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An Overview of Recent Projects to Study Thermal Protection In Liferafts, Lifeboats and Immersion Suits

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ABSTRACT

In a marine evacuation, passengers may find themselves in lifeboats, liferafts or in the water. Survival is more challenging in cold regions and a person's ability to survive until rescue depends on many factors, including the amount of protection the evacuees have against the cold, as well as the quality of breathing air in liferafts and lifeboats that are enclosed. Currently, international regulations do not provide specific thermal protection and ventilation performance criteria for lifeboats or liferafts. In addition, methods for approval testing of immersion suits have not been standardised and there is resistance in certain jurisdictions to the use of thermal manikins because regulating authorities are unsure of the correspondence between manikins and human.

This paper provides an overview of several projects that have been completed and one ongoing by the Maritime and Arctic Survival Scientific and Engineering Research Team (MASSERT) to address the knowledge gaps in these areas. The results contribute relevant knowledge to close these gaps and are being used to advance international standards. They also show the value of using thermal manikins in combination with numerical models to predict the performance of lifesaving appliances when it is impractical or ethically unacceptable to conduct experiments with humans. The tools developed are being applied to create performance criteria and evaluate the performance of Arctic survival gear.

INTRODUCTION

In a passenger ship abandonment situation in cold water, survivors may be wearing very little personal protective clothing. Therefore, lifeboats and liferafts provide the only significant thermal protection against the cold ocean environment, supplemented by a thermal protective aid (TPA) if available. Evacuees may need to wait for days to be rescued, with children, the elderly, the weak and the injured being particularly vulnerable. Thus, for vessels operating in cold bodies of water such as the frigid North Atlantic and the Arctic, thermal protection of lifesaving appliances is very important to ensure survival in the event of evacuation.

Under Canadian and international law, all large vessels are required to provide survival craft for evacuation. Survival craft on Canadian ships comply with the Life Saving Regulations of the

Canada Shipping Act and are certified to the requirements of the International Convention for the Safety of Life at Sea (SOLAS), in the International Life-Saving Appliance (LSA) Code of the International Maritime Organization (IMO). Unfortunately, no specific thermal performance and ventilation criteria are identified. Thermal protection and ventilation are related. Inside a liferaft or lifeboat, low ventilation rates quickly result in unacceptable air quality for occupants; conversely, the heat loss can be unacceptable at higher ventilation rates. A high concentration of carbon dioxide could adversely affect occupants' ability to perform survival tasks. Thus, a reasonable compromise is required. In addition, TPAs are provided to only 10% of the number of persons the liferaft is permitted to accommodate (LSA, 2009). Moreover, IMO Guidelines for Ships Operating in Polar Waters (IMO, 2010) provide a list of equipment in the suggested survival kits, such as immersion suits, tents etc. Again, no specific performance criteria are identified for the equipment and compliance with the guidelines is not compulsory.

Similarly in the offshore sector, thermal protection and ventilation of lifesaving appliances is of critical importance. Hypothermia can set in quickly, even when a person wearing an insulated suit enters the water from an incident such as helicopter ditching or man overboard. Heat stress can occur in lifeboats and helicopters. So, operators, regulators and training providers must be aware that people could suffer from cold or heat stress as well as high concentration of carbon dioxide. Precautions should be taken to prevent exposure of people to life threatening conditions.

The purpose of this paper is to: (1) provide an overview of recent thermal protection projects MASSERT completed involving lifesaving appliances; (2) describe what progress has been made to close knowledge gaps and to improve regulations; (3) inform what evaluation and prediction tools were developed; (4) demonstrate the value of using thermal manikins in combination with numerical models to predict performance of lifesaving appliances; and (5) show how these technologies are applicable to the evaluation of Arctic protective equipment.

