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Comparison of Immersed Insulation Values Between Two Thermal Manikins

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Executive Summary

Immersion suits are life saving appliances designed to protect people from the dangers of sudden immersion in cold water, and delay the onset of hypothermia. To ensure that they provide a sufficient level of thermal insulation to protect people from cold water, immersion suits are certified to various national and international standards. The thermal insulation tests for immersion suits can be physically grueling for the human participants, requiring them to endure freezing water temperatures for hours. Thermal manikins are an attractive alternative to using humans for determining the thermal insulation of immersion suits as it does not subject people to these grueling tests. Even though various thermal manikins exist throughout the world, many national and international standards do not accept them as a valid test method for immersion suits. One of the reasons for this lack of acceptance is due to the variability between the different thermal manikins and the laboratories that they are tested in. To help address the question of inter-manikin variability, a test program was undertaken to test two thermal manikins in the same conditions, using the same procedure, and compare the results.

Two thermal manikins, TIM and NEMO, were tested in the National Research Council of Canada’s Thermal Measurements Lab. Each thermal manikin performed three immersions in three different clothing ensembles. Two of the clothing ensembles included insulated immersion suits (Mullion and Survivtec), while the third was an uninsulated suit (Viking). After dressing the thermal manikin in the ensemble, it was secured to a metal stretcher and immersed in ~4°C stirred water. Each test lasted until at least 60 minutes of thermal steady state data was recorded.

For each of the three ensembles, TIM reported a higher mean immersed thermal insulation value (clo) compared to NEMO. For the Mullion ensemble, TIM reported a mean immersed thermal insulation value of 0.813 clo compared to 1.094 clo as reported by NEMO. For the Survivtec ensemble, TIM measured an immersed thermal insulation value of 0.833 clo while NEMO measured 1.129 clo. Both thermal manikins measured a much lower immersed thermal insulation value for the Viking ensemble, with TIM measuring 0.397 clo and NEMO measuring 0.478 clo.

There are a few possible reasons for the observed differences between the immersed thermal insulation values reported by TIM and NEMO for the different ensembles. First, it was observed that even during tests with the same thermal manikin and ensemble, there could be at least 5% variation between tests. This is most likely due to variations in how the thermal manikin was dressed between tests. A second possible source of variation was that due to TIM being physically larger than NEMO, all the ensembles had a snugger fit. With a snugger fit on TIM, there was less of a chance for the clothing fabric to roll over on itself, which can increase the insulation in certain areas. Additionally, being physically larger, TIM could possibly displace more air inside the suit compared to NEMO, decreasing the overall measured thermal insulation. Another possible source of variation between the two thermal manikins is how much of the total surface area that each uses to calculate the immersed thermal insulation values. If a value used for surface area is lower than the total one that heat loss occurs over, then this could result in a conservative calculation of thermal insulation for a given ensemble.

Even though there were differences in the absolute mean immersed thermal insulation values reported by TIM and NEMO, there was a strong correlation between the results. This suggests that there is very good agreement in how the two thermal manikin perform their measurements. Each thermal manikin measured similar insulation values for the Mullion and Survivtec ensembles, and much lower ones for the Viking ensemble.

After testing both thermal manikins across three different ensembles in the same conditions, and using the same procedure, it was found that there was a strong correlation between their results. The findings from this work suggest that thermal manikins can be considered a viable method for measuring the thermal insulation of immersion suits. Potential future work could use thermal manikins to measure immersed thermal insulation values of various suits that have already been approved using human participants. Using suits already approved via human testing would allow for the immersed thermal insulation value required for approval to be determined by the various thermal manikins over the world. This would allow for future tests to be conducted by thermal manikins, and not subject human participants to grueling conditions for immersion suit certification.

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1.0 Introduction

In the event of a marine emergency, the order may be given for all personnel on board to abandon the vessel. While ships carry life saving appliances (LSA) such as lifeboats and liferafts that can act as temporary safe refuges until rescue arrives, there does exist the risk that a person may become accidentally immersed in the cold water. Cold water immersion is a serious threat to survival as it can result in drowning from the respiratory components of the cold shock response (Tipton, 1989), or the development of hypothermia if the person is immersed for extended periods of time (Stocks et al., 2004).

Immersion suits are LSA that help protect from the cold shock response and delay the onset of hypothermia. Immersion suits are a critical piece of safety equipment that are often required by different regulatory agencies to be carried in sufficient quantities to ensure every person on board the vessel has one.

To ensure that the immersion suits carried on board a vessel will provide the necessary level of safety, they are certified to various national and/or international standards that prescribe the required level of performance (ISO, 2012; IMO, 2017). The tests prescribed in the standards require different aspects of the suit to be tested such as: durability; flammability; water ingress; and thermal protection.

For the thermal protection tests, many standards require the tests to be performed with human participants. The participants are required to perform an immersion in 2°C water for six hours, and if they do not experience a drop in deep body (core) temperature of 2°C, then the suit passes the thermal protection test (ISO, 2012; IMO, 2017). These immersion tests are physically grueling to complete, logistically complicated, costly, and ethically questionable (Barwood and Tipton, 2011).

An alternative to subjecting human participants to these grueling immersion test is using a thermal manikin to measure the thermal protection of an immersion suit. Compared to humans, thermal manikins can measure the thermal protection provided by an immersion suit in a significantly shorter amount of time, for less cost, and does not require any participants to endure significant discomfort to determine if a product is “good enough” for sale (Barwood and Tipton, 2011).

While thermal manikins offer clear advantages over humans for measuring the thermal protection of immersion suits, many standards over the world do not accept them as a valid method for doing so. Various thermal manikins exist across the world, and there remains some uncertainty on how they compare to each other. To help address this uncertainty, an International Organization for Standardization (ISO) working group has been established to develop a standard to assist with harmonizing the results from thermal manikins. This working group has conducted round robin tests using a standardized immersion ensemble tested on different thermal manikins in various laboratories around the world.

These results from these round robin tests have shown that the various thermal manikins reported different thermal insulation values for the standardized immersion ensemble. A follow on question from these round robin tests is if the differences in the measured thermal insulation values are due to differences in the thermal manikins themselves, or due to the unique setup of each laboratory and their procedures for performing the tests. To help address this question, Transport Canada has requested the National Research Council of Canada (NRC) to perform a series of tests with two different thermal manikins in its facility.

The objective of this study is:

- Compare the results from two different thermal manikins, dressed in three different immersion ensembles, tested in the same facility so that any differences due to laboratory setup and test procedures can be eliminated.

2.0 Materials and Procedure

2.1 Thermal Manikin – NEMO

One of the thermal manikins used was NEMO, which is a 23-zone submersible thermal manikin (Figure 1). Each of the 23 independently heated zones contain a heater, and two thermistors for measuring skin temperature. NEMO uses two thermistors immersed in the water to measure the temperature of it. NEMO has a height of 1.77m; a mass of 71kg; and a surface area of 1.86m^2. The surface area each individual zone are listed in Appendix A.

