Human thermal responses in extreme conditions

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TITLE

HUMAN THERMAL RESPONSES IN EXTREME CONDITIONS

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SUMMARY

The thermal responses of 12 volunteers were measured over 3 hour immersions in 5°C water and air in a calm condition, (Calm) and in a condition that included wind and increased water velocity (Weather). Immersions in the Weather condition resulted in a significantly greater increase in mean skin heat flow (MSHF) compared to Calm. Immersions in the Weather condition resulted in a significantly greater rate of change of mean skin temperature compared to Calm. There were no significant differences in the rate of change of deep body temperature, mean body temperature, and oxygen consumption between the two conditions.

The use of a flume system in this experiment allowed for the successful replication of the increase in heat flow due to waves in a facility that was not capable of wave generation.

Wind and waves, and the addition of water underneath the immersion suit, will cause a significant increase in MSHF compared to calm conditions while dry inside the suit. This increase in MSHF may be compensated for by people, but at great effort on their part. When testing people in immersion suits, it is important to consider the effort expended to maintain a stable deep body temperature in the specific test conditions. More severe conditions than those tested, may push people past their thermoregulatory capabilities, resulting in falls in deep body temperature.

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HUMAN THERMAL RESPONSES IN EXTREME CONDITIONS

TR-2011-14

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July 2011

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GLOSSARY

NRC	National Research Council of Canada
IOT	Institute for Ocean Technology
OEB	Offshore Engineering Basin
TC	Transport Canada
PERD	Program for Energy Research and Development
REB	Research Ethics Board
PFD	Personal Flotation Device
CSR	Cold Shock Response
LSA	Life Saving Appliances
JONSWAP	Joint North Sea Wave Analysis Project
SD	Standard Deviation
T_{SK}	Mean Skin Temperature (°C)
MBT	Mean Body Temperature (°C)
MSHF	Mean Skin Heat Flow ($W \cdot m^{-2}$)
$\dot{V}O_2$	Oxygen Consumption ($L \cdot min^{-1}$)

HUMAN THERMAL RESPONSES IN EXTREME CONDITIONS

1.0 INTRODUCTION

Across the world, many people in varying industries work or travel over open water. Since the majority of the planet is covered in water that is below human thermoneutral temperatures, the use of life saving appliances that offer thermal protection is often required. If an unprotected human was to become suddenly immersed in cold water (< 15°C) a series of physiological responses termed the "Cold Shock Response" occur that are responsible for the majority of drowning deaths within the first few minutes of immersion (27). Even in unprotected individuals, hypothermia (a drop in deep body temperature of 2°C or more) does not usually occur before 30 minutes of immersion (11).

Life Saving Appliances (LSA), such as Personal Flotation Devices (PFD), liferafts, and lifeboats, are required on any sea-faring vessel in order to improve the survival changes of those on board; the best approach to protecting people from the cold water is to keep them out of it. In an emergency situation however, there is always a chance that the people will be immersed. In these situations, immersion suits can greatly increase the chance of a person being able to avoid the CSR, and prolong their survival time.

Current Transport Canada (TC) regulations require immersion suits to be carried on board all class 9 ships and higher, in a sufficient quantity for every person on board. Offshore oil installations follow a similar policy. The immersion suits are usually a one-piece suit system that provides thermal protection and buoyancy to the wearer (1).

Current Canadian General Standards Board (CGSB) requirements for marine abandonment suits (CAN /CGSB-65.16-2005) are for them to be tested for material strength, flame resistance and thermal protective properties. The thermal protective properties can be tested using a thermal manikin or human participants. For human participant tests, a rectal thermometer measures deep body temperature; the skin temperatures of the index finger and large toe are also measured. The participant is immersed in calm, circulating 0-2°C water for up to 6 hours. The test is terminated if the deep body (core) temperature of the participant drops 2°C lower than baseline conditions, if the finger or toe temperature drops below 5°C, or the if the attending physician determines the participant should not continue (1).

A knowledge gap currently exists between the calm water testing conditions used to determine human thermal responses in immersion suits, and a marine accident. This knowledge gap between how people in immersion suits perform in controlled laboratory conditions and during a marine accident can lead to what Tipton referred to as "unexpectedly, poor performance" when the latter occurs (26). Unfortunately, recent marine accidents with people in immersions have occurred that have resulted in "unexpectedly, poor performance" compared to predicted survival times.

In February 2008 off the North East coast of Newfoundland, the Checkmate III began taking on water forcing the two crew members to don immersion suits and abandon ship into the water. The crew members managed to radio for help before abandoning ship and Search and Rescue

(SAR) assets were deployed to the area. In less than 2 hours, a SAR fast rescue craft recovered the two men from the water, only to find that they had both perished. Later reports into the accident found that while the immersion suits were donned properly, they were in poor condition (12). In the expert opinion of the Coast Guard captain of the ship that recovered the men "….the suits must either have suffered a spectacular failure, or the suits were not properly fitted prior to the casualties abandoning the vessel" (12).

On March 12th 2009, Cougar flight 491 crashed off the eastern coast of Newfoundland, killing 17 of the 18 occupants of the helicopter. The sole survivor of the incident was wearing a helicopter transportation immersion suit that, while certified to a different standard (CAN/CGSB-65.17-99) than marine abandonment suits, passed the same thermal protective tests required by CAN/CGSB-65.16-2005. Even though the sole survivor was in the water for only approximately 90 minutes, his deep body temperature was near lethal values (~29°C) by the time he arrived at the hospital less than 2 hours after the crash. Predicted survival times for the survivor were higher than what was actually observed (3) .

Previous works conducted by other authors have investigated the change in performance of humans and immersions in moving calm water, to conditions that include wind and waves. Tipton reported a 30% reduction in predicted survival times for participants wearing a non-insulated immersion suit when they were immersed in wind and waves compared to calm water (26). Ducharme and Brooks found that wave heights 30cm and above produced a significantly greater increase in heat flow for participants wearing an un-insulated immersion suit compared to calm water, but no drop in deep body temperature (4).

Other authors have found contradictory results with regards to the effect of rough weather compared to calm water immersions. Hayes et al. found that wave motion did not significantly increase the rate of body cooling compared to calm conditions across a variety of clothing ensembles, ranging from swimming trunks to flight suits with long underwear underneath (10). Later work carried out by Steinman et al. examined the effects of rough seas on the thermal performance of several anti-exposure garments ranging from wet suits to dry immersion suits (22). When the participants wore loose fitting wet suits, mean rectal temperature and back skin temperature decreased significantly in rough conditions compared to calm (22). When the participants wore two different kinds of dry immersion suits, there was no significant difference in the rate of change of rectal temperature between immersions in calm and rough water for one suit. The other suit had a significantly greater change in rectal temperature for calm immersions compared to rough conditions (22).

The contradictions in the literature on the effects of wind and waves on the thermal responses during immersion were the rationale for the formulation of the project: "Human Thermal Regulation in Wind and Waves". This multi-year project was funded by both Transport Canada and the Program for Energy Research and Development, and consisted of three separate studies. In March 2008, we tested the effects of four separate environments on 12 immersed participants (18). The environments for the one-hour immersions were: Calm water (Calm), wind only (Wind), Waves only (Waves), and Wind and Waves (Wind + Waves). We found that Wind + Waves caused a significantly greater increase in mean skin heat flow (MSHF), but no significant differences in the change of deep body temperature was measured. The lack of change of deep body temperature was attributed to the short immersion durations, and relatively warm water (~10°C) and air (~17°C) temperatures.

Building upon the results of the March 2008 study, a new study conducted in March 2009 examined thermoregulatory responses during 3 hour immersions in varying wind and wave conditions (20). Twelve healthy males performed 3 hour immersions in the following conditions: Calm water (Calm); 0.34m waves and 3.5m·s-1 wind (Weather 1); and in 0.67m waves and 4.6m·s-1 wind (Weather 2). Similar to our earlier findings, the two weather conditions (Weather 1 and 2) produced a significantly greater increase in MSHF compared to Calm. Also similar to our previous findings, there were no significant differences in the measured change in deep body temperature, which was attributed to the warm water (~11°C) and air (~17°C) temperatures, and the high quality of the immersion suit used (20).

A third study in the project was conducted in March 2010 and built upon the findings of the previous two. Current CGSB standards assume that water ingress into immersion suits is an eventuality, and water leakage was reported in the immersion suit of the sole survivor of Cougar Flight 491 (3). To simulate water leakage into immersion suits, 500mL of water was applied underneath the immersion suits worn by our 12 male participants in the March 2010 study over their torsos. Tipton and Blami reported that 500mL of water applied over the torso of their participants resulted in a 30% degradation in clothing insulation of their un-insulated immersion suits (28). We hypothesized that the addition of the 500mL of water underneath the immersion suit, in combination with wind and waves, would result in a significant decrease in deep body temperature.

There were no significant decreases in deep body temperature measured across all immersion conditions with the 500mL of water applied to the torsos of our participants (19). Even with the water underneath the immersion suit, the participants were able to successfully thermo regulate in the conditions and maintain a stable deep body temperature. One of our recommendations following that study was to conduct immersions with wind and waves in colder water and air temperatures. A higher thermal gradient between the participants and external environment may result in them not being able to thermo regulate and maintain a stable deep body temperature (19).

Our recommendation to conduct further testing in colder water and air temperature was the rationale for the work described in this report. The Ice Tank at NRC-IOT is capable of producing, and maintaining, air temperatures below –20°C, but has no wave generation capability. To replicate the increase in heat loss due to wave action, NRC-IOT fabricated a "thermal flume". The thermal flume was designed to allow water to travel past a participant at a rate equivalent to that of the largest waves used in our previous experiments.

1.1 Experimental Hypotheses

1. Immersions in cold conditions that include wind and increased water movement (flow) past the participants will cause a significantly greater increase in mean skin heat flow compared to calm conditions.

2. Immersions in cold conditions that include wind and flow will cause a significantly greater decrease in deep body temperature compared to calm conditions.

2.0 TEST SETUP

All experimental trials were conducted in the National Research Council of Canada's Institute for Ocean Technology's (NRC-IOT) Ice Tank. The Ice Tank is a rectangular tank 90m in length, 12m in width, and 3m in depth. The Ice Tank uses an ammonia based refrigeration system to allow for temperatures as low as –30°C. A tow carriage runs along a series of rails on the north and south side of the Ice Tank.

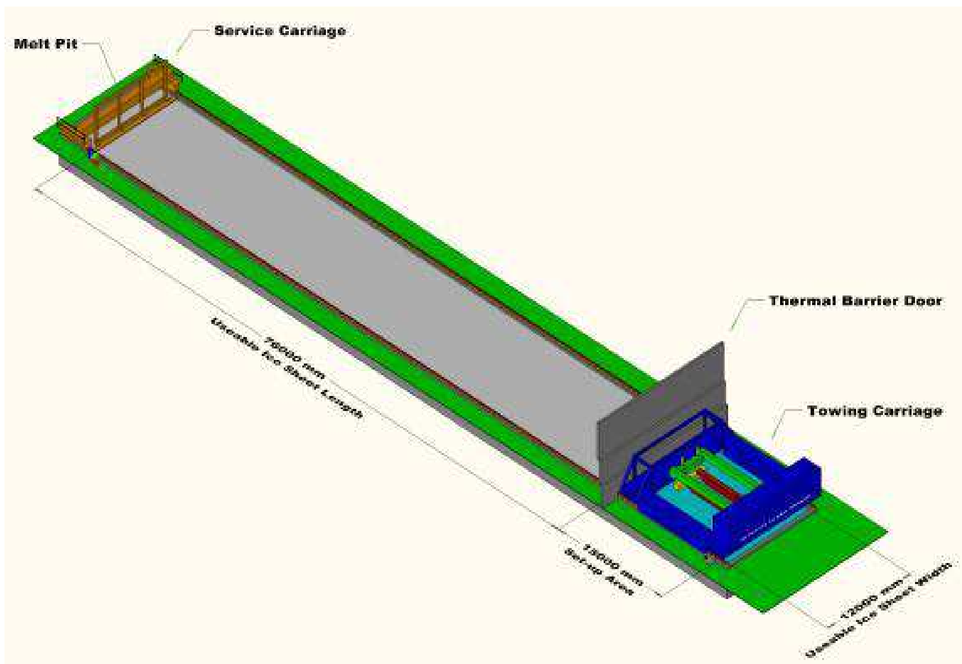

Figure 2.1: Concept drawing of the Ice Tank located at NRC-IOT

On the east end of the Ice Tank, scaffolding was erected and a movie screen was secured to it to allow participants to watch movies during the immersions. At the base of the scaffolding was a single, analog controlled fan that generated wind. A stairway was built from additional scaffolding to allow the participants to walk into and out of the water.