MARITIME AND ARCTIC SURVIVAL SCIENTIFIC AND ENGINEERING RESEARCH TEAM (MASSERT) and RECENT PROJECTS

MASSERT is a unique multi-disciplinary team of international experts drawn from academia, industry, government agencies and the safety community. Since 2006, the team has completed five large-scale, complex research projects and is currently midway through a sixth (Table 1). The team's objective is to perform research and development to enhance health and safety, operational performance and emergency survival for people working and travelling in the Arctic

Table 1. Recent MASSERT projects

Thermal Protection Research for Maritime and Arctic Environment • Thermal Protection in Liferafts (2006-2009) • Assessment of Thermal Protection and Microclimate of SOLAS Approved Lifeboats for Arctic Environment (2007-2010) • Thermal Requirements for Surviving a Mass Rescue Incident in the Arctic (2009-2012) Correlation of Immersion Suit Thermal Protection Measurement with Manikins and Humans • Thermal Manikin Calibration Standard (2007-2010) • International Organization for Standardization (ISO) Thermal Manikin Working Group Immersion Suit Approval Test Standard (2007-2009) • Thermal Protection Measurements of Immersion Suits (2009-2011)

and harsh ocean environments, to contribute to Canada's ability to meet future challenges and to advance knowledge in the international community. The team's expertise includes:

- Engineering, Thermal manikins, Industrial materials, Modelling, Lab testing & Field trials
- Human thermal and work physiology, Human protection, Human factors, Cognitive psychology, Maritime & arctic survival research
- Complex adaptive systems, System of systems integration, Search and rescue, Survival and emergency response training.

THERMAL PROTECTION IN LIFERAFTS

To assess thermal protection in liferafts, the test program shown in Table 2 was carried out in the NRC-IOT Towing Tank and Ice Tank (Mak et al, 2009). First, it was established that heat loss decreases considerably with floor insulation; heat loss increases non-linearly with leeway levelling off above 0.5 m/s leeway speed; and wave height effect is less important with leeway and may be ignored as a first approximation to reduce the number of environmental variables.

Table 2. Thermal Protection in Liferafts Test Program

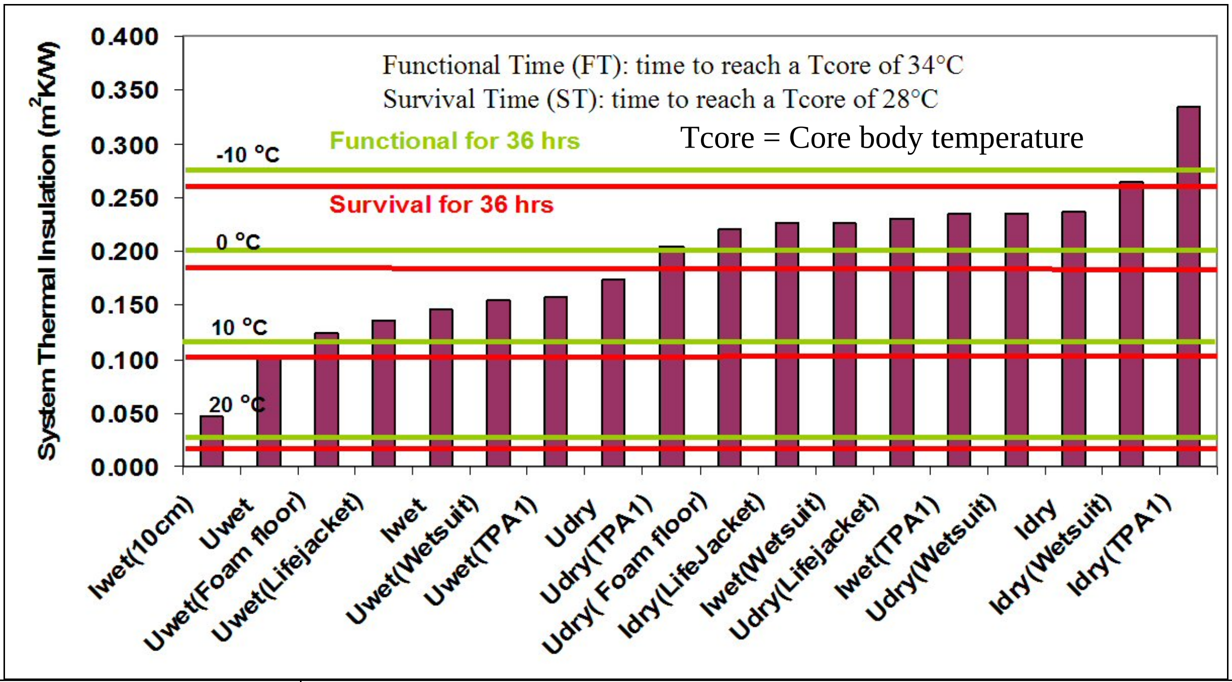
Phase	T_{air} [ºC]	T_{water} [ºC]	Wind [m/s]	Wave Height [m]	Leeway Speed [m/s]	Test Duration [min]	Human Subject or Thermal Manikin
1	19	16	NA	Up to 1m	0, 0.5, 1	30	Human
2	19	16	5	NA	0.5	135	Human
3	5	5	5	NA	0.5	240 - 480	Human & Manikin

