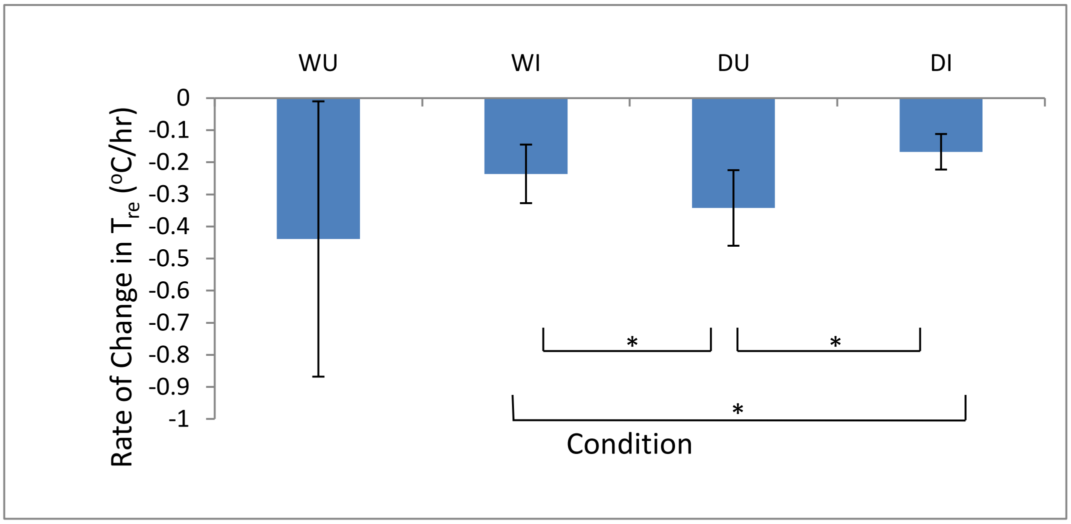


Figure 4.4 Mean rate of change in rectal temperature for each condition.

T_{ty} decreased to similar values across all four conditions: WU (35.63 ± 0.47 ^{o}C), WI (35.12 ± 0.82 ^{o}C), DU (35.34 ± 0.58 ^{o}C), and DI (35.30 ± 0.41 ^{o}C). Figure 4.5 shows that the rate of change in T_{ty} is similar across all four conditions: WU (-0.14 ± 0.16 ^{o}C/hr), WI (-0.12 ± 0.04 ^{o}C/hr), DU (-0.14 ± 0.09 ^{o}C/hr), and DI (-0.11 ± 0.06 ^{o}C/hr).

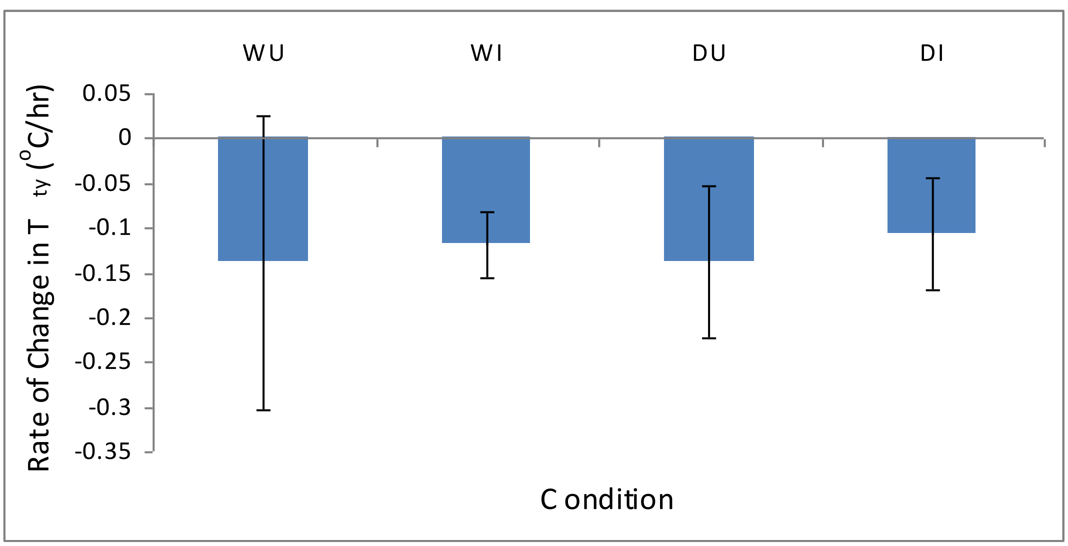


Figure 4.5 Mean rate of change in tympanic temperature for each condition.

4.6 Mean body temperature

The rate of decrease in T_B is significantly ($p=0.002$) greater for the wet conditions, WU (-0.36 ± 0.13 $^oC/hr$) and WI (-0.34 ± 0.07 $^oC/hr$), compared to the dry conditions, DU (-0.29 ± 0.08 $^oC/hr$) and DI (-0.21 ± 0.05 $^oC/hr$),). Even though the floor insulation has no significant ($p=0.131$) effect on T_B, the rate of decrease in T_B is significantly less for DI compared to all other conditions (Figure 4.6).

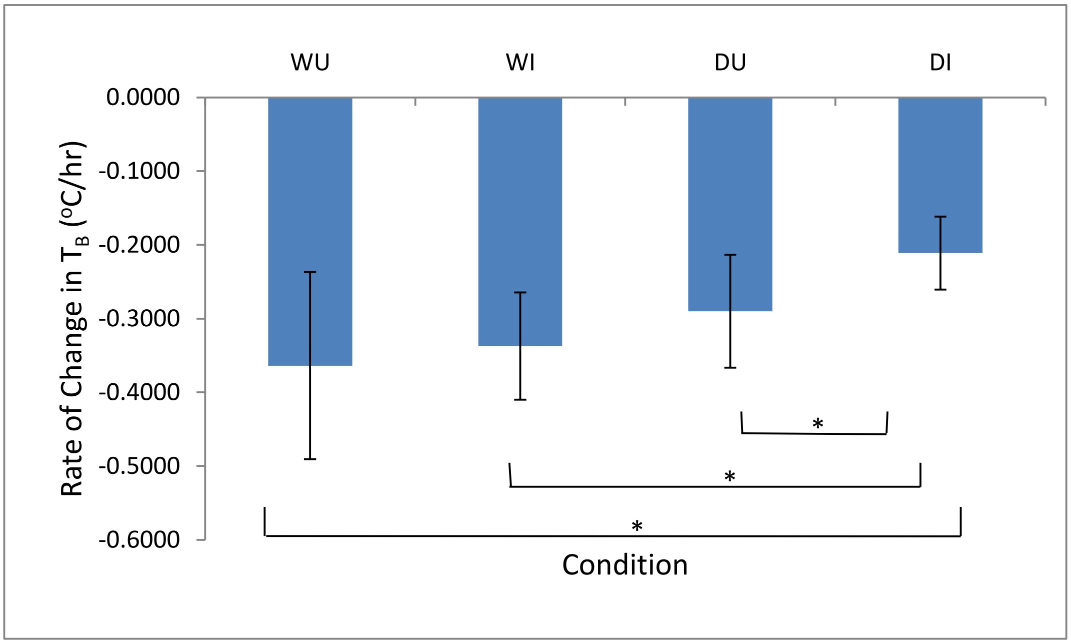


Figure 4.6 Mean rate of change in mean body temperature for each condition.