Figure 1: Thermal manikin NEMO.

2.2 Thermal Manikin – TIM

The second thermal manikin used was TIM, which is a 13-zone submersible thermal manikin (Figure 2). Similar to NEMO, each of the 13 independently heated zones contain a heater, and two thermistors for measuring skin temperature. TIM uses four resistance temperature detectors (RTD) immersed in the water to measure the temperature of it. TIM has a height of 1.83m; a mass of 94.5kg; and a surface area of 1.74m^2. The surface area for each individual zone are listed in Appendix A.

Figure 2: Thermal manikin TIM.

2.3 Thermal Measurements Lab

All tests were conducted in NRC's thermal measurements lab (TML). The TML is a temperature controlled facility that is capable of maintaining an air temperature (T_a) over a range of 4-30°C, which is monitored by a pair of thermistors located on the North side of the room. For all tests, T_a was 4°C. The TML contains an immersion tank which was filled with ~4°C water. Over the course of the tests, the water temperature (T_w) ranged from ~4–7°C as it was heated by the manikins. The water in the immersion tank is temperature controlled through the use of a refrigeration system, and is continuously circulated using mechanical stirrers located on either side of it. Ten thermistors are positioned throughout the immersion tank to measure water temperature. For all tests, the thermal manikins were secured to a metal stretcher (198 cm long, 66 cm wide) with mesh webbing on the back, which was lowered into the immersion tank (Figure 3). The stretcher itself was secured in the tank for all tests.

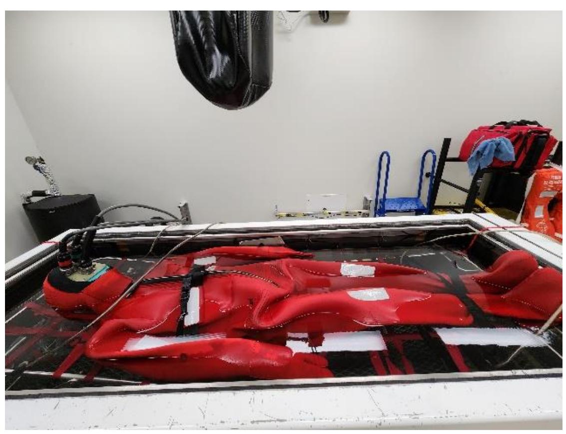

Figure 3: TIM secured on the stretcher in the TML immersion tank.

2.4 Immersion Ensembles

Three different immersion ensembles were tested with both thermal manikins:

The Mullion ensemble (Figures 4 and 5) which consisted of the following:

- Underwear briefs
- Wool socks
- Denim jeans
- Short sleeved t-shirt
- Long sleeved flannel shirt
- Mullion insulated immersion suit

Figure 4: NEMO dressed in the underclothing of the Mullion ensemble (all clothing except the immersion suit).

Figure 5: NEMO dressed in the full Mullion ensemble.

The Survivtec ensemble (Figure 6) which consisted of the following:

- Underwear briefs
- Wool socks
- Denim jeans
- Short sleeved t-shirt
- Long sleeved flannel shirt
- Survivtec insulated immersion suit

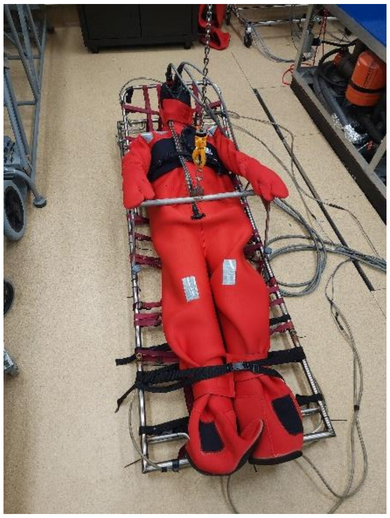

Figure 6: TIM dressed in the full Survivtec ensemble.

The Viking ensemble (Figures 7 and 8) which consisted of the following:

- Underwear briefs
- Wool socks
- Denim jeans
- Short sleeved t-shirt
- Long sleeved shirt
- Long sleeved sweater
- Viking uninsulated immersion suit

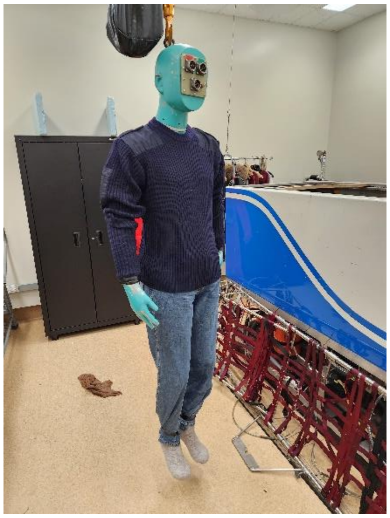

Figure 7: TIM dressed in the underclothing of the Viking ensemble (all clothing except the immersion suit).

Figure 8: TIM dressed in the full Viking ensemble.

2.5 Procedure

Prior to each tests, all clothing was weighed to measure its pre-test mass. For the NEMO tests with the Survivtec ensembles, the clothing masses were measured using a Sartorius scale, and a Toledo model: 8132 scale. For all other mass measurements, an Ohaus model: TD52P scale was used.

The manikin began each test nude and then dressed in the immersion ensemble. The socks, denim jeans, long sleeved shirt, long sleeved sweater (Viking ensemble only) were secured at the ankles and wrists using electrical tape. After the manikin was dressed in the immersion ensembles, a short length of Tygon tubing was inserted between its face and the immersion suit. The manikin was then secured to the metal stretcher using two straps: one secured around its chest underneath the arms, and another across its shins. The upper section of the metal stretcher was inclined 20° relative to the lower section (Figure 6). An overhead crane was used to lift the manikin and the metal stretcher into the water.

Once the manikin was in the water, four ropes were tied to each corner of the metal stretcher to allow the correct freeboard distances to be set on them. Due to buoyancy differences between TIM and NEMO, the latter had the four ropes ran through pulleys on the bottom of the immersion tank that allowed it be pulled down; the former used the ropes to raise it out of the water. The rope system was used to adjust the freeboard on the manikins so that their feet were 150mm above the water, and its mouth was 95mm. Once the correct freeboard distances were obtained, the Tygon tubing was removed from the face seal and test began. A side by side visual comparison of the two manikins in each of the different immersion ensembles are given in Figures 9 – 11.

Figure 9: TIM (left) and NEMO (right) in the Mullion immersion ensemble in the immersion tank.

Figure 10: TIM (left) and NEMO (right) in the Survivtec immersion ensemble in the immersion tank.