Next, the results demonstrated good agreement in system insulation values obtained using human subjects and a thermal manikin in 4 conditions (Table 3). There is also good repeatability with manikin results. This gave confidence to use the manikin in assessments of liferaft thermal protection in various test conditions, which was more cost effective than using human subjects.

Table 3. System thermal insulation values [(m^2°C)/W] from manikin and human subjects

Tests	Inflated Floor; Dry Clothing (Idry)	Inflated Floor; Wet Clothing (Iwet)	Uninflated Floor; Dry Clothing (Udry)	Uninflated Floor; Wet Clothing (Uwet)
Manikin	0.236	0.146	0.177	0.101
Manikin repeat test	NA	NA	0.171	0.104
8 Human subjects average	0.224±0.023	0.145±0.017	0.185±0.022	0.116±0.006

Figure 1 shows the proposed thermal protection criterion for liferafts. A mathematical model simulating the liferaft internal environment was integrated with the Cold Exposure Survival Model (Tikuisis, 2005) to predict liferaft occupant heat loss and was used to establish the minimum system insulation required for survival at various temperatures. Predictions are shown as the horizontal lines. Each line represents an insulation value that will give a survival time (ST) or functional time (FT) of 36 hours from -10 to +20°C. The temperature used here is an average of air and water temperatures. Vertical bars represent the insulation values measured with the thermal manikin under various conditions ranging from wet clothing with 10 cm of water on the inflated raft floor up to dry clothing plus a thermal protective aid (TPA) and an inflated floor. Wherever the top of a bar is higher than a line, it can be expected that the ST or FT will be longer than 36 hours at the temperature corresponding to that line. The figure shows the importance of keeping dry, the value of TPA and the value of floor insulation. The model can also be used to predict functional and survival time as a function of temperature for specific clothing and raft conditions to assist Search and Rescue (SAR) planning. Figure 2 shows results of a carbon dioxide concentration test with 11 persons in the liferaft. It was observed to reach over 5000 ppm in less than 1 hour inside the raft with closed canopy and natural ventilation.



Iwet (10 cm)	Inflated floor; 10 cm high water on the raft floor
Uwet	Uninflated floor; wet clothing
Uwet (Foam floor)	Closed cell foam floor placed on uninflated floor; wet clothing
Uwet (Lifejacket)	Uninflated floor; wet clothing; sitting on own lifejacket
Iwet	Inflated floor; wet clothing
Uwet (Wetsuit)	Uninflated floor; wet clothing and wetsuit (3mm neoprene)
Uwet (TPA1)	Uninflated floor; wet clothing and TPA
Udry	Uninflated floor; dry clothing
Udry (TPA1)	Uninflated floor; dry clothing and TPA
Udry (Foam floor)	Closed cell foam floor placed on uninflated floor; dry clothing
Idry (Lifejacket)	Inflated floor; dry clothing; sitting on own lifejacket
Iwet (Wetsuit)	Inflated floor; wet clothing and wetsuit (3mm neoprene)
Udry (Lifejacket)	Uninflated floor; dry clothing; sitting on 2nd lifejacket
Iwet (TPA1)	Inflated floor; wet clothing and TPA
Udry (Wetsuit)	Uninflated floor; dry clothing and wetsuit (3mm neoprene)
Idry	Inflated floor, dry clothing
Idry (Wetsuit)	Inflated floor, dry clothing and wetsuit (3mm neoprene)
Idry (TPA1)	Inflated floor, dry clothing and TPA

Figure 1. System thermal insulation required for Survival Time or Function Time of 36 hours