4.7 Heat production

Mean MR was greater during the exposures than baselines for all conditions with a more significant ($p<0.0001$) increase during the wet conditions, WU (65.17 ± 27.12 $W \cdot m^{-2}$) and WI (69.48 ± 44.39 $W \cdot m^{-2}$), compared to the dry conditions, DU (37.90 ± 28.89 $W \cdot m^{-2}$) and DI (5.44 ± 39.00 $W \cdot m^{-2}$). Similar to T_{sk} and HF, the floor has no significant ($p=0.158$) effect on the change in mean MR during exposure. However, the mean MR during DI is significantly less than the mean MR for all other conditions. As well, the mean MR is significantly ($p=0.006$) less during DU compared to WI (Figure 4.7).

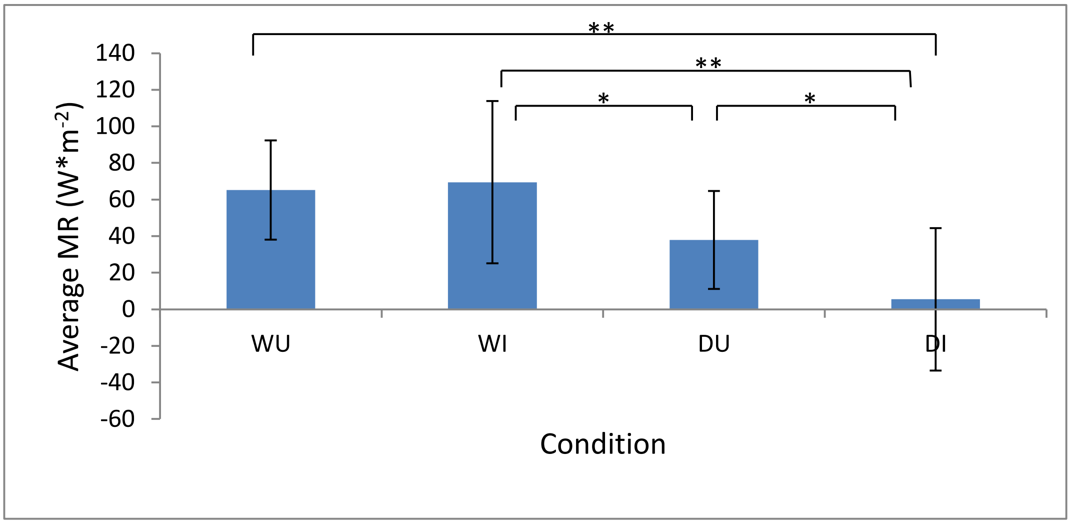


Figure 4.7 Mean metabolic rate for each condition.

4.8 Thermal comfort level

The participant's change in thermal comfort level agrees with T_{sk}, HF, T_B, and MR, showing a more significant ($p=0.001$) effect of clothing wetness, WU (-4.81 ± 1.00) and WI (-4.19 ± 1.53), compared to floor insulation, DU (-3.81 ± 0.80) and DI (-2.31 ± 1.16). Participants reported that the thermal condition was significantly less comfortable for all conditions compared to DI (Figure 4.8).

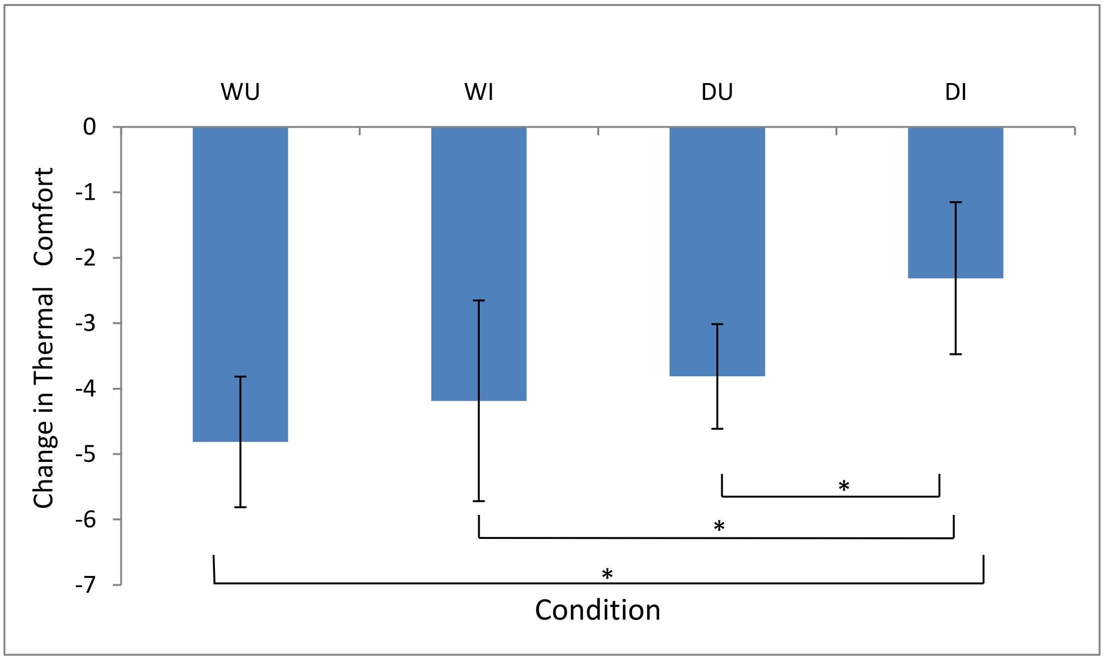


Figure 4.8 Change in thermal comfort level after cold exposure for each condition.