Figure 11: TIM (left) and NEMO (right) in the Viking immersion ensemble in the immersion tank.

For the Mullion and Survivtec immersion ensembles, TIM was programmed to maintain a mean skin temperature ($\bar{T}_{skin}$) of 34.5°C. For the Viking immersion ensemble, TIM was programmed to maintain a $\bar{T}_{skin}$ of 21.75°C.

For all tests with NEMO, its $\bar{T}_{skin}$ was set to 35°C.

Each test lasted until at least 60 minutes of steady state data was collected. The manikin was considered to be in steady state when there was less than 3% variation in the measured thermal insulation of the immersion ensemble.

Upon completion of the tests, the manikin was removed from the immersion tank and excess surface water was dried using hand towels. Once dried, the immersion suit was removed from the manikin, and a visual examination of the underclothing was performed to check for water ingress. The immersion suit and underclothing were then removed and weighed to get the post-test mass.

Each immersion ensemble was tested three times by each thermal manikin, for a total of 18 tests.

2.6 Calculations

2.6.1 TIM Heater Power Output Calculations

The total heater power output for TIM was calculated using the following equation:

$$P_{total} = \sum P_{zone} \qquad \textit{Equation 1}$$

Where:

P_{total} = Manikin total heater power output (W)
P_{zone} = Manikin individual zone heater power output (W)

2.6.2 TIM Thermal Insulation Calculations

TIM's onboard custom software automatically calculates the overall clo value for the ensemble using the parallel method. The equation used is:

$$R_{clo} = \frac{SA}{\left(\sum \frac{(P_{zone} \cdot 0.155)}{(T_{skin} - T_W)}\right)} \qquad \textit{Equation 2}$$

Where:

R_{clo} = parallel clo value (clo)

SA = Surface area of TIM (m^2)

P_{zone} = Zone power output (W)

T_{skin} = Zone average skin temperature (°C)

T_W = Water temperature (°C)

2.6.3 NEMO Heater Power Output Calculations

The total heater power output for NEMO was calculated using the following equation:

$$P_{total} = \sum ({}^{Q}/_{A} \cdot A_i) \qquad \textit{Equation 3}$$

Where:

${}^{Q}/_{A}$ = Zone area weighted heat flux ($W \cdot m^{-2}$)

A_i = NEMO zone surface area (m^2)

2.6.3 NEMO Thermal Insulation Calculations

NEMO's onboard software (ThermDac) automatically calculates total thermal resistance using the parallel method (parallel thermal resistance) for each zone during the tests using the following equations specified in its operator's manual (Thermetrics, 2007):

$$R_{ct} = \frac{T_{skin} - T_W}{({}^{Q}/_{A})} \qquad \textit{Equation 4}$$

Where:

R_{ct} = Zone thermal resistance ($m^2 \cdot °C \cdot W^{-1}$)

After the zone thermal resistance was calculated, parallel thermal resistance was calculated using the following equation:

$$R_{wtd}(parallel) = \frac{1}{\sum \frac{A_i}{(A_{tot} \cdot R_{ct})}} \qquad \textit{Equation 5}$$

Where:

$R_{wtd}(parallel)$ = parallel thermal resistance ($m^2 \cdot °C \cdot W^{-1}$)

A_{tot} = Total surface area of NEMO (m^2)

Parallel thermal resistance values were converted to clo units using the following equation (Thermetrics, 2007):

$$R_{clo} = R_{wtd}(parallel) \cdot 6.45$$ *Equation 6*

All parallel clo values measured and reported are immersed clo values.

2.6.4 Garment Wetting

The estimated amount of wetting for each garment was estimated using the following formula:

$$M_{wet} = M_{post} - M_{pre}$$ *Equation 7*

Where:

M_{wet} = Estimated garment wetting (g)

M_{post} = Garment mass post-test (g)

M_{pre} = Garment mass pre-test (g)

3.0 Results

3.1 Garment Wetting

The estimated garment wetting based on mass differences during the tests with the Mullion ensemble are given in Table 1.

Table 1: Estimated garment wetting (g) for all Mullion ensemble tests for both thermal manikins.

Manikin and Test Number	Estimated Garment Wetting (g)					
	Socks	Underwear	T-Shirt	Long Sleeved Shirt	Denim Jeans	Mullion Immersion Suit
TIM						
Test #1	-6.0	-2.0	-2.0	-16.0	-28.0	612.0
Test #2	0.0	-2.0	0.0	2.0	0	594.0
Test #3	-12.0	0	0.0	-2.0	0	636.0
Mean [SD]	-6.0 [6.0]	-1.3 [1.2]	-0.7 [1.2]	-5.3 [9.5]	-9.3 [16.2]	614.0 [21.1]
NEMO						
Test #1	-6.0	-2.0	-4.0	-10.0	-16.0	578.0
Test #2	-6.0	-2.0	-4.0	-12.0	-8.0	552.0
Test #3	-4.0	0	-2.0	-8.0	-12.0	608.0
Mean [SD]	-5.3 [1.2]	-1.3 [1.2]	-3.3 [1.2]	-10.0 [2.0]	-12.0 [4.0]	579.3 [28.0]

The estimated garment wetting based on mass differences during the tests with the Survivtec ensemble are given in Table 2.

Table 2: Estimated garment wetting (g) for all Survivtec ensemble tests for both thermal manikins.

Manikin and Test Number	Estimated Garment Wetting (g)					
	Socks	Underwear	T-Shirt	Long Sleeved Shirt	Denim Jeans	Survivtec Immersion Suit
TIM						
Test #1	-6.0	-2.0	60.0[1]	246.0	-14.0	550.0
Test #2	6.0	-2.0	-4.0	-14.0	12	642.0
Test #3	-2.0	-2.0	-4.0	-14.0	4.0	608.0
Mean [SD]	-0.6 [6.1]	-2.0 [0.0]	17.3 [37.0]	72.7 [150.1]	0.7 [13.3]	600.0 [46.5]
NEMO						
Test #1	2.0	1.0	2.0	7.0	3.0	588.0
Test #2	-5.0	-3.0	-4.0	-12.0	-13.0	733.0
Test #3[2]	N/A	N/A	N/A	N/A	N/A	N/A
Mean [SD]	-1.5 [5.0]	-1.0 [2.8]	-1.0 [4.2]	-2.5 [13.4]	-5.0 [11.3]	660.5 [102.5]

[1] TIM was accidentally fully submerged at the end of this test, resulting in water entering around the face seal of the immersion suit. This caused the T-Shirt and Long Sleeved Shirt to become wetted after the test was completed.
[2] The ensemble garments were not able to be weighed after this test was completed, preventing the estimated garment wetting from being calculated for this test.

The estimated garment wetting based on mass differences during the tests with the Viking ensemble are given in Table 3.