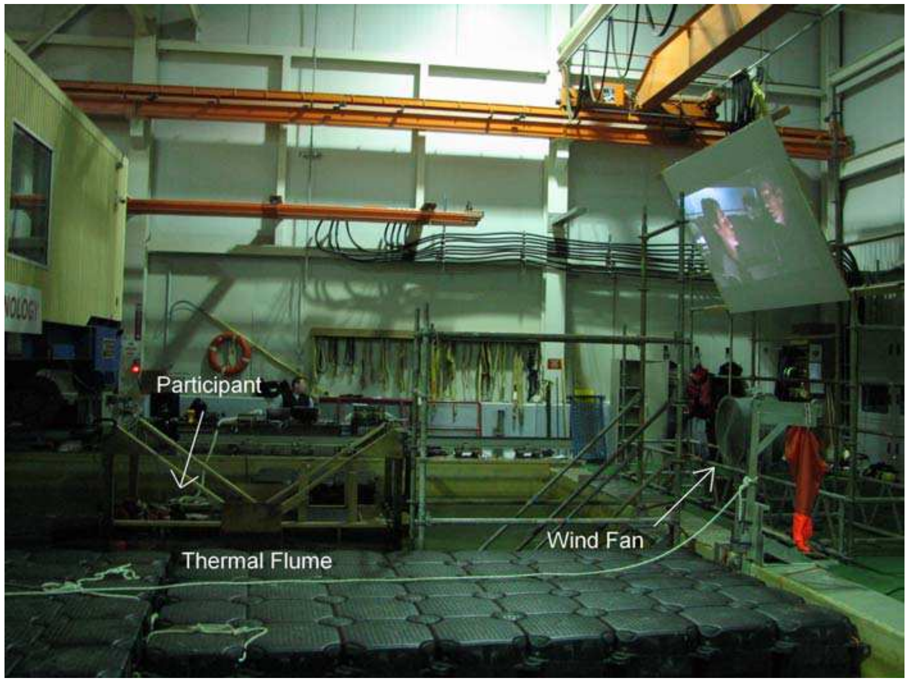

Figure 2.2: Test setup.

2.1 Thermal Flume

In order to produce the necessary current speeds equivalent to the wave particle velocity associated with 0.67m waves, the volume of water to be moved past the participant had to be reduced. A box fabricated from sheets of plywood was constructed to reduce the total volume of water around the participant. The box was open on the top and back end. At the front end of the box were a series of cylinders that were used to straighten the flow of water past the participants. Five DC powered Duramaxx trolling motors were attached to the outside of the box and pushed water through the cylinders, which subsequently straightened the flow of water, and past the participants. Six Pitot tubes were installed in the box to measure flow speed.

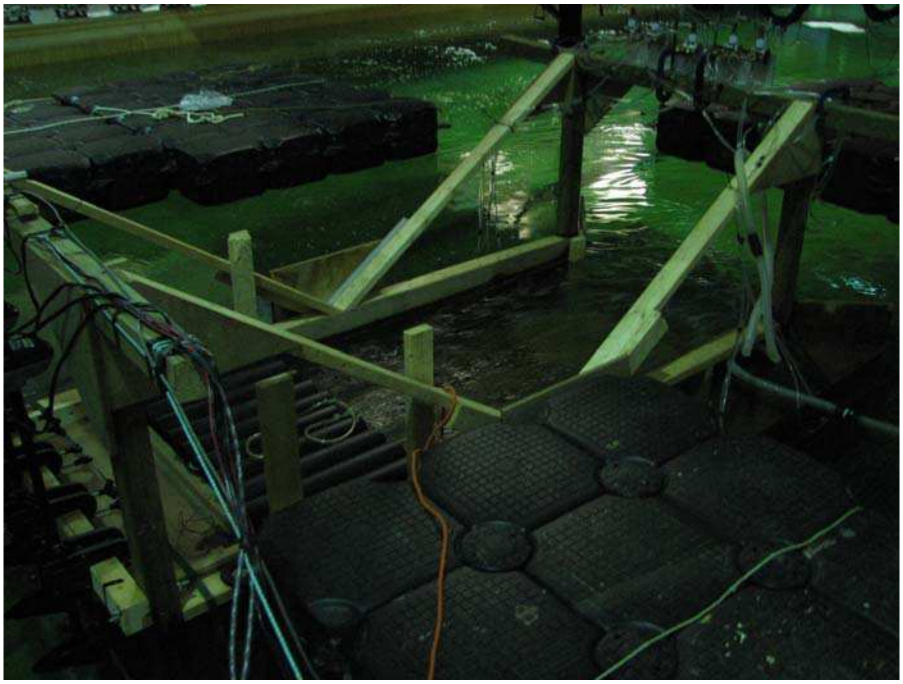

Figure 2.3: NRC-IOT Thermal Flume.

2.2 Environmental Conditions

Table 2.1 provides the wind speeds, flow velocity, water temperature, and air temperature of the two immersion conditions. The flowspeed used was equivalent to the wave particle velocity of a wave with a height of 0.67m, and period of 1.71s.

Table 2.1: Immersion conditions.

Condition	Mean Flow Speed ($m \cdot s^{-1}$)	Mean Wind Speed ($m \cdot s^{-1}$)	Mean Water Temperature (SD) (°C)	Mean Air Temperature (SD) (°C)
Calm	0	0	4.7 (0.1)	5.0 (0.1)
Weather	0.80	4.6	4.8 (0.1)	4.8 (0.1)

In order to prevent the risk of injury to the participant from physical contact with the equipment, the wind speed was calibrated prior to any human immersions. A custom-built wind anemometer was placed in the flume in the location where the participants would be during the tests, with a second one mounted on the leading edge of the flume. The wind speed was calibrated with the two anemometers in place, and the anemometer in the location of the participant was removed. All further Weather conditions were run with the calibrated drive signal voltage. The remaining anemometer was used to ensure the correct drive signal was being used.

3.0 PARTICIPANTS

A required sample size of 11 participants was determined using a power calculation (95% confidence interval, $\sigma = 0.5$, $\beta = 0.3$); however 12 healthy individuals volunteered for this study. All participants gave their written informed consent to participate, and NRC's Research Ethics Board approved the protocol (NRC-REB#: 2010-43). Before starting any of the tests, the participants underwent a medical screening by a certified doctor to determine if they were physically fit to participate. The anthropometric data of the participants is given in Table 3.1.

Table 3.1: Participant anthropometric data.

***n* = 12**	**Age**	**Height (cm)**	**Weight (kg)**	**Body Fat %**	**Surface Area (m^2)**
Mean	25.5	180.75	87.93	20.3	2.10
SD	5.9	5.15	17.17	5.5	0.23

3.1 Immersion Suits

White's Marine Abandonment Suit was selected for use during this study, pictured in Figure 3.1.

Figure 3.1: White's Marine Abandonment Suit.

3.2 External Bladders

In order to allow the participants to urinate throughout the 3-hour immersion, an external bladder was attached to them. The external bladder consisted of a condom catheter, a urine collection bag, and the absorbent powder from the Travel John disposable urinal (Reach Global Industries, Irvine, CA, USA) in the bag. The external bladder was worn by the participants underneath their clothing, and allowed them to urinate throughout the immersion. The pre-immersion weight of the external bladder was subtracted from the post immersion weight to calculate the amount of urine produced during the trial.

4.0 INSTRUMENTATION

4.1 Heat Flow Sensors

Heat flow sensors manufactured by Concept Engineering (Old Saybrook, CT, USA) were used to measure both heat flow and skin temperature at 12 different sites on the body based on the Hardy and DuBois weighting formula, with a slight modification as no measurements were taken from the hand (9). The sites used were: the right foot; left shin; right calve; right quadriceps; left hamstring; left abdominal; right lower back; left scapula; right pectoral; underside of the right forearm; top of left forearm; and the forehead.

Figure 4.1: Heat flow sensor.

The heat flow sensors were connected to self-contained data loggers manufactured by ACR data systems (Surrey, BC, Canada). Two separate types of ACR data loggers were used: a logger that could measure the heat flow, and a second that was able to measure skin temperature. The loggers were self-contained and the data collected during the immersion was stored and downloaded immediately after the trial was completed. Heat flow and skin temperature were measured once every 8 seconds.

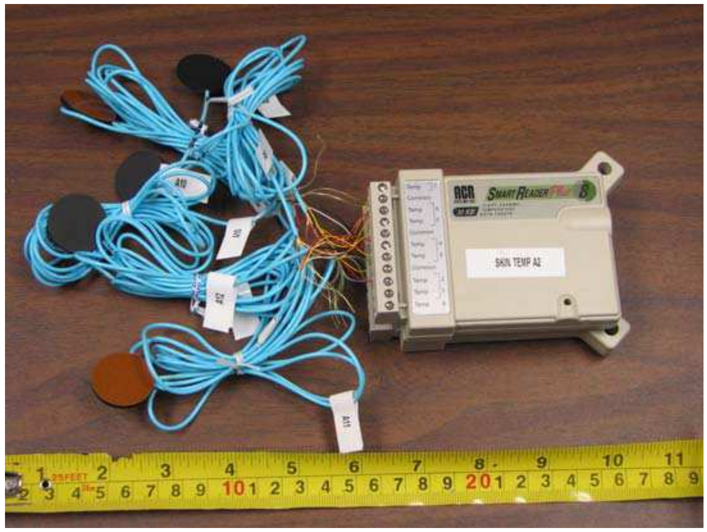

Figure 4.2: Self contained data loggers connected to heat flow sensors (second logger is magnetically attached behind logger "Skin Temp A2" pictured in photo.)

The logger and heat flow sensor system were protected from mechanical stress during the immersion by being attached to a plastic guard by Velcro, and then sealed inside a splash-proof bag. The logger packages were then placed inside a thin mesh vest, which provided little to no thermal insulation, worn by the participants over their test clothing, seen in Figure 4.3.

Figure 4.3: Logger package in the vest worn by a participant.

4.2 Gastrointestinal pills

Gastro-intestinal temperature (T_{GI}) was measured using CorTemp Ingestible Sensor pills manufactured by HQ Inc (Palmetto, FL, USA). The pills measure 22.4mm long with a diameter of 10.9mm, and contain a temperature sensor.

Figure 4.4: CorTemp Ingestible Sensor pill.

The pills transmitted the readings wirelessly to the CorTemp Data Recorder (also manufactured by HQ Inc.) that was housed inside the vest worn by the participants. This was the same vest that contained the data loggers packages.

Figure 4.5: CorTemp Data Recorder.

In turn, the data recorder stored the measurements from the pills and transmitted the values wirelessly in real time to a base station computer. This allowed the research team to monitor the T_{GI} of the participants to ensure that no one experienced a drop of more than 2°C. T_{GI} was measured once every 20 seconds through the use of the pills.

4.3 Heart Rate Monitor

Heart rate was measured using a Polar Heart Rate monitor manufactured by Polar Inc. (Lake Success, NY, USA). The heart rate monitor consists of a band worn around the chest, with conducting gel applied to the back of the band.

Figure 4.6: Polar Heart Rate monitor.

The polar heart rate monitor measured the heart rates of the participants and was recorded wirelessly by the CorTemp Data Recorder. The CorTemp Data Recorder then transmitted the heart rate data wirelessly, in real time, to a shore-based computer where the research team could monitor it. The heart rate was measured and recorded once every 20 seconds.

4.4 Metabolic Measurements

$\dot{V}E$, $\dot{V}O_2$, and $\dot{V}CO_2$ measurements were made every 15 seconds using a Cardio Coach CO_2, manufactured by KORR Medical Technologies (Salt Lake City, UT, USA.) Participants wore disposable latex facemasks that allowed their exhaled gases to travel through a ~12m tube to the Cardio Coach CO_2 located on the shore.

Figure 4.7: Cardio Coach CO_2

Table 4.1 summarizes the different measuring devices, respective sample rates, and units of measure during immersions.

Table 4.1: Measurements acquired from the participants during the immersions.

Measurement	Units	Sample Rate
Heat Flow	$W \cdot m^{-2}$	0.125 Hz
Skin Temperature	°C	0.125 Hz
Deep body temperature	°C	0.05 Hz
Heart Rate	BPM	0.05 Hz
$\dot{V}E$	$L \cdot min^{-1}$	0.06 Hz
$\dot{V}O_2$ / $\dot{V}CO_2$	$L \cdot min^{-1}$	0.06 Hz

4.5 Body Composition Measurements

Participant's body fat percentage was measured using two separate methods:

Method 1: A body composition analyzer manufactured by Tanita Corporation of America Inc. (Arlington Heights, IL, USA). Before each immersion, the participants had two measurements taken using the body composition analyzer: the first measurement was using the scale with the person's profile set to "normal", the second with the profile set to "athlete". Given the rather broad description of "athlete" by the manufacturer, the research team recorded both readings for body fat percentage from the analyzer.

Figure 4.8: Tanita Body Composition Analyzer (Method 1).

Method 2. Skinfold thickness measurements were also taken on each participant. Skin fold thickness was measured using skin fold callipers manufactured by Beta Technology (Santa Cruz, CA, USA). After the participants performed their last immersion, skin fold thickness was measured at the locations according to the Durnin and Womersly method for estimating body fat percentage (5).

Figure 4.9: Beta Technology Skin Fold Callipers (Method 2).

5.0 PROCEDURE

Participants were instructed to refrain from consuming alcohol the night before a test, and not to consume caffeine at least 3 hours before arriving at the facility. Upon arrival at the facility for their test, participants were tested to see if they still had a gastro-intestinal pill present from a previous trial. If they did not have a pill, they ingested a new one with a small amount of water at room temperature. If a pill was already present in the participant's body, they did not consume a second and continued on with the protocol.

In a separate warm room, the participants put on a pair of swim trunks, and then attached the external bladder themselves. A research team member attached the 12 heat flow sensors to the participants in the locations illustrated in Figure 5.1:

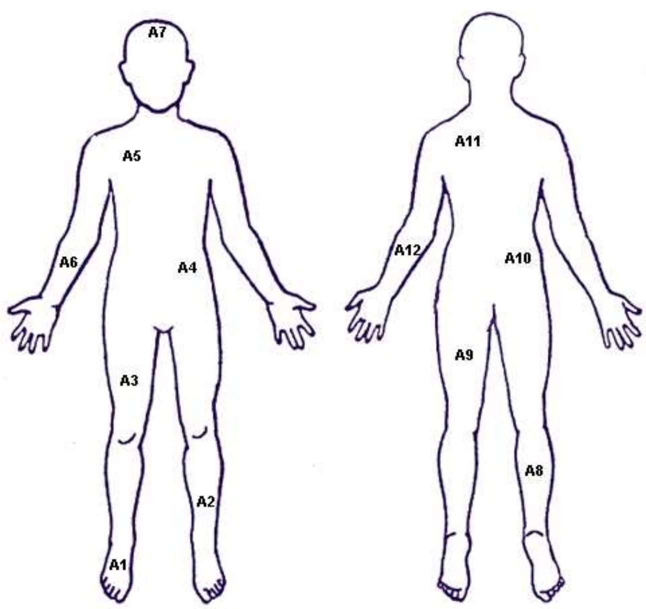

Figure 5.1: Heat flow sensor placement.

