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Thermal requirements for surviving a mass rescue incident in the Arctic phase 1 test report - thermal resistance tests on clothing ensembles with thermal manikins & preliminary modeling

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Thermal Requirements for Surviving a Mass Rescue Incident in the Arctic
Phase 1 Test Report - Thermal Resistance Tests on Clothing Ensembles with Thermal Manikins & Preliminary Modeling

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SUMMARY

Maritime and air traffic through the Arctic has increased in recent years. Cruise ship and commercial jet liners carry a large number of passengers. With increased traffic, there is a higher probability that a major disaster could occur. Cruise ship and plane accidents could be catastrophic and may require mass rescue. Due to the remote location, limited search and rescue resources, time for these resources to get to the accident location and large number of survivors, the retrieval time could be several days. Therefore, survivors may be required to survive on their own for days while they await rescue.

Recognizing that the International Maritime Organization does not have specific thermal performance criteria for liferafts and lifeboats and personal and group survival kits, a team of researchers from 14 Canadian and international government agencies, universities, companies and regulatory authority initiated a research project to improve safety and provide input for advances to regulations. The objective of the project is to investigate if the current thermal protective equipment and preparedness available to people traveling 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. This project builds on the results and tools developed in other research projects conducted by the team on thermal protection of liferafts, lifeboats and immersion suits. The project is divided into three major phases – clothing ensemble testing with thermal manikins, a physiology experiment on sustainable shivering duration and ensemble testing in Arctic conditions with human subjects. A numerical model uses these data to simulate survival scenarios.

In the first phase of this project, the thermal resistance values of the protective clothing typically available to cruise ship and aircraft passengers were measured using two thermal manikins. The ensembles included Cabin Wear, Deck Wear, Expedition Wear, Abandonment Wear and protective clothing from Canada Forces Major Air Disaster Kit (MAJAID). Tests were conducted on dry and wet ensembles at 5°C and -15°C with and without wind.

There is very good agreement between the thermal resistances measured by the two manikins. The differences in thermal resistances observed are likely caused by variations in fit and wrinkles and folds in the ensembles from dressing. With no wind, the thermal resistance is lowest with Cabin Wear and highest with MAJAID clothing inside the down-filled casualty bag. The Expedition Wear, the Abandonment Wear and the MAJAID clothing have about the same thermal resistance. With 7 metre-per-second wind, the thermal resistance of all ensembles decreased significantly by 30% to 70%. These results highlight the importance of having a shelter as a windbreak. For wet clothing ensembles at 5°C, the initial wet thermal resistance was 2 to 2.5 times lower than the dry value, and drying times ranged up to 60 hours. This highlights the importance of staying dry.

Preliminary predictions from the numerical model show that the survivors in Expedition Wear, even with sleeping bag and tent, can be mildly hypothermic and need to depend heavily on shivering to maintain thermal balance. In a shelter, the predicted metabolic rate is roughly double the resting rate; it is triple the resting rate without protection from the wind.

Further research is required to study shivering fatigue and age effects. Research on mass rescue scenarios for cruise ships and airplanes survivors should ideally involve subjects of both genders and the elderly.

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Thermal Requirements for Surviving a Mass Rescue Incident in the Arctic
Phase 1 Test Report

Thermal Resistance Tests on Clothing Ensembles with Thermal Manikins
&
Preliminary Modeling

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1.0 Introduction

With increased maritime and air traffic, there is a higher probability that a major maritime or air disaster could occur, which would include, for example, disabling of a ship by collision, fires, loss of propulsion or machinery failure, the grounding or sinking of a ship, or a plane crash. An air or maritime disaster of this magnitude may require mass rescue.

The Government Consulting Group report (1991) suggested that the consensus of Arctic rescue would take 10 days (probable worst-case scenario) but could take twice as long for the worst-case scenario of mid-winter darkness coupled with bad weather. The International Maritime Organization (IMO) Sub-Committee on Radiocommunications and Search and Rescue (COMSAR) has proposed to extend the “time to recover” period to 5 days, which is the length of time beginning with the completion of the ship abandonment and ending when all persons have been recovered from survival craft into a 'place of safety' or a 'temporary place of safety' (IMO, 2006).

It takes the Canadian Forces more than a day to send Hercules aircraft and helicopters northward. The Coast Guard has icebreakers in Arctic waters during the summer but such vessels must rely on the assistance of private vessels (CBC News, 2008). At the 2008 Canadian Arctic Summit (CBC News, 2008b), US and Canadian officials as well as those of other Arctic nations are questioning their own abilities to handle cruise ship accidents. Such limitations highlight the importance of personal and group survival equipment to sustain survivors for days while they await rescue.

