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Correction factors for assessing immersion suits under harsh conditions

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Abstract

Many immersion suit standards require testing of thermal protective properties in calm, circulating water while these suits are typically used in harsher environments where they often underperform. Yet it can be expensive and logistically challenging to test immersion suits in realistic conditions. The goal of this work was to develop a set of correction factors that would allow suits to be tested in calm water yet ensure they will offer sufficient protection in harsher conditions. Two immersion studies, one dry and the other with 500 mL of water within the suit, were conducted in wind and waves to measure the change in suit insulation. In both studies, wind and waves resulted in a significantly lower immersed insulation value compared to calm water. The minimum required thermal insulation for maintaining heat balance can be calculated for a given mean skin temperature, metabolic heat production, and water temperature. Combining the physiological limits of sustainable cold water immersion and actual suit insulation, correction factors can be deduced for harsh conditions compared to calm. The minimum in-situ suit insulation to maintain thermal balance is $1.553 - 0.0624 \cdot T_W + 0.00018 \cdot T_W^2$ for a dry calm condition. Multiplicative correction factors to the above equation are 1.37, 1.25, and 1.72 for wind + waves, 500 mL suit wetness, and both combined, respectively. Calm water certification tests of suit insulation should meet or exceed the minimum in-situ requirements to maintain thermal balance, and correction factors should be applied for a more realistic determination of minimum insulation for harsh conditions.

Keywords: Immersion suits; hypothermia; correction factors.

1.0 Introduction

Many industries require their personnel to work or travel over open water, which in the vast majority of cases is well below the thermoneutral water temperature of 35.5°C for naked humans to maintain a deep body temperature of ~37°C (Park et al., 1983). As a result, supplemental thermal protection is required to increase safety and survival. An immersion suit is a lifesaving appliance (LSA) designed to provide flotation, reduce the severity of the Cold Shock Response (CSR), and delay the onset of hypothermia (CGSB, 2005). As prescribed by the International Maritime Organization (IMO), a certified insulated immersion suit should minimize the CSR and prevent a drop in deep body temperature from exceeding 2°C after six hours of immersion in 0-2°C calm, circulating water (IMO, 2010). Various standards across the world (e.g. Canadian General Standards Board (CGSB, 2005); International Organization for Standardization (ISO, 2002)) specify a similar test protocol for certifying the thermal protective properties of insulated and non-insulated immersion suits.

Recent marine accidents such as the sinking of the *Check Mate III* (Frampton and Savage, 2008) and the crash of Cougar Flight 491 (TSB, 2010) have called into question the accuracy of predicting the performance of immersion suits under harsh conditions based on calm water certification tests. Previous investigations by others on the thermoregulatory responses of people in immersion suits compared the effects of wind and waves to calm water that have resulted in equivocal findings. Previous studies by Hayes et al., (1985), Steinman et al., (1987), and Ducharme and Brooks, (1998) found that immersion in a wind and wave condition increased heat loss without any significant decrease in deep body temperature. A subsequent study by Tipton (1991) found that immersion in turbulent conditions caused an uncompensable level of heat loss that exceeded the capability of the thermoregulatory system which resulted in a significant decrease in deep body temperature.

These discrepancies were the justification for our recent experimental investigation of the effects of wind and waves on predicted survival times (Power et al., 2015). We confirmed that immersions in wind and waves will significantly increase heat loss compared to calm water, and that predicted survival time is reduced as a consequence, which is exacerbated as water temperature decreases. However, with adequate insulation protection to ensure that the heat loss is compensable thus keeping deep body temperature stable , the predicted survival times can exceed 36 hours, at which point factors other than hypothermia will most likely be the cause of death with continued immersion (Keefe and Tikuisis, 2008).

The results from our previous work emphasize the importance of testing immersion suits in conditions more representative of those found during mid to high latitude marine accidents (i.e. wind, waves, and near freezing temperatures) since testing in “calm, circulating water” will likely overestimate insulation performance. Among the challenges associated with testing immersion suits in wind and waves, there are few facilities in the world capable of creating wind and wave conditions representative of offshore environments in a repeatable manner. Additionally, it is expensive and logistically challenging to test in these unique facilities, and the cost of doing so may be beyond the resources of immersion suit manufactures.

A much more feasible and cost effective method for testing immersion suits is to convert the measured suit insulation under temperature-controlled calm conditions to harsher conditions by factoring in the increased heat loss due to wind and waves. The development of such correction factors is the aim of this paper.

2.0 Methods

2.1 Participants

Two human experimental studies were conducted to acquire the data necessary to analyze heat loss and to calculate the insulation requirements. The National Research Council of Canada (NRC) Research Ethics Board approved both studies (REB#:2008-68; 2009-67) in which a total of 22 healthy participants took part. Twelve males participated in Study 1 (Mean [SD] Age: 23.9 [3.3] yrs; mass: 83.2 [4.9] kg; height: 1.8 [0.05] m; surface area (SA): 2.0 [0.1] m^2; body fat percentage (BF%): 16.8 [4.1]%) and 10 participated in Study 2 (Age: 25.0 [5.6] yrs; mass: 79.2 [6.8] kg; height: 1.8 [0.02] m; SA: 2.0 [0.1] m^2; BF%: 18.1 [2.9] %). All subjects gave their informed consent to participate and were medically screened to ensure that they had no pre-existing health conditions that could be result in injury during the study. Due to time and budget limitations, the two studies were separated by one year. Two males participated in both studies.

