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Thermal Protection in Inflatable Liferafts – Human and Thermal Manikin Testing to Quantify Training Issues, Assess Occupant Heat Balance and Develop Performance Criteria

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ABSTRACT

Inflatable liferafts are used worldwide as a means of evacuation and survival from almost all ocean-going vessels, regardless of their size, purpose or region of operation. Vessel size ranges from fishing and other commercial vessels with small crews to offshore oil installations and passenger ships with thousands of persons onboard. While International Maritime Organisation (IMO) standards currently require inflatable liferaft components to “provide insulation” or “be sufficiently insulated”, no performance criteria accompany these requirements. This paper will outline the methodology and results from a three year research project involving a multidisciplinary team which utilised human subjects and a thermally instrumented manikin to investigate the gaps in knowledge for the thermal performance of inflatable liferafts in cold environments. Tests were conducted in a controlled laboratory environment with a 16 person SOLAS-approved liferaft and air and water temperatures as cold as 5°C. The main variables investigated were clothing wetness (wet and dry) and liferaft floor insulation (insulated and uninsulated).

The project’s four main objectives were to: 1) develop thermal protection criteria for inflatable liferafts assuming otherwise unprotected occupants, 2) propose an objective methodology for testing inflatable liferaft thermal protection performance, 3) develop tools for search and rescue planners to predict survival times of liferaft occupants and 4) provide guidance to training authorities and manufacturers.

The study found that: 1) the thermal insulation of a combined system of clothing and liferaft using a thermal manikin gave good agreement with measurements using humans, as long as proper corrections for differences between manikin and humans are appropriately applied, 2) system insulation values coupled with a cold exposure survival model can be expected to give search and rescue planners reasonable predictions of survival time in liferafts where hypothermia is the main risk factor and 3) the factors substantially affecting the survival time of liferaft occupants are: whether any type of thermal protective aid (TPA) is worn, clothing wetness, liferaft floor insulation and liferaft ventilation rate.

INTRODUCTION

Inflatable liferafts are found worldwide on virtually all passenger, fishing and commercial vessels, as well as onboard helicopters and on offshore oil installations. In a passenger ship abandonment situation in cold water, passengers may be wearing very little personal protective clothing. Therefore, liferafts provide the only significant thermal protection against the cold ocean environment while survivors await rescue. Depending on the geographical location, search and rescue assets available, weather and ocean conditions, a survival time of several days may be required before rescue occurs. In such conditions, the young, old, weak and injured are particularly vulnerable. Thus, for vessels operating in cold bodies of water such as the frigid North Atlantic, the thermal protection offered by liferafts is very important to ensure survival, in the event of abandonment.

Currently, the IMO does not provide any specific thermal protection performance criteria for SOLAS-approved liferafts in the LSA Code (IMO, 1997). Unfortunately, without such thermal protection performance criteria, it is difficult, in practice, to select and test survival equipment to determine its suitability for use in various cold ocean environments. Similarly, in the absence of thermal protection performance criteria, the comparative evaluation of equipment is not supported and certification of survival equipment is impossible. Furthermore, the provision of thermal protective aids (TPAs) may only be supplied for 10% of a survival craft’s rated complement (IMO 1997). This paper outlines a 2.5 year research project undertaken in Canada with a 16-person, commercially available SOLAS-approved liferaft to help address the knowledge gaps related to thermal protection in inflatable liferafts.

OBJECTIVES

The objectives of this research were to:

1. Develop thermal protection criteria for inflatable liferafts, assuming unprotected occupants in a passenger ship abandonment situation.
2. Propose an objective methodology for testing inflatable liferaft thermal protection performance.
3. Develop tools for search and rescue (SAR) planners to predict survival times of liferaft occupants.
4. Provide guidance to authorities and liferafts manufacturers on effective methods to meet the thermal protection criteria for inflatable liferafts.
5. Provide guidance to training authorities and providers on the knowledge and skills required to optimise the thermal protection provided by liferafts.

METHODOLOGY

The project was composed of multiple phases of experimentation, which were conducted in the controlled test environment of the National Research Council Canada, Institute for Ocean Technology (NRC-IOT) in St. John's, Newfoundland & Labrador, Canada (Figure 1). The differences among the various phases are summarised in Table 1.