Table 3: Estimated garment wetting (g) for all Viking ensemble tests for both thermal manikins.

Manikin and Test Number	Estimated Garment Wetting (g)						
	Socks	Underwear	T-Shirt	Long Sleeved Shirt	Denim Jeans	Long Sleeved Sweater	Viking Uninsulated Suit
TIM							
Test #1	-6.0	0.0	0.0	-6.0	-4.0	-2.0	226.0
Test #2	0.0	8.0	6.0	4.0	12.0	20.0	320.0
Test #3	-2.0	0.0	-2.0	2.0	6.0	-6.0	296.0
Mean [SD]	-6.7 [3.1]	2.7 [4.6]	1.3 [4.2]	0.0 [5.3]	4.7 [8.1]	4.0 [14.0]	280.7 [48.8]
NEMO							
Test #1	-2.0	-2.0	-2.0	-4.0	-12.0	4.0	224.0
Test #2	-8.0	-2.0	-10.0	-6.0	-8.0	-12.0	278.0
Test #3	-6.0	-4.0	-11.0	-8.0	-6.0	-14.0	266.0
Mean [SD]	-5.3 [3.1]	-2.7 [1.2]	-7.7 [4.9]	-6.0 [2.0]	-8.7 [3.1]	-7.3 [9.9]	256.0 [28.4]

3.2 Power Output

The total heater power output for each test for with the Mullion ensemble with both thermal manikins is given in Table 4.

Table 4: Total heater power output (W) for each of the Mullion ensemble tests with both thermal manikins.

	Mullion Ensemble Total Heater Power Output (W)	
	TIM	**NEMO**
Test 1	427.3	332.1
Test 2	377.6	309.7
Test 3	391.5	324.6
Mean [SD]	398.8 [25.6]	322.1 [11.4]

The total heater power output for each test for with the Survivtec ensemble with both thermal manikins is given in Table 5.

Table 5: Total heater power output (W) for each of the Survivtec ensemble tests with both thermal manikins.

	Survivtec Ensemble Total Heater Power Output (W)	
	TIM	**NEMO**
Test 1	399.4	300.3
Test 2	390.9	311.5
Test 3	384.4	320.8
Mean [SD]	391.6 [7.5]	310.8 [10.3]

The total heater power output for each test for with the Viking ensemble with both thermal manikins is given in Table 6.

Table 6: Total heater power output (W) for each of the Viking ensemble tests with both thermal manikins.

	Viking Ensemble Total Heater Power Output (W)	
	TIM	NEMO
Test 1	430.1	758.2
Test 2	416.8	713.2
Test 3	442.9	668.4
Mean [SD]	429.9 [13.0]	713.2 [44.9]

The mean total heater power output for thermal manikin in each immersion ensemble is given in Figure 12.

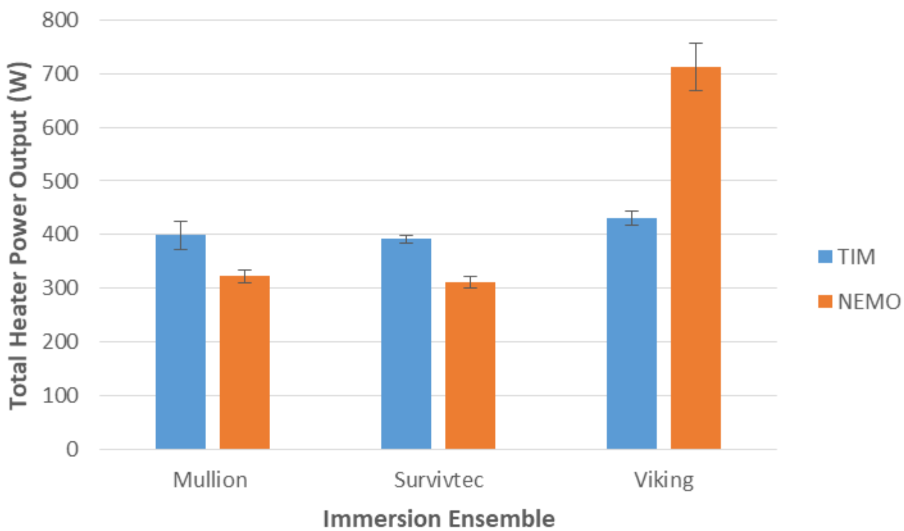

Figure 12: Mean [SD] total heater power output (W) for each thermal manikin for each immersion ensemble.

3.3 Thermal Insulation

The water temperature values as measured by TIM's RTD were lower than that measured using the immersion tank. The values from the 10 thermistors in the immersion tank were averaged to get a single water temperature value, which was used for T_w in Equation 2 to recalculate clo values for all tests with TIM.

The immersed thermal insulation values for each of the Mullion ensemble tests are given in Table 7.

Table 7: Immersed thermal insulation values (clo) for each of the Mullion ensemble tests with both thermal manikins.

	Mullion Ensemble Immersed Thermal Insulation Values (clo)	
	TIM	NEMO
Test 1	0.779	1.089
Test 2	0.833	1.123
Test 3	0.829	1.071
Mean [SD]	0.813 [0.30]	1.094 [0.026]

The immersed thermal insulation values for each of the Survivtec ensemble tests are given in Table 8.

Table 8: Immersed thermal insulation values (clo) for each of the Survivtec ensemble tests with both thermal manikins.

	Survivtec Ensemble Immersed Thermal Insulation Values (clo)	
	TIM	**NEMO**
Test 1	0.819	1.180
Test 2	0.830	1.137
Test 3	0.850	1.071
Mean [SD]	0.833 [0.015]	1.129 [0.055]

The immersed thermal insulation values for each of the Viking ensemble tests are given in Table 9.

Table 9: Immersed thermal insulation values (clo) for each of the Viking ensemble tests with both thermal manikins.

	Viking Ensemble Immersed Thermal Insulation Values (clo)	
	TIM	**NEMO**
Test 1	0.388	0.459
Test 2	0.399	0.473
Test 3	0.404	0.503
Mean [SD]	0.397 [0.008]	0.478 [0.023]

The mean immersed thermal insulation values for all ensembles with both manikins are given in Figure 13.