2.2 Test Conditions

In both studies, each participant performed three, 3 hour immersions in the Offshore Engineering Basin (OEB – NRC, St. John’s, Newfoundland and Labrador) under the conditions listed in Table I. The waves were generated using hydraulic drive wave makers located on one wall of the OEB, which provided a reproducible wave pattern representative of those found offshore. A 20-minute Joint North Sea Wave Analysis Project (JONSWAP) wave spectrum was used in both studies based on data collected from a wave buoy deployed off the south east coast of Newfoundland, Canada. The subjects were oriented with their feet forward into the oncoming unidirectional waves.

Table I. Immersion conditions for Studies 1 and 2.

Study	**Condition**	**Max Wave Height (m)**	**Mean Wind Speed ($m \cdot s^{-1}$)**	**Mean Water Temperature (°C) [SD]**	**Mean Air Temperature (°C) [SD]**
# 1	Calm	0	0	11.1 [0.2]	17.2 [0.5]
	Weather 1	0.34	3.5	10.9 [0.4]	17.4 [0.4]
	Weather 2	0.67	4.6	10.9 [0.3]	17.3 [0.4]
# 2	Calm	0	0	8.5 [0.9]	16.6 [0.7]
	Weather 1	0.34	3.5	8.3 [0.6]	16.7 [0.5]
	Weather 2	0.67	4.6	8.5 [0.5]	16.7 [0.5]

For both studies, 11 speed-controlled custom built fans (SEA Ltd, Columbus, Ohio, USA) generated air flow (wind) controlled by a precision voltage reference to adjust wind speed at the location of the participant.

2.3 Equipment

Subjects wore a Transport Canada (TC) approved marine abandonment immersion suit (White’s Manufacturing, Victoria, BC, Canada) certified to the standard CAN/CGSB-65.16-2005. This immersion suit was selected owing to latex wrist and neck seals that greatly reduced the chance of water leaking into the immersion suit. The underclothing provided to the subjects was standardized and based on that prescribed by CAN/CGSB-65.16-2005, similar to that prescribed in the majority of immersion suit standards tests. It consisted of wool socks, swimming trunks, cotton trousers, cotton undershirt, and a long sleeved cotton shirt. Swimming trunks were provided to the subjects so that they could enter a hot water bath (40°C) to rewarm once the immersions were completed.

Skin heat loss and temperature were measured using heat flow transducers (Concept Engineering, Old Saybrook, CT, USA) attached to the subjects using porous adhesive tape to the following locations: right foot; left shin; right quadriceps; left abdominal; right pectoral; underside of right forearm; forehead; right calf; left hamstring; right lower back; left shoulder; and topside of the left forearm. These sites were chosen based on a similar protocol used by Ducharme and Brooks (1998), which was similar to the Hardy and Dubois (1938) modified 12 point system. The heat flow transducers were connected to self-contained data loggers (ACR Data Systems, Surrey, BC, Canada) that measured and recorded all 12 sensors once every 8 s.

2.4 Procedure

On the day of their immersion, participants changed into swimming trunks, were weighed, and self-attached an external bladder to enable in-test urination. This external bladder was attached via a condom catheter which prevented females from being eligible to participate. A research team member then attached the heat flow transducers and assisted the subjects in donning the rest of the underclothing. In Study 1, the subjects completely donned the immersion suit and proceeded to the testing area.

In Study 2, pre-wetting was performed similar to a condition in the experiment described by Tipton and Balmi (1996) as the authors reported a significant change in deep body temperature when only the torso was wetted. Our participants donned the immersion suit up to the waist while a research team member sprayed their torso (excluding the arms) with 500 mL of room temperature water uniformly across the front and back. This completely saturated the long sleeved shirt worn by the subjects, and any excess water run-off was caught by the immersion suit. Once wetting was complete, the participants finished donning the immersion suit, but left it unzipped and proceeded to the testing area.

2.5 Calculations

Body fat (BF) percentage was estimated using the Durnin and Womersley method (1969) from the sum of skinfold thickness from four sites: biceps; triceps, subscapular; and iliac crest.

Surface area (SA) of the participants was calculated using the following formula as described by Gehan and George (1970):

$SA\ (m^2) = 0.1644 \cdot WT^{0.51456} \cdot HT^{0.42246}$ (1)

where:

WT = Mass (kg)

HT = Height (m)

Mean skin heat loss (MSHL) ($W \cdot m^{-2}$) and mean skin temperature ($\overline{T}_{SK}$)(°C) were calculated by weighting each of the 12 measurement sites by the respective values as reported by Hardy and Dubois (1938), then using the following equation:

MSHL or $\overline{T}_{SK} = \sum(\text{Measurement Site} \cdot \text{Weighting Value})/0.95$ (2)

The sum of all the weighted measurement sites was divided by 0.95 to account for the lack of a hand measurement. This was similar to the procedure used by Ducharme and Brooks (1998).