Once the heat flow sensors were applied, the participants changed into a clothing ensemble that consisted of two pairs of wool socks, cotton sweat pants, cotton undershirt, swim trunks, and a long sleeved cotton shirt. The clothing ensemble was based on CGSB testing standards (1), with the exception of the extra pair of wool socks added for this protocol to help reduce the risk of a non freezing cold injury. After the participants were dressed they donned the immersion suit and gloves, leaving it unzipped, and proceeded to the Ice Tank.

At the Ice Tank, the participant sat quietly on a chair while the loggers were initialized and checked for functionality. The immersion suit was then fully donned and a disposable metabolic face mask (KORR Medical Technologies, Salt Lake City, UT, USA) was secured to the participants. Five minutes of baseline data was collected while they sat quietly on the chair. After the baseline data collection the immersion suit was zipped closed, vented and then the participants descended the stairs into the ice tank where a research team member manoeuvred them into position into the flume. Once in the flume, a research team member secured their feet through an ankle tethered made out of plastic Taigon tubing. The research team member also helped the participant don a pair of leather mittens over the immersion suit gloves. This extra pair of gloves was used to help reduce the risk of a non-freezing cold injury from occurring. Participants were instructed to keep their hands out of the water, and to place them on their thighs.

The termination criteria for the immersions were:

1) A 2°C drop in deep body temperature from pre-immersion values.
2) 3-hour time limit was reached.
3) Participant request.
4) Finger or toe temperature dropped below 8°C for more than 15 minutes.

After the immersion was ended, the participants exited the water by the same set of stairs they used to enter, and all data was downloaded from the loggers at the monitoring station next to the experimental area. The participants returned to the warm room used for instrumentation where a research team member removed the immersion suit, sensors, and all clothing except the swimming trunks. The external bladder was removed by the participant and was then weighed. Participants were re-warmed in a circulating water bath filled with 40°C water. Once the deep body temperature of the participant approached pre-immersion values, they exited the water bath and changed into their street clothing. The participants were then offered hot beverages and snacks while they completed the exit questionnaire. After their well-being was assured, the participants were allowed to exit the facility.

5.1 Calculations

5.1.1 Mean Skin Temperature and Mean Body Temperature

Mean Skin Temperature (T_{SK}) was calculated by weighting the measurements obtained from the 12 heat flow sensors by the values based on the work by Hardy and DuBois (9). The weighting values used in this report are given in Table 5.1

Table 5.1: Skin temperature and heat flow measurement site weighting values (9).

Measurement Site	Weighting Value
Right Foot	0.07
Left Shin	0.065
Right Quadricep	0.095
Left Abdominal	0.0875
Right Pectoral	0.0875
Right Underarm	0.07
Forehead	0.07
Right Calve	0.065
Left Hamstring	0.095
Right Lower Back	0.0875
Left Shoulder	0.0875
Left Overarm	0.07

Due to the lack of the hand measurements, the calculated T_{SK} value was divided by 0.95. The formula used for calculating T_{SK} was:

$$T_{SK}(°C) = (\sum \text{(Measurement Site * Weighting Value)})/0.95 \quad (1)$$

Previous work by Burton (2) has shown that Mean Body Temperature (MBT) is a combination of both deep body temperature (T_{GI} in the present experiment) and T_{SK}. MBT is calculated as the following:

$$MBT(°C) = (64\% \cdot T_{GI}°C) + (36\% \cdot T_{SK}°C) \quad (2)$$

The change MBT and T_{SK} was determined by averaging the values from a 5 minute segment at the beginning of the immersion, and subtracting from that the value calculated MBT and T_{SK} during a 5 minute segment at the end of the immersion. This value was then divided by the length of the immersion to give the change of MBT and T_{SK} per hour ($°C \cdot hr^{-1}$).

5.1.2 Mean Skin Heat Flow

Mean Skin Heat Flow (MSHF) was calculated using the same weighting values as described in 5.1.1 from measurements taken at 1 hour into the immersions.

5.1.3 Surface Area

Participant Surface Area (SA) was calculated by the following formula developed by Gehan and George (7):

$$SA(m^2) = 0.1644 \cdot Weight(kg)^{0.51456} \cdot Height(m)^{0.42246} \quad (3)$$

5.1.4 Metabolic Rate

Oxygen consumption ($\dot{V}O_2$) for each condition was calculated by averaging the values measured during last 30 minutes of the immersion. $\dot{V}O_2$ was used to calculate the metabolic rate ($\dot{M}$) for the participants using the following formula from Peronnet and Massicotte (17):

$$\dot{M}\ (W \cdot m^{-2}) = (281.65 + 80.65 \cdot RER) \cdot (\dot{V}O_2)/SA \quad (4)$$

RER was given a value of 1.0 due to the low sensitivity of $\dot{M}$ to RER (23).

5.1.5 Clo Value

Clo value was calculated based on the formula as reported by Romet et al. (21).

$$Clo\ (°C/W/m^2) = ((T_{SK} - T_{WATER})/MSHF)/0.155 \quad (5)$$

5.1.6 Predicted $\dot{V}O2$ to Maintain Thermal Balance

Equation (5) can be rearranged to predict MSHF ($MSHF_P$) for a given Clo value, water temperature, and T_{SK}.

$$MSHF_P = (T_{SK} - T_{WATER}) / (Clo \cdot 0.155) \quad (6)$$

Substituting $MSHF_P$ for $\dot{M}$ in equation (4) allows the calculation of the predicted $\dot{V}O_2$ ($\dot{V}O_{2\ P}$) required to equal the heat lost to the environment, keeping the participants (with a SA of ~$2.1m^2$) in thermal balance, for a given Clo value, water temperature, and T_{SK}.

$$\dot{V}O_{2\ P} = (_{MSHFP} \cdot SA) / (281.65 + 80.65 \cdot RER) \quad (7)$$

5.2 Statistical Analyses

The Shapiro Wilks test was used to test for normal distribution. A within subject, repeated measures study design was used for this experiment, and a between subject design was used when comparing the data to previous results. Analysis of variance (ANOVA) was performed on all collected results. Tamahrene T2 post hoc tests were performed to determine significance, with a P value of less than 0.05 considered as significant.

6.0 RESULTS

Two of the twelve participants requested to end the immersion before the 3-hour time limit during the Calm condition. Six of the twelve participants requested to end the immersions before the 3-hour time limit during the Weather condition. Many participants reported feeling pain in their hands and feet as the reason for ending the immersions early, while others reported feeling too cold to continue.

Due to the large number of immersions with varying durations, Mean Skin Heat Flow (MSHF) is reported at 1-hour into both the Calm and Weather conditions; Gastro Intestinal Temperature (T_{GI}), Mean Skin Temperature (T_{SK}), Mean Body Temperature (MBT) are reported as rates of change per hour ($°C \cdot hr^{-1}$); and $\dot{V}O_2$ is reported during the last 30 minutes of the immersions.

The data for the back skin temperatures of one participant during the Weather immersion was not available, reducing the number of skin temperature measures to seven. Since the standard error when calculating mean skin temperature can double when using only seven sites (23), the skin temperature data from this participant was dropped when reporting T_{SK} and MBT.

6.1 Urine Production

Two participants did not urinate in the external bladder after their two immersions; as a result their data is not included in the analysis.

There was no significant difference in the rate of urine production ($g \cdot hr^{-1}$) between the two conditions (Figure 6.1). Urine production was 335.09 ± 216.92 $g \cdot hr^{-1}$ in Calm, and 349.61 ± 173.59 $g \cdot hr^{-1}$ in Weather.

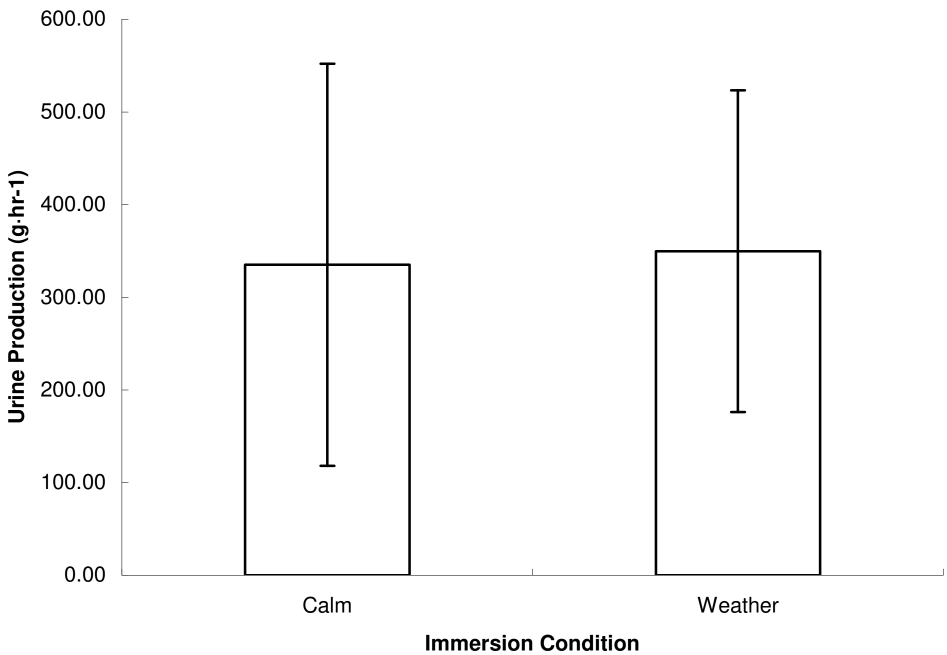

Figure 6.1: Rate of urine production (Mean [SD]. *n* =10).

6.2 Mean Skin Heat Flow

Participants had a significantly greater MSHF in Weather compared to Calm after being immersed for 1 hour (Figure 6.2). MSHF in Calm was 84.68 ± 5.61 W·m^{-2} and 105.79 ± 10.81 W·m^{-2} in Weather.

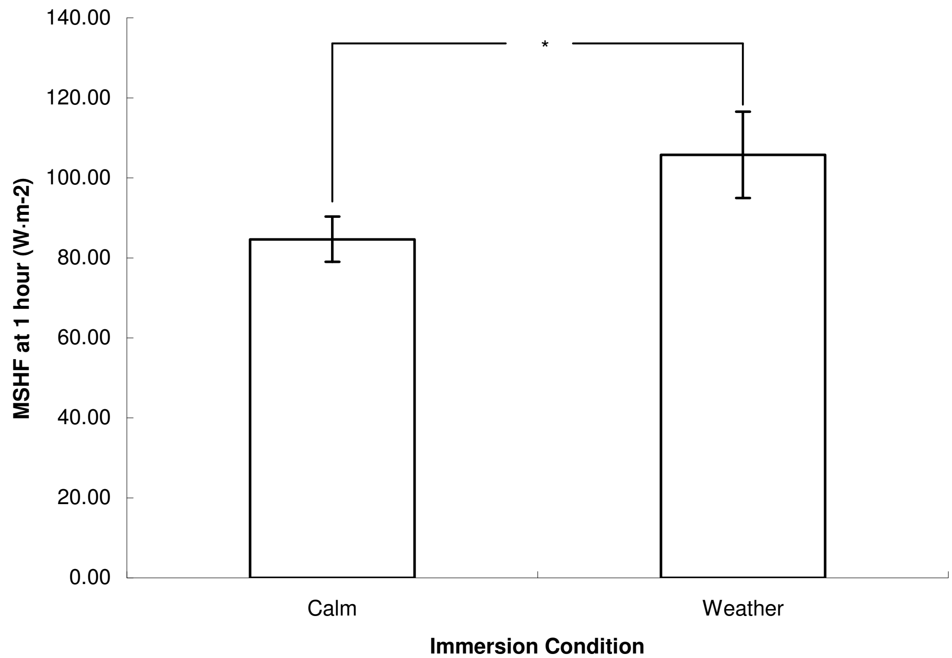

Figure 6.2: MSHF at 1 hour (Mean [SD]. *n* =12. * = P < 0.05).

6.3 Mean Skin Temperature Change

Immersions in Weather produced a significantly greater rate of change of T_{SK} compared to Calm (Figure 6.3). The rate of fall of T_{SK} in Calm was $-1.21 \pm 0.27°C \cdot hr^{-1}$ and $-1.62 \pm 0.41°C \cdot hr^{-1}$ in Weather.