Phase 1 testing consisted of a one-week pilot experiment aimed at better understanding the sensitivity of occupant and liferaft heat loss to the various environmental and equipment variables under the control of the project team. Phase 1 also provided an opportunity to validate the proper functioning of all equipment and to collect data for preliminary investigation. The primary focus was to assess heat loss from direct contact with the raft floor through conduction. The air temperature and water temperature were 19ºC and 16ºC respectively.

Phase 2 was designed to assess occupant heat loss and liferaft thermal protection in mild cold (19ºC air temperature and 16ºC water temperature) conditions. Similarly, Phase 3 was designed to assess the effect of more extreme cold conditions (5ºC air temperature and 5ºC water temperature). Testing in Phases 1 and 2 used only human subjects, while Phase 3included a mixture of human subjects and a thermal manikin.

Figure 1 Liferaft setup between the towing carriage and the service carriage at NRC-IOT

Based on the results of Phases 1 and 2, the tests in Phase 3 were designed to allow the research team to focus on assessing the effects of floor insulation (inflated or uninflated) and clothing wetness (dry or wet). The tests used to characterise human thermal and metabolic rate response and to compare thermal insulation values between human subjects and manikin included four baseline cases:

1. Inflated raft floor; dry clothing (Idry)
2. Inflated raft floor; wet clothing (Iwet)
3. Uninflated raft floor; dry clothing (Udry)
4. Uninflated raft floor; wet clothing (Uwet)

Eight instrumented primary human subjects (five males and three females) were exposed in pairs to the above four randomly assigned conditions inside the raft. Basic primary subject characteristics are provided in Table 2. Primary subjects were those instrumented to provide the necessary detailed data for the study. Secondary subjects represented additional occupants of the liferaft who are there to create the microclimate inside the raft. A matrix of baseline and special case tests using human subjects and the thermal manikin is given in Table 3.

Table 1 Test program environmental conditions

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

Human subject tests in Phase 3 varied from 4 to 8 hours in duration depending on how long the subjects felt capable of remaining in the cold environment inside the raft or if their core body temperature dropped to a pre-determined level below their starting point. Each human subject baseline test was repeated eight times and the average insulation values were compared to those of from the thermal manikin. The order of conditions was randomised for each pair of subjects.

Thermal manikin tests lasted approximately 1 hour 15 min each. The manikin was dressed in the same clothing ensemble as the human subjects and then positioned inside the liferaft. The manikin was operated in constant temperature control mode in which the set point temperature of each zone was specified at 20ºC. The manikin test was terminated when it reached steady state, with surface temperatures of each zone steady around their set points and average heat flux was constant.

Table 2 Subject data (mean±standard deviation)

Age [years]	26.3 ± 6.1
Weight [kg]	84.4 ± 18.5
Height [cm]	176.0 ± 9.7
Body fat [%]	23.69 ± 9.10
Surface area [m^2]	2.04 ± 0.27

Table 3 Test Matrix

Nomenclature ✓ = Test conducted R = Repeat test conducted **Tests**	Inflated Floor; Dry Clothing (Idry)	Inflated Floor; Wet Clothing (Iwet)	Uninflated Floor; Dry Clothing (Udry)	Uninflated Floor; Wet Clothing (Uwet)
Human subjects with lifejacket (baseline cases)	✓, R	✓, R	✓, R	✓, R
Manikin with lifejacket (baseline cases)	✓	✓	✓, R	✓, R
Human subject with TPA from manufacturer 1				✓
Manikin with TPA from manufacturer 1	✓	✓	✓	✓
Manikin with TPA from manufacturer 2				✓
Manikin sitting on an inflatable pillow	✓			
Manikin sitting on his own lifejacket	✓			✓
Manikin with lifejacket sitting on a second lifejacket			✓	
Manikin sitting on insulated floor sample from manufacturer A - a ***closed cell foam with aluminised layer*** is placed on top of the inflatable raft floor, either inflated or uninflated as indicated.	✓		✓	✓
Manikin sitting on insulated floor sample from manufacturer B - ***a heavy duty bubble wrap sheet with aluminised layer*** is placed on top of the inflatable raft floor, either inflated or uninflated as indicated.			✓	✓
Manikin with one piece neoprene wet suit (3mm thick)	✓	✓	✓	✓
Human subject with lifejacket sitting in 10 cm of water		✓		
Manikin with lifejacket sitting in 10 cm of water		✓		

The focus of this paper is on the overall test programme results from the standpoint of providing guidance to training authorities and training providers regarding the knowledge and skills required to optimise the thermal protection provided by liferafts. For a more in-depth presentation of project methodology and results, the reader is referred to Mak et al. (2009), Mak et al. (2008), Cahill et al. (2008) and DuCharme et al. (2007).