The minimum required in-situ clo value[1]can be calculated using the following formula reported by Romet and colleagues (1991):

$clo_{in\text{-}situ\_min}\ (°C \cdot m^2 \cdot W^{-1}) = (\overline{T}_{SK} - T_W)/MSHL/0.155$ (3)

where:

$\overline{T}_{SK}$= Mean skin temperature (°C)

T_W = Water temperature (°C)

MSHL = Mean skin heat loss ($W \cdot m^{-2}$)

Metabolic heat production can be calculated using the following formula as described by Peronnet and Massicotee (1991):

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

where:

$\dot{M}$ = Metabolic heat production ($W \cdot m^{-2}$)

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[1] In-situ clo value is defined as the clo value measured while immersed.

RER = Respiratory exchange ratio

$\dot{V}O_2$ = Oxygen consumption ($L \cdot min^{-1}$)

SA = Surface area (m^2)

RER was given a value of 1.0 since a change of ±0.15 (maximum physiological range for non-protein oxidation) from a reference value of 0.85 would lead to an error of less than 3.6% in $\dot{M}$ (Tikuisis, 1999). Hence,

$$\dot{M}(W \cdot m^{-2}) = 362.3 \cdot (\dot{V}O_2/SA) \tag{5}$$

To maintain steady state heat loss without incurring further heat debt, the metabolic heat production must equal total heat loss, which comprises body surface heat loss and respiratory heat loss (Q_r), hence:

$$\dot{M}(W \cdot m^{-2}) = MSHL + Q_r \tag{6}$$

Q_r can be approximated by (Tikuisis, 1999):

$$\begin{aligned} Q_r\,(W \cdot m^{-2}) &= \dot{M} \cdot [0.0014 \cdot (34 - T_a) + 0.0173 \cdot (5.87 - RH \cdot \exp\{16.6536 - 4030.183/(T_a + 235)\}] \\ &= \dot{M} \cdot f\,(T_a, RH) \end{aligned} \tag{7}$$

where

T_a=Ambient air temperature (°C); assumed to be equal to T_w due to the proximity of the head to the surface of the water.

RH =Relative Humidity (%); assumed to be 100% since a spray shield may be deployed creating a microclimate where the air is completely saturated.

By substituting MSHL in Eq. 3 using Eqs. 5 -7, the required in-situ insulation for steady state heat balance becomes:

$$\begin{aligned} clo_{in\text{-}situ\_min} &= [(\overline{T}_{SK} - T_W)/(\dot{M} - Q_r)]/0.155 \\ &= 0.0178 \cdot SA \cdot (\overline{T}_{SK} - T_W)/\dot{V}O_2/(1 - f) \end{aligned} \tag{8}$$

The above can be simplified by substituting the following regression assuming $T_a = T_W$ and RH = 100% (r = 0.998):

$$(1 - f)^{-1} = 1.1634 - 0.003636 \cdot T_W \tag{9}$$

such that the required insulation becomes:

$$clo_{in\text{-}situ\_min} = (SA/\dot{V}O_2) \cdot (\overline{T}_{SK} - T_W) \cdot (0.0207 - 0.00006472 \cdot T_W) \tag{10}$$

2.6 Statistical Analyses

Repeated measures analysis of variance (ANOVA) was performed to detect significant differences between the immersion conditions, with a P value less than 0.05 considered as significant. If significant differences were detected, Tukey’s post hoc tests were performed. Results are presented as means with standard deviation [SD] unless otherwise stated.

3.0 Results

All participants completed the three, 3 h immersions in both studies and no water ingress was evident during the immersions.

The addition of wind and waves caused significant reductions (27 and 28%) in in-situ clo value compared to that seen in calm water ($P < 0.001$) in Studies 1 and 2, respectively (Table II). There was no significant difference in in-situ clo values between the Weather 1 and Weather 2 conditions, even though the latter had larger wave heights and faster wind speeds. However, in-situ clo values were significantly lower across all conditions in Study 2 compared to Study 1 ($P < 0.001$).

When combined, the reduction in in-situ clo value due to 500 mL of water ingress (-20%) and wind and waves (-27%) was -42% (Table II)

Table II: In-situ clo values at the end of the three-hour immersions in Studies 1 and 2 (** = $P < 0.001$ compared to Calm, No leakage)

Study	Condition	Mean Clo value (clo) [SD]	% Change from Calm, No leakage
# 1 – No leakage (*n* = 12)	Calm	1.87 [0.13]	-
	Weather 1	1.45 [0.14]**	-22%
	Weather 2	1.36 [0.13]**	-27%
# 2 – 500 mL leakage (*n* = 10)	Calm	1.50 [0.18]	-20%
	Weather 1	1.17 [0.13]**	-38%
	Weather 2	1.09 [0.06]**	-42%