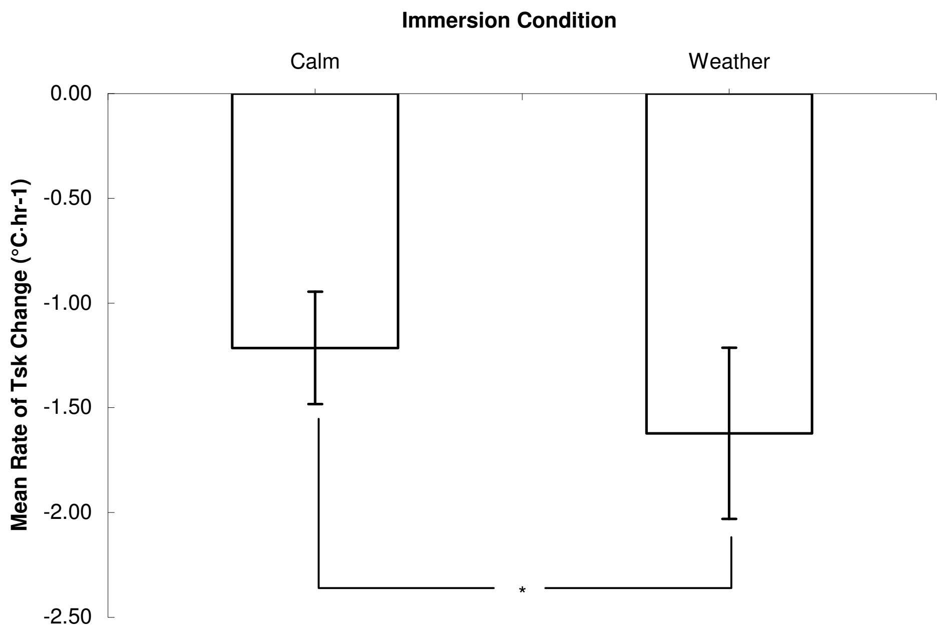

Figure 6.3: Rate of change in T_{SK} (Mean [SD] *n* =11. P < 0.05).

6.4 Gastro Intestinal Temperature Change

There was no significant difference in the rate of change of T_{GI} between immersions in Calm and Weather (Figure 6.4). The rate of change of T_{GI} in Calm was 0.07 ± 0.10°C·hr^{-1}, and –0.04 ± 0.12°C·hr^{-1} in Weather.

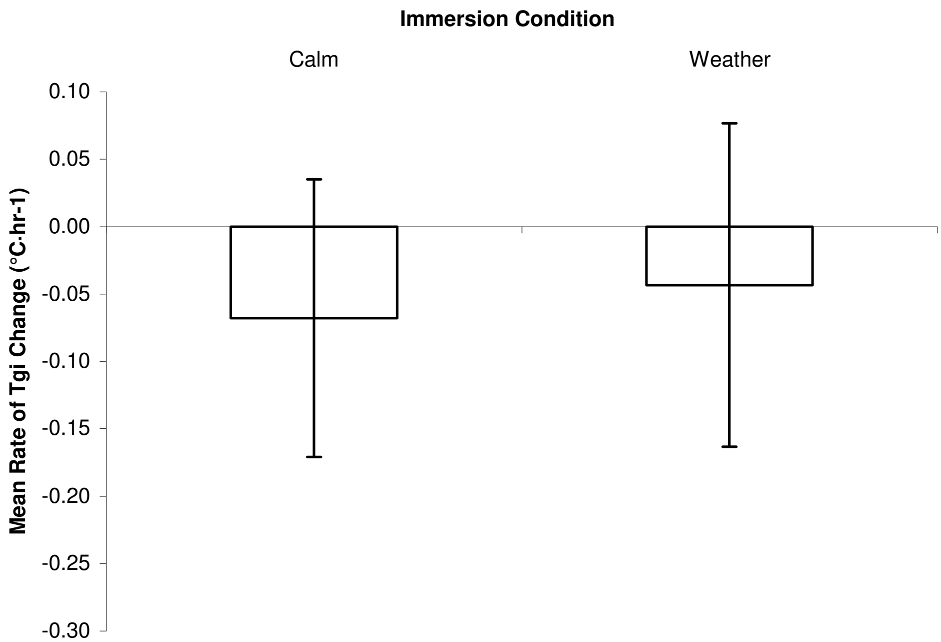

Figure 6.4: Rate of change of T_{GI} (Mean [SD]. *n* = 12).

6.5 Mean Body Temperature Change

There was no significant difference in the rate of change of MBT between immersions in Calm and Weather (Figure 6.5). The rate of change of MBT in Calm was –0.48 ± 0.10°C·hr^{-1}, and –0.61 ± 0.14°C·hr^{-1} in Weather.

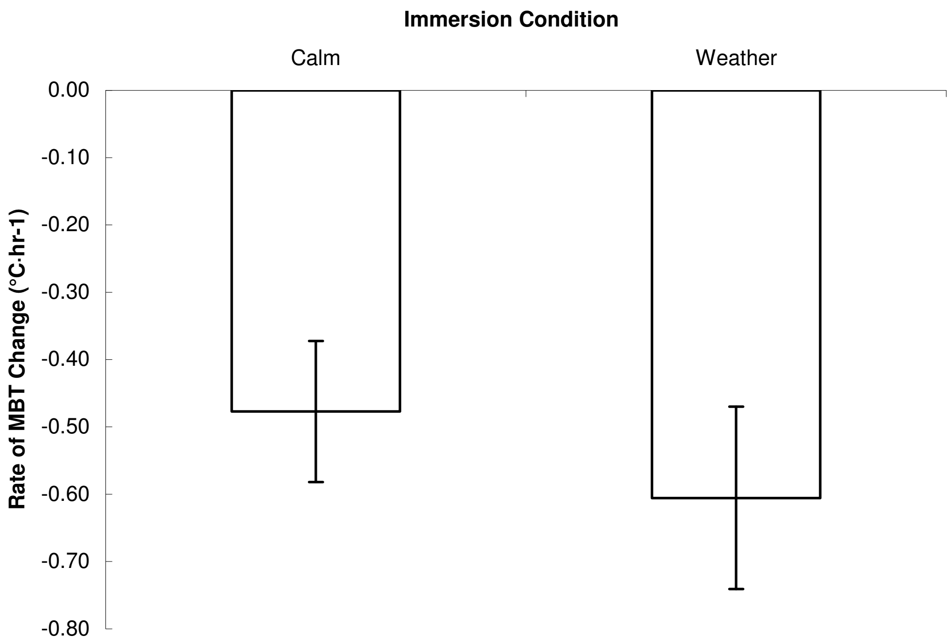

Figure 6.5: Rate of change of MBT (Mean [SD]. *n* = 11).

6.6 Oxygen Consumption

There was no significant difference in $\dot{V}O_2$ between immersions in Calm and Weather (Figure 6.6). $\dot{V}O_2$ in Calm was 459.53 ± 80.06 mL·min^{-1}, and 527.61 ± 120.63 mL·min^{-1} in Weather.

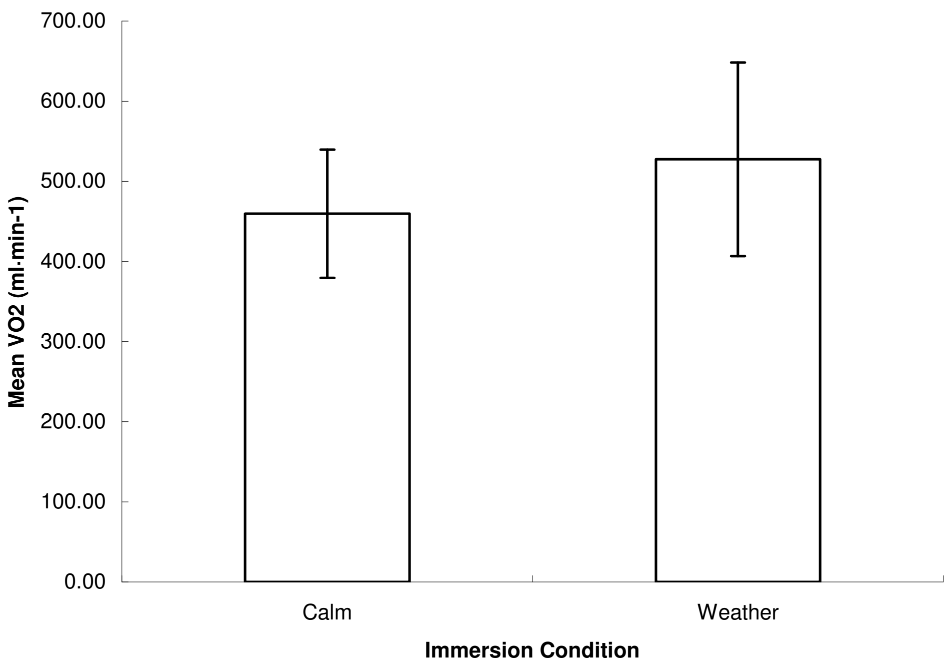

Figure 6.6: $\dot{V}O_2$ during the last 20 minutes of immersion (Mean [SD]. *n* = 12.).

6.7 Clo Value

For the current experiment, immersions in the Weather condition resulted in a significantly lower Clo value compared to Calm (Figure 6.7 – Nov 10). The Clo value was 1.88 ± 0.14 Clo in Calm and 1.38 ± 0.19 Clo in Weather.

Our previous work that examined the effect of wind and waves on human thermal responses is presented in Figure 6.7 (20). The "Weather" condition for the Mar 2009 data consisted of a 20-minute irregular JONSWAP wave spectrum with a maximum wave height of 0.67m and a period of 1.71s, and a mean wind speed of $4.6 m \cdot s^{-1}$. Immersions in this condition resulted in a significantly lower Clo value compared to Calm (Figure 6.7). The Clo value was 1.87 ± 0.13 Clo in Calm, and 1.36 ± 0.13 Clo in Weather.

There were no significant differences between Clo values for Calm immersions in our current work (Nov 2010) and our previous work (Mar 2009). There were no significant differences between Clo values for Weather immersions in the current (Nov 2010) and previous work (Mar 2009).

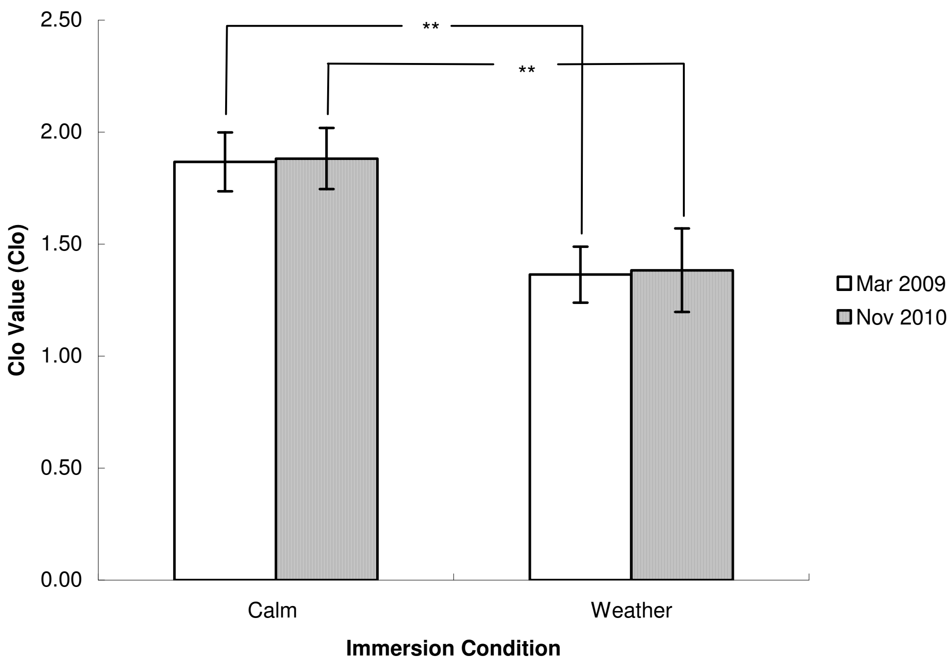

Figure 6.7: Clo values for the present experiment (Nov 2010) and previous work (Mar 2009). (Mean [SD]. ** = P < 0.001. *n*= 11 for Nov 2010; *n* = 12 for Mar 2009).

7.0 DISCUSSION

The results collected from this present experiment support the hypothesis that immersions in wind and flowing water will significantly increase heat flow compared to calm water. However, the results do not support the hypothesis that immersions in wind and flow will result in a significantly greater decrease in deep body temperature compared to calm water in the conditions tested.

Our previous work examined the effect of wind and waves on the thermal responses of people when they were dry inside immersion suits (18, 20) and with 500mL of water underneath the suit (19). The findings of the current study are in agreement with our previous results: immersions in turbulent conditions will result in a significantly greater increase in heat flow compared to calm water. Remarkably, the increase in heat flow moving from calm water to the wind and flow in the present study is equivalent to the increase seen when moving to wind and waves in our previous work (20). In the present study, MSHF significantly increased by ~26% when moving from Calm to Weather (Figure 6.2). In our previous work, MSHF increased by ~26% when moving from Calm to Weather 2 (wind and waves) (20). The change in Clo value (measure of insulation) was identical between both studies when moving from Calm to Weather conditions. In the present study, the White's Marine Abandonment Suit had a Clo value of 1.88 in Calm and 1.38 in Weather. In the March 2009 study, the same suit had a Clo value of 1.87 in Calm, and 1.36 in Weather 2. There were no significant differences in the calculated Clo values for the Weather condition in the present study, and the Weather 2 condition in the March 2009 study (Figure 6.7). This extremely good agreement in the changes in MSHF and Clo values between the two studies indicates that we were successful in replicating the increased thermal stress caused by wind and waves in a facility that had wind an a flow of water equivalent to the wave particle velocity of the waves tested in 2009.

In the present study, the increased MSHF due to the wind and current in the Weather condition did not result in a significant difference in the rate of T_{GI} change when compared to Calm (Figure 6.4). This lack of significant difference is similar to that seen in our earlier work (20), and the work by other authors. The earlier work of Hayes et al. found that wave motion did not significantly increase the rate of body cooling, compared to calm conditions, when using un-insulated immersion suits (10).

Even though $\dot{V}O_2$ was higher in the Weather condition compared to Calm, the result was not statistically significant (Figure 6.6). This suggests that the human participants compensated for the significantly increased MSHF in the Weather condition (Figure 6.2) by a thermoregulatory response in addition to a slight increase in shivering. The significantly greater rate of change of T_{SK} in Weather compared to Calm (Figure 6.3) suggests that participants compensated for the increased MSHF by a stronger vaso-constrictive response, reducing the thermal gradient between their deep body and the external environment.