Chapter 5 Discussion

5.1 Introduction

In recent years, more Arctic shipping lanes have opened up resulting in an increase in passenger vessel activity and in discussions of increased activity in petroleum exploration in the Arctic region. With this increase of activity also comes an increase in probability of a maritime disaster occurring in these colder regions. In light of this increased probability of a maritime disaster occurring in the Arctic, the maritime industry must ensure that the available survival equipment can provide the proper thermal protection to all persons while awaiting rescue.

While the IMO (1996) states that all SOLAS approved life rafts must provide sufficient insulation against the cold, reports still indicate that there are incidences of hypothermia among life raft survivors (Marine Accident Investigation Branch, 2014). These reports of hypothermia are an indication of shortcomings in the construction of life rafts. To date life raft design has been driven by tests on the individual components of the life raft, while no previous testing has been performed on the entire life raft – occupant system. This study evaluates the thermal properties of the life raft – occupant system to determine the effects of floor insulation and clothing wetness on the occupant's thermal response.

The results of this study indicate that life raft floor insulation and clothing wetness during cold exposure do impact the thermal response of a life raft occupant. This chapter will discuss the thermal responses of a life raft occupant without additional thermal protection exposed to cold conditions.

5.2 Occupant Thermal Response

5.2.1 Duration of condition

Trials were terminated based on any one of the following criteria: core temperature (both T_{re} and T_{ty}) dropped to 35^{o}C, the scheduled trial end time was reached (max 8.25 hrs), or the participant refused to continue. Out of a 32 individual trials approximately 22% were terminated because the core temperatures dropped to 35^{o}C, approximately 53% endured the full scheduled exposure without a core temperature drop to 35^{o}C, approximately 19% were terminated upon the participant's request due to discomfort caused by the cold, approximately 3% were terminated due to participants discomfort caused by the need to urinate, and 3% were terminated due to equipment error.

Five of the seven trials that were terminated due to a drop in core temperature were during dry conditions. Four of these five trials were during uninflated floor conditions. Only two wet trials were terminated due to a drop in core temperature. There were less wet compared to dry trials terminated due to a drop in core temperature because more participants refused to continue during the wet trials before a core temperature of 35^{o}C was achieved. Five of the six trials terminated upon participants request were during wet conditions. These requests were due to pain or cramping from the cold and shivering. There was one dry trial where a participant refused to continue because of the need to urinate. The one occurrences of equipment error involved malfunction of the tympanic temperature sensor for participant 2 during the wet-inflated condition. This resulted in a reduced exposure time of 4.83 hrs.

Overall the DI and WI conditions had the longest and shortest average exposure times, respectively (Figure 4.1). While one might have expected WU to have the shortest exposure time, there was no significant difference between the exposure times for WU and WI. The duration of exposures with wet clothing were significantly shorter compared to the duration of exposures with dry clothing, and the floor inflation had no significant effect on exposure time. Since there were a number of termination criteria, exposure time alone is not a good measure to determine the impact of floor insulation and clothing wetness on survival time. Thus, the effects of floor insulation and clothing wetness on thermal responses are discussed in this chapter.

5.2.2 Mean skin temperature and heat flow

Clothing wetness had a significant effect on the rate of decrease in T_{sk} and mean HF (section 4.4). Since water has a thermal conductivity 25 times greater than air (Brooks, 2003), it is no surprise that the rate of decrease in T_{sk} and mean HF were significantly greater with wet clothing compared to dry clothing. In addition to the increased convective heat loss because water has a greater thermal conductivity than air, when clothing is wet the insulating layer of air is compressed and the clo units of insulation decrease (Noakes, 2000). In the instance of the Four Inns Walking Competition disaster where people died from hypothermia, the wet clothing found on those who died had about one-tenth the clo units as the same clothing when dry (Pugh, 1966). This emphasizes the importance of staying dry during a life raft survival situation.

While floor insulation had no significant effect on rate of change in T_{sk} and mean HF, both the rate of decrease in T_{sk} and mean HF were slightly greater for the uninflated floor conditions compared to the inflated conditions. The little difference between uninflated and inflated floor conditions may have been the result of the participants' postures. The size of the contact area is one of the factors that impact the amount of heat loss by conduction (Golden & Tipton, 2002). Since the participants assumed a sitting fetal posture for the majority of the trials the contact area with the floor was minimized, reducing conductive heat loss to the floor. However, if a person is injured or unconscious and unable to assume a position that reduces the contact area with the floor, the floor insulation may have a greater effect on that life raft occupant's heat loss. It is important to minimize the contact area with an uninsulated life raft floor. This can be achieved by inflating the floor or removing your life jacket to sit on. It is recommended that the life raft is stable before removing your life jacket.

5.2.3 Rectal and tympanic temperature

In Phase 2 a significant decrease in T_{re} was observed for all test conditions. The greatest decrease in T_{re} was measured during the DU condition with no significant change in T_{sk}, HF or MR (Appendix E). Therefore, it was necessary to assess if the rectal temperature is a true indicator of the body core temperature when localized cooling is taking place around the buttocks. Basset et al (2011) from our research group did conduct a study to compare the response of three indices of core temperature: rectal, tympanic, and esophageal during exposure to localized cooling. This experiment confirmed that prolonged lower body surface cooling resulted in a localized cooling effect that compromises the validity of the T_{re} as a core temperature index. There was no difference in measurement between tympanic and esophageal probes throughout the different phases of the secondary experiment. The use of tympanic probes in the life raft setting was verified and tympanic probes were added to Phase 3 human participant testing.

At the end of all the trials in Phase 3, T_{re} and T_{ty} had decreased from the baseline measurements for all conditions. Clothing wetness and floor inflation had no significant effect on the rate of change in T_{re} and T_{ty} (section 4.5). However, the localized cooling effect was observed with greater rate of decrease in T_{re} during the uninflated conditions compared to the inflated conditions (Figure 4.4), while there was very little difference in the rate of decrease in T_{ty} between all four conditions (Figure 4.5). While the rate of decrease in the core temperatures was not significant, the DI condition had the lowest rate of decrease in T_{re} and T_{ty} compared to all other conditions. Therefore, the onset of hypothermia can be delayed if a life raft occupant has dry clothing and is sitting on an inflated floor compared to wet clothing and/or uninflated floor.