4.0 Development of Correction Factors

In the previous study by Tipton (1991) participants wore two different helicopter passenger suits: “A” (‘Dry’ suit composed of a composite fabric with Gortex membrane and Nomex outer layer) and “B” (‘Dry’ inflatable suit made from two layers of polyester nylon with an interlay of ‘Tuftane’). When participants wore suit “A” they were unable to stabilize deep body temperature during the tests and, as a consequence they had a shivering $\dot{V}O_2$ of 1.14 L·min^{-1}.This value can be used as the $\dot{V}O_2$value associated with a maximum shivering response evoked by the falls in skin and deep body temperature of individuals in immersion suits in turbulent conditions. Harsher conditions (e.g. “naked”) may allow greater metabolic responses, such as the $\dot{V}O_2$ value of 1.57 L·min^{-1} measured during peak shivering as previously reported (Eyolfson et al., 2001). Since the lower value from the study by Tipton (1991) was measured from subjects wearing an immersion suit in turbulent conditions, it is likely to be more representative of what can be achieved by individuals in these conditions. Using a lower value also errs on the side of caution in terms of required immersion suit performance (lower assumed heat production = greater demand for suit insulation)

Rearranging equation 3, a given water temperature can be estimated for the amount of MSHL to the environment for a given water temperature, $\overline{T}_{SK}$, and in-situ clo value when the individual is maximally vasoconstrcited. This MSHL value can be entered into equation 6 to determine the total amount of metabolic heat output to remain in thermal balance with the heat loss to the environment and respiratory heat loss. The predicted $\dot{V}O_2$ value ($\dot{V}O_{2P}$) required to maintain this metabolic heat output can then be calculated by inverting Eq. 8 across a range of skin temperatures and in-situ clo values. The $\dot{V}O_{2P}$ values required by a person with a SA of 2.0 m^2 to remain in thermal balance (i.e. heat production equals heat loss) in 2°C water across a range of $\overline{T}_{SK}$[2] and clo values are given in Figure 1.

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[2] The $\overline{T}_{SK}$values used are to establish the thermal gradient with the water to predict heat flow, and are not meant to represent values that drive thermoregulatory responses.

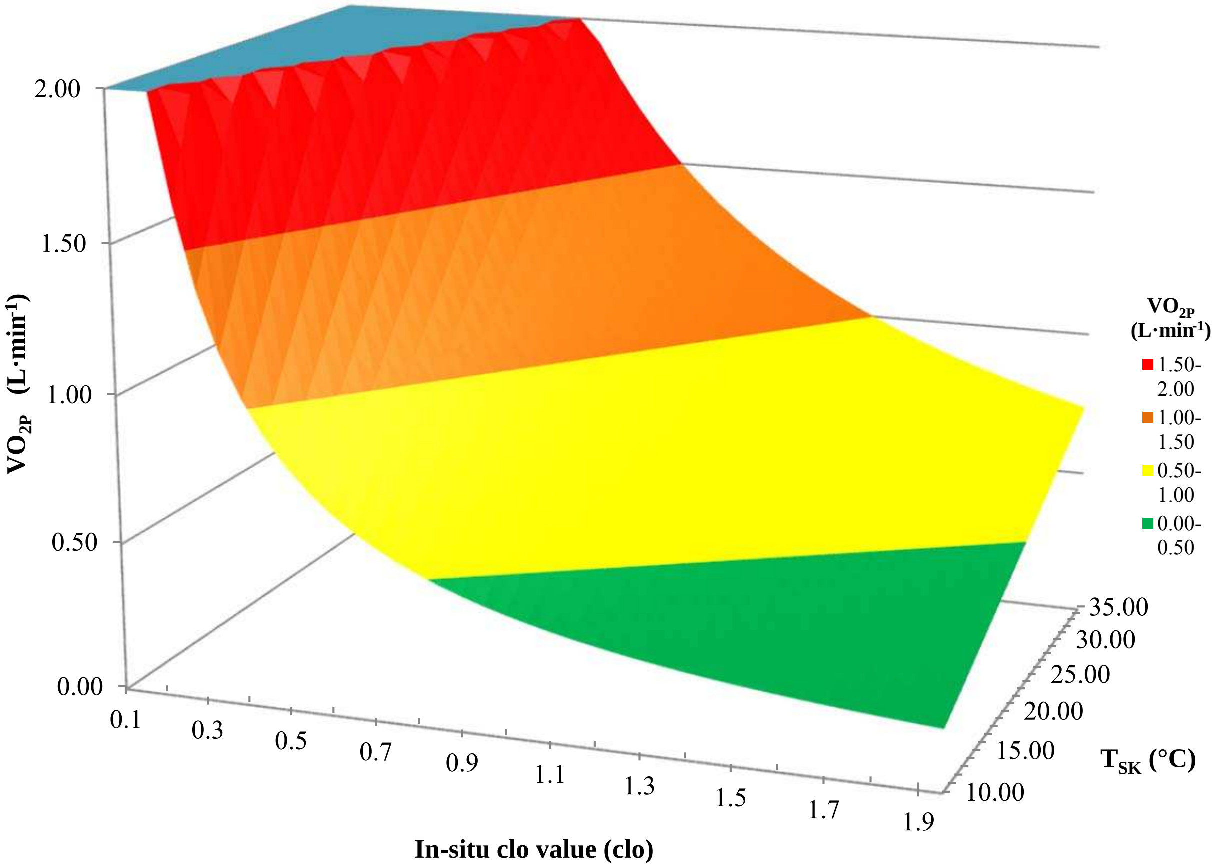

Figure 1. Mean $\dot{V}O_{2P}$ (L·min^{-1}) required to remain in thermal balance in 2°C air and water for a 2.0 m^2 person for varying $\overline{T}_{SK}$and clo values. (🟩= Low level of $\dot{V}O_2$; 🟨= medium level of $\dot{V}O_2$ 🟧 = high level of $\dot{V}O_2$;🟥 = unobtainable level of $\dot{V}O_2$through shivering.)