INSTRUMENTATION

A wide range of complex instrumentation and computerised data acquisition systems were used to collect the test data in this project as outlined below under the headings Human Subjects, Liferaft and Manikin:

Human Subjects (Figure 2):

- The heart rate of the primary human subjects was logged every 5 seconds using a heart rate monitor which transmitted data to a wrist-based logger wirelessly.
- Thirteen heat flow sensors were used on each of the primary human subjects.
- Oxygen consumption, carbon dioxide output, minute ventilation, and respiratory exchange ratio were continuously recorded with two automated breath-by-breath systems.
- Core body temperatures of the primary and secondary human subjects were recorded using tympanic and rectal probes

Liferaft:

- Five heat flow sensors on the floor
- Four heat flow sensors on the floatation chambers
- Four heat flow sensors on the canopy
- A carbon dioxide sensor
- Two wind sensors
- Two air temperature sensors
- Pressure sensors for raft floatation tube and floor
- Two infrared video cameras
- One wind sensor outside the raft
- Two water temperature sensors

Figure 2 Heat flow sensor locations on primary human subject (left) and primary subject dressed in clothing ensemble, wearing breath-by-breath metabolic system.

Thermal Manikin:

A 23-zone submersible thermal manikin (Figure 3) manufactured by Measurement Technology Northwest (Seattle, Washington, USA) was used in this study. Its stature represents a 50th percentile adult North American male, weighting 71 kg. The manikin shell is made of aluminum. Each thermal zone is isolated thermally from each other and equipped with heaters to generate uniform heating of the aluminum shell and two precision thermistors to measure skin temperature.

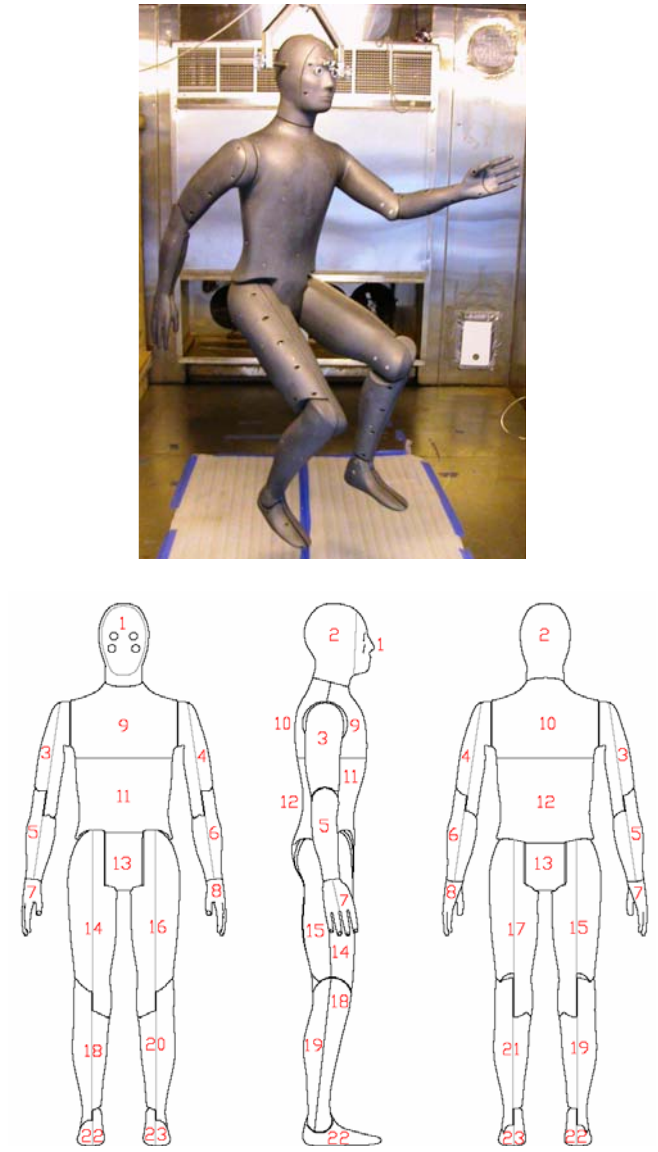

Figure 3 23-zone submersible thermal manikin zones

RESULTS AND DISCUSSION

The overall thermal insulation values for various manikin tests in Phase 3 are shown in Table 4. The results show that:

- The two repeatability tests demonstrated that the thermal manikin results are repeatable for both Udry and Uwet
- Insulation provided by closed foam and bubble wrap floors are comparable to that provided by the inflatable floor.
- Use of a TPA provided considerable additional insulation compared to all baseline cases. The insulation increased most considerably in wet clothing cases (an increase of 61% and 54% in Iwet and Uwet cases respectively). A test with a human subject wearing a TPA in the Uwet case showed an improvement of 48% over the baseline case.
- TPA provided more additional insulation than the wet suit in all cases except the Udry case.
- In the Idry case, the best scenario, the insulation obtained by sitting on an inflatable pillow (0.243 (m^2°C)/W) or a lifejacket (0.241 (m^2°C)/W) is comparable

to sitting directly on an inflated floor (0.236 (m^2°C)/W) or closed cell foam floor (0.236 (m^2°C)/W).

- In the Uwet case, the worst scenario, the insulation obtained by sitting on a lifejacket (0.149 (m^2°C)/W) is less than wearing a TPA (0.158 (m^2°C)/W). Both of these are better than sitting directly on an uninflated floor (0.104 (m^2°C)/W) or a closed cell foam floor (0.129 (m^2°C)/W).
- There is a significant decrease in insulation value sitting in 10 cm of water (0.05 (m^2°C)/W). Two human subject tests show an insulation value of 0.079 (m^2°C)/W and 0.081 (m^2°C)/W respectively (A number of special test cases were explored with a thermal manikin. A limited number of human subjects were also used in some special test cases. The human subject results may not be representative of the general population)
- Comparing the insulation value measured using human subjects with that from the thermal manikin indicates good agreement (DuCharme et al., 2008). The results are summarised in Table 5.

Based on test results, a mathematical model was developed to predict the transport of heat from liferaft occupants through their clothing to the liferaft and hence to the external air and water (Farnworth, 2009). The various heat transfer coefficients were derived from measurements of heat flow with heat flow transducers on the subjects, on the raft canopy, chambers and floor, and from manikin results. The model also takes into account the effect of number of occupants and raft ventilation rate on the interior raft air temperature. This model of the clothing and raft was interfaced to the Cold Exposure Survival Model of Tikuisis (2005).

Predictions of the combined model and measurements on the human subjects were compared after 4h of exposure in the raft with generally good agreement. The quantity that is most important for the prediction of survival is the increase in metabolic rate because of shivering. This increased heat production enables victims to achieve a stable body temperature despite a high heat loss. The model predicts a functional time (FT), defined as the time for core temperature to drop to 34°C, and a survival time (ST), defined as the time for core temperature to drop to 28°C.

The comparison of metabolic rates estimated from the model and measured from the human subject experiments is shown in Figure 4. While the agreement is not exact (deviations are from 1 to 15%), the results indicate that the model can be expected to give reasonable predictions of ST and FT. In Figure 4, the four points from left to right represents the four cases, Uwet, Udry, Iwet and Idry, respectively.

Table 4 Manikin system thermal insulation values

Tests	Inflated Floor; Dry Clothing (Idry)	Inflated Floor; Wet Clothing (Iwet)	Uninflated Floor; Dry Clothing (Udry)	Uninflated Floor; Wet Clothing (Uwet)
	[(m^2°C)/W]			
Manikin with lifejacket (baseline cases)	0.236	0.146	0.177	0.101
			0.171	0.104
Manikin with TPA from manufacturer 1	0.334	0.235	0.204	0.158
Manikin with TPA from manufacturer 2	--	--	--	0.149
Manikin sitting on an inflatable pillow	0.243	--	--	--
Manikin sitting on his own lifejacket	0.241	--	--	0.149
Manikin with lifejacket sitting on a second lifejacket	--	--	0.244	--
Manikin sitting on insulated floor sample from manufacturer A - a ***closed cell foam with aluminised layer*** is placed on top of the inflatable raft floor, either inflated or uninflated as indicated.	0.225	--	0.221	0.124
Manikin sitting on insulated floor sample from manufacturer B - ***a heavy duty bubble wrap sheet with aluminised layer*** is placed on top of the inflatable raft floor, either inflated or uninflated as indicated.	--	--	0.236	0.129
Manikin with one piece neoprene wet suit (3 mm thick)	0.264	0.227	0.236	0.155
Manikin with lifejacket sitting in 10 cm of water	--	0.050	--	--