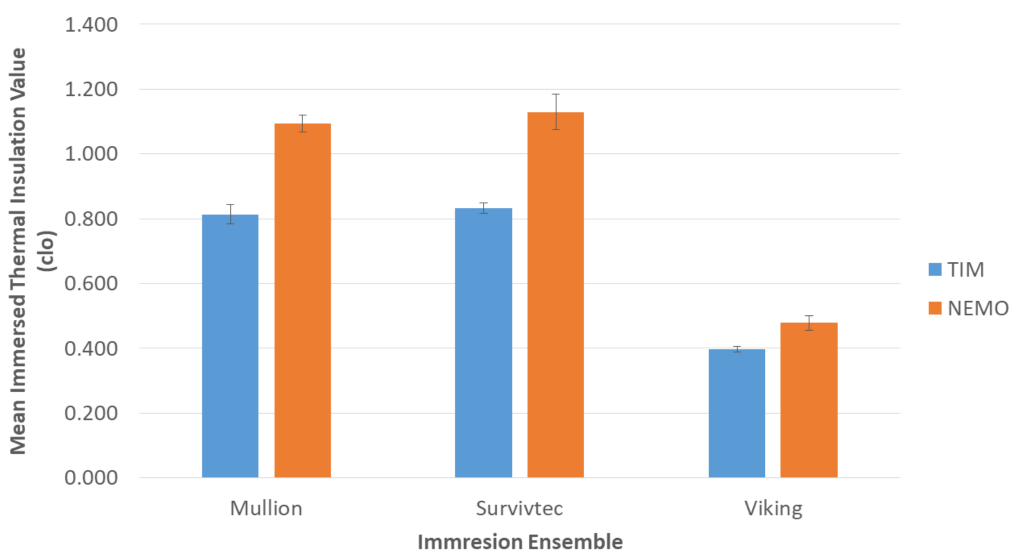

Figure 13: Mean [SD] immersed thermal insulation values (clo) for all ensembles with both thermal manikins.

4.0 Discussion

Given the importance of immersion suits in helping to increase the safety and survival of people who accidentally become immersed in cold water, it is vital that the thermal insulation of this LSA is measured to ensure it is sufficient. While some standards require human participants to be used to test the sufficiency of the thermal insulation of an immersion suit, the high costs, complexity, and ethically questionable nature (Barwood and Tipton, 2011) of these grueling tests make them a challenge to perform. The acceptance of thermal manikins as a method to measure the thermal insulation of immersion suits would help reduce these challenges, provided that several technical questions are addressed first. One of these questions is how different thermal manikins compare to each other, and what differences may exist between them when testing immersion suits. The objective of this study was to test two different thermal manikins, TIM and NEMO, in the same laboratory using the same equipment and procedures in order to eliminate as much variation as possible. Three different immersion ensembles were tested on both thermal manikins.

4.1 Water Leakage

Water leakage underneath the immersion suit can cause a significant reduction in the amount of thermal insulation provided by the ensemble (Light et al., 1987). If various amount of water leakage occurred during the current tests, then this would have introduced a variable that could result in differences between the values reported by the thermal manikins. Table 1 gives the estimated garment wetting for all articles of clothing in the Mullion ensemble for all tests with TIM and NEMO. All garment masses, with the exception of the immersion suit, had lower masses after the tests compared to before. This demonstrates that no water leakage occurred during the tests, and the manikins actually dried the clothing out during the test, causing the small amounts of moisture present in them at the start to evaporate. The Mullion immersion suit itself weighed more at the end of the tests due to the outer surface of the suit becoming saturated during the tests; no water leakage was observed on the inside of the suit.

Table 2 provides the estimated garment wetting for the Survivtec ensembles during tests with both manikins. For the first test in the Survivtec ensemble with TIM, the manikin was accidentally fully submerged at the end of the test, causing water to enter around the face seal of the immersion suit, wetting the T-shirt and long sleeved shirt, resulting in higher estimated garment wetting masses (Table 2). It is highly likely that this wetting was the result of this accidental submersion, and not leakage during the test, as there were was very little difference between the immersed thermal insulation values for the Survivtec ensembles when tested with TIM (Table 5). For the third test with the Survivtec ensemble with TIM, there was a small amount of water leakage observed on the denim jeans on the lateral side of the right ankle. No water leakage was observed with the Survivtec ensembles during the tests with NEMO. Similar to the Mullion ensembles, the increased mass of the Survivtec immersion suit was due to the outer surface becoming saturated

Small amounts of water leakage was observed during the first and second test with TIM in the Viking ensemble (Table 3). For the first test, a small amount of wetting was visible on the denim jeans which was believed to have been caused by a leak in a seam on the back of the suit. Aquaseal Repair Adhesive (GEAR AID, Bellingham, WA, USA) was applied to this seam and allowed to cure before the second test. During the second test, more garment wetting was observed which was due to two small holes in the right glove of the immersion suit. Aquaseal Repair Adhesive was applied to these holes and allowed to cure before the third test with TIM. No water leakage was observed during the third test with TIM in the Viking ensemble, which is supported by the low garment masses recorded for the under garments (Table 3). No leakage was observed during all three tests with NEMO in the Viking ensemble. Like the previous two ensembles, the increased mass of the Viking immersion suit was due to saturation of the outer layer of the fabric.

4.2 Total Heater Power Output

For both the Mullion and Survivtec ensembles, TIM had a higher total heater power output (398.8 [25.6] W; 391.6 [7.5] W) compared to NEMO (322.1 [11.4] W; 310.8 [10.3] W) (Tables 4&5; Figure 12). For the Viking ensemble, NEMO had a significantly higher total heater power output (713.2 [44.9] W) compared to TIM (429.9 [13.0] W).

This large difference in total heater power output between TIM and NEMO in the Viking ensemble was to be expected as the former had a lower $\bar{T}_{skin}$ (21.75°C) compared to the latter thermal manikin (35°C). As the thermal gradient was larger with NEMO in the Viking ensemble compared to TIM, it is expected that the total heater power output would be higher. However, for the Mullion and Survivtec ensembles, the thermal gradient between the skin temperatures of the manikins (TIM: 34.5°C; NEMO: 35°C) and the water was very similar. Even though the thermal gradients in the Mullion and Survivtec ensembles were similar between the two manikins, TIM had a much greater total heater power output (Mullion: 398.8 [25.6] W; Survivtec: 391.6 [7.5] W) compared to NEMO (Mullion: 322.1 [11.4] W; Survivtec: 310.8 [10.3] W).

4.3 Thermal Insulation

The mean immersed thermal insulation values measured by TIM for the Mullion ensemble (0.813 [0.030] clo) was lower than NEMO (1.094 [0.026] clo) (Table 7). Both manikins had similar variations in immersed thermal insulation (TIM: 6.7%; NEMO: 4.7%).

Similar to the Mullion ensembles, the mean immersed thermal insulation values for the Survivtec ensembles was lower when tested with TIM (0.833 [0.015] clo) compared to NEMO (1.129 [0.055] clo) (Table 8). Unlike the Mullion ensemble, NEMO had a larger variation in its mean immersed thermal insulation values (~9.7%) compared to TIM (~3.6%).