As a result of vaso-constriction, the blood volume distribution of the body changes. The redirection of warm blood away from the limbs of the body to the torso in an effort to reduce heat loss through the periphery results in an increase in urine production (8). While there was no significant difference in the rate of urine production between the two conditions (Figure 6.1), the mean rate for the two conditions of 349 $g \cdot hr^{-1}$ could prove to be detrimental to people immersed for prolonged periods of time. Tipton and Balmi found that 500mL of water applied over the torso of people in un-insulated immersion suits resulted in significantly increased skin heat flow (28). Assuming a urine density of $1mL \cdot g^{-1}$, after only 90 minutes of immersion participants could produce an amount of urine in the suit that could prove to be detrimental to their survival if they were unable to resist the urge to urinate, and it was to spread over the torso.

The current body of work is in agreement with some previous studies, but contradicts others. Previous studies (4, 10) reported that wind and waves would have no effect on deep body temperature, compared to calm immersions, which is supported by this study. However, previous studies have show that immersions with simulated weather conditions can indeed cause a drop in deep body temperature in work coveralls (22), and Tipton has shown that predicted survival times can be reduced by as much as 30% in participants wearing un-insulated immersion suits in simulated weather conditions, compared to calm water (26).

The current study builds upon previous work funded by Transport Canada and the Program for Energy Research and Development (PERD). In our previous work, it was suggested that one of factors that may have resulted in no measured significant changes in deep body temperature was the environmental temperatures. Our previous studies (18-20) had water temperatures ranging from 8-11°C, and air temperatures between 15-18°C. Even though wind and waves significantly increased MSHF to the external environment, participants were able to compensate for it with their thermoregulatory responses. The goal of the current study was to test participants in colder water and air temperatures (5°C) in the hopes of exceeding their thermoregulatory responses, resulting in a drop in deep body temperature. The results from the current study show that even with the colder temperatures, participants were still able to thermo regulate in the immersion suits and prevent hypothermia from occurring.

7.1 Cold Exposure Survival Model Predictions

Data from our previous studies (19, 20) were inputted into the Cold Exposure Survival Model (CESM). The CESM is a software program designed to predict the survival time of people exposed to cold conditions (13, 24). The CESM predicts the amount of time it will take for a person's deep body temperature to drop to the lethal level of 28°C (13). The CESM predicts survival time up to a maximum of 36 hours.

Survival time predictions were generated for two groups of our previous participants: the March 2009 group that performed 3 hour immersions while dry in their immersion suits ("Dry"), and the March 2010 group that performed 3 hour immersions with 500mL of water underneath their suits ("Wet") (25). The predicted survival times are given in Figure 7.1.

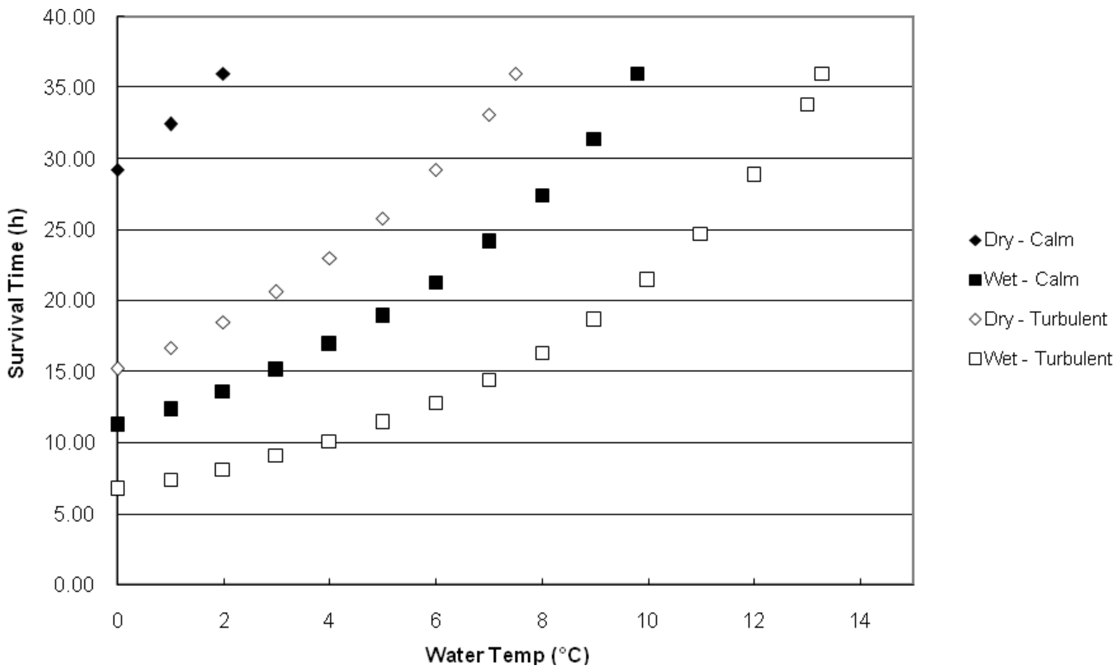

Figure 7.1: CESM predicted survival times for two separate groups of participants. ("Dry" = no water underneath immersion suit, "Wet" = 500mL of water underneath immersion suit. "Turbulent" = wind and waves) (25).

The predicted survival times for the participants in our previous studies are in agreement with the reported results. When our previous participants where immersed in calm and wind and wave conditions, while dry in the immersion suit, there were no significant decreases in deep body temperature (20). The CESM predicted survival times for the water temperatures this group of participants were immersed in (~11°C) are in excess of 36 hours for both calm and wind and wave conditions (25).

A separate group of participants in a subsequent study who where immersed in calm and wind and wave conditions, with 500mL of water underneath the immersion suit, also had no significant decreases in deep body temperature (19). The CESM predicted survival time for the specific water temperature this group of participants were immersed in (~8.5°C) was approximately 27 hours in calm conditions, and approximately 16 hours in wind and waves (25). Given the lack of measured significant changes in deep body temperature for the participants in that study, it is not unexpected that predicted survival times would be extremely long for the conditions tested.

For the current experiment with immersions in 5°C water and air, we measured no significant differences in the rate of T_{GI} change across both immersion conditions; with the rate of change for Calm (0.07 ± 0.10°C·hr^{-1}) and Weather (-0.04 ± 0.12°C·hr^{-1}) being extremely low (Figure 6.4). These low values of T_{GI} change during the present experiment show that the participants were able to successfully thermo regulate and maintain a stable deep body temperature. These findings agree with the CESM predicted survival times of greater than 36 hours for people in calm, 5°C water, and dry inside their immersion suit. When moving to the Weather condition, the CESM predicted survival time drops to 26 hours.

The CESM results suggest that wind and waves can reduce predicted survival times, but in the water temperatures we have tested in, and the level of insulation provided by the White's Suit, those times still remain high (> 15 hours). It is not until the water temperature nears 0°C and the insulation of the immersion suit is further reduced by the addition of 500mL of water that predicted survival times are under 10 hours (25).

7.2 Change in Clo Value

Using data collected from our previous work (19, 20), the change in Clo value moving from being dry in calm water to other conditions can be calculated (Figure 7.2).

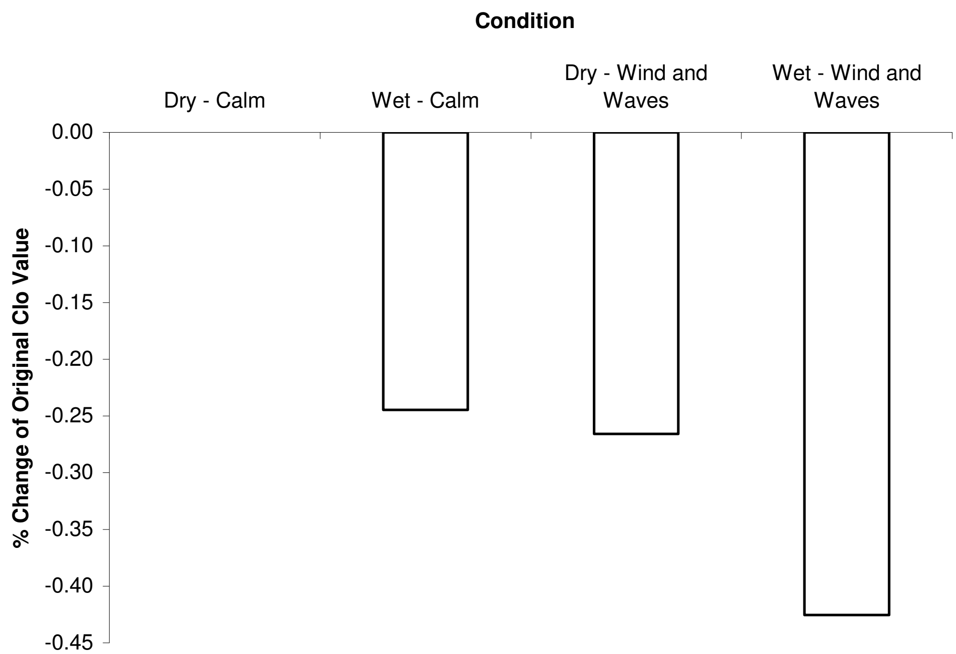

Figure 7.2: % change in Clo from calm water values in various immersion conditions.

Adding 500mL of water underneath the White's Marine Abandonment Suit resulted in a 24% drop in Clo value compared to when people were dry in the suit. Clo value dropped by 27% when moving from calm water to wind and waves, but still dry inside the immersion suit. The greatest decrease in Clo Value was observed when the participants were wet inside the immersion side in an environment with wind and waves, resulting in a 43% decrease. The reduction of Clo value in changing environmental conditions, compared to calm water, is important since it will result in significantly greater increases in heat flow from immersed people without any change in water or air temperature.

7.3 $\dot{V}O2$ Required to Maintain Thermal Balance

In our past two experiments, and in the current one, all participants were able to successfully thermo regulate in all the test conditions, even with the increased thermal strain due to wind and waves. Our participants were able to achieve this thermal balance via reduction in skin blood flow (vaso-constriction) and increasing metabolic heat production to closely match the heat lost the environment (shivering).

Figure 7.3 plots the predicted $\dot{V}O_2$ ($\dot{V}O_{2\,P}$) required by a 2.1m^2 person to equal the heat flow lost to 0°C water across a range of skin temperatures (T_{SK}) and Clo values to remain in thermal balance.

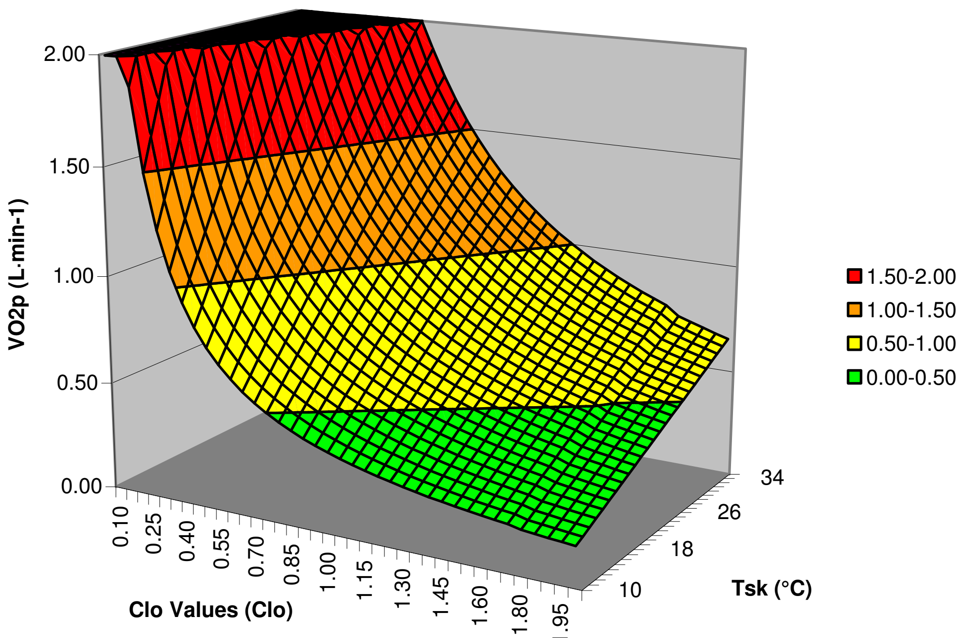

Figure 7.3: Predicted $\dot{V}O_2$ to maintain thermal balance in 0°C water for a 2.1m^2 person.

Eyolfson and Tikuisis et al. reported a mean $\dot{V}O_2$ of1.57L·min^{-1} associated with maximum shivering intensity in their study participants (6). At higher Clo (> 1.7) values, a $\dot{V}O_{2\,P}$ of 0.70L·min^{-1} is required to match the heat flow to the environment, at a slightly lower than normal T_{SK} (32°C); less than half the mean maximum $\dot{V}O_2$ a person can achieve. This would suggest that a person would be able to remain in thermal balance at a slightly lower than resting T_{SK} with a moderate amount of shivering.