5.2.4 Mean body temperature

When looking at the thermal response of humans, the body can be subdivided into the core and the peripheral (Parsons, 2003). In this study temperature of the core and peripheral are represented by T_{ty} and T_{sk}, respectively. Mean body temperature (T_B) is the averaged temperature over the whole body and is a weighted balance between the temperatures of the core and peripheral (Parsons, 2003). When the body is exposed to cold stresses the cold thermal receptors in the skin increase firing rates, signalling the thermal control centers of the brain to decrease blood flow to the shell in an attempt to maintain temperature of the core. Therefore, any changes in core temperature are dependent on the capacity of the peripheral to reduce heat loss (Jessen, 2000). In this study, the rate of decrease in T_B was significantly greater for the wet conditions compared to the dry conditions, similar to that of T_{sk}, while there was no significant difference in rate of decrease in T_{ty} across the conditions.

If the environmental thermal stress is great enough, significant changes in T_B may not be reflected in changes to the core temperature (Jessen, 2000). In this study the rate of decrease in T_B was greater than the rate of decrease in T_{ty} for all conditions. Similarly, Webb (1993) demonstrated a greater decrease in T_B of approximately 5^oC compared to a decrease in T_{re} of approximately 1.5^oC. While core temperature helps define hypothermia, it does not change linearly when the body is under thermal stress. Therefore, it is important to take into consideration the whole body temperature when determining survival time or the rate at which hypothermia progresses.

Even though the floor insulation has no significant effect on T_B, the rate of decrease in T_B is significantly less for DI compared to all other conditions (Figure 4.6). This suggests that a life raft occupant with dry clothing sitting on an inflated floor will have a greater survival time compared to if they were wearing wet clothing and/or sitting on an uninflated floor.

5.2.5 Heat production

The action of shivering can increase MR to be five times greater than resting MR (Eyolfson et al, 1998; Rintamaki, 2007). In this study the intermittent shivering did not increase MR by five times for any conditions. However, MR did increase during the exposures compared to the baselines for all conditions, with a more significant increase during the wet conditions compared to the dry conditions (Figure 4.7). During the WU and WI conditions MR was approximately 1.75 and 1.7 times greater during the exposures compared to the baselines, and only 1.37 and 1.06 times greater during the DU and DI conditions respectively. Thus, the shivering duration and/or intensity were greater during wet conditions compared to dry conditions.

Similar to T_{sk} and HF, the floor had no significant effect on the average MR during exposure. However, the average MR was significantly greater during the DU condition compared to the DI condition. Therefore, in a dry life raft environment the addition of floor insulation may decrease the rate of energy expenditure which could increase survival time.

Overall, the average MR during DI was significantly less than the average MR for all other conditions. As well, the average MR was significantly less during DU compared to WI. Since MR is an indication of shivering intensity, it can be conclude that the shivering intensity was less during the DI condition. The greater the average MR, the faster the energy stores will be depleted resulting in a shorter duration of shivering and survival time. Therefore, a life raft occupant has a great chance of survival if they have dry clothing and an insulated floor compared to wet clothing and/or uninsulated floor.

5.2.6 Thermal comfort level

The participants’ change in thermal comfort level agrees with T_{sk}, HF, T_B, and MR, showing a more significant effect of clothing wetness compared to floor insulation. Participants reported that the thermal condition was significantly less comfortable for all conditions compared to DI (Figure 4.8). As discussed in the section on exposure duration, five out of the six exposures where participants refused to continue due to cold related discomfort were wet conditions.

Cold sensation is generally related to mean T_{sk}. However, cooling of the hands and feet may correlate with whole body thermal sensation rather than mean T_{sk} (Parsons, 2003). While extra thermal protection was provided for the hands and feet during this study, some participants did report discomfort because of cold hands and feet. That being said, T_{sk} likely did influence thermal comfort since T_{sk} and thermal comfort were less for all conditions compared to DI.

5.3 Occupancy Level and Ventilation

In Phase 1 a 4.4^{o}C increase in air temperature within a 16-person life raft at 69% capacity was observed in less than two hours (Mak et al, 2009c). However, it was not determined what impact this increase in air temperature had on the occupants' thermal response. In Phase 2, during mild cold exposure testing there were no noticeable differences in the thermal responses between the conditions involving 2 versus 6 occupants (Mak et al, 2009b). Thus, the heat generated with a relative occupancy level of 37.5% (i.e. 6 persons in a 16-person life raft) did not reduce heat loss compared to 12.5% occupancy level. Further testing can be conducted to determine if body-to-body heat transfer or occupancy level will impact heat loss in a cold life raft environment.

During the Phase 1 test with a 16-person life raft at 69% capacity the CO_2 concentration reached an uncomfortable level (> 5000 ppm) in less than an hour when the canopy was closed and no active ventilation was used. Further testing of the 16-person life raft at 12.5% and 37.5% capacity determined that a ventilation rate produced by wind fans at $5 m \cdot s^{-1}$ was sufficient to prevent significant CO_2 build-up. Therefore, no additional ventilation was used during this current study. However, it is recommended that rafts should have a mechanism for controlling ventilation to a level which is adequate for breathing but which will allow the internal temperature to rise to a comfortable, protective level.

5.4 Alternative Insulation

During Phase 3 additional testing was carried out (Mak et al, 2009a). A thermal manikin and limited number of human participants were used to assess the effect of different clothing and life raft floor scenarios on heat loss. Since there were a limited number of participants for the additional testing it is important to note that the results may not be representative of the general population.

Tests were carried out to determine if a thermal protective aid (TPA) would provide additional insulation. The manikin tests showed that the addition of a TPA provides considerable additional insulation in all conditions. The insulation increased most considerably in wet clothing conditions (61% and 54% in WI and WU conditions, respectively). A test with a human participant showed that wearing a TPA in the WU condition provided 48% more insulation compared to without a TPA. The difference between the manikin and human may be attributed to the fact that the contact area and behaviour of the human was not corrected for. The additional insulation provided by a TPA decreases heat loss and reduces energy expenditure (Golden & Tipton, 2002), increasing survival time.

Additional tests were carried out on two alternative barriers between the life raft floor and occupant: inflated pillow and lifejacket. In the DI condition, there was very little difference in insulation sitting on an inflated pillow or lifejacket compared to sitting on the inflated or closed cell foam floor of the life raft. In the WU condition, sitting on a life jacket provided great insulation compare to sitting directly on the uninflated floor or closed cell foam floor.