For example, if a 2.0 m^2 person was immersed in a 0.75 clo suit in 2°C water and had a $\overline{T}_{SK}$ of 28°C, we would estimate that they would lose 297.87 $W \cdot m^{-2}$ of heat through both skin and respiratory heat loss. For this person to remain in thermal balance they would have to generate 297.87 $W \cdot m^{-2}$ of heat through shivering. This would require them to have a $\dot{V}O_{2P}$ of 1.43 $L \cdot min^{-1}$ (Figure 1). Since this value exceeds the 1.14 $L \cdot min^{-1}$ reported by Tipton (1991), the person would not be able to replace the heat lost to the environment and respiration through shivering; in this example, the thermal stress would be uncompensable. In order for the thermal strain to become compensable in this example, the in-situ clo value would have to increase to 0.95; which would reduce the amount of heat loss to a level where it can be replaced by shivering at a very high intensity ($\dot{V}O_{2P}$ between 1.0 – 1.14 $L \cdot min^{-1}$).

Current IMO LSA regulations require that the thermal protective properties of immersion suits prevent a 2°C fall in deep body temperature in 0° to 2°C calm, circulating water during a 6 hour immersion (IMO, 2010). If the test participants (~ SA of 2.0 m^2) wore an insulated immersion dry suit with an immersed clo value of 0.85, the data in Figure 1 suggests that a $\dot{V}O_{2P}$ of 1.11 $L \cdot min^{-1}$ (in 2°C water) would be required to remain in thermal balance with a $\overline{T}_{SK}$of 25°C. According to the conditions of the present theoretical test, the insulated immersion suit "pass" would be expected to pass since the participants should be able to shiver at a sufficient intensity to remain in thermal balance.

Referring to Table II, it is expected that when moving to an environment with wind and waves the immersion suit clo would decrease 27% changing the immersed clo value from 0.85 to 0.62. Referring to Figure 1, with this new clo value, a calculated $\dot{V}O_{2P}$ value of 1.52 $L \cdot min^{-1}$ would be required to remain in thermal balance (with a $\overline{T}_{SK}$ of 25°C). Since this $\dot{V}O_2$is greater than the assumed threshold shivering value of $1.14 L \cdot min^{-1}$, the average heat production response would not match the heat lost to the environment which would therefore become uncompensable and result in a further fall in deep body temperature as $\overline{T}_{SK}$ continues to fall. When $\overline{T}_{SK}$ falls to 18°C participants should, theoretically, be able to match the heat flow to the environment through maximum shivering – i.e. the resulting condition would be just compensable. The drop of $\overline{T}_{SK}$ to a lower value would create a larger thermal gradient within the body, possibly leading to the development of hypothermia not observed during certification.

The reduction in clo values in more realistic conditions (wind, waves and water leakage) compared to those measured in calm water highlight how the performance of immersion suits can be over-estimated. In calm, benign conditions, the immersed clo value of an immersion suit may allow individuals to thermoregulate successfully in 2°C water, but at a high level of "physiological cost" to the thermoregulatory system. The pass/fail criterion for the thermal protective properties of immersion suits overlooks the physiological cost required to ensure that deep body temperature does not drop more than 2°C. Moving to more challenging conditions will result in increased strain on the thermoregulatory system of the participants due to the reduction in in-situ clo. If the participants were near their maximum ability to thermoregulate in calm, benign conditions, more challenging conditions will increase the thermal stress, resulting in an increase in heat loss to the external environment that may not be compensated by the thermoregulatory system. This uncompensable increase in heat loss will result in the development of hypothermia. Focusing solely on whether or not hypothermia was developed in calm water tests, and not the physiological cost required to pass the test, increases the chances of overestimating the performance of immersion suits in more severe conditions.

However, for financial and practical reasons it may not always be possible to test in severe conditions. A more practical solution may be to develop corrections factors for testing immersion suits in calm water, as suggested by Tipton (1995). By factoring in the reduction in total insulation caused by wind and waves, it may be possible to test immersion suits in calm water conditions and still achieve an acceptable level of performance in conditions with wind and waves. Using the data presented in Table II and Figure 1, we have undertaken a first attempt to produce such correction factors.