Table 5 System insulation values derived from manikin and human subject experiments

Tests	Inflated Floor; Dry Clothing (Idry)	Inflated Floor; Wet Clothing (Iwet)	Uninflated Floor; Dry Clothing (Udry)	Uninflated Floor; Wet Clothing (Uwet)
	[(m^2°C)/W]			
Manikin with lifejacket (baseline cases)	0.236	0.146	0.177	0.101
			0.171	0.104
Human subjects average (baseline cases)	0.224 ±0.023	0.145 ±0.017	0.185 ±0.022	0.116 ±0.006

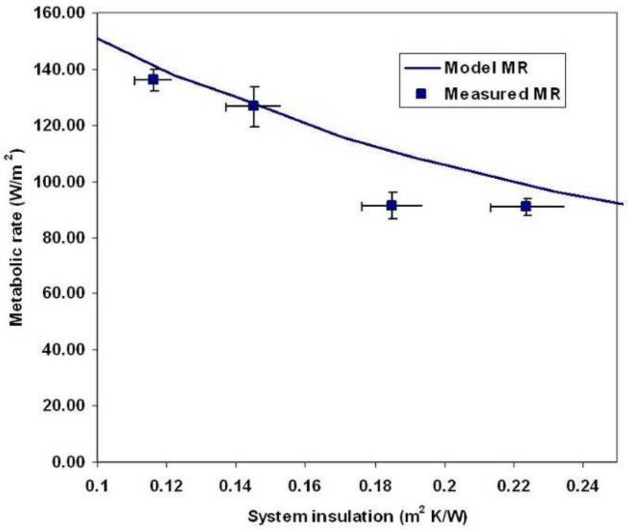

Figure 4 Comparison of the metabolic rates (MR) estimated from the experimental data and predicted by the model as a function of system thermal insulation

The impact of various clothing and raft properties and environmental conditions on ST and FT was studied with a combination of manikin measurements and model predictions. Unfortunately, the model does not make predictions beyond 36h since the uncertainties become too great at longer times. The resulting data are presented in Figure 5 as the combination of environmental temperature and system thermal insulation that will give ST for FT of at least 36h.

In Figure 5, the horizontal lines represent the system insulation values required for ST or FT of 36h at external raft temperatures (average of air and water) from -10 to +20°C. Vertical bars represent the insulation values measured in experiments with the thermal manikin under various conditions ranging from wet clothing with 10 cm of water on the raft floor (inflated) up to dry clothing plus a thermal protective aid (TPA) and an inflated floor. In the Figure, if the top of a vertical bar is above a horizontal line, then it can be expected that the ST or FT will be longer than 36h at the temperature corresponding to that line. These results pictorially show the importance to keep dry, the value of TPA and the value of floor insulation.

In addition, model predictions were made to quantify the effect of the number of occupants in the liferaft and the liferaft ventilation rate on ST. In Figure 6, the minimum ambient temperature for 36h ST is shown for conditions of either 3 or 16 occupants of a 16-person raft and either the minimum ventilation rate needed to keep the carbon dioxide level in the raft below 5000ppm or eight times that rate. As can be seen, number of occupants can substantially affect survival time if the ventilation rate is controlled, but has no effect at a high ventilation rate.

Key to the x-axis labels for Figure 5:

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 3mm neoprene wetsuit
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