Under Canadian and international law, all large commercial vessels and passenger vessels are required to provide survival craft for the evacuation of passengers and crew should vessel abandonment be required. Survival Craft on Canadian ships comply with the Life Saving Regulations of the Canada Shipping Act and are generally certified to the requirements of the International Convention for the Safety of Life at Sea (SOLAS). The SOLAS standards for survival craft are set out by the IMO in the International Life-Saving Appliance (LSA) Code (Resolution MSC.48[66]) and Testing and Evaluation of Life-Saving Appliances (Resolution MSC.81[70]). Some of these performance goals address the protection of lifeboat occupants after evacuation as identified in the general requirement that such survival craft “…provide protection for its complement against wind, rain and spray, adequate ventilation and protection for its complement at all ambient temperatures between -15 ºC and +30 ºC” (IMO, 1983).

Similarly, for liferafts, the LSA Code specifies “the floor of the liferaft shall prevent the ingress of water and shall effectively support the occupants out of the water and insulate them from cold”. It also specifies that the canopy “shall provide insulation against heat and cold by means of either two layers of material separated by an air gap or other equally efficient means." (LSA, 2009).

Unfortunately, no specific thermal performance criteria are identified to support these general requirements for lifeboats and liferafts. Therefore, in the testing of survival craft, there is no meaningful assessment of thermal protection or ventilation. In addition, thermal protective aids (TPA) are provided only to 10% of the number of persons the liferaft is permitted to accommodate. (LSA, 2009).

IMO Guidelines for Ships Operating in Polar Waters (IMO, 2010) provided a list of equipment in the suggested personal and group survival kits. Again, no specific performance criteria are identified for the equipment in the personal and group survival kits. Also, the guideline is not compulsory and operators are not required to provide all the equipment in the survival kits.

2.0 Objectives, Scope and Limitation

The objective of this project is to investigate if the current thermal protective equipment and preparedness available to people traveling 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.

The sub-objectives include:

1. Measuring the thermal resistance of protective systems available to cruise ship and aircraft passengers.
2. Defining the minimum thermal resistance of protective systems required for a 5-day survival of a mass rescue scenario in the Arctic, assuming a sustained and adequate metabolic rate,
3. Identifying the thermal protective equipment and improvements required to meet the minimum requirements.
4. Identifying the level of preparedness of passengers and crew to survive a mass rescue operation in the Arctic.
5. Sharing information with industry, government agencies and training providers to ensure that thermal protection is recognized as a vital component in developing improved lifesaving appliances for vessels traveling in Polar waters.

In Phase 1 of the project, which is being reported here, 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, a thermal-physiological model was used to simulate typical survival scenarios. The preliminary results from Phase 1 are presented in this report.

3.0 Test Program

Ten clothing ensembles that could be worn by survivors after a cruise ship abandonment situation or a plane crash in the Arctic were tested at 5°C and -15°C in still air and 7 metre-per-second (m/s) wind in both dry and wet conditions. These environmental conditions are representative of the Canadian Arctic summer as reported in Alert, Eureka and Resolute (MEDS, 2009). Table 1 and 2 show the clothing ensembles and test matrix respectively.

Table 1. Clothing ensembles

Ensemble	Description
1 (CW)	Cabin Wear (Aircraft or cruise ship) Denim Jeans, 100% cotton long sleeve flannel shirt, 90% cotton socks (9% nylon + 1% Lycra Spandex), 100% cotton briefs, and Leather shoes.
2 (DW)	Deck Wear Cabin Wear plus long underwear (long sleeve shirt and pants), Soft pile fleece jacket and pants, and Water vapour permeable (WVP) jacket and pants.
3 (EW1)	Expedition Wear #1 Deck Wear with wool socks instead of cotton socks, Wool toque with fleece lining, Thinsulate mitts and - 40°C rubber boot with five-layer liner.
4 (EW2)	Expedition Wear #2 Expedition Wear #1 with weatherproof flotation suit instead of WVP jacket and pants.
5 (AW1a)	Abandonment Wear #1a Deck Wear with Thinsulate gloves instead of mitts, Wool socks instead of cotton socks, PU coated Nylon non-insulated immersion suit, and SOLAS Life Vest.
6 (AW1b)	Abandonment Wear #1b Deck Wear with Thinsulate gloves instead of mitts, Wool socks instead of cotton socks, Anti-exposure coverall, and SOLAS Life Vest.
7 (AW2)	Abandonment Wear #2 Deck Wear with Thinsulate gloves instead of mitts, Wool socks instead of cotton socks, and SOLAS Immersion Suit (don with only wool socks without footwear)
8 (MAJ1)	Canada Department of National Defence Major Air Disaster Kit #1 (MAJAID#1) Cabin wear without leather shoes, MAJAID parka, pants, mittens, toque, boots
9 (MAJ2a)	MAJAID#2a MAJAID#1 ensemble inside Down filled casualty bag
10 (MAJ2b)	MAJAID#2b MAJAID#1 ensemble inside synthetic filled casualty bag

Table 2. Test matrix

Ambient Temperature	Wind	Ensemble
5°C	0 m/s	1, 2, 3, 4, 5, 6, 7, 8, 9, 10 dry
5°C	0 m/s	1, 3, 8 wetted
5°C	7 m/s	1, 2, 3, 4, 5, 6, 7, 8, 9, 10 dry
5°C	7 m/s	1, 3, 8 wetted
-15°C	0 m/s	1, 3, 8 wetted

4.0 Thermal Manikins

Two thermal manikins were used in the study. The first was the submersible NEMO manikin owned by the National Research Council Canada, Institute for Ocean Technology (NRC-IOT). The second was The CORD Group's Thermal Immersion Manikin (TIM).