In the previous study by Tipton (1991) in which suits "A" and "B" were tested in turbulent conditions participants were able to stabilize their deep body temperature when wearing suit B. The mean $\dot{V}O_2$ value of the participants when they wore this suit was reported to be 0.72 $L \cdot min^{-1}$ (Tipton, 1991). This value is less than that used earlier and associated with "maximum" shivering in these conditions (1.14 $L \cdot min^{-1}$), but at a sufficient level to maintain deep body temperature during immersions in cold, turbulent water. As a result, a $\dot{V}O_2$ of 0.72 $L \cdot min^{-1}$ was chosen as a value that allows for shivering at a moderate intensity in order to maintain a stable deep body temperature in challenging immersion conditions (Tipton, 1991). Referring to equation 5, this yields $\dot{M}$ a value of 130.43W·m^{-2}. Hence, the total amount of heat loss from both the skin and respiration should not exceed 130.43W·m^{-2}.

A $\overline{T}_{SK}$ of 27°C was chosen for these calculations based on measurements in the previous study by Tipton (1991). While subjects wore the suit that gave the $\dot{V}O_2$value of 0.72L·min^{-1}, $\overline{T}_{SK}$ fell to 29°C after 45 minutes of immersion. $\overline{T}_{SK}$ values were not reported after 45 minutes except for one participant measured at 24°C after 6 hours. Twenty-seven degrees Celsius was chosen for $\overline{T}_{SK}$ since it is mid way between the average $\overline{T}_{SK}$ reported at 45 minutes for the group, and 24°C at six hours for one participant, and was therefore selected as the representative $\overline{T}_{SK}$ for the corrections calculations. With a $\dot{V}O_2$of 0.72 L·min^{-1}, a SA of 2.0 m^2, and a $\overline{T}_{SK}$of 27°C, an in-situ clo value can be calculated for a given water temperature using equation 10. For example: an in-situ clo value of 1.55 clo is required for an immersion in 0°C water and can thus be considered the "minimum" value to ensure shivering does increase above a level associated with a $\dot{V}O_2$of 0.72 L·min^{-1}. Hence, the physiological strain to thermoregulate is not greater than moderate.

The reduction in in-situ clo value due to leakage and wind and waves is given in Table II. Leakage (500 mL of water) under the immersion suit will reduce in-situ clo values by 20%; to account for this reduction, the minimum in-situ clo value of 1.55 should be increased to 1.94 clo in order to ensure total heat loss does not exceed 130.4 W·m^{-2} in 0°C water. Wind and waves will reduce in-situ clo values by 27%; the minimum in-situ clo value of 1.55 should be increased to 2.12 clo to account for this. Wind, waves, and 500 mL of leakage will further reduce in-situ clo values by 42%; the minimum clo value of 1.55 should be increased to 2.68 clo to account for those factors. An in-situ clo value of 2.68 clo may be challenging to achieve. In Study 1, the in-situ clo value for an immersion suit ensemble with participants wearing cotton pants, a cotton t-shirt and long sleeved shirt and wool socks and no leakage in calm water was 1.86. Achieving 2.68 in-situ clo may be possible but would require adding extra insulation to the immersion suit, or extra clothing underneath, which would increase its bulkiness making it cumbersome. An ideal approach would be to ensure as little water leakage as possible and compensate for the reduction in clo value caused by environmental effects only. For suits where this cannot be done, as there is no requirement in some international standards for suits to prevent water leakage, a recommended lower limit of the water temperature in which they can be used should be provided.

The predicted in-situ clo values to compensate for leakage, wind, and waves are given in Figure 2 when measured in calm water. The equation to calculate the minimum in-situ clo value in calm water is found by substituting SA = 2.0 m^2, $\dot{V}O_2$ = 0.72 $L\cdot min^{-1}$, and Tsk = 27ºC into equation 10:

Minimum (Calm Water):

$clo_{in\text{-}situ\_min} = 1.553 - 0.0624 \cdot T_W + 0.00018 \cdot T_W^2$

The multiplicative correction factors for the minimum in-situ clo value in calm water to compensate for wind and waves, leakage, and both combined are:

WW (Wind and Waves)

$1.37 \cdot clo_{in\text{-}situ\_min}$

500 mL of Water Leakage:

$1.25 \cdot clo_{in\text{-}situ\_min}$

WW + 500 mL of Water Leakage:

$1.72 \cdot clo_{in\text{-}situ\_min}$

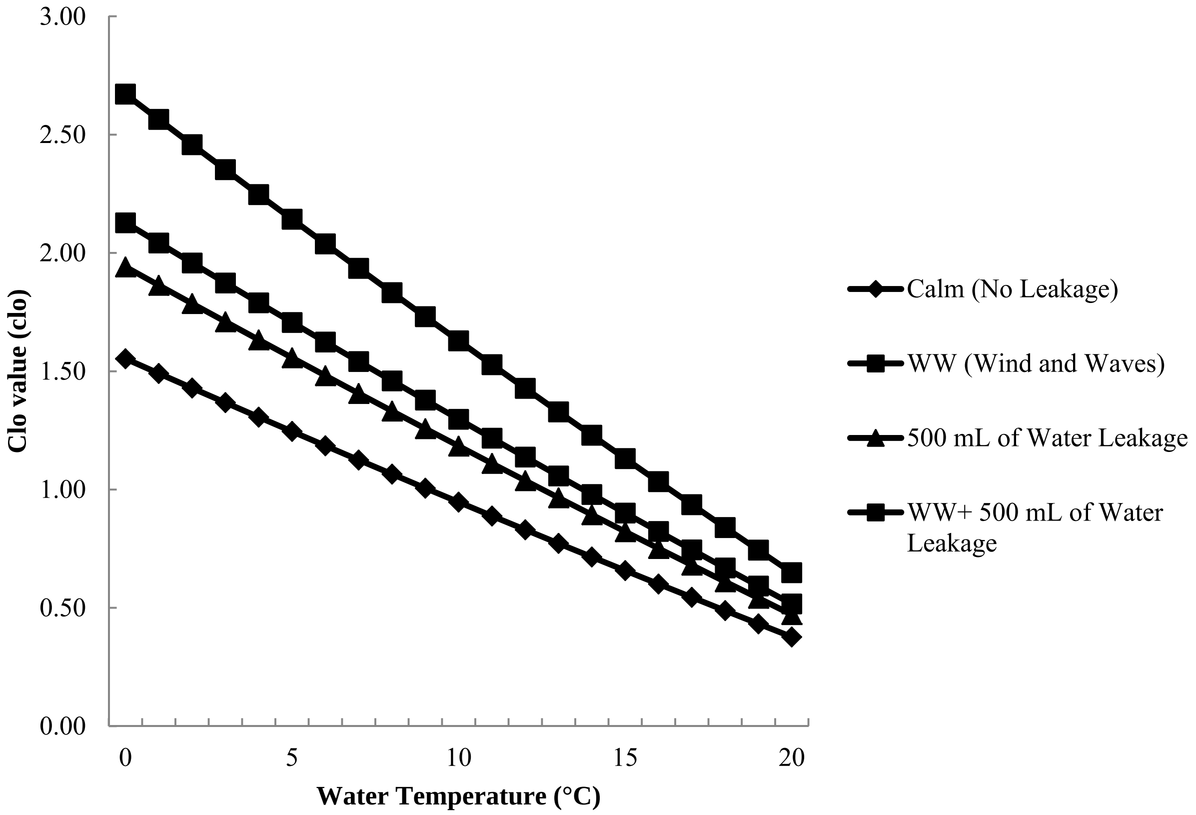

Figure 2. Mean predicted minimum in-situ clo values, measured in calm water, to remain in thermal balance for a given water temperature for an individual with a SA of 2.0m^2, a $\overline{T}_{SK}$ of 27°C and a $\dot{V}O_2$of 0.72 L·min^{-1} (WW = wind and waves).

In theory, these correction factors can be used to determine the minimum clo value that an immersion suit should have during a calm water test to predict performance in harsher conditions in a given area of operation where the requirement is to keep the wearer in thermal balance with moderate thermoregulatory effort. For example, if an offshore oil operator wanted to select an immersion suit for their facility that was located in an area that had a mean water temperature of 7°C with calm seas, then they could choose the "Calm – No Leakage" equation to calculate the clo value an immersion suit should achieve in calm water tests: 1.13 clo (Figure 2). If they wanted to account for leakage, then they could use the "500 mL of Water" calculation to determine a clo value an immersion suit should achieve when dry during calm water tests: 1.41 clo (Figure 2). If the same operator had an offshore facility located in an area that had an average water temperature of 0°C with frequent stormy seas, then they could use (at a minimum) the

“WW” equation to determine a clo value to achieve during calm water tests to account for wind and waves: 2.12 clo, (Figure 2); or “WW + 500 mL Water Leakage” to account for rough seas and 500 mL of leakage: 2.67 clo (Figure 2). Clearly, these equations provide a safety margin against unexpected poor performance in a real accident.

The correction factors presented here are predicated on the assumption that the target survival conditions for the immersed individual are a $\overline{T}_{SK}$ of 27°C and a $\dot{V}O_2$ of 0.72 $L{\cdot}min^{-1}$ with T_a equal to T_w; any deviation from these values would change the minimum in-situ clo value requirements to be determined by Eq. 8.For every 1.0°C variation in $\overline{T}_{SK}$ or T_W (with a $\dot{V}O_2$ of 0.72 $L{\cdot}min^{-1}$), $clo_{in\text{-}situ\_min}$ will vary by 0.06 clo. For an immersion ensemble that has an in-situ clo value of 0.75, this would result in an 8% variation in total insulation for every 1.0°C of change for $\overline{T}_{SK}$ or T_W. The level of variation for $clo_{in\text{-}situ\_min}$ for changing $\dot{V}O_2$ values is not a linear relationship like that for $\overline{T}_{SK}$ or T_W. An increase in $\dot{V}O_2$ from 0.3 – 0.4 $L{\cdot}min^{-1}$ will result in a change in clo value from 3.43 -2.57 clo. Increasing $\dot{V}O_2$from 1.0 - 1.1 $L{\cdot}min^{-1}$ will produce a change in clo value from 1.03 – 0.93 clo.