When tested in the Viking ensemble with the uninsulated immersion suit, both TIM and NEMO measured lower mean immersed thermal values compared to the other two ensembles that used insulated immersion suits (Table 9). The mean immersed thermal insulation value for the Viking ensemble was again lower with TIM (0.397 [0.008] clo) compared to NEMO (0.478 [0.023] clo) (Table 6). Again, TIM had a lower variation in its immersed thermal insulation values (~4.0%) compared to NEMO (~9.3%).

Across all three immersion ensembles, TIM measured a lower mean immersed thermal insulation value compared to NEMO (Figure 13). For the Mullion ensemble, the difference was 0.281 clo (~25.7% lower); for the Survivtec ensemble the difference was 0.296 clo (~26.2% lower); and for the Viking ensemble the difference was 0.081 clo (~17.0% lower) (Figure 13).

Figure 14 plots the clo values for each of the nine individual tests for TIM (x-axis) against NEMO (y-axis).

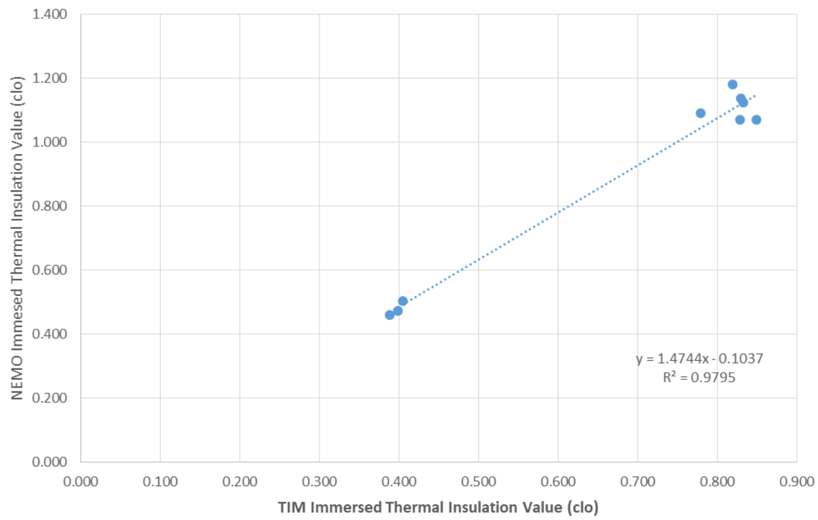

Figure 14: Immersed thermal insulation values (clo) for individual tests with TIM (x-axis) and NEMO (y-axis).

Even with the absolute difference in mean immersed thermal insulation values for each immersion ensemble between the two manikins, the results have a very strong correlation (r = 0.99), suggesting a good agreement in how the two manikins measured the immersion ensembles.

4.4 Possible Reasons for Inter-Manikin Variability

The objective of this study was to test two different thermal manikins in the same conditions, using the same clothing ensembles and procedures. This was done to eliminate as many variables as possible, so that any differences observed in the test results will be most likely due to differences in the manikins themselves, and not due to different laboratory setups or procedures. Both thermal manikins were successfully tested with the same ensembles and procedures, which resulted in the physical setup of them being identical (Figures 9-11).

While a large amount of variation was removed by testing both thermal manikins in the same laboratory with the same ensembles and procedures, some variability did still exist which can influence the final measurements. As observed in Tables 7-9, even in tests with the same manikin and ensemble, the immersed thermal insulation value can vary by almost 5% for TIM, and almost 10% for NEMO. These between tests, intra-manikin differences are most likely due to slight variations in how the manikins are dressed between tests, which is to be expected (ASTM, 2016). Therefore, it is reasonable to expect that there will be a variation of at least 5% between tests, even when comparing thermal manikins under the same conditions.

The differences reported in the measured mean immersed thermal insulation values between the two thermal manikins is greater than the ~5% due to dressing variations (Figure 13). NEMO reported immersed thermal insulation values ~25.7% higher for the Mullion ensemble compared to TIM; ~26.2% higher for the Survivtec ensemble; and ~17.0% higher for the Viking ensemble. These differences are greater than the ~5% variation expected due to dressing, which suggests there are additional reasons for them. One possible reason for this is that TIM is physically larger than NEMO, and thus occupies more space in the immersion suits. With the immersion suits fitting snugger on TIM due to its larger stature, it is less likely for the fabric of the suit to fold over on itself, increasing the insulation in some areas. With NEMO being physically smaller, and the ensembles fitting looser on it, there is a greater chance for the immersion suit fabric to fold over on itself, varying the insulation in some areas. The higher variability between tests with NEMO (~10%) in the same ensemble supports this theory.

In addition to the fit of the ensemble, the physical size of the manikin may impact the amount of air trapped in the immersion suit. Since still air is an excellent insulator, trapped pockets of it can increase the overall immersed thermal insulation values of the ensemble. With TIM being physically larger, it is logical to assume it will displace more air in the immersion suit compared to NEMO. If NEMO did allow more air to be trapped in the suit by physically displacing less of it compared to TIM, it is possible that this increased the overall immersed thermal insulation values as well.

It was observed during the tests that significant pockets of air would get trapped in the immersion suit on the anterior side of the thermal manikins (Figures 9–11). Ideally, as the thermal manikins were lowered into the water, hydrostatic pressure would force the air out of the immersion suits via the Tygon tubing inserted in the face seal. In practice, the hydrostatic pressure would only act on the air trapped on the posterior side of the manikin as the anterior surface was never submerged below the water (Figures 9 – 11). It is recommended that in the future, testing procedures be modified to require the thermal manikin to be submerged up to the face seal to increase the likelihood that hydrostatic pressure will force as much air out as possible, reducing the variation between tests. In the current setup, this could be achieved by lowering the feet of the thermal manikin, so that it is angled below the surface of the water. The feet of the thermal manikin could be lowered to the point where the water level was near the face seal for a period of 30 seconds, and then the feet raised back up to the 150mm freeboard position. This would increase the consistency between tests by allowing hydrostatic pressure to act on the anterior and posterior sides of the thermal manikins to help force as much air out as possible.

Even with removing as many variables as possible between the tests with the two thermal manikins, the differences in immersed thermal insulation values ranged from 16.9 - 26% (Figure 13). While at least 5% of the difference would be expected due to dressing variation, this would leave approximately 15 – 21% difference between the thermal manikins. While fit of the suit, and trapped air, may certainly account for variations between the two thermal manikins, it is unlikely that they would account for all of the remaining 15 – 21% difference. Therefore, it is possible that there exists another reason as to why the thermal manikins reported different immersed thermal insulation values.