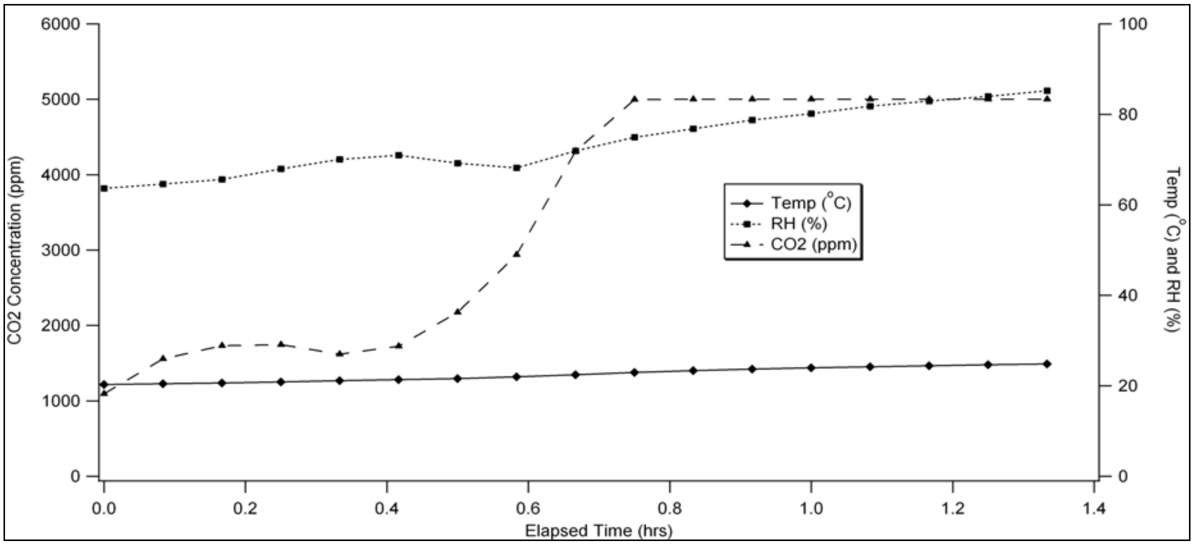


Figure 2. Liferaft microclimate

The main conclusions of this study are:

1. Thermal insulation of a combined system of clothing and liferaft measured by a manikin give good agreement with measurements on humans after correcting for contact area differences.
2. The minimum system insulation required for a 36-hour survival or functional time at various temperatures with various raft and clothing configurations was summarized in a single figure.
3. System insulation values coupled with a thermo-physiological model can give SAR planners reasonable predictions of survival time in liferafts where hypothermia is the main risk factor.
4. Factors which substantially affect the survival time are: (a) Wearing of a TPA; (b) Clothing wetness; (c) Liferaft floor insulation; and (d) Liferaft ventilation rate.

THERMAL PROTECTION IN LIFEBOATS

The test program developed to assess thermal protection in lifeboats included (Mak et al, 2010):

- Passive and forced ventilation rate tests on a 72-person and a 20-person lifeboat, not moving and sailing at 3 and 6 knots (full speed).
- Tests to determine the heat transfer coefficients of different areas in the two lifeboats.
- Human subject tests to study the microclimate of the 72-person lifeboat.
- Manikin tests to assess the insulation of different clothing systems in the 72-person lifeboat.

Figure 3 shows a dilution test used to establish the ventilation rate of three passive ventilation conditions – a fully sealed lifeboat, lifeboat with only vents open and lifeboat with vents and side hatches open. The data collected are shown in red and the fitted curve is shown in blue. The fully sealed lifeboat has very little leakage, with ventilation rate estimated at 1 litre per second. The ventilation rate from open vent only was estimated to be 2 litres per second. The ventilation rate with side hatches and vents open was estimated to be 95 litres per second.

Assuming 1 Metabolic Equivalent (MET) physical activity (similar to someone sitting down watching TV), each person will consume approximately 3.5 ml/min/kg of oxygen ($VO_{2\ resting}$). If the respiratory exchange ratio, RER, is 0.85 (Tikuisis, 1999), the rate of carbon dioxide production for a 75 kg person (50th percentile North American male) can be estimated to be 3.8 millilitres per second carbon dioxide.To keep carbon dioxide concentration below the 5000 ppm safety limit (ACGIH, 2004), each person needs a ventilation rate of 0.75 litres per second. For a 72-person lifeboat, the minimum ventilation rate required is 54 litres per second. The 1 MET metabolic rate is very conservative. It is possible that occupants may exert themselves carrying out survival tasks. If lifeboat occupants have 2 MET physical activity, the minimum ventilation rate required is 108 litres per second. This shows an inadequate ventilation rate unless the side hatches are open.