A final test was carried out to determine the effect of 10 cm of water on overall insulation value. Both the manikin and human tests found a significant decrease in insulation value. This emphasises the importance of taking the appropriate action to prevent water entry into the life raft and bail additional water. Overall chances of survival during cold exposure are greater with dry clothing. Adding a TPA is of substantial benefit and insulating the floor is of a lesser benefit. Having 10cm of water on the floor is greatly detrimental to a life raft occupant’s chance of survival.

5.5 Future Life Raft Standard Testing

To determine the insulation value of a life raft it is important to test the life raft – occupant system as one unit, opposed to tests on individual components. Wet clothing has significant adverse effect on occupant heat loss. Therefore, it is important to assess the impact of wet clothing on the system insulation. Floor insulation, although not as critical as dry clothing, is important in reducing occupant heat loss by conduction to the cold ocean. Floor insulation is an important part of system insulation. Innovative methods can be used to increase floor insulation without significantly increasing the bulkiness of the life raft. TPAs provided considerable additional insulation during exposures compared to baselines in all test conditions. It is important to include all auxiliary equipment and clothing as part of the system assessment. Ventilation rate control and number of occupants have moderate effects on occupant heat loss and comfort. It is usually not practical to reproduce realistic ventilation and occupant loading conditions. However, the testing should be done as closely as possible to realistic conditions.

Chapter 6 Conclusions and Recommendations

The primary question addressed by this study was whether or not clothing wetness or floor insulation affected the physiological thermal response and thermal comfort of human life raft occupants exposed to cold ambient temperatures.

If the study did not find that clothing wetness nor floor insulation had an effect on the thermal response of life raft occupants, there would be no reason to change the standards for thermal protection in life rafts. However, this study demonstrated that both clothing wetness and floor insulation have an effect on the physiological thermal response and thermal comfort of life raft occupants wearing minimal protective clothing. Clothing wetness had a significant effect on physiological thermal responses of T_{sk}, HF, T_B, and MR, and thermal comfort. While floor insulation did not have any significant effect on the physiological thermal response and thermal comfort, floor insulation did have the biggest effect on the T_{re}.

The recommendations for life raft standards or design are:

1. Life raft occupants should make every effort to stay dry. Since this is near impossible in most abandonment scenarios, life rafts should include some form of thermal protective apparel for every occupant.
2. Life rafts should include a system to keep the floor dry or enable every occupant to sit above the level of water on the floor.
3. Life raft floors should be insulated or every occupant should be able to sit on an insulated surface.
4. Life rafts should have a mechanism for controlling ventilation to a level which is adequate for breathing but which will allow the internal temperature to rise.

If these changes are implemented, it could decrease heat loss and increase survival time of life raft occupants wearing minimal protective clothing during cold exposures.

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Appendix A: Recruitment Poster

Want to participate in a research study?

Volunteers are needed for a study that will evaluate how the body temperatures of life raft occupants change in simulated evacuation scenarios.

- Contribute to our understanding of the thermal properties of liferaft design and enhance our abilities to save life at sea.

Who can participate?

- Anyone between 19-55 years of age.
- Healthy individuals

Who cannot participate?

- suffer from any medical condition aggravated by exposure to cold
- suffer from any medical condition affecting the rectal area
- suffer from any heart or respiratory illnesses
- currently take any heart or lung medications
- frightened of enclosed or confined places
- pregnant

Experimental Procedure: A few recording devices will be attached to your body and you will have to wear a lifejacket. You will sit in a liferaft, alone or with other persons, and will be towed under various conditions in a tow or ice tank.

Duration of subject participation: Approximately 5 hours

Where: NRC-Institute of Ocean Technology Building

When: Beginning December 2006

Risks and Discomforts: You will be exposed to cold environments that will cause you to feel uncomfortably cold and shiver. You will also be exposed to a moving environment, which may cause you to experience symptoms of motion sickness. You may also experience discomfort due to the insertion of the rectal probe and the shaving and cleaning of the skin in preparation for heat flux sensors. Since we are asking you to sit passively for up to 3 hours during the data collection, you might experience boredom or drowsiness.

To find out more, contact:

Kerri-Ann Evely, Institute for Ocean Technology, NRC, St. John's
743-4188 or Kerri-Ann.Evely@nrc-cnrc.gc.ca

Appendix B: Consent Form

School of Human Kinetics and Recreation
Memorial University of Newfoundland
And
Institute for Ocean Technology
National Research Council

Consent to Take Part in Research

TITLE: **Thermal Protection in Liferafts: Assessment of Occupant Heat Balance and Development of Performance Criteria**

INVESTIGATOR(S): **Scott MacKinnon, Ph.D.; Lawrence Mak, M. Eng., P. Eng., MBA; Kerri-Ann Evely BKin(Hons)**

SPONSOR: **Search and Rescue Secretariat**

You have been invited to take part in a research study. It is up to you to decide whether to be in the study or not. Before you decide, you need to understand what the study is for, what risks you might take and what benefits you might receive. This consent form explains the study.

The researchers will:

- **discuss the study with you**
- **answer your questions**
- **keep confidential any information which could identify you personally**
- **be available during the study to deal with problems and answer questions**

If you decide not to take part or to leave the study this will not affect your student or employment status or reputation within the community.

1. **Introduction/Background:**
Worldwide, inflatable liferafts are the primary evacuation units used by the majority of vessels at sea. In the event of an emergency vessel evacuation all passengers don the provided survival equipment, such as a lifejacket, and enter the liferaft from the vessel or water. If the passengers do not have additional thermal protection they are largely dependent on the thermal protection of the liferaft to prevent or minimize heat loss. While international standards currently require inflatable liferaft components to "provide insulation" there are no performance criteria for these requirements. In order to successfully assess and develop performance criteria, the study will gather information on how environmental conditions, raft factors and occupant factors affect thermal protection of the liferaft occupants and relate these variables to human temperature measures.

2. **Purpose of study:**
The purpose of this research is to measure subject heat loss while occupying a liferaft.

 Initials: ________

3. Description of the study procedures and tests:

When you arrive for testing you will be asked to change into the undergarments and shirt and shorts you brought with you. Your height and weight will then be recorded. You may then be instructed about the insertion of a disposable rectal probe and asked to complete the task. Once you are comfortable with this procedure, we will leave you to do this in private.