4.1 NEMO

NEMO is a 23-zone submersible thermal manikin designed by Measurement Technology Northwest (Seattle, Washington, USA). Its stature represents a 50th percentile adult North American male, weighting 71 kilograms with a surface are of 1.8 square metres. (Figures 1 and 2)

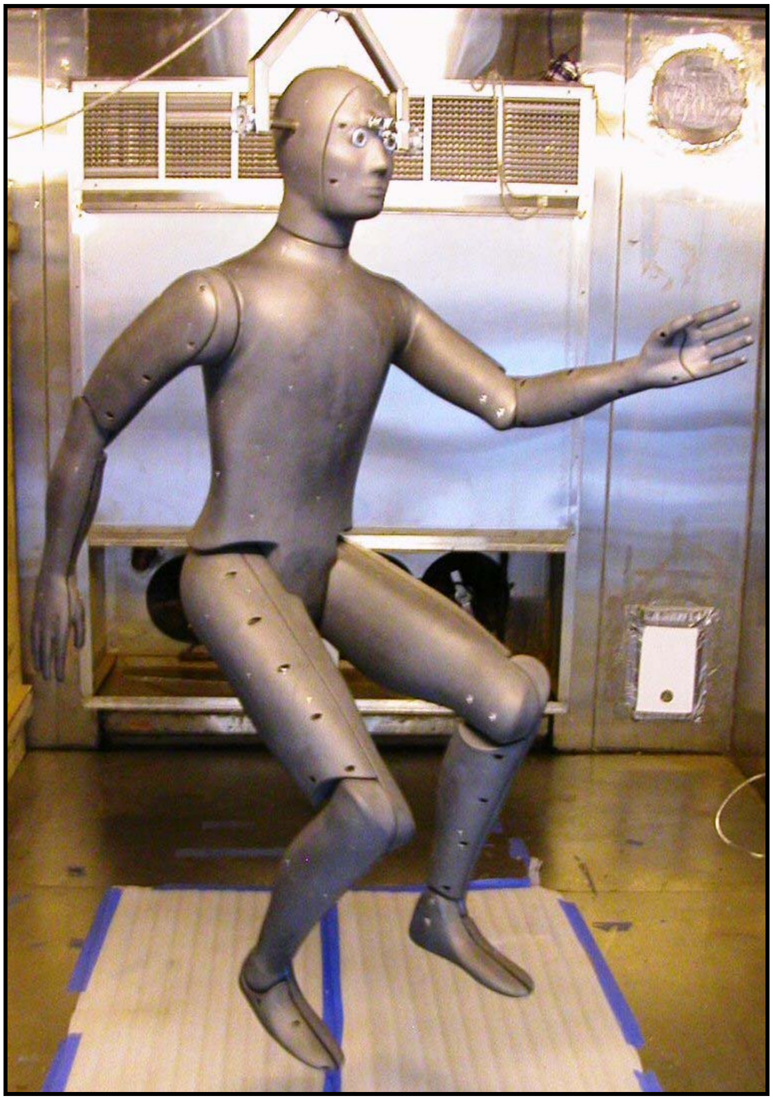

Figure 1. NEMO 23-zone submersible thermal manikin

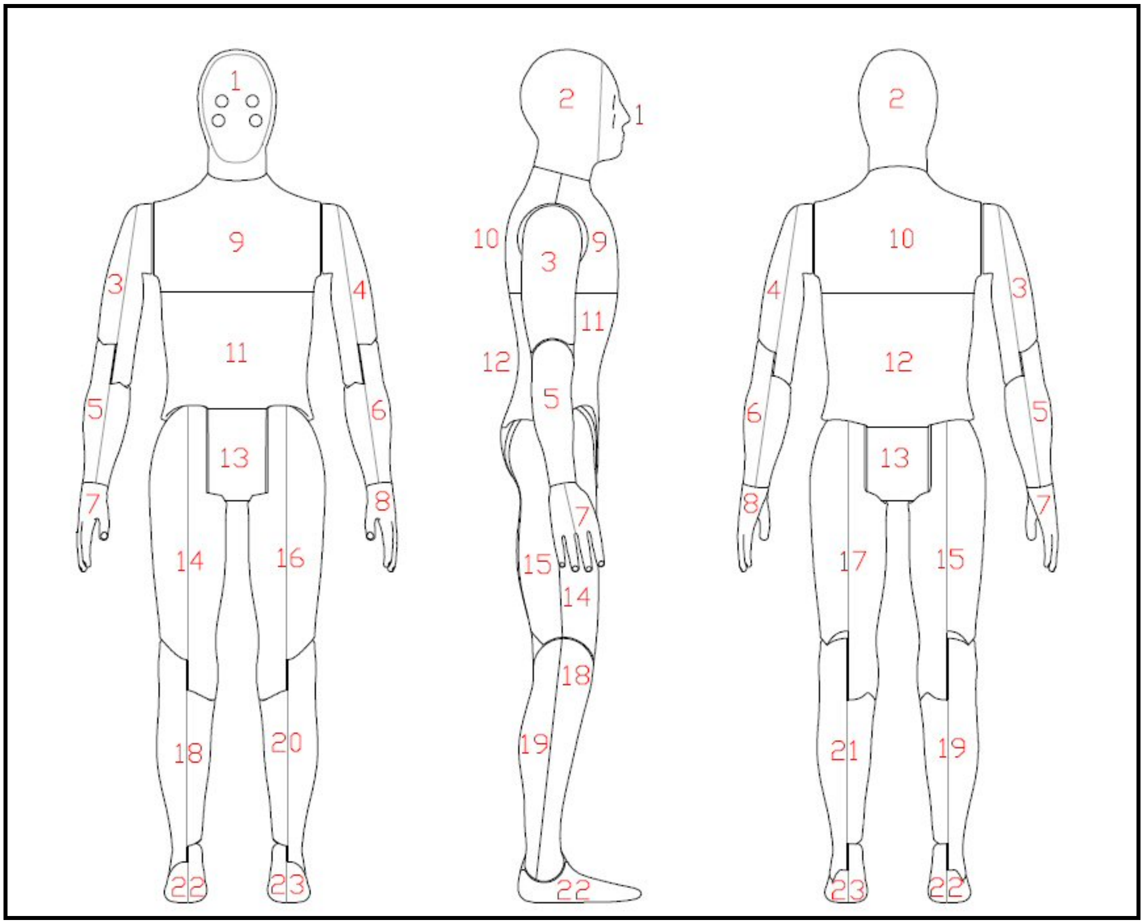

Figure 2. NEMO submersible thermal manikin zones

The main components of the manikin system include (Figure 3):

- the aluminium manikin shell equipped with heaters, sensors and internal controllers for regulation and monitoring,
- a power supply enclosure, which includes the heater power supply, ground isolation meter, serial data converter module, master zone controller, and an air pressure regulator,
- ambient sensors (relative humidity, wind speed and 2 temperature),
- electrical cabling and an air pressure supply hose and
- a laptop with ThermDAC control software.

The NEMO thermal manikin operates on 60-hertz electrical power at 200-250 volts AC with a maximum current of 20 amps. Each of its 23 thermal zones is equipped with a heater to generate uniform heating of the aluminium shell and two precision thermistors to measure skin temperature. The zones can be individually controlled using either a temperature control, constant heat flux or comfort equation output. The heaters are operated by ThermDAC control software, a 32-bit Windows-based program that controls, records and displays real-time zone information numerically and graphically.