The current IMO Life Saving Appliances Code requires that insulated immersion suits prevent a 2°C drop in deep body temperature in 0-2°C calm, circulating water during a 6 hour immersion (16). If a completely dry immersion suit with an immersed Clo value of 0.80 is tested according to current IMO standards, Figure 7.3 indicates that a $\dot{V}O_{2\ P}$ of 1.31 L·min^{-1} (i.e. shivering at approximately 66% of their maximum ability) would be required by a 2.1m^2 person, with a T_{SK} of 28°C, to replace the heat lost to the environment and remain in thermal balance. Based on the results in Figure 7.2, we can expect a 27% drop in Clo value of the immersion suit when moving from calm water to an environment with wind and waves. This would change the immersed Clo value from 0.80 to 0.58. Referring back to Figure 7.3, this would result in a $\dot{V}O_{2\ P}$ of approximately 1.75 L·min^{-1} required to remain in thermal balance. Since this $\dot{V}O_2$ is greater than the maximum shivering value of 1.57 L·min^{-1}, the human would not be able to match the heat lost to the environment and would quickly enter heat debt. It is not until the T_{SK} of the human dropped to 24°C that they would be able to theoretically match the heat flow to the environment, and even then only at their maximum ability to shiver.

In the above theoretical example, it was assumed that the immersion suit was completely dry. Before the beginning of the thermal tests, the IMO LSA code requires that immersion suits go through water ingress tests to calculate water leakage after a jump from a sufficient height to completely immerse the person, and a period of flotation in calm water for 1 hour, or swimming for 20min for a distance of at least 200m (16). After the jump test, the suit should not take on more than 500g of water, and after the swim test, the suit shall not take on more than 200g of water (16). Work conducted by the CORD Group Ltd. has suggested that these test methods will significantly underestimate the amount of water that could leak into a suit (15). If current LSA test standards do not provide a rigorous enough challenge of the ability of immersion suits to remain water tight, then it is possible that a significant amount of water may leak into the suits.

The addition of as little as 500mL of water inside the immersion suit can result in a reduction in Clo value of 24%, even when remaining in calm water (Figure 7.2). If a dry immersion suit had a Clo value of 0.80 in calm, circulating water, the addition of 500mL of water underneath it in wind and waves would see that value reduced to 0.46. With a Clo value of 0.46, in 0°C water, and a T_{SK} of 28°C, the $\dot{V}O_2$ required to remain in thermal balance is 2.33L·min^{-1}. In this scenario, the T_{SK} of a person shivering at their maximum ability would have to drop to 18°C before thermal balance could be achieved (Figure 7.3).

In comparison to IMO standards, current CGSB standards for marine and helicopter immersion suits require that they provide an insulation value of at least 0.75 Clo when tested with a thermal manikin in 40cm waves (1). The new draft standard of the helicopter passenger transportation suit system standard (CAN/CGSB-65.17) will require that suits have at least 0.75 Clo in 20-25cm waves and 20-25 kph wind if using thermal manikins. If using humans, the environmental conditions remain the same with the exception that the water and air temperature is between 0-2°C. In 0°C water, a 2.1m^2 person wearing a 0.75 Clo suit, would need to shiver at maximum ability ($\dot{V}O_2$ ~ 1.57 L·min^{-1}) to maintain a T_{SK} of 30°C. In a recent study by the CORD Group

Ltd., participants performed 6 hour immersions in 0°C water with 15-30cm waves and 18-25 km·h^{-1} wind wearing a custom clothing ensemble that had a Clo value of 0.75 (14). Prior to the beginning of the tests, the participants had a T_{SK} of 33.1°C. At the end of the 6- hour immersion, the participants (with a mean surface area of 1.99m^2) had a reported T_{SK} of 22.7°C, with a MSHF of 254 W·m^{-2}. For a 1.99m^2 person to replace 254 W·m^{-2} of heat lost to the external environment, they would have to shiver at a calculated $\dot{V}O_2$ of ~1.42 L·min^{-1}; a rate that is close to their maximum ability. In the conditions tested by the CORD Group, the majority of the participants were able to maintain a stable deep body temperature, possibly with great effort required on their part. Moving to environments with harsher conditions may result in an increase in heat lost to the environment, pushing people past their ability to thermo regulate, translating to a drop in deep body temperature.

It is concluded, that in conditions where the human body can thermo regulate, small, if any, changes may be measured in deep body temperature. The addition of wind, waves, water leakage, and colder water temperatures will increase skin heat flow to the external environment, placing more strain on the thermoregulatory system. If the thermoregulatory system can compensate for this increased strain, no change in deep body temperature may be measured, even in conditions that are perceived to be more challenging. Overestimation of performance of people in immersion suits will occur if generalized conclusions are made from tests without taking into consideration the conditions of the test, and the effort being made by the participants to maintain a stable deep body temperature. If participants are close to the limit of their ability to thermo regulate (i.e. maximum shivering), but still maintain a stable deep body temperature in a given set of conditions, harsher conditions may push them past their limits, resulting in a fall in deep body temperature. Therefore, it is important that when testing humans and immersion suits, to test them in conditions as realistic as possible, or be able to predict the effects that the conditions will have.

8.0 RECOMMENDATIONS

1. When assessing the performance of humans who have an active thermoregulatory system, it is important to measure both sides of the thermal balance equation, i.e. heat lost from the system, and heat put back into the system. An active thermoregulatory system may mean that a stable deep body temperature can be measured in two very different environments (e.g. calm, and wind and waves), since humans will try to regulate this variable. The difference between two conditions may not just be a significant increase in heat flow, but a significant increase in effort from the participants to regulate their deep body temperature through vaso-constriction and shivering. In circumstances where the body can thermo regulate, the definitive variable may not be body temperature.

2. It is recommended that the performance of humans and immersion suits be tested in conditions as representative of the area of operation as possible. If this is not possible due to either financial, or mechanical, limitations, a correction factor or safety margin should be added into the final results. For example, if in the thermal tests as prescribed by the LSA code, a human is able to maintain a stable deep body temperature through a high level of shivering (i.e. $\dot{V}O_2$ near 1.50 $L{\cdot}min^{-1}$), moving into conditions with wind and waves will result in increased thermal strain, exceeding the thermoregulatory system. If the tests could only be conducted in calm circulating water, Figure 7.2 provides possible correction factors for how much the Clo value of a suit can change when moving to the more challenging environments. By applying these correction factors, the amount of extra heat lost to the environment due to wind and waves can be calculated, allowing for an indication of how much effort a person would require to thermo regulate to maintain a stable deep body temperature (Figure 7.3). If this calculated increase in heat loss due to harsher conditions exceeds the thermoregulatory system, suit insulation can be increased to compensate for it.

3. If a facility lacks the ability to replicate waves found in the area of operation, an alternative may be to create a flume system similar to that described in this report. By moving water past the participants at the same rate of wave particle velocity, the heat loss effects can be replicated allowing for a more accurate assessment of performance in realistic conditions.

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APPENDIX A

Cold Exposure Survival Model Survival Time Predictions Reports

Predictions of Survival Time for Individuals Immersed in Water and Wearing a Survival Suit

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Report on survival time estimations for PJ 2264 prepared for Jonathan Power, NRC Institute of Ocean Technology.

Introduction

Search and Rescue is reliant on tools that guide decisions on rescue planning and operations, as for example having an estimation of a casualty's survival status. One such tool is the Cold Exposure Survival Model (CESM), which is designed to predict the survival time (ST) of individuals exposed to cold, whether exposed to air or immersed in water (Tikuisis 1997; Keefe and Tikuisis 2008). This report presents the predictions of the survival status of individuals wearing a White's Marine Abandonment Suit that was used in a series of cold water immersion experiments conducted by Power et al. (2008, 2009).

The first section of this report presents a comparison of measured and predicted values at the end of 3 h of the experimental immersion conditions reported by Power et al. (2009). The second section presents survival time predictions for hypothetical situations in which water leaks into the suits. This will demonstrate the incapacitation of survival suits when degraded by water leakage whether due to accident, poor fit, or poor maintenance. The final section will summarize the findings with recommendations for further inquiry.

Comparison of Measured and Predicted Thermal Status of Experimental Subjects

In brief, the experiment involved 3 hours of head-out immersion of 12 males (mean age 24 yrs, height 1.81 m, weight 83.2 kg, and body fat 16.8%) wearing a survival suit (White's Marine Abandonment Suit with undergarment) in water at about 11°C under both calm and turbulent conditions (Power et al. 2009). The in-situ insulation of the survival suit was measured using a manikin purposely designed for such an evaluation (CORD 2008). Under calm (windless flat water) and turbulent (5.5 m/s wind and 0.67 m waves) conditions, the survival suit's in-situ insulation were 1.098 and 0.796 clo, respectively.

As a survival prediction model, CESM is designed to estimate the time taken for an individual's deep body temperature to reach 28°C, assumed as the point of imminent death due to hypothermia (Keefe and Tikuisis 2008). As such, the vast majority of this cooling time is characterized by either a continuous decline in body temperature or steady state heat balance, depending on the severity of the cold insult. That is, if heat loss is less than the individual's maximum possible heat generation from shivering, then the individual should reach a steady state heat balance with no further decrease in body temperature until shivering fatigue (Tikuisis et al. 2002; Tikuisis 2003). Under this latter condition, which pertains to the experimental situation, the relatively short period of initial net heat loss upon immersion, typically characterized by a transient rise in deep body temperature due to vasoconstriction of the skin, is bypassed in CESM. In practical terms, CESM's prediction just after the start of immersion reflects the thermal response beyond the transient period and therefore will indicate lower body temperatures than actually measured. This is because the 'modelled' body is allowed to cool sufficiently so that the predicted rate of heat loss can be countered by the predicted shivering heat production, which is driven by decreases in both deep body and skin temperatures. The eventual prediction of survival time based on deep body cooling to 28°C is not sensitive to the transient period given the relative shortness of the latter period to the former.

Assuming that the transient period is approximately 1 h for the immersion conditions of the study[*], Table 1 compares the CESM-predicted thermal response values after 2 h of immersion with the measured values of the subjects at the end of their 3 h of immersion. Table 1 also shows the predicted thermal status of the subjects at the end of 36 h of immersion, which is the limit of CESM's predictive range (causes of death other than hypothermia are more likely to occur if individuals survive 36 h of immersion). An additional caveat of CESM is that it does not have an input field for wave height; instead, it only allows for either light or heavy seas. In the present circumstance, 'light' is assumed for the calm condition and 'heavy' is assumed for the turbulent condition (i.e., with wind and waves irrespective of their values provided that the individual experiences significant water movement, which is assumed for both Weather #1 and #2 conditions).

The predicted decreases in body temperatures are much greater than measured, which was not unexpected, as explained above. The predicted metabolic rate is higher than measured, driven by the predicted decreases in body temperatures. Notwithstanding the limitations of CESM, an

[*] Of the subjects whose deep body temperatures initially rose upon immersion (6 and 9 for the calm and high turbulent conditions, respectively), they returned to their starting values after respective mean times of 73 and 62 min of immersion.

additional explanation for these overpredictions is taken up in the Discussion. That the measured heat loss exceeds the measured metabolic rate indicates that the subjects had not attained heat balance at the end of 3 h of imersion, which concurs with the further predicted decreases in body temperatures and increase in metabolic rate predicted after 36 h of simulated immersion.

Table 1. Measured and predicted changes in thermal status for the experimental test conditions. Water temperature was 11°C, and respective wind speed and wave height were 3.5 m/s and 0.34 m for Weather #1, and 4.6 m/s and 0.67 m for Weather #2. Predicted values for the turbulent condition apply to both Weather #1 and #2.

Condition	Change in Deep Body Temperature (°C)			
	Meas ± SD	Pred 2 h	Pred 36 h	
Calm	0.10 ± 0.31	1.03	1.23	
Weather #1	0.29 ± 0.30			
Weather #2	0.20 ± 0.28	1.21	1.45	
	Change in Mean Skin Temperature (°C)			
	Meas ± SD	Pred 2 h	Pred 36 h	
Calm	2.96 ± 0.43	6.39	6.51	
Weather #1	3.46 ± 0.72			
Weather #2	3.95 ± 0.66	8.40	8.53	
	Mean Body Heat Flow and Metabolic Rate (W/m^2)			
	Meas BHF ± SD	Meas MR ± SD	Pred MR 2 h	Pred MR 36 h
Calm	63.0 ± 3.0	55.8 ± 7.6	68.5	82.5
Weather #1	76.8 ± 6.3	57.9 ± 19.0		
Weather #2	79.5 ± 6.2	62.6 ± 11.5	93.9	96.8

Under no condition did CESM predict that the subjects' deep body temperature would reach lethal hypothermia (drop of 9°C) within 36 h of immersion. Indeed, the predicted changes in the subjects' thermal status at the end of this period are not markedly higher than predicted after 2 h of immersion indicating that the subjects were close to attaining steady state heat balance soon after and should not sucumb to hypothermia unless leakage of water compromised their suit's insulation, which is considered in the next section.

Predicted Survival Status of Individuals During Various Hypothetical Immersion Conditions

This section provides estimations of the subjects' survivability if the survival suits that they wore developed a leak. Four levels of wetness are assumed for this demonstration: ingress of 0.1 L/m^2 (equivalent to an even spread of 0.1 mm height of water or a total of 200 mL for a body surface area of 2 m^2) considered damp, 1 L/m^2 considered moderately wet, 5 L/m^2 considered soaked, and nude (for comparative purposes). Figure 1 shows the predicted survival times (up to 36 h) for calm and turbulent (applies to both Weather #1 and #2 conditions) immersions in water from 0 to 20°C. Included in this display are estimations for the survival suit when kept dry.

As indicated earlier, the subjects are predicted to survive at least 36 h of immersion while wearing the dry survival suit in the experimental water temperature of around 11°C. Note, however, that the survival time reaches the 36 h prediction limit in water less than 2°C under calm conditions and less than 8°C in turbulent water. In the extreme case of dry suit immersion in 0°C turbulent water, the predicted survival time diminishes to less than 16 h.