This large change in $clo_{in\text{-}situ\_min}$ variation over a range of $\dot{V}O_2$ values provides another justification for choosing 0.72 $L{\cdot}min^{-1}$ for $\dot{V}O_{2P}$ when developing the correction factors. The mean change in $clo_{in\text{-}situ\_min}$ when $\dot{V}O_{2P}$ varies by 0.02 $L{\cdot}min^{-1}$ through a range from 0.66 – 0.76 $L{\cdot}min^{-1}$ is 0.04 clo, which is very close to the variation in clo when varying $\overline{T}_{SK}$ or T_W by 1.0°C. Using a value of 0.72 $L{\cdot}min^{-1}$ for $\dot{V}O_{2P}$ ensures that the sensitivity of $clo_{in\text{-}situ\_min}$ to its variation is nearly equivalent to changes in $\overline{T}_{SK}$ or T_W.

5.0 Discussion

The findings of this study were that wind and waves will significantly reduce the insulation of immersion suits compared to calm water (Table II) although our data also suggest that a threshold for maximum reduction was reached at a wave height of 0.34 m and wind speed of 3.5 $m.s^{-1}$ (i.e. Weather 1 conditions; see Table I); above these levels further reductions in insulation were not evident. This suggests that the weather conditions need not exceed these wind speeds and wave heights to deteriorate insulation further; this is supported by the work of Witherspoon et al. (1971) who found that the convective heat loss caused by moving water reaches maximum levels at a velocity of 0.75 $m{\cdot}s^{-1}$. If water velocity exceeds 0.75 $m{\cdot}s^{-1}$, there will be minimal additional increase in convective heat loss. This suggests that sea states which may be perceptually mild can still cause a reduction in insulation equivalent to that caused by stormy seas, as long as the water passing by the immersed individual (caused by wave action) is travelling at 0.75 $m \cdot s^{-1}$ or above. This also suggests that a water velocity of 0.75 $m \cdot s^{-1}$ does not need to be exceeded for laboratory based tests in order to account for the maximum decrease in immersion suit insulation caused by waves.

Our data agree with previous work which found that immersions with wind and waves will increase heat loss compared to calm water (Hayes et al., 1985; Steinman et al., 1987; Tipton, 1991; Ducharme and Brooks, 1998). While some of these studies found that heat loss was significantly greater in wind and waves compared to calm water, there was no significant difference in deep body temperature (Hayes et al., 1985; Steinman et al., 1987; Ducharme and Brooks, 1998) a finding that can be attributed to the heat loss being compensable by the thermoregulatory system. In contrast, the conditions experienced by the participants in the study by Tipton (1991) represented a level of heat loss that was uncompensable; resulting in falling deep body temperatures. The results from previous studies highlight an important concept when testing immersion suits using humans: as long as the heat loss is reduced to a level at which it is compensable by the thermoregulatory system (via vasoconstriction and shivering) deep body temperature will be stabilized, at least for a period of time until shivering fatigue occurs (Keefe and Tikuisis 2008). However, once heat loss reaches a point at which it becomes uncompensable (exceeds that which, at maximum vasoconstriction, can be generated by shivering) the body will enter heat debt and hypothermia will eventually develop. It follows that the questions to ask of protective clothing are: 1. Does it allow the body to thermoregulate? 2. If so, at what physiological cost? These same responses and approach apply to heat exposure (Corbett et al., 2014).

The target survival conditions ($\overline{T}_{SK}$ = 27°C; $\dot{V}O_{2P}$ = 0.72 $L \cdot min^{-1}$) for in-situ clo value calculations for a given water temperature were chosen based on previous immersion studies with the participants able to maintain a stable deep body temperature with a moderate amount of strain on the thermoregulatory system. These target survival conditions were proposed with consideration given towards balancing a reasonable amount of insulation in the immersion suit, and a moderate level of thermoregulatory strain on the immersed individual.

6.0 Study Limitations

The correction factors for the testing of immersion suits in calm water presented here offer a method of predicting performance in harsh conditions. These correction factors are theoretical and should be validated through actual physical testing to ensure the required predicted clo values measured in calm water allow people to remain in thermal balance in harsher conditions. Physical testing would also ensure that the target physiological parameters suggested here for an immersed individual are both achievable and sustainable during immersions.

All tests performed in the two studies were conducted on one brand of immersion suit. It is possible that other immersion suit brands may be more or less susceptible the effects of wind, waves, and water leakage. If so then the required predicted clo value, derived from these correction factors, to be measured in calm water would have to be adjusted accordingly.

7.0 Conclusions

It is concluded that immersions in wind and waves significantly increase MSHL compared to calm water immersions. If this increase in heat loss cannot be compensated for by the thermoregulatory system, a drop in deep body temperature may occur that was not observed during more benign tests. Therefore, it is recommended that when measuring the performance of immersion suits, tests should be conducted in conditions that are as representative of the range of conditions which are expected in the operational area for the immersion suit. If this is not possible, then the conceptual approach and equations described in this paper should be considered with the knowledge that they provide correction factors (or a safety margin) for the reduction in clo value when conditions change from calm to rough water that includes wind, waves and leakage. Future work should be undertaken to extend and validate these correction factors given the important potential benefits for marine safety, as they could be used to compensate unexpectedly poor level of performance of immersion suits in wind and waves even when certified in calm water conditions.

7.0 Conflict of Interest

None of the authors have any conflicts of interest associated with this study.

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