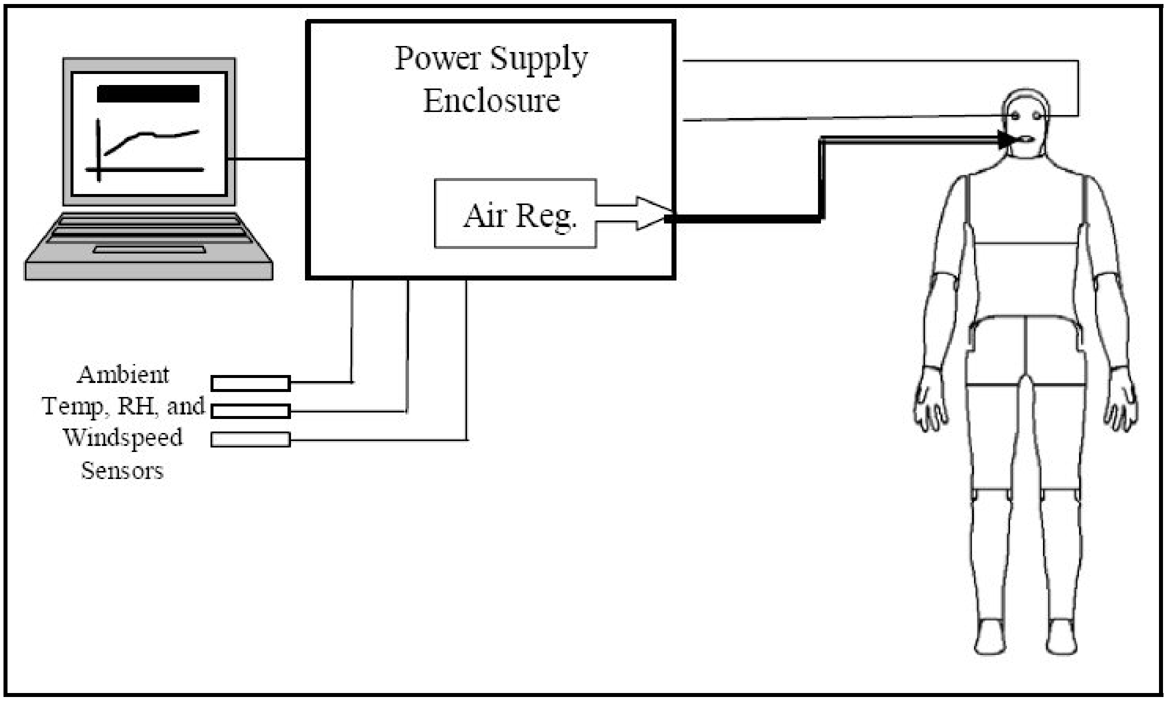

Figure 3. NEMO Thermal Manikin Block Diagram

4.2 TIM

The second submersible thermal manikin used in this study was TIM, manufactured by the CORD Group (Figures 4 and 5). TIM has 15 independently controlled zones, weights 94.5 kilograms and has a surface area of 1.8 square metres. The system consists of a hollow aluminum manikin equipped with temperature sensors and electric heaters connected to a computer system. The control module maintains and monitors uniform temperature over the manikin surface through sensors embedded in the manikin shell.

The control module houses the programmed data acquisition system, the heater relays and other circuit components. The data acquisition system receives data from the temperature sensors on the manikin and controls the heater relays so the manikin surface temperature remains constant. It also measures the environment temperature and the power applied to the manikin; it is programmed with the surface area measurements of the manikin. With this temperature, power and area data, it calculates the insulation value of the garment and passes this, along with other pertinent data, to the computer.

The computer acts as a control and display terminal and post-processor. The computer controls the internal heaters to maintain the skin of the manikin at a set temperature and measures the electrical power required to do so. The control software features a windows interface, menu-driven hardware parameter setup and system calibration, an auto-diagnostics function and scientific-quality real-time graphics capability.

Specifications

MANIKIN

Manikin sections:

1 - Head
2 - Chest
3 - Back
4 - Left Arm
5 - Right Arm
6 - Left Hand
7 - Right Hand
8 - Abdomen
9 - Buttocks
10 - Left Thigh
11 - Right Thigh
12 - Left Calf
13 - Right Calf
14 - Left Foot
15 - Right Foot

Surface area: 1.8 ± 0.1 m^2 (19.4 ± 1 ft^2) including section dividers

Arm and leg joints: single-axis rotatable

Immersion depth: 1.8 m (6 ft)

Dimensions (±1/2"):

- Height: 1778 mm (70")
- Shoulder height (arm pivot to heel): 1387 mm (54.6")
- Arm length (shoulder pivot to wrist pivot): 533 mm (21")
- Leg length (hip pivot to heel): 930 mm (36.6")
- Crotch height: 833 mm (32.8")
- Circumference at shoulders: 1321 mm (52")
- Circumference around hands, abdomen and buttocks with arms at the sides: 1524 mm (60")