Further decreases in survival time are apparent with water leakage into the survival suit, as evident in Fig.1. Survival time is seen to diminish markedly under the damp condition, cutting almost a third of the time compared to the dry condition. Increasing wetness further also demonstrates a disproportionate decrease in survival time. For example, increasing wetness by an order or magnitude (10x) from the damp to wet condition diminishes survival time by roughly another third. Finally, a completely soaked survival suit will afford better protection than if the subject was nude, but the advantage dissipates quickly as water temperature decreases.

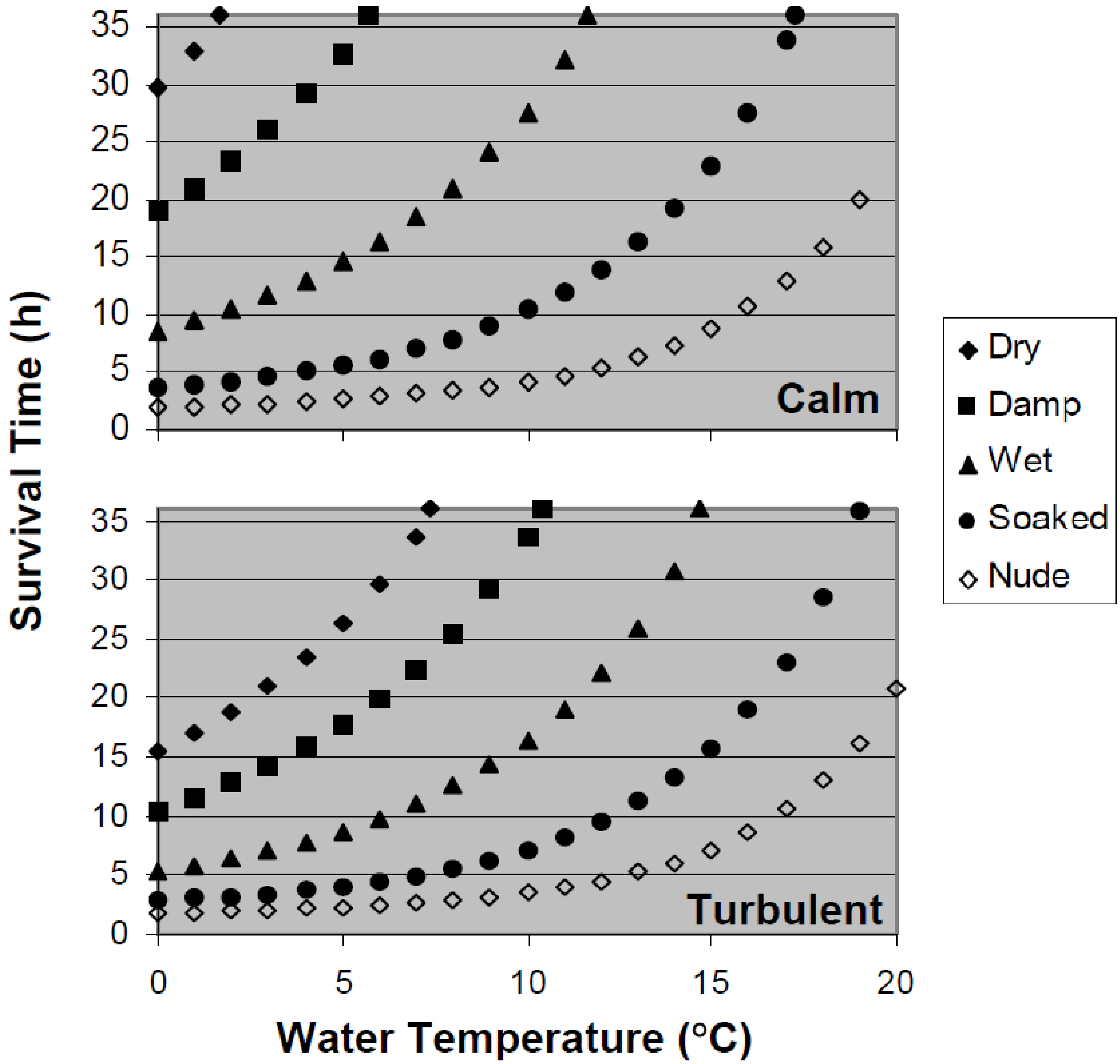

Figure 1. Survival time predictions for calm and turbulent water immersions for the subjects wearing the survival suit under dry and various wetness conditions, in addition to a nude condition.

It is also instructive to consider the range of survival times as individual body sizes/shapes vary. The predicted survival times for the leanest and largest subjects of the study based on body fatness are shown in Fig. 2 for immersion in turbulent water under dry and wet survival suit conditions. When the survival time is less than 36 h for both subjects, the largest subject is predicted to survive at least twice as long as the leanest subject.

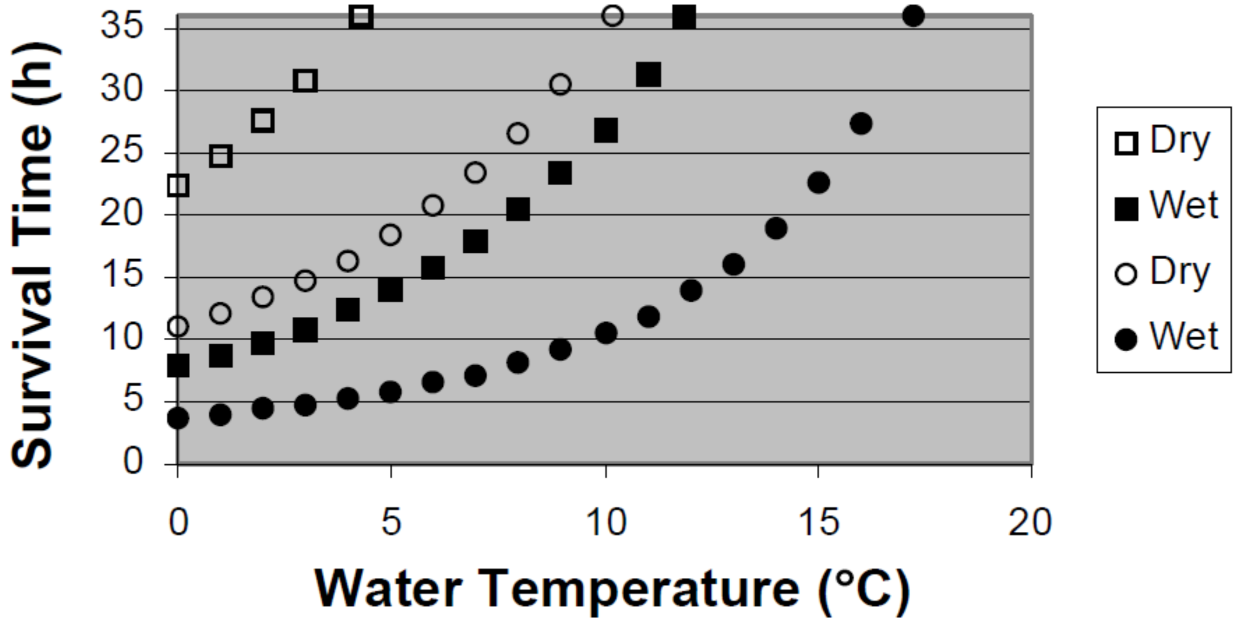

Figure 2. Comparison of predicted survival times for the leanest (○●; 1.77 m, 68 kg, 10.3% body fat) and largest (□■; 1.75 m, 95 kg, 24.4% body fat) subjects immersed in turbulent water under dry and wet survival suit conditions.

Discussion and Recommendations

Although CESM is not designed to predict the early response of individuals immersed in cold water, comparison with the measured values nevertheless suggests that the decreases in body temperatures and increase in metabolic rate are over predicted. This disparity might be partially explained by the possibility of varying survival suit insulation. Given that the insulation of the survival suit is based on a steady state condition measured on a manikin from 75 min to 4 h after the start of immersion (CORD 2008), it is conceivable that the suit's insulation is initially higher due to the time taken for the suit to fully adjust to the environmental condition (e.g., with further compression of clothing insulation). If so, then a resultant higher initial insulation would impose a lesser cold insult to the body leading to a slower initial decline in body temperatures and consequent lower metabolic rate than predicted by assuming the steady state value of insulation.

The most striking finding in this report is the marked decrease in survival time if the survival suit is compromised by water leakage, even a modest amount. Similar to wind chill where the initial increment in air movement has a disproportionally high impact on surface cooling, the initial increment of water leakage causes significant degradation in suit insulation. It is noteworthy that even if a survival suit did not leak, sweating due to high exertional effort would degrade suit insulation. Hence, future studies should consider trials with wetted suits, whether on humans or manikins, to fully appreciate the consequences of leakage for educational/instructive and contingency design purposes. Also reinforced in this report is the vast difference in survival times between low and high fat individuals. To promote the survivability of the former, consideration should also be given to over-sizing their suits to allow for extra clothing/ undergarments that would provide additional protective insulation.

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Predictions of Survival Time for Individuals Immersed in Water and Wearing a Wetted Survival Suit: Phase 2

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Report on survival time estimations for Phase 2 of Contract No. 743545 prepared for Jonathan Power, NRC Institute of Ocean Technology.

Introduction

This report presents the predictions of the survival status of individuals wearing a wetted White's Marine Abandonment Suit that was used in a cold water immersion experiment conducted by Power et al. (2010). It follows the earlier Phase 1 report (Tikuisis 2010) on the survival status of similar individuals wearing the same suit, but under a dry condition. The reader is referred to the Phase 1 report for an introduction to the Cold Exposure Survival Model (CESM; Tikuisis 1997; Keefe and Tikuisis 2008) used for survival time predictions including underlining assumptions and caveats regarding its use.

The first section of this report compares measured and predicted values of the subjects' thermal status at the end of the 3 h experimental immersion study conducted by Power et al. (2010). The second section presents survival time predictions for various other degrees of wetness including a dry condition. This will demonstrate the incapacitation of survival suits when degraded by water leakage whether due to accident, poor fit, or poor maintenance. The third section compares the survival predictions for the leanest and largest individuals of the study, which will re-emphasize the natural insulative benefit of high body fatness under conditions of cold exposure. The final section will summarize the findings.

Comparison of Measured and Predicted Thermal Status of Experimental Subjects

The experiment involved 3 hours of head-out immersion of 12 males (mean age 26 yrs, height 1.81 m, weight 82.7 kg, and body fat 18.8%) wearing a survival suit (White's Marine Abandonment Suit with undergarment) in water of about 8.5°C under both calm and turbulent conditions (Power et al. 2010). The in-situ insulation of the dry survival suit was measured using a manikin purposely designed for such an evaluation (CORD 2008). Under calm (windless flat water) and turbulent (5.5 m/s wind and 0.67 m waves) conditions, the survival suit's in-situ dry insulation (including undergarment) were 1.098 and 0.796 clo, respectively. In the current experiment, subjects were wetted by having 250 mL of water applied to each side of their torso while wearing the undergarment for a total wetness of 500 mL. Using an estimation of the degradation of insulation dervived from the data of Allan et al. (1985), the resultant in-situ insulation of the survival suit is estimated to decrease to 61% of its dry value when wetted by this amount of water (implicit is the uniform transfer of some wetness from the undergarment to the suit once the subject is fully encapsulated). Thus, the in-situ wetted survival suit's ensemble insulation values assumed in this study were 0.670 and 0.486 clo under the calm and turbulent conditions, respectively.

CESM (Cold Exposure Survival Model) is designed to predict the time taken for an individual's deep body temperature to reach 28°C, assumed as the point of imminent death due to hypothermia (Keefe and Tikuisis 2008). Given that the vast majority of cooling time is characterized by either a continuous decline in body temperature or steady state heat balance depending on the severity of the cold exposure, the model bypasses the relatively short initial transient adjustment of deep body temperature upon immersion. Hence, CESM's prediction immediately after the start of immersion reflects the thermal response beyond the transient period and consequently will indicate lower body temperatures and higher metabolic rates than actually measured.

Deep body temperatures initially rose upon immersion in about half of the subjects and these temperatures returned to their starting values in average times of about 81 and 105 min under the calm and turbulent conditions, respectively. As an approximation, therefore, the measured thermal responses with a lead of 1.5 h were compared to the predicted responses. That is, Table 1 compares the CESM-predicted thermal response values after 1.5 h of immersion with the measured values of the subjects at the end of their 3 h of immersion. No distinction was made for the two 'Weather' conditions (i.e., wind speeds and wave heights of 3.5 m/s and 0.34 m for Weather #1, and 4.6 m/s and 0.67 m for Weather #2) since the dry survival suit's insulation was measured under one turbulent condition and CESM does not have an input field for wave height. Instead, it only allows for either light or heavy seas, which in the present circumstance is assumed for the calm and turbulent conditions, respectively.

The predicted decreases in body temperatures are much greater than measured, which was expected, as explained above. The predicted metabolic rate is also higher than measured, driven by the predicted decreases in body temperatures. Additional explanations for these overpredictions are discussed in the Phase 1 report (Tikuisis 2010) and in the summary of this report. The measured heat losses exceed the measured metabolic rate for the turbulent condition and suggest that the subjects had not attained heat balance at the end of 3 h of imersion, which concurs with further predicted decreases in body temperatures and increase in metabolic rate predicted beyond 3 h of simulated immersion. Under all test conditions, CESM predicted that the subjects' deep body temperature would reach lethal hypothermia (drop of 9°C from 37°C) within 36 h of immersion.

Table 1. Measured and predicted changes in thermal status for the experimental test conditions. Water temperature was approximately 8.5°C, and respective wind speed and wave height were 3.5 m/s and 0.34 m for Weather #1, and 4.6 m/s and 0.67 m for Weather #2. Predicted values for the turbulent condition apply to both Weather #1 and #2.