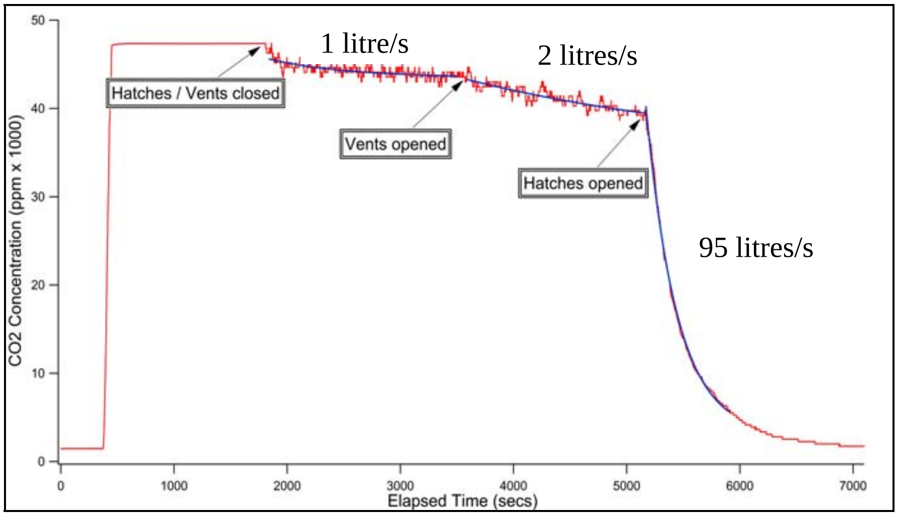


Figure 3. Carbon dioxide dilution tests to estimate the ventilation rates of three conditions (fully sealed, vents open only and side hatches and vents open); passive ventilation; 6-knots speed

To show that this estimation method works, the forced ventilation rate was controlled at 45 litres/s (30 person x 0.75 litres/s x safety factor of 2) as shown in Figure 4. On the day of testing, 21 human subjects entered the lifeboat. During the one-hour experiment, the carbon dioxide concentration increased sharply initially but stabilized around 3500 ppm.

Using the experimental data collected from the lifeboat, the manikin and the ambient environment, a numerical model of heat loss from the lifeboat was constructed to predict the internal air temperature for any condition of ambient environment, number of occupants, clothing systems and engine heat input. The heat balance model considers the heat losses through the hull and by ventilation and the heat input from the engine, the metabolic heat production of the occupants and change in internal energy of the system.

Figure 5 shows model prediction for regions of cold or heat stress of occupants, when the lifeboat is half occupied, engine off, occupants are wearing dry reference clothing (cotton T-shirts, cotton briefs, one-piece cotton coveralls and SOLAS life jackets), and metabolic rate is assumed to be 100 W. With a ventilation rate of 27 litres/s (0.75 litres/s per person), occupants wearing dry reference clothing would not experience cold or heat stress between 0 and 10°C. Occupants with wet clothing will begin to experience cold stress below 0°C. Below -10°C, occupants with dry clothing will experience cold stress. When the engine is running, the model predicts that heat stress rather than cold stress becomes the dominant concern.