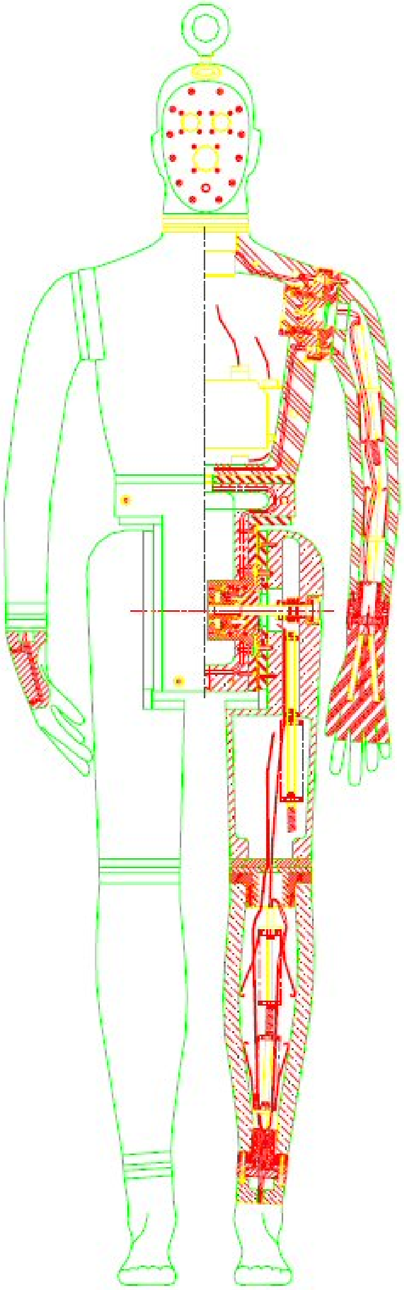

Figure 4. TIM 15-zone submersible thermal manikin

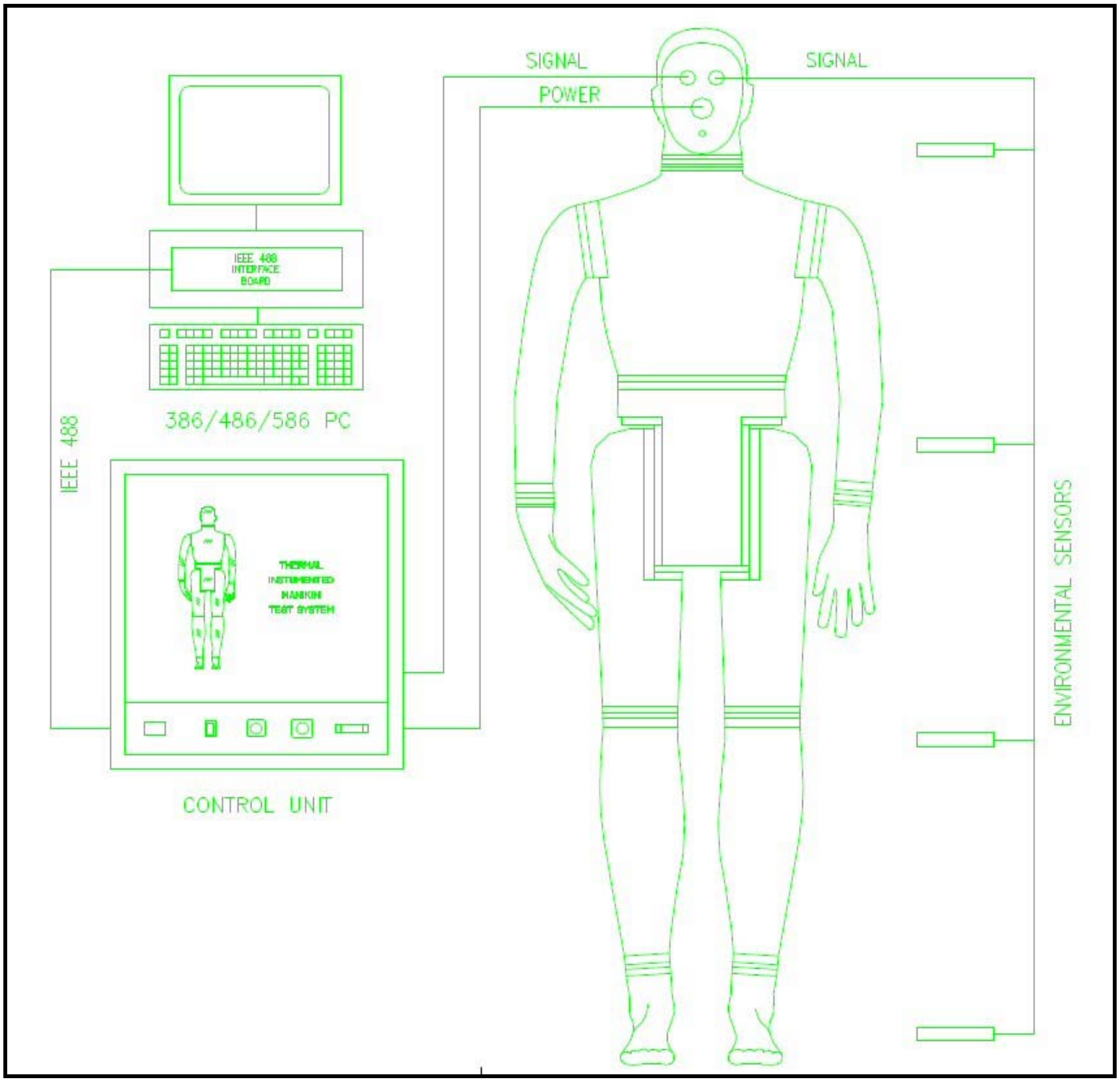

Figure 5. TIM Thermal Manikin General Setup

5.0 Experimental Facilities and Setup

The experiments were conducted in the CORD Group wind tunnel facility (Figure 6), and the Temperature/Humidity Chamber of the Environmental Simulation Labs of Composites Atlantic Limited in Dartmouth, Nova Scotia.

Figure 6. CORD Group wind tunnel facility

In the wind tunnel, tests were conducted in still air and with a wind speed of 7 m/s. The air temperature was not controlled and varies with the outdoor temperature between 5°C and 9°C. This does not affect the thermal resistance values calculated from thermal manikin measurements because thermal resistance is computed from temperature difference not absolute temperature. An anemometer was placed just in front of and between the two manikins. The two temperature sensors of TIM manikin were placed in between the manikins, while the two temperature sensors of NEMO manikin were place above it.

The Temperature/Humidity Chamber of Composites Atlantic Limited was manufactured by the Elliott-Williams Company Ltd. of Indianapolis (Figure 7). This chamber can achieve temperatures between -73°C and +85°C with relative humidity between 20% and 95%. Tests were conducted in the environmental chamber at -15°C. The two manikins were set up similarly in the chamber as they were in the wind tunnel.