A researcher may attach up to 14 heat sensors to standardized locations on your skin. A male researcher will assist male subjects and a female researcher will assist female subjects in this process. The skin locations will be shaved and cleaned with rubbing alcohol prior to application. The sensors will be placed on the right side of the body and the locations include: Temple, Hand, Forearm, Upper Arm, Dorsal Trunk (Upper), Dorsal Trunk (Lower), Ventral Trunk (Upper), Ventral Trunk (Lower), Buttocks, Ventral Thigh, Dorsal Thigh, Ventral Shank, Dorsal Shank and Foot. These wires and sensors will then be held close to your body with mesh-like stockings. A researcher will then carefully insert a tympanic temperature probe in your ear. Finally, you will put on a pair of coveralls and sandals and these wires will be connected to a data collection system to verify that the system is working properly. As well, a heart rate monitor may be secured around your chest.

Throughout the experiment, the researchers will be monitoring changes in your temperature. For safety reasons, if we observer a decrease of core body temperature below 35°C, the testing session will be stopped. Before you enter the liferaft you will be seated comfortably on a wooden chair in a thermal neutral room to record baseline skin and core temperatures.

You will be asked to wear a CSA approved lifejacket, not because of a risk of entering the water, but because lifejackets are worn in typical abandonment scenarios and will provide an insulating affect upon the subject.

You will then be instructed how to use the two-way communications between the liferaft and the researchers. This will allow you to let the researchers know if you are uncomfortable or feeling ill. It is best to stop the trial when someone starts to feel ill rather than let it escalate and have someone get sick in the life raft. The researchers will also be monitoring you with a video camera while you are in the liferaft.

When you are ready you will be placed in a standardized location in the liferaft and asked to sit passively throughout the duration of the trials. This test may last anywhere between 2 hours and 10 hours. In some tests, only one person will be in the liferaft, perhaps with sandbags. In other tests, a manikin equipped to record data similar to yours will accompany you, and in some, up to 16 research subjects will be in the liferaft.

During these trials, the liferaft will be towed at various speeds in a tow tank located at the Institute for Ocean Technology, National Research Council Canada (NRC-IOT), St. John's, Newfoundland. Depending on the test conditions, there will be waves, different winds, your clothing might be dry or wet, the floor insulation will vary, and the canopy may be open or closed. We may ask you to sit of to lie down on the liferaft floor.

For some tests, the air will be at 20°C and the water temperature will be at 8°C. Some tests will be conducted in an Ice Tank. The air temperature will be at 5°C. The temperature of the water will be 5°C. Some persons will be asked to wear an immersion suit instead of the lifejacket.

Once the trial is over, the researcher will remove the sensors and instruct you to remove the rectal probe. There are shower facilities available for you to re-warm and clean up following the experiment.

Before you decide if you still wish to participate in this study we will explain the protocol to you, including both the tow and ice tank facilities. When scheduling you in, the researcher will inform you of whether you will be tested in the tow or ice tank. This will provide you an opportunity to decide if you still which to participate in the described trial.

4. **Length of time:**
The duration of the testing protocol will last 2 hours up to 10 hours. Approximately 1 hour will be spent preparing for data collection, the duration of data collection in the liferaft will be dependent on your rate of core body temperature loss and approximately .5 hours to remove the experimental equipment. All testing will take place at the NRC-IOT building.

5. **Possible risks and discomforts:**
You will be exposed to cold environments that will cause you to feel uncomfortably cold and shiver. You will be able to communicate with the researchers to let us know if the temperature is making you uncomfortable. Because the liferaft is moving on water, you may experience some symptoms of motion sickness. You will not be provided or allowed to take anti-histamine or anti-nauseant drugs during the study. Again, we will stop the data collection if you are becoming uncomfortable. The researchers are trained in basic first aid and emergency response.
Due to the possibility of long duration trials you may have to excrete bodily fluids before the trial is ended. If at any time during the test you have to excrete, you should inform the researchers and the trial will be terminated.
The following adverse reactions have been reported to be associated with the use of temperature probes during the insertion procedure or while the devices were in use. The order of listing is alphabetical and does not indicate frequency or severity.
Reported adverse reactions include: airway obstruction, aspiration pneumonitis, bronchial insertion, electrical burns due to aberrant electrosurgical pathways, colon perforation, epistaxis, esophageal abrasion, esophageal perforation, rectal bleeding, tracheal insertion, and trauma to pharynx.

Please be aware that you are free to withdraw from the study at any time.

6. **Who can participate?**
You should be healthy, between 19-55 years of age and ready to be involved with cold water in a confined space (the space under the liferaft's canopy). You are NOT allowed to participate in the study if you:

- suffer from any medical condition aggravated by exposure to cold
  - previous frost bite or cold injuries
  - cold wounds
  - cardiovascular diseases
  - peripheral vascular disease, etc.
- suffer from any medical condition affecting the rectal area
- suffer from any medical condition affecting the ear area
- currently taking prescribed medications
- currently suffer from heart or lung related conditions
- suffer from hypoglycaemia or related diseases where frequent food and/or fluid intake is necessary
- frightened of enclosed or confined places
- pregnant

7. **Benefits:**
   It is not known whether this study will benefit you.

8. **Liability statement:**
   Signing this form gives us your consent to be in this study. It tells us that you understand the information about the research study. When you sign this form, you do not give up your legal rights. Researchers or agencies involved in this research study still have their legal and professional responsibilities.

9. **Confidentiality:**
   At no time will individual results be discussed by others than those on the research team. You will be provided with a subject identification code and your given names will not be used to identify the data we collect from you.

   Listed below are the names of all personnel who can access all data:
   Scott Netson MacKinnon, Lawrence Mak, Kerri Ann Evely

   As well NRC Ottawa Research Ethics Board and the MUN Human Investigation Committee will have access to data, for monitoring purpose.

10. **New Information during the study**
    If at any time new information becomes apparent to the investigators, which may affect you, you will be informed.