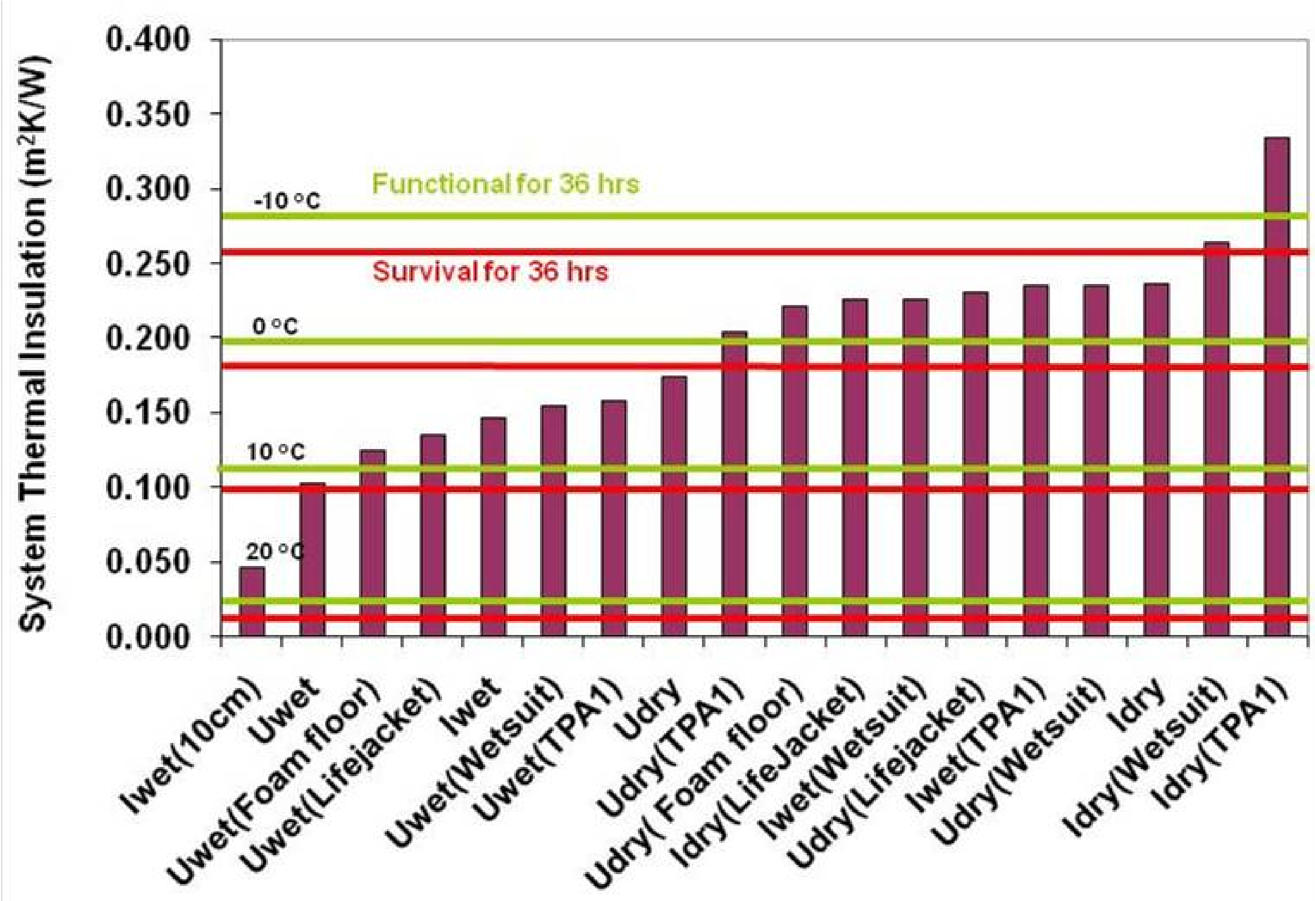

Figure 5 System thermal insulation required for functional and survival time of 36 h at various temperatures (horizontal lines) compared to values measured with a thermal manikin (vertical bars). For a description of what the x-axis labels mean, refer to the key presented on the preceding page.

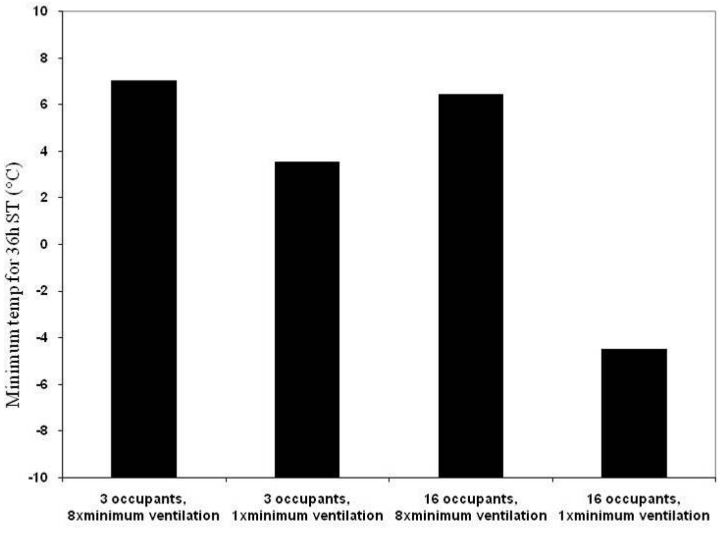

Figure 6 Comparison of ventilation rates and number of liferaft occupants on survival time