Figure 7. Temperature / Humidity Chamber

6.0 Methodology

A thermal manikin is a means of evaluating insulation of protective clothing. The manikin is dressed in the clothing ensemble to be tested and placed in the test environment. The computer controls the heaters to maintain the manikin skin temperature and measures the electrical power required to do so. This power is equivalent to the heat loss through the clothing to the environment due to the temperature gradient.

The manikin constant temperature control mode was used in all the tests. The set point temperature of each zone was specified at 30ºC except in conditions where this set point temperature could not be attained (i.e., in extreme cold, wet or high wind conditions). In these cases, the set point temperature was set to the highest skin temperature that all zones of the manikin could consistently maintain. In all cases, the temperature difference between the manikin skin temperature and the environment was at least 10ºC. In most cases, the temperature difference was 25ºC.

The thermal manikin test was terminated when steady state was reached, with average surface temperatures of all zones steady within 0.005ºC of the set point temperature and constant average heat flux within a standard deviation of less than 0.2 watts per square metre (W/m^2) for 30 consecutive minutes. The last 30 minutes of steady state data was used to compute thermal resistance.

The zone thermal resistance and the overall thermal resistance were calculated using the parallel method, as shown in Equations 1 and 2 respectively.

$$R_i = \frac{(T_{skin} - T_{amb})}{Q/A} \qquad \text{Equation 1}$$

where

R_i = Zone thermal resistance
T_{skin} = Zone average temperature
T_{amb} = Ambient temperature
Q/A = Area weighted heat flux

$$R_{wtd}(parallel) = \frac{1}{\Sigma(A_i/(A_{tot}R_i))} \qquad \text{Equation 2}$$

where

R_{wtd}(parallel) = Thermal resistance calculated using the parallel method
R_i = Zone resistance
Ai = Zone surface area
A_{tot} = Total surface area

6.1 Manikin Setup Procedure in Dry Tests

The manikin was dressed in the required clothing ensemble. All zipper, closures, cinch straps and attachments including hoods were closed and secured. The manikin was hung on underarm hooks so that the manikin was standing upright with the feet firmly touching the floor. The environmental sensors were positioned around the manikin. The manikin was set to the set point temperature and the test begun.

6.2 Manikin Setup Procedure in Wet Tests

The manikin was dressed in the required clothing ensemble. All zipper, closures, cinch straps and attachments including hoods were closed and secured. The manikin was lifted by the head and lowered into a water tank to the neck level such that all of the clothing was submerged. After 1 minute of immersion, the manikin was hoisted fully out of the water and the footwear was removed. The clothing was allowed to drain for 5 minutes. At the end of the 5 minutes, the footwear was put back on the manikin. The toque was dipped in water, lightly wrung out and placed on the manikin head. The environmental sensors were positioned around the manikin. The manikin was set to the set point temperature and the test begun.

6.3 Casualty Bag Tests

When testing Ensembles 9 and 10 with casualty bags from MAJAID kit, our test method did not follow ASTM F1720-06 “Standard Test Method for Measuring Thermal Insulation of Sleeping Bags Using a Heated Manikin”. These ensembles were tested vertically in the same manner as the other ensembles to facilitate direct comparison and because experience shows survivors are likely standing or sitting two-thirds of the time.

7.0 Human Thermal Model

Wissler (2010) developed the Human Thermal Model used in the present study. It represents human geometry as 21 cylindrical elements, as shown in Figure 8. In each major element, temperature is computed as a function of time at 15 points along 12 equally spaced radius vectors. Each cylindrical element is divided into 157 small regions defined by 15 cylindrical shells subdivided into 12 angular sections (Figure 9).

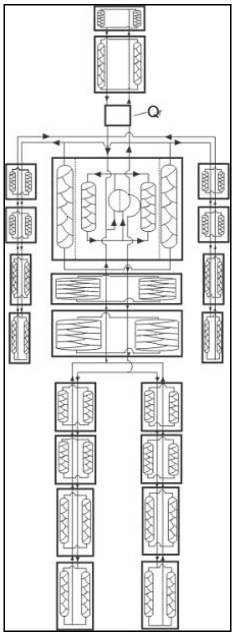

Figure 8. Twenty-one elements Human Thermal Model

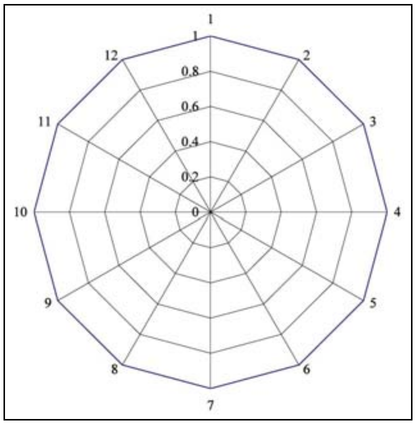

Figure 9. Twelve angular positions at which temperatures are computed. Not shown are some of the15 radial nodes located along the radius vectors.