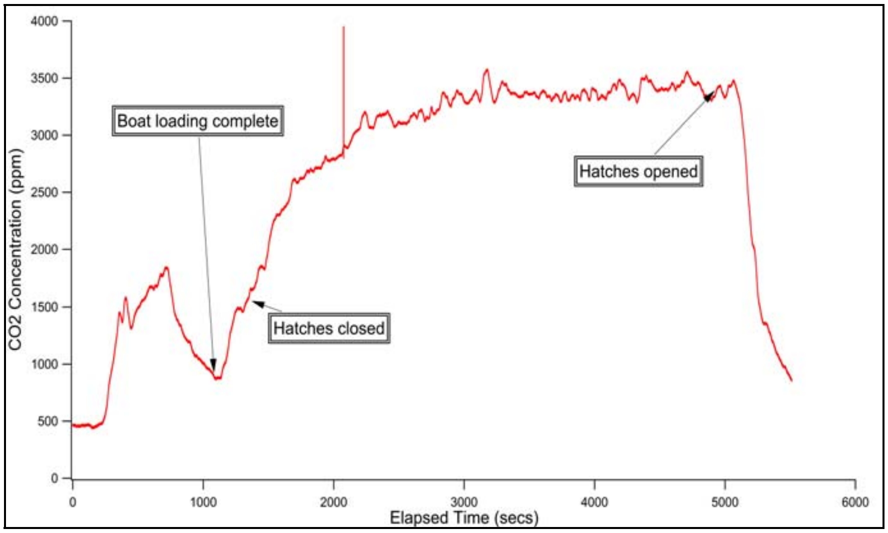


Figure 4. Carbon dioxide concentration with 21 human subjects in a 72-person lifeboat; ventilation rate 45 litres/s; 6-knot speed

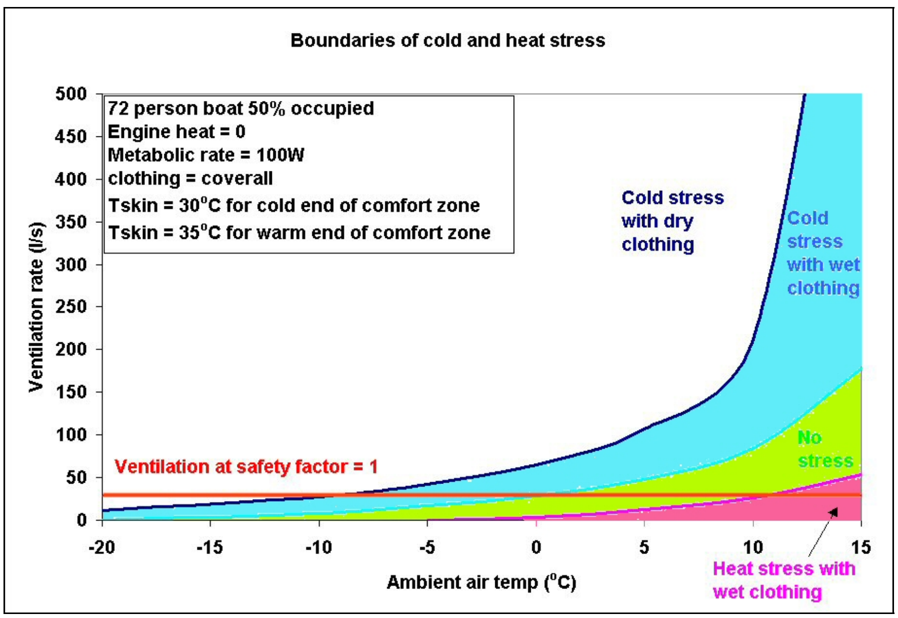


Figure 5. Model result of occupant cold or heat stress; ventilation rate 27 litres/s; 6-knots speed

The main conclusions of this study are:

1. In a 72-person lifeboat, the minimum ventilation rate needed to keep carbon dioxide concentration below 5000 ppm is 54 litres/s if occupants have 1 MET physical activity.
2. System thermal resistance of a lifeboat is required to assess ventilation effects inside a lifeboat. It is a complex measurement that requires modelling because of multiple heat sources, heat sinks and heat loss paths.
3. Thermal manikins and mathematical models can be used to assess heat and cold stress of lifeboat occupants under different environmental conditions, number of occupants, clothing systems, metabolic rates, ventilation rates, engine heat output etc.
4. Using a model, the analysis shows a reasonable compromise between thermal protection and ventilation rates is achievable.