Tables 4 and 5 give the total heater power output for both thermal manikins in the Mullion and Survivtec ensembles. In these two ensembles, the thermal gradient (manikin $\bar{T}_{skin}$ – T_w) between the two manikins were very similar, with the difference between them being less than 0.5°C (the Viking ensemble is not considered due to the different $\bar{T}_{skin}$ set points for each thermal manikin). Even with the thermal gradient, physical setup, immersion suit, and test procedure being virtually identical between both manikins, TIM still reported higher total heater power output (Mullion: 398.8 [25.6] W; Survivtec: 391.6 [7.5] W) compared to NEMO (Mullion: 322.1 [11.4] W; Survivtec: 310.8 [10.3] W). This demonstrates that TIM required more power for its heaters to maintain a thermal gradient equivalent to NEMO in the same immersion ensemble and test conditions, indicating it was losing more heat when both were in a thermal steady state condition. This raises the question: why would TIM be losing more heat than NEMO in virtually identical conditions when in a thermal steady state?

A possible reason for TIM losing more heat than NEMO is that the former could have a larger surface area compared to the latter. The larger the surface area of an object, the greater the physical area that heat can be transferred from. While TIM is physically taller than NEMO (1.83m and 1.77m respectively), and has a greater mass (94.5kg and 71kg respectively), its reported surface area is smaller (1.74m^2 and 1.86m^2 respectively). As shown in equations 2 and 5, manikin surface area is a required value in order to calculate immersed thermal insulation. Therefore, if the reported manikin surface area is less than the total physical area that heat can be transferred over, then immersed thermal insulation value may be calculated conservatively.

Several formulae derived from human studies can be used to estimate surface area based on the height and mass of a person. Gehan and George (1970) reported that surface area can be estimated from the following equation:

$SA = 0.1644 \cdot M^{0.51456} \cdot H^{0.42246}$ *Equation 8*

Where:

SA = surface area (m^2)

M = mass (kg)

H = height (m)

Mosteller (1987) reported that surface area can be estimated from the following equation:

$$SA = \sqrt{\frac{Hcm * M}{3600}} \qquad \textit{Equation 9}$$

Where:

H_{cm} = height (cm)

Tikuisis et al. (2001) reported that surface area can be estimated from the following equation:

$$BSA = 128.1 \cdot M0.44 \cdot H_{cm} \qquad \textit{Equation 10}$$

Where:

BSA = body surface area (cm^2)

BSA can then be converted into SA with the following equation:

$$SA = \frac{BSA}{10000} \qquad \textit{Equation 11}$$

Using the reported height and mass values for TIM and NEMO, surface areas for both can be estimated using the previous formulae (Table 10).

Table 10: Estimated surface areas for TIM and NEMO using equations by Gehan and George (1970), Mosteller (1987), and Tikuisis et al. (2001).

Manikin	Gehan and Geroge (1970) SA (m^2)	Mosteller (1987) SA (m^2)	Tikuisis et al. (2001) SA (m^2)	Mean SA (m^2)
TIM	2.20	2.19	2.16	2.18
NEMO	1.88	1.87	1.87	1.87

Averaging the values calculated from equations 8, 9, and 11, TIM is estimated to have a surface area of 2.18m^2, and 1.87m^2 for NEMO (Table 10). The reported and estimated surface areas for NEMO are nearly identical (1.86m^2 and 1.87m^2 respectively), but the reported and estimated surface areas for TIM differ (1.74m^2 and 2.18m^2 respectively) by ~25.6%.

If the assumption is made that TIM is losing heat over an area larger than 1.74m^2 (the value used for SA in equation 2), then this could result in a change in the calculation of immersed thermal insulation values. Using the value of 2.18m^2 for SA in equation 2, new immersed thermal insulation values can be calculated for each immersion ensemble (Table 11).

Table 11: Immersed thermal insulation values (clo) using an estimated surface value of 2.18m^2 for TIM for each ensemble test.

	Immersed Thermal Insulation Value Using Estimated Surface Area of 2.18m^2 for TIM (clo)		
	Mullion Ensemble	**Survivtec Ensemble**	**Viking Ensemble**
Test 1	0.978	1.029	0.488
Test 2	1.046	1.042	0.501
Test 3	1.041	1.067	0.508
Mean [SD]	1.022 [0.038]	1.046 [0.019]	0.499 [0.010]

The mean immersed thermal insulation values calculated using the estimated surface area of 2.18m^2 for TIM for each immersion ensemble, and those measured by NEMO, are given in Figure 15.

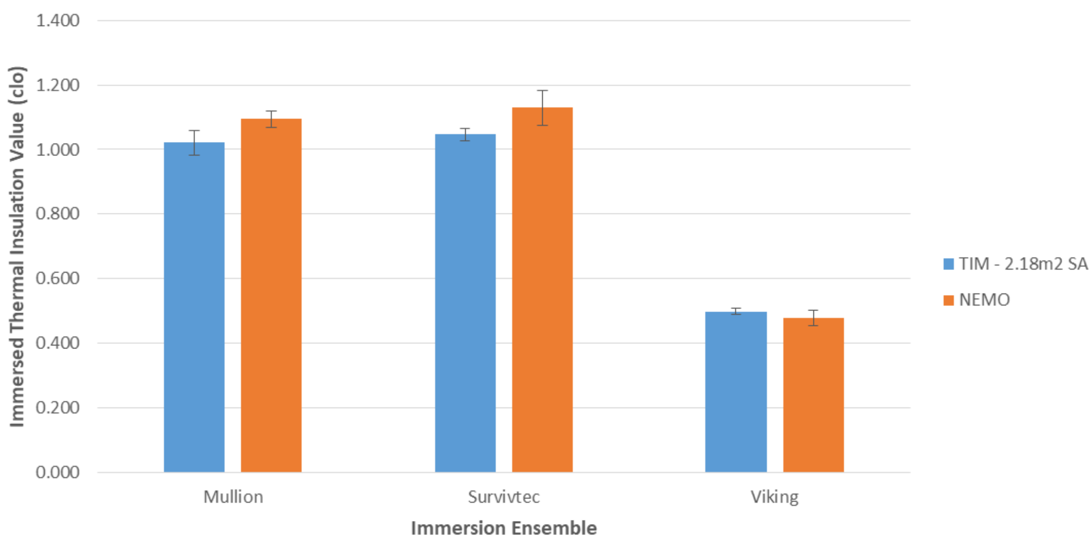

Figure 15: Mean [SD] immersed thermal insulation values (clo) for TIM (using an estimated surface area of 2.18m^2) and NEMO for each immersion ensemble.

When an estimated surface area of 2.18m^2 is used for TIM to calculate immersed thermal insulation, the values increase compared to when using its reported surface area of 1.74m^2 (Tables 7-9, 11). This is to be expected as if the thermal gradient and heater power output remains constant, but surface area increases, then thermal insulation will rise as a result (equation 2). When using the estimated surface area of 2.18m^2, the new immersed thermal insulation values as reported by TIM for each ensemble are very similar to NEMO (Mullion: 1.022 clo; 1.094 clo; Survivtec: 1.046 clo; 1.129 clo; Viking: 0.499 clo; 0.478 clo). These new immersed thermal insulation values for TIM only differ from NEMO by ~4-7%; a range that the expected 5% dressing variation falls within.