GUIDANCE FOR TRAINING

Based on the research findings of this project, a review of the training element was conducted by:

- reviewing current training standards related to liferaft use in cold environments,
- analysing training needs to determine how occupant actions can improve survival in cold environments, and
- identifying the training needs required to provide essential knowledge and build critical skills relating to the performance issues examined.

Review Current Training Standards:

International and Canadian standards were reviewed as they relate to survival in liferafts:

- Standards of Training, Certification and Watchkeeping, 1995 Amendment (STCW '95)
- Transport Canada Marine Emergency Duties Training Standards (MED)
- Canadian Association of Petroleum Producers Training and Qualifications Guidelines (CAPP-T&Q)
- Safety of Life at Sea (SOLAS)
- Offshore Petroleum Industry Training Organisation (OPITO)

Considerable training competencies exist in the regulations for general survival, including in liferafts. However, little or no guidance is provided on training competencies for survival in liferafts in cold environments, except as outlined in the sections presented in Table 6.

Table 6 Existing guidance in training standards for liferaft use in cold environments

Transport Canada MED Training Programme – TP4957E(1998)		
Course	**Syllabus Section**	**Instruction & Competency Requirements**
MED-A1 Basic Safety Course (Section 5)	Syllabus Section 6: Survival	- 3 hours instruction to cover aspects of survival ranging from immersion in water to abandonment in lifeboats (open and closed) and liferafts - Only specific reference to thermal considerations is to discuss “Medical aspects of survival including thermal balance, water balance and energy balance” - Competency assessed in writing, orally and by practical demonstration
MED-A2 Small Passenger-Carrying Vessel Safety Course (Section 6)	Syllabus Section 6: Survival	
STCW Basic Safety Course (Section 10)	Syllabus Section 9: Survival	
Proficiency in Survival Craft and Rescue Boats other than Fast Rescue Boats Course (Section 11)	Syllabus Section 3: Principles of Survival	- 0.75 hours instruction to cover principles of survival ranging from the need for regular onboard drills to abandonment and survival - Only specific reference to thermal considerations is to note that an “immersion suit or thermal protective aid must be worn if required”
	Syllabus Section 4: Use of Personal Survival Equipment	- 3 hours of practical instruction including: - “unpack and don a thermal protective aid in a liferaft/lifeboat” - “put a thermal protective aid on a person simulating unconsciousness in a liferaft/lifeboat”

Analyse Training Needs:

In the context of this project, two main gaps exist in the regulations:

1) Performance gap – this exists in the engineering domain and refers to the lack of knowledge of how the liferaft will perform thermally in a given set of environmental conditions.
2) Knowledge/skills gap – this exists in the training domain and refers to the lack of useful characterisation of the magnitude of risk to life safety from a thermal standpoint.

While SOLAS regulations require liferafts to have an insulated floor, the level of insulation required to adequately protect occupants is not specified. One may ask if training occupants and operators will overcome liferaft thermal performance design issues. Research results from this project have quantified the important factors that could help in the training of persons who might be required to survive or help others survive in a liferaft at sea. It is safe to assume that even without a basic understanding of the mechanisms of heat loss in liferafts, users will try to attain thermal comfort in order to survive. However, with an understanding of the relative importance of the different heat loss mechanisms and what can be done on an individual level, chances of survival would certainly be improved.

Identify Training Needs:

Based on the research findings for the specific areas identified in the previous section, the strategy provided in Figure 7 is recommended for use by trainers of liferaft users to ensure the best chance of survival in cold conditions. While Figure 7 presents little new information for maritime personnel or trainers with a basic understanding of survival in cold environments, from a training perspective, it does give an indication the *magnitude* of the benefit provided by each of the different strategies presented.