11. **Questions:**
    If you have any questions about taking part in this study, you can meet with the investigator who is in charge of the study at this institution. That person is:

Scott N. MacKinnon, Ph.D. – 709-777-8746

Or you can talk to someone who is not involved with the study at all, but can advise you on your rights as a participant in a research study. This person can be reached through:

Office of the Human Investigation Committee (HIC) at 709-777-6974
Email: hic@mun.ca

NOTE : National Research Council's Research Ethics Board had also reviewed this project since NRC researchers are involved in this project. They can be reached at :

Secretary, NRC Ottawa Research Ethics Board
Tel : (613) 991-9920
Fax : (613) 991-0398
Email : OREB-CERO@nrc-cnrc.gc.ca

Initials: ________

Signature Page

Study title: **Thermal Protection in Liferafts: Assessment of Occupant Heat Balance and Development of Performance Criteria**

Name of principal investigator: **Scott Netson MacKinnon, PhD**

To be filled out and signed by the participant:

	Please check as appropriate:	
I have read the consent..	Yes { }	No { }
I have had the opportunity to ask questions/to discuss this study.	Yes { }	No { }
I have received satisfactory answers to all of my questions.	Yes { }	No { }
I have received enough information about the study.	Yes { }	No { }
I have spoken to Dr. MacKinnon (or designate) and he/she has answered my questions	Yes { }	No { }
I understand that I am free to withdraw from the study	Yes { }	No { }

- at any time
- without having to give a reason
- without affecting my student or employment status or reputation in the community

I understand that it is my choice to be in the study and that I may not benefit. Yes { } No { }

I agree to take part in this study. Yes { } No { }

_________________________________ _______________________
Signature of participant Date

_________________________________ _______________________
Signature of witness Date

To be signed by the investigator:

I have explained this study to the best of my ability. I invited questions and gave answers. I believe that the participant fully understands what is involved in being in the study, any potential risks of the study and that he or she has freely chosen to be in the study.

_________________________________ _______________________
Signature of investigator Date

Telephone number: _______________________

Appendix C: Medical History Questionnaire

Medical History Questionnaire

Name:___________________________ Date:_____________________

Age:________________ Mass (kg): Stature (mm):

Sex: Male / Female

	Please circle response	
1. Have you recently been ill	Yes	No
- if 'yes' how long ago was this?		________days
2. Have you recently had a fever?	Yes	No
- If 'yes' how long ago was this?		________days
3. Are you currently pregnant?	Yes	No
4. Is there a possibility you could be pregnant?	Yes	No
5. Do you suffer from any medical condition aggravated by exposure to cold?	Yes	No
6. Are you frighten of being in closed or confined spaces?	Yes	No
7. Are you diabetic?	Yes	No
8. Do you take any medication to control blood sugar?	Yes	No
9. Have you been diagnosed with heart disease?	Yes	No
10. Are you currently taking any cardiovascular-related medications?	Yes	No
11. Are you taking diuretics?	Yes	No
12. Have you ever been diagnosed with any blood pressure disorders?	Yes	No
13. Do you currently take medication to control blood pressure?	Yes	No
14. Have you had a stroke?	Yes	No
15. Have you been diagnosed with neuromuscular disease? (ie. Nerve and /or muscle diseases)?	Yes	No
16. Do you have any respiratory (ie breathing) ailments?	Yes	No
17. Do you currently take any respiratory-related medications?	Yes	No
18. Have you been diagnosed as having a hypo or hyperthyroid?	Yes	No
19. Are you currently taking any antihistamine medication?	Yes	No
20. Are you currently taking any anti-nauseant medication?	Yes	No
21. Do you suffer from any medical condition affecting the rectal area? (ie. Irritable bowel syndrome, colitis, etc.)?	Yes	No

Subject Signature:_______________________________ Date: _________________________

Witness Signature: ______________________________

Appendix D: Validation of Skin Heat Loss Measurements Using Heat Flow Transducers

Skin heat loss was measured in the present study by using 13 heat flow transducers (HFTs) fixed on the surface of the skin. Heat flow transducers (HFTs) are being typically used to measure exclusively the dry component of the body heat loss. In the present study, since the wet component of the body heat loss was a significant portion of the total body heat loss, we needed to validate the use of the HFTs for our application.

A contract was given to the University of Ottawa to validate the use of heat flow transducers in the measurement of the total skin heat loss when a significant portion of the skin heat loss originated from evaporation of water from the skin and clothing when exposed to a cold wet environment.

The study that was conducted at the University of Ottawa was a duplication of the conditions used in Phase 3 of the present study. In summary, the tests were conducted on 10 subjects (5 males and 5 females) having the following characteristics: age: 27 ± 6 years; height: 171.9 ± 6.2 cm; weight: 74.2 ± 9.8 kg; body surface area: 1.87 ± 0.14 m^2; percent body fat: 25 ± 9%. The subjects were dressed with the same clothing as in Phase 3 and were exposed to a 90 min test where Tair = 7.2 ± 0.2 ^oC and rh = 83 ± 3% (the average for Phase 3 of the present test were Tair = 7.8 ± 0.1 ^oC and rh = 86 ± 1%). During the first 30 min of the test, the subjects were seated in a climatic room at rest. The purpose of this first 30 min period was to pre-cool the subjects to minimize the time spent into the calorimeter. The subjects were then transferred into an air calorimeter (housed few meters away in the climatic chamber) for the remaining of the test. The calorimeter was maintained at the same environmental conditions as the climatic chamber. At the end of the first 30 min exposure in the calorimeter, the clothing of the subjects was wetted with 1 L of water using a similar method used in Phase 3. The subjects were then exposed to the same environment for a further 30 min period. During the exposure in the calorimeter, the subjects were resting on a chair. During that time, skin temperature and heat flow were measured by 13 heat flow transducers (using the same body locations as in Phase 3) and rectal temperature was measured continuously. In addition, metabolic rate, dry heat loss, and wet heat loss were measured continuously by using direct and indirect calorimetry.

The results of the study showed that during the dry portion of the test (first 30 min into the calorimeter when 98% of the skin heat loss was dry) there was no significant difference ($P \leq 0.05$) between the total body heat loss (excluding the respiratory heat loss) as measured by direct calorimetry (170 ± 23 W) as compared to the heat loss as measured by HFTs (165 ± 25 W). During the wet portion of the test (second 30 min into the calorimeter when 66% of the skin heat loss was dry) there was no significant difference ($P \leq 0.05$) between the total body heat loss (excluding the respiratory heat loss) as measured by calorimetry (175 ± 30 W) as compared to the heat loss as measured by HFTs (196 ± 32 W).

From that study, it was concluded that the use of HFTs for the measurement of the total skin heat loss from human subjects exposed to a cold wet environment is a valid method. HFTs could measure accurately the dry and wet heat lost components of the total skin heat loss.

Appendix E : ICEE Poster

EFFECT OF WETNESS AND FLOOR INSULATION ON THE THERMAL RESPONSES DURING COLD EXPOSURE IN A LIFERAFT

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INTRODUCTION

A typical passenger may be wearing little protective clothing during an evacuation of a seagoing vessel, resulting in the liferaft providing the only significant thermal protection against the cold environment. While regulatory agencies often require commercial liferafts to provide thermal protection within its design, there exists limited guidance regarding the amount of protection needed. The aim of the present study was to characterize the thermal responses of lightly dressed subjects exposed to mild cold conditions in a liferaft when two factors affecting heat transfer were modified: the floor insulation of the liferaft and the wetness of the occupants. This study is part of a larger investigation looking at the thermal requirement for long-term survival in various sea environments.