THERMAL PROTECTION MEASUREMENT OF IMMERSION SUITS

The International Organization for Standardization (ISO) does not currently endorse the use of manikins in suit approvals though there is provision in the ISO standard for immersions suits for either human or manikin testing. The Canadian General Standards Board (CGSB) standards for immersion suits and helicopter passenger suit systems allow both human subject and manikin testing and the manikin test is used in most instances. Results from a pilot test preliminary to a planned larger study indicate that heat loss from either of two thermal manikins (NEMO manufactured by Measurement Technology Northwest, Seattle, USA and TIM from CORD Group, Halifax, Canada) is representative of heat loss from two human subjects under identical conditions. Figure 6 shows a comparison of insulation values for manikins and human subjects. HFS are values derived from heat flow sensor (HFS) measurements on both thermal manikins and human subjects. Powers are values derived from the power measurements on the thermal manikins. Materials only are hot plate results with no air gaps. It is concluded that within a scatter of about ±18%, the whole body thermal insulation on humans and manikins agrees for immersion suits insulated with closed cell foam and increases linearly with foam thickness. The variation in human values (±13%), the variation in manikin values (±6%), and the differences between manikin and human (±12%) are all of the same order of magnitude (DuCharme, 2010). These results suggest that thermal resistances measured with a manikin are suitable for use in a human thermal model to predict the fall in body core temperature under specified conditions.

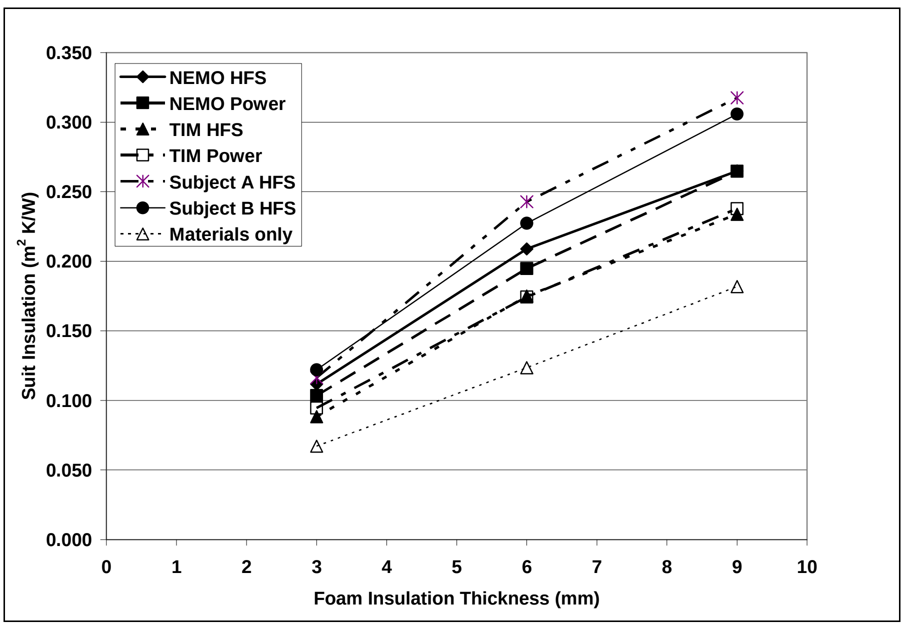


Figure 6. Whole body suit thermal insulation values for manikins and humans

THERMAL REQUIREMENTS FOR SURVIVAL IN THE ARCTIC

The objective of this project is to investigate if the current thermal protective equipment and preparedness available to people travelling in the Canadian Arctic are adequate for surviving a major air or cruise ship disaster and to identify the minimum thermal protection criteria for survival. In Phase 1 of the project, the thermal resistance values of the different protective clothing available to cruise ship and aircraft passengers were measured using two thermal manikins. Using this information, the Human Thermal Model (Wissler, 2010) was used to simulate typical survival scenarios.

Two plausible scenarios were simulated for the first 24 hours following an accident in which passengers abandon a cruise ship when the air temperature is 0^{o}C and the wind speed is 25 km/hr (7 m/s). Passengers are assumed to be wearing Expedition Wear (0.48 (m^2 °K)/W dry and 0.19 (m^2 °K)/W wet after 70 hours of drying) that is wet below the waist due to being in an enclosed liferaft with water on the floor. While in the raft, passengers are protected from the wind, but the air temperature in the raft remains close to the outside temperature. In both scenarios we assume that passengers remain in the liferaft for six hours before making their way onto land. During the transit from liferaft to land, which lasts two hours, passengers perform light work (40 W) while exposed to cold and wind. In the first scenario, we assume that passengers on land have access to tents and light sleeping bags with a thermal insulation of 4 clo (0.62 m^2°K/W), and in the second scenario we assume that passengers remain exposed to the elements. Whether in a tent or exposed, the passengers remain on land for 16 hours. Computed core and mean skin temperatures and the metabolic rate are plotted in Figures 7. Filled and open circles identify the first and second scenarios, respectively.