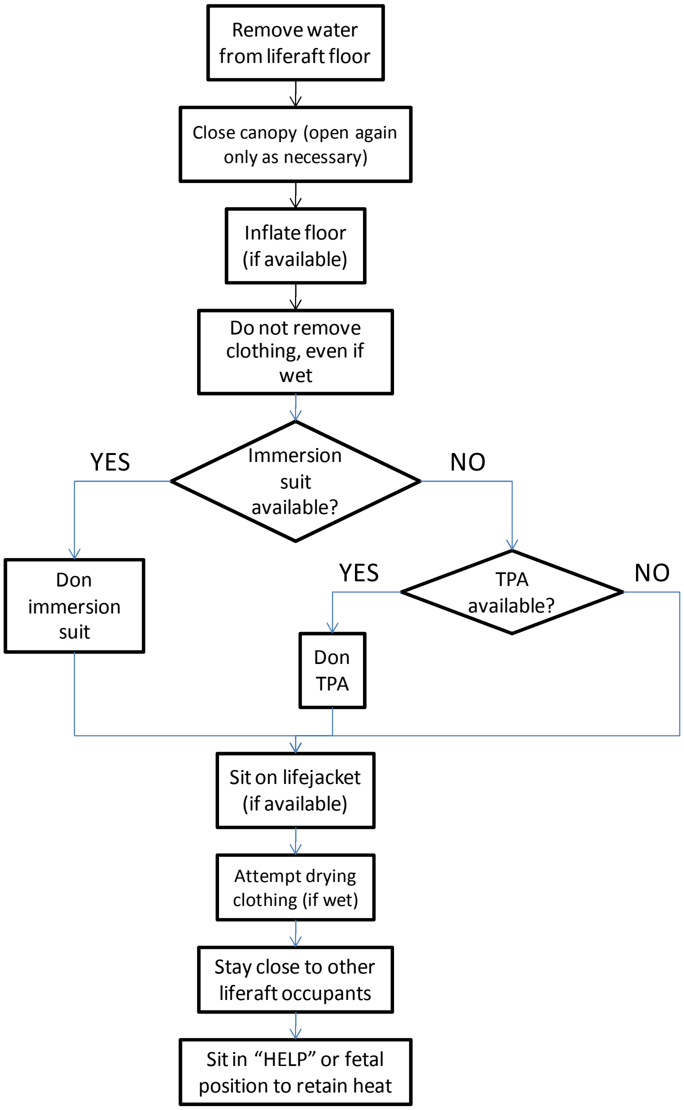

Figure 7 Recommended strategy for training guidance on survival in liferafts in cold environments

Based on the data presented above from experiments and modelling, it is clear that being dry inside a liferaft is of the utmost importance to ensure survival for 36h in temperatures below freezing. In such conditions, 80% of the cases where the model predicts functional survival is possible require the strategy to include being dry. The other main strategies that contribute significantly to ensuring functional survival in such conditions are: adding an insulating barrier between the occupant and the liferaft floor in direct contact with the ocean (80% of strategies include insulation of some type), and wearing some sort of thermal protective aid (60% of strategies include some type of TPA).

CONCLUSIONS AND RECOMMENDATIONS

The conclusions of the study are:

1. Manikin measurements of the thermal insulation of a combined system of clothing and liferaft give good agreement with measurements on humans.
2. System insulation values coupled with a Cold Exposure Survival Model can be expected to give reasonable predictions of survival time in liferafts where hypothermia is a limitation.
3. Liferaft system insulation can be measured with a thermal manikin.
4. Factors which substantially affect the survival time are:
    - Wearing of a TPA
    - Clothing wetness
    - Raft floor insulation
    - Raft ventilation rate
5. Results from this study have provided the following recommendations for improvements in liferaft standards and design:
    - Rafts should include a TPA for every occupant
    - Rafts should include a system to keep the floor dry or enable every occupant to sit above the level of the water on the floor.
    - Raft floors should be insulated or every occupant should be able to sit on an insulated surface.
    - Rafts should have a mechanism for controlling ventilation to a level, which is adequate for breathing but which will allow raft internal temperature to rise.
6. Current training standards provide minimal focus on the importance of thermal consideration when surviving in liferafts.

Based on the findings of this research, it is recommended that training standards and practice be revised to include some of the details presented herein. This should be specifically in the form of the level of importance of the different strategies to help liferaft occupants attain heat balance in cold survival situations.

ACKNOWLEDGEMENT

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