Figure 1. Subject dressed and ready for the exposure trial in the liferaft.

METHODS

Subjects. 5 males and 3 females with the following mean (± SD) characteristics:

age:	26.5 ± 4.1 years;
height:	175 ± 9 cm;
weight:	79.8 ± 15.8 kg;
BMI:	25.8 ± 2.7;
body fat:	21.6 ± 8.0 %.

The subjects wore a one-piece cotton coverall, a cotton t-shirt and brief, an inflated SOLAS approved lifejacket, and neoprene gloves and boots (Figure 1).

Test conditions. The subjects were exposed in pairs for 135 min to four randomly assigned conditions inside a liferaft.

Udry: Subjects dry, floor of liferaft uninflated (~0.2 cm thick);
Uwet: Subjects wet, floor of liferaft uninflated;
Idry: Subjects dry, floor of liferaft inflated (~15 cm thick);
Iwet: Subjects wet, floor of liferaft inflated.

The four conditions were repeated with an additional 4 subjects (secondary subjects) in the liferaft for a total of 6 occupants (Udry6; Uwet6; Idry6; Iwet6) to examine the effect of multiple occupants on the thermal responses of the two primary subjects (Figure 2).

Figure 2. Liferaft set-up for the multiple occupant trials showing one primary subject with two secondary subjects. The same configuration was used for the other half of the liferaft for a total of 6 subjects.

Ambient conditions. Representative of mild sea conditions: 16°C water temperature, 19°C air temperature, 60 % relative humidity, and 5 m/s wind speed. To simulate for the leeway effect and sea state (increased convection), the liferaft travelled over water at a speed of 0.5 m/s.

Liferaft. A 16-person raft with a closed canopy (3.3 m circumference, 1.7 m height) was used (Figure 3). A constant flow of fresh air (2 occupants conditions: 19 L/sec; 6 occupants conditions: 38 L/sec) was added to the raft to keep the CO2 concentration below 1000 ppm.

Figure 3. The 16-person liferaft was tethered to a carriage traveling at a speed of 0.5 m/s over water. Four fans generated 5m/s wind towards the liferaft.

Mesured parameters. Metabolic rate (M), mean skin temperature (Tsk) and heat loss (HF) at 12 sites, and rectal temperature (Tre) were continuously measured on the two instrumented subjects. Thermal comfort rating was obtained at the end of the exposures.

RESULTS

No differences were observed in the thermal responses between the conditions involving 2 versus 6 occupants: the data were therefore pooled for the statistical analysis.

Figures 4 to 7 show the average results for all subjects at baseline and during the last 10 min of the exposures.

Figure 4: Floor inflation and wetness are significant factors affecting average Tsk.
Figure 5: Wetness is a significant factor affecting average HF.
Figure 6: Floor inflation is a significant factor affecting average Tre.
Figure 7: None of the factors studied affected significantly M.

The thermal comfort ratings were significantly affected by the wetness (wet conditions: 4.6 ± 1.1 [between cold and very cold]; dry conditions: 6.7 ± 1.0 [between uncomfortably cool and cool but fairly comfortable]) and floor inflation (inflated conditions: 5.0 ± 1.1 [cold]; uninflated conditions: 6.2 ± 0.9 [uncomfortably cool]).

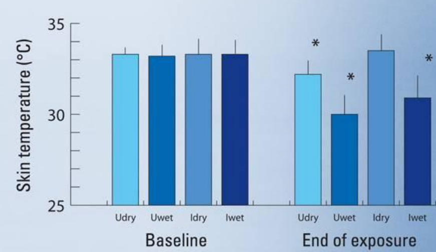

Figure 4. Average skin temperature (°C) during baselines and at the end of the exposures for all subjects.
*: significantly different from baseline at p < 0.05 level.

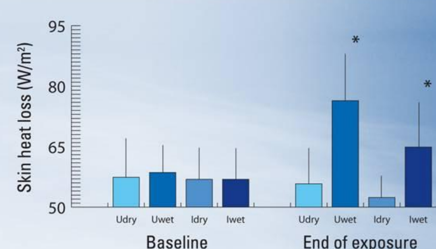

Figure 5. Average skin heat loss (W/m2) during baselines and at the end of the exposures for all subjects.
*: significantly different from baseline at p < 0.05 level.

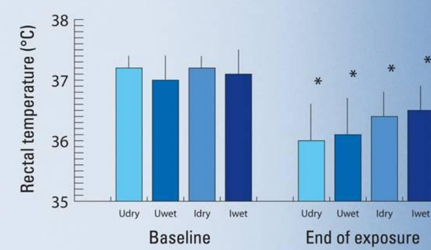

Figure 6. Average rectal temperature (°C) during baselines and at the end of the exposures for all subjects.
*: significantly different from baseline at p < 0.05 level.

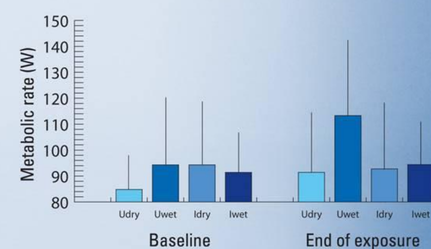

Figure 7. Average metabolic rate (W) during baselines and at the end of the exposures for all subjects.

CONCLUSIONS

The present study showed that even during exposure to mild cold environments inside a closed liferaft, the wetness of the clothing worn by the occupants and the absence of floor insulation will both significantly decrease the mean skin temperatures of the occupants while only the wetness of the clothing will increase the heat loss from the subjects. However, the thermal stress imposed by the different conditions tested was not sufficient to significantly and consistently increase the metabolic rate of the occupants through shivering. Despite the mild responses to cold during the exposures (Tsk above 30°C, HF increased by < 15%; no definitive shivering), Tre significantly decreased for all conditions tested by as much as 1.1°C. This was particularly the case for the condition Udry where the Tsk was on average 32°C by the end of the exposure, and both HF and M had not increased from baseline. If the observed rate of decrease in Tre for that condition is extrapolated, it could be predicted that the occupants would not survive for more than 18 hours inside a liferaft originally designed for a multi-days survival in much colder environments. It is concluded that to estimate survival time inside a liferaft, or to evaluate the thermal protection of a liferaft, the short-term decrease in Tre from the occupants should not be the only or primary factor taken into consideration.

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