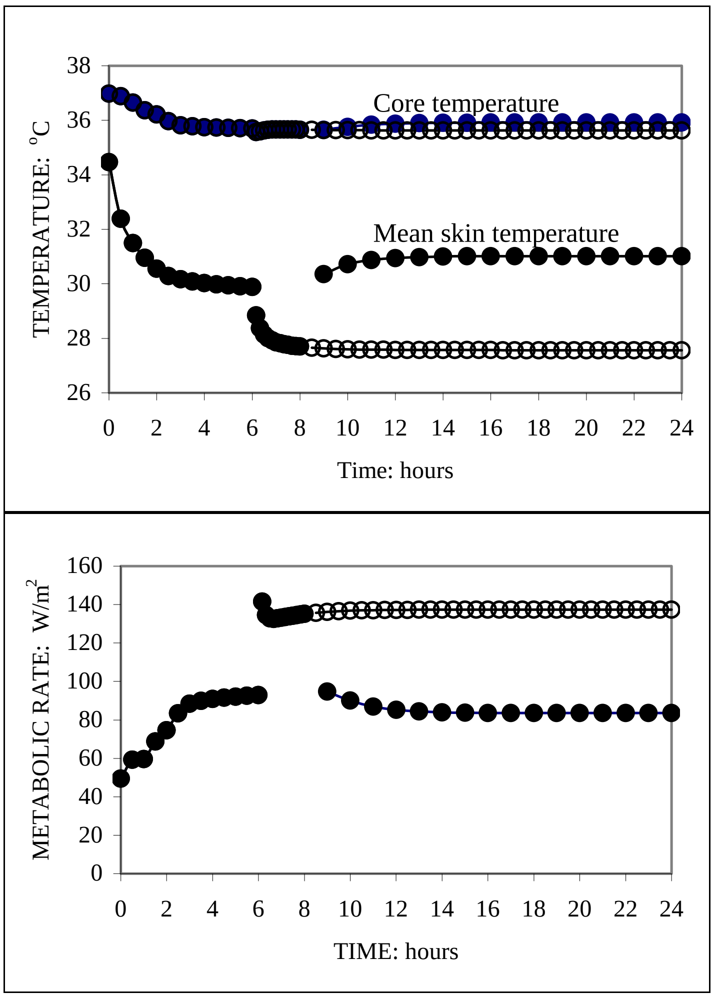


Figure 7. Core and mean skin temperatures, and metabolic rates for two different 24-hour scenarios. Closed circles identify use of a sleeping bag in a tent during the last 16 hours, and open circles identify continuous exposure without a tent or sleeping bag.

The key conclusions in Phase 1 of this project are:

1. There is very good agreement between the thermal resistances measured by the two manikins.
2. Preliminary 24-hour survival simulation predicts that survivors are mildly hypothermic and depend strongly on shivering (3 times the resting metabolic rate) to maintain thermal balance. It is unknown if such level of shivering could be maintained for prolonged cold exposure.
3. The numerical model predicts that a sleeping bag and tent would provide considerable protection for survivors. The predicted metabolic rate with shelter is roughly double the resting rate and triple the resting rate without protection from the wind.

CONCLUSIONS

1. MASSERT has successfully correlated thermal insulation values between human subjects and thermal manikins in liferafts and in immersion suits.
2. In lifeboats and liferafts, thermal protection and ventilation are related. With a model, it has been shown that a reasonable compromise is achievable between these two variables.
3. The team has demonstrated the value of manikins as an evaluation tool, as well as the value of numerical models as prediction tools in setting new standards for protective equipment as well as for SAR planning. System insulation values coupled with models can give reasonable predictions of survival time when hypothermia is a limiting factor.
4. In the liferaft project, one possible presentation of thermal protection criteria has been presented, which can be adopted for the Arctic.
5. To better understand Arctic survival requirements, we need to measure thermal protection of available equipment; determine the maximum long-term sustainable metabolic rate; identify minimum thermal protection required; and identify gaps between current and proposed thermal protection.

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