While it is tempting to simply use the estimated surface area of 2.18m^2 for TIM as it causes its immersed thermal insulation values to become very similar to those measured by NEMO, caution must be exercised before doing so. All the formulae use to estimate the surface area (Gehan and George, 1970; Mosteller, 1987; Tikuisis et al., 2001) were derived from *human participants* and not thermal manikins. It is possible that the density of TIM is different from the humans used in those studies, while the density of NEMO may be similar. If this was indeed the case, then it would not be unexpected that the estimated surface area for TIM to differ from the reported value, while NEMO's remain similar. Therefore, the surface area of TIM may be less than 2.18m^2 if it has a greater density than the average human values used to derive the surface area formulae.

5.0 Conclusions and Recommendations

Thermal manikins are extremely useful tools to help test immersion suits without subjecting human volunteers to gruelling conditions. Various thermal manikins exist across the world, with different laboratory setups which can contribute to variations in reported thermal insulation values for a given clothing ensemble. The objective of this study was to compare the results from two different thermal manikins (TIM and NEMO) tested in the same conditions, and using the same procedure, to eliminate as much variation as possible.

Both thermal manikins were successfully tested in an identical fashion across three different immersion ensembles. Even though the absolute values for each immersion ensemble were different between the two thermal manikins, the results correlated extremely well. This suggests that there is very good agreement in *how* the two thermal manikins perform their measurements; that is: how the immersed thermal insulation value for each immersion ensemble compared to the other was the same for each manikin (e.g. the Mullion and Survivtec ensemble values were similar, while the Viking ensemble values were much lower).

It was noted during the tests that air would become trapped on the anterior side of the thermal manikins, even with the Tygon tubing inserted in the face seal to facilitate its escape. Since still air is an excellent thermal insulator, differing amounts of it between tests could introduce variability in the results. It is recommend that for future tests, when the thermal manikin is initially lowered into the water, that its feet be submerged to the point where the water line is near the face seal for a period of 30 seconds. This would allow the hydrostatic pressure to force trapped air out of the suit in a more consistent fashion, reducing the variability it could introduce between tests.

Along with the trapped air, another possible source of variability was the fit of the suit on the thermal manikin. TIM is physically larger than NEMO, and a result, the immersion suits had a snugger fit on it, reducing the amount of trapped air and loose fabric. Loose fabric may roll over on itself, effectively doubling up the amount of insulation in some areas. An immersion suit that has a snugger fit on one manikin may have a lower thermal insulation value compared to when being worn by a physically smaller thermal manikin.

Another possible reason for the variability in results between the two thermal manikins is the TIM manikin may be calculating immersed thermal insulation values in more conservative fashion compared to NEMO. The surface area used by TIM to perform the calculations may be less than the total area that heat is being lost from, resulting in a conservative value for immersed thermal insulation. As surface area is a required value for calculating thermal insulation, it is recommended that it be measured for all thermal manikins through a method such as whole body scanning, which may help reduce the differences in their results.

The recommendations based on the findings from this work are:

1. Thermal manikins can be considered a viable method for measuring the thermal insulation of immersion suits.
2. The ISO 15027 procedure be modified to submerge the feet of the thermal manikin at the beginning of the test to allow for a more consistent method of evacuating air from the immersion suit.
3. The surface area of thermal manikins be measured, and this value used in calculating thermal insulation.
4. Future round robin tests with thermal manikins should be conducted with immersion suits that have already been certified using human participants. This would enable the immersed thermal insulation value of suits, which allow humans to survive for at least six hours in 2°C water, to be confirmed across multiple thermal manikins.

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7.0 References

ASTM. (2016). Standard Test Method for Measuring the Thermal Insulation of Clothing Using a Heated Manikin. *ASTM International.* ASTM F1291-16.

Barwood, M. and Tipton, M. (2011). Surviving prolonged cold water immersion - An evaluation of immersion dry suit test performance standards. *World Conference on Drowning Prevention*, Vietnam, May 2011.

Gehan, E.A., and George, S.L. (1970). Estimation of body surface area using height and weight. *Cancer Chemotherapy Reports,* 54, p.225-235.

International Maritime Organization (2017). *International Life-Saving Appliance (LSA) Code.*

International Organization for Standardization (2012). *Immersion suits — Part 3: Test methods* (ISO Standard No. 15027-3:2012). https://www.iso.org/standard/52166.html

Light, I.M., Avery, A., and Grieve, A.M. (1987). Immersion suit insulation: the effect of dampening on survival estimates. *Aviation Space and Environmental Medicine,* 58(10), p.964-9.

Mosteller, R.D. (1987). Simplified calculation of body-surface area. *New England Journal of Medicine,* 317, p.1098.

Stocks, J.M., Taylor, N.A., Tipton, M.J., and Greenleaf, J.E. (2004) Human physiological responses to cold exposure. *Aviation Space and Environmental Medicine,* 75, p. 444-57.

Thermetrics (Measurement Technology Northwest). (2007). *Submersible Thermal Manikin Operator's Manual.* Seattle, WA, United States of America: Author.

Tikuisis, P., Meunier, P., and Jubenville, C. (2001). Human body surface area: measurements and prediction using three dimensional body scans. *European Journal of Applied Physiology,* 85, p. 264-271.

Tipton, M. (1989). The initial responses to cold water immersion in man. *Clinical Science (London)*, 77(6), p.581-8.

Appendix A – Manikin Surface Areas

Table 10: TIM zone specific surface areas (m²).

Zone	Surface Area (m^2)
Head	0.1357
Chest	0.1557
Back	0.1663
Abdomen	0.0549
Buttocks	0.0861
Right Arm	0.1136
Left Arm	0.1020
Right Leg	0.3563
Left Leg	0.3319
Right Hand	0.0491
Left Hand	0.0482
Right Foot	0.0685
Left Foot	0.0674
Total	1.7357

Table 11: NEMO zone specific surface areas (m^2).

Zone	Surface Area (m^2)
Face	0.0360
Head	0.1097
Right Upper Arm	0.0956
Left Upper Arm	0.0956
Right Forearm	0.0628
Left Forearm	0.0628
Right Hand	0.0418
Left Hand	0.0418
Chest	0.1003
Shoulders	0.1037
Stomach	0.1053
Back	0.1067
Cod Piece	0.0612
Right Thigh Front	0.1193
Right Thigh Back	0.1159
Left Thigh Front	0.1193
Left Thigh Back	0.1159
Right Calf Front	0.0621
Right Calf Back	0.0637
Left Calf Front	0.0621
Left Calf Back	0.0637
Right Foot	0.0582
Left Foot	0.0582
Total	1.8615