Condition	Decreases in			
	Deep Body Temperature (°C)		Mean Skin Temperature (°C)	
	Meas ± SD	Pred 1.5 h	Meas ± SD	Pred 1.5 h
Calm	0.37 ± 0.28	1.22	2.76 ± 0.73	10.96
Weather #1	0.27 ± 0.26		3.20 ± 0.92	
Weather #2	0.28 ± 0.23	1.23	3.61 ± 0.65	13.07
	Mean Body Heat Flow and Metabolic Rate (W/m^2)			
	Meas BHF ± SD	Meas MR ± SD	Pred MR 1.5 h	
Calm	81.2 ± 9.3	83.1 ± 10.7	112.7	
Weather #1	103.3 ± 11.2	88.8 ± 7.6		
Weather #2	107.5 ± 3.6	93.0 ± 19.6	135.8	

Predicted Survival Status of Subjects During Various Immersion Conditions

This section provides estimations of the subjects' survivability under various levels of wetness including the experimental, dry, and nude conditions. Specifically, five levels are considered:

dry, wetnesses of 0.1 L/m^2 (equivalent to an even spread of 0.1 mm height of water or a total of 200 mL for a body surface area of 2 m^2) considered damp, 0.25 L/m^2, which represents the experimental '500 mL' condition, 5 L/m^2 considered soaked, and nude (for comparative purposes). Figure 1 shows the predicted survival times (up to 36 h) for calm and turbulent (applies to both Weather #1 and #2 conditions) immersions in water from 0 to 20°C.

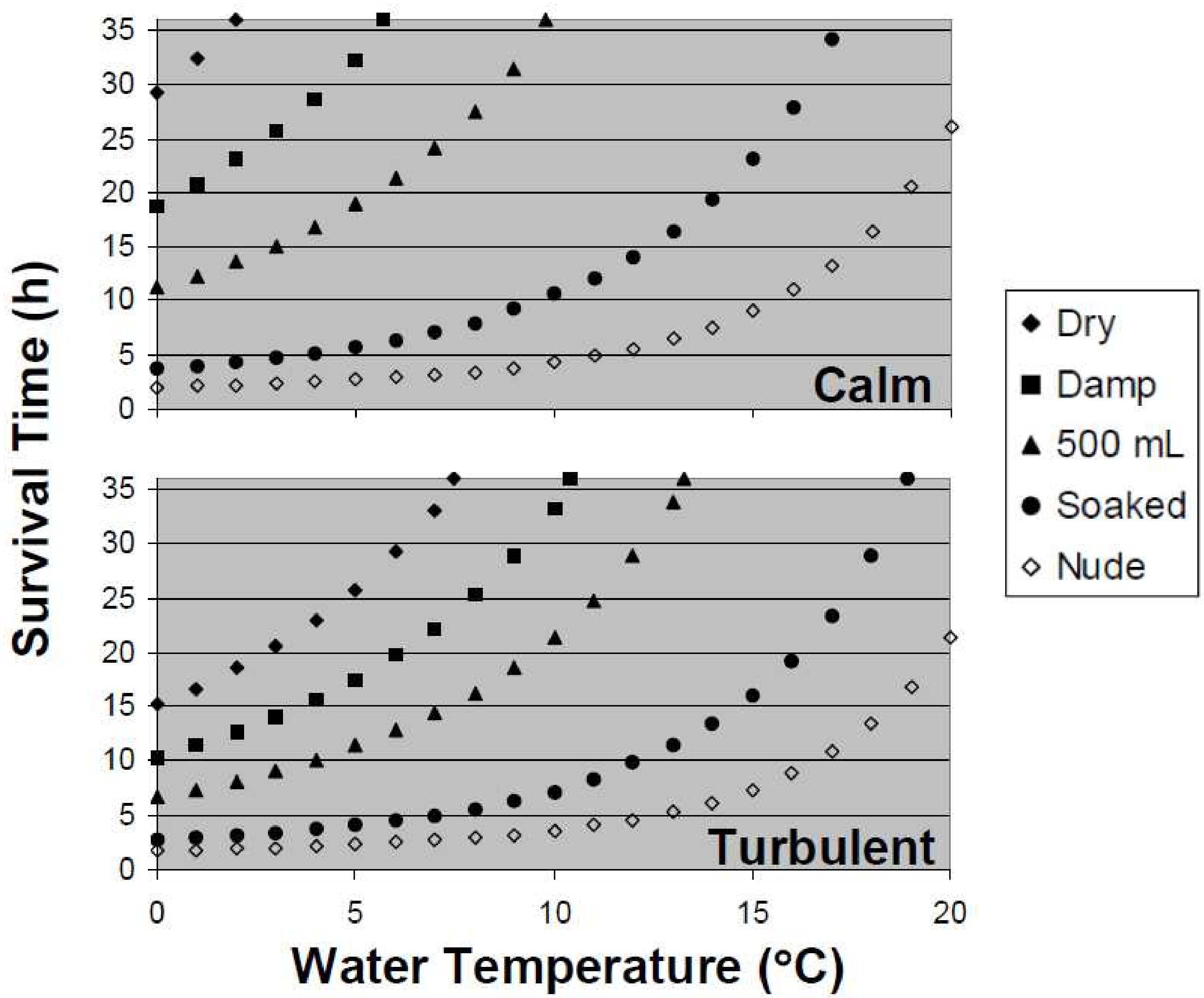

Figure 1. Survival time predictions for calm and turbulent water immersions for the average subject wearing the survival suit under dry and various wetness conditions, in addition to a nude condition.

As indicated earlier, the subjects are not predicted to survive 36 h of immersion while immersed with the wetted survival suit in the experimental water condition of about 8.5°C. However, if the suit was dry, the survival time reaches the 36 h prediction limit in water less than 2°C under calm conditions and less than 8°C in turbulent water. Further, the 36 h limit is reached under various levels of wetness at higher water immersion temperatures, except for the nude condition in which case the predicted survival time for the average subject is less than 36 h, even in water at 20°C. The marginally higher predicted survival times compared to Fig. 1 in the Phase 1 report (Tikuisis 2010) is attributed to the slightly higher average body fatness of the subjects in the current study. The observation of a disproportionate decrease in survival time with increasing wetness reported in the Phase 1 report is replicated here, noting in particular that the application of 500 mL of water to the subjects' clothing degraded the survival suit's insulation to 61% of its dry value leading to diminished survival times by 38 and 44% compared to a dry condition under calm and turbulent water, respectively.

Predicted Survival Status of the Leanest and Largest Subjects During Various Immersion Conditions

As in the Phase 1 report, consideration is given to the range of survival times for varying individual body sizes/shapes. This was done by comparing the predicted survival times for the leanest and largest subjects of this study based on body fatness, as shown in Fig. 2 for immersions in both calm and turbulent water under dry and wetted survival suit conditions. When the survival time is less than 36 h for both subjects, the largest subject is predicted to survive about 50% longer than the leanest subject.

In order for the leanest subject to survive as long as the largest subject under the same environmental conditions, additional insulation is required. This increase can be calculated by increasing the in-situ clo value until the predicted survival time of the leanest subject matches that of the largest subject without any adjustment of the latter's insulation value. Interestingly, the additional insulation varies according to the environmental condition. Under the calm water condition, the leanest subject requires approximately 13 and 21% additional 'in-situ' insulation to survive as long as the largest subject for the dry and wetted (500 mL) conditions, respectively. Under the turbulent water condition, the required increases are 17 and 30% for the dry and wetted conditions, respectively. These estimates indicate that wetness increases the required additional insulation by about another two-thirds compared to the dry condition.

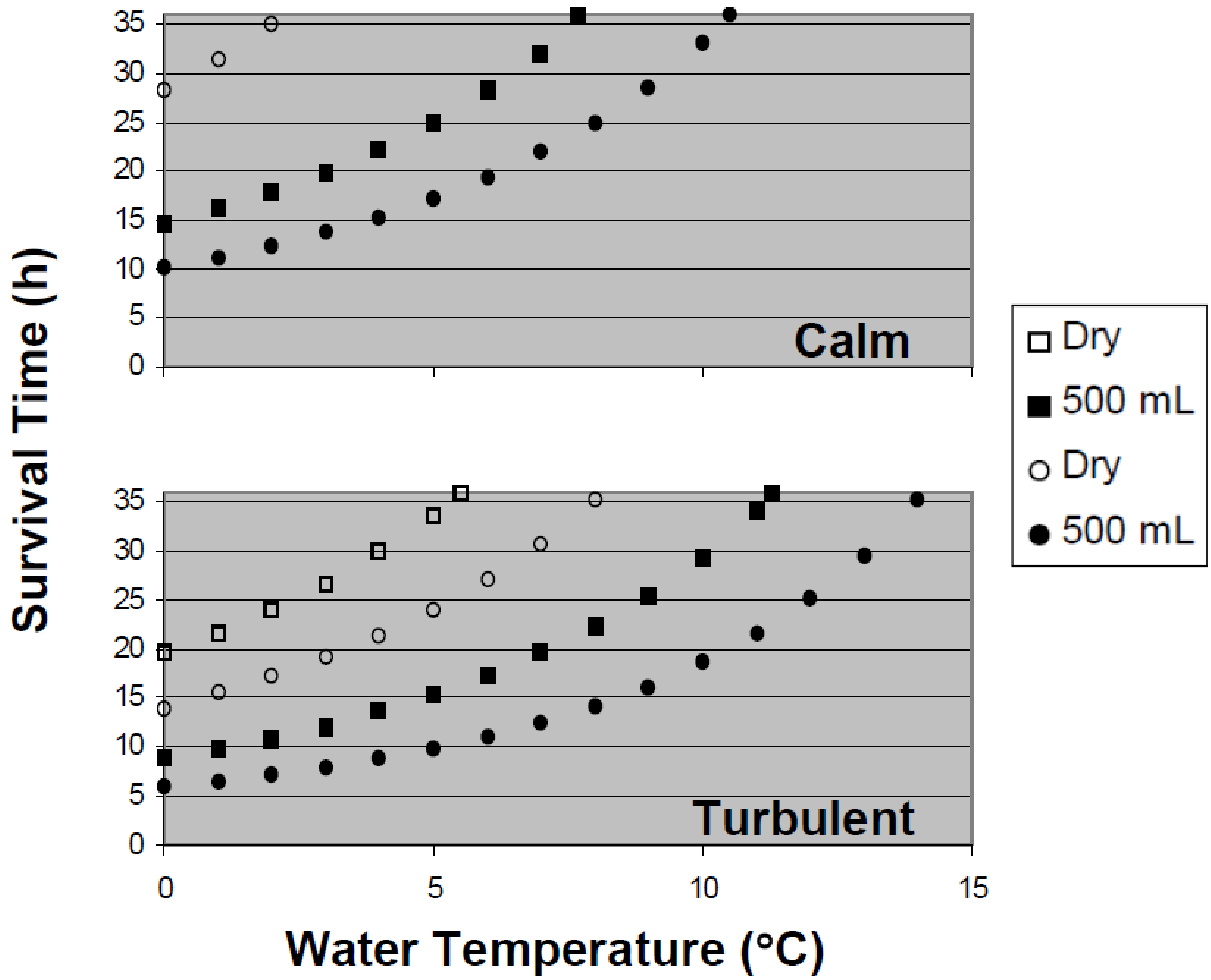

Figure 2. Comparison of predicted survival times for the leanest (○●; 1.79 m, 70 kg, 14.6% body fat) and largest (□■; 1.89 m, 99 kg, 22.8% body fat) subjects immersed in calm and turbulent water under dry and wetted survival suit conditions.

<u>Summary</u>

Although the predicted changes in body temperatures greatly exceed the measured values (Table 1), the subjects cannot be considered 'hypothermic' at the end of 3 h of immersion in 8.5°C water. Hypothermia begins at a deep body temperature of below 35°C (Auerbach 2001), which was not exceeded by either measurement or prediction. Hence, the broader interpretation is that the CESM prediction concurs with the qualitative thermal status of the subjects.

In addition to the explanations offered in the Phase 1 report (Tikuisis 2010) for the overprediction of changes in body temperatures, there is also the possibility in this study that the effect of wetness assumed for the prediction was exaggerated. That is, the 500 mL of water applied to the subjects was assumed to have been evenly spread, which would represent the most severe situation. This is because insulation is degraded disproportionally higher with the initial increment of wetness and less so with further wetness. Hence, if the 500 mL of water was unevenly distributed, then regions with excess wetness would not have had the proportional impact as other regions with less or no wetness, and the resultant cold stress on the subjects would have been less than assumed.

The marked decrease in survival time due to internal wetness of the survival suit, even by a modest amount, was noted in the Phase 1 report (Tikuisis 2010) and is again emphasized in this report. The addition of 500 mL of water to the subjects' clothing diminished predicted survival times by 38 and 44% compared to a dry condition under calm and turbulent water, respectively. However, even when wet, the insulative value of the survival suit is significant when considering how much longer an individual can survive when compared to the nude condition. With 500 mL of water, the suit still extends survivability by about 500 - 800% under calm conditions and between 400 – 600% under turbulent conditions compared to nude (see Figure 1).

Interestingly, turbulence amplifies the degradation of insulation beyond the addition of wetness. This was further demonstrated when comparing the survival times between the leanest and largest subjects of the study. Under a dry condition, the leanest subject would require 13 and 17% more insulation under calm and turbulent water, respectively, to survive as long as the largest subject, and these values increased to 21 and 30% with the addition of 500 mL water to the clothing. Consequently, consideration should be given to the addition of insulation to lean people to provide a similar survival opportunity compared to large people, and that this increase should accommodate the possibility of internal suit wetness, which elevates the required additional amount of insulation.

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