Temperature and physical and physiological properties (such as density, specific heat, thermal conductivity, rate of metabolic heat generation and perfusion rate) are computed for each of the 157 small regions. An additional 6 radial shells divided into 12 angular sections are used to define the properties of clothing on each major element. Longitudinal conduction of heat is neglected, and transport of heat between major elements is affected by arterial and venous blood flow. The model makes allowance for counter-current heat transfer between arterial and venous blood in each element.

An atlas of human anatomy was used to position bone, brain, lung, viscera, muscle, fat, and skin in each section, and information regarding the distribution of bone, muscle, and fat were obtained from the literature and used to place an appropriate amount of each material in each element. Regional thicknesses of subcutaneous fat are assigned according to gender and the mean skinfold thickness.

Local heat generation rates in excess of the resting metabolic rate are defined by the kind and intensity of exercise performed and the contribution of shivering metabolism when appropriate. Blood flow to muscle is defined by the metabolic requirement for oxygen. In addition, it is assumed that vasoconstriction reduces the perfusion rate of inactive muscle during exposure to cold. Skin blood flow responds to several factors that include central arterial blood temperature, mean skin temperature, local skin temperature, and intensity of exercise. Sweating and shivering are defined by the thermal state of the system.

Temperatures are computed at 1.5-second intervals at approximately 5,000 nodes in a fully clothed person. An alternating-direction implicit method is used to solve the bio-heat equation.

The model was enhanced in this project to allow for seamless transitions of survivors from an enclosed liferaft to standing on land, which enabled direct analysis of a scenario in which survivors spend a period of time in a liferaft before going ashore. Simulating a twenty-four hour real-time period requires less than 10 minutes on a typical personal computer.

8.0 Results and Discussion

The results from Phase 1 include thermal resistance of clothing ensembles typically available in an Arctic mass rescue scenario and predictions from the Wissler numerical model.

8.1 Manikin Results

The thermal resistance of dry clothing ensembles at 5°C in still air and 7 m/s wind are summarized in Tables 3 and 4 respectively. There is very good agreement between the thermal resistances measured by the two manikins, despite the differences in number of zones, zone partitions, sizes and clothing fits and being dressed by two teams. With the exception of two ensembles in each table, differences in thermal resistances of all other ensembles measured by the two manikins fall below 10%. In half of the ensembles, the differences in thermal resistances are below 5%.

Table 3. Thermal resistance of dry clothing ensembles in 5°C, 0 m/s wind

Ensemble	R_{wtd}(parallel) [(m^2 °K) / W]		% Difference Between Manikins
	NEMO	TIM	
1 (CW)	0.21	0.20	0.2
2 (DW)	0.34	0.34	1.2
3 (EW1)	0.48	0.45	6.0
4 (EW2)	0.56	0.54	3.9
5 (AW1a)	0.53	0.50	5.4
6 (AW1b)	0.49	0.47	3.8
7 (AW2)	0.49	0.51	5.4
8 (MAJ1)	0.48	0.42	11.8
9 (MAJ2a)	1.23	1.05	14.7
10 (MAJ2b)	0.67	0.61	9.3

Table 4. Thermal resistance of dry clothing ensembles in 5°C, 7 m/s wind

Ensemble	R_{wtd}(parallel) [(m^2 °K) / W]		% Difference Between Manikins
	NEMO	TIM	
1 (CW)	0.06	0.06	5.3
2 (DW)	0.24	0.23	5.8
3 (EW1)	0.22	0.24	10.5
4 (EW2)	0.31	0.34	9.3
5 (AW1a)	0.33	0.33	0.2
6 (AW1b)	0.23	0.26	10.7
7 (AW2)	0.30	0.32	6.9
8 (MAJ1)	0.19	0.17	9.7
9 (MAJ2a)	0.49	0.49	0.2
10 (MAJ2b)	0.41	0.41	0.2

The observed differences in thermal resistances are believed to be caused mainly by variations in fit and wrinkles and folds in the ensembles from dressing because NEMO manikin power was validated in a full body water calorimeter to within 2% accuracy 3 months after the present experiment and TIM manikin power was also previously validated in the same calorimeter to within 4% accuracy.

In Table 3, with no wind, the thermal resistance is lowest with Ensemble 1 (Cabin Wear) and highest with Ensemble 9 (Major Air Disaster Kit (MAJAID) clothing with down-filled casualty bag). Ensemble 2 (Deck Wear) has the second lowest thermal resistance. The Expedition Wear, Abandonment Wear and MAJAID clothing alone (Ensembles 3-8) have about the same thermal resistance. The MAJAID clothing with synthetic filled casualty bag has the second highest thermal resistance.

The effect of wind on thermal resistance is shown in Table 4. With 7 m/s wind, the thermal resistance of all the ensembles decreased significantly. The percent reduction in thermal resistance ranged from 30% to 70%. The thermal resistance of Ensemble 9 is still the best, but wind reduced its effectiveness by 60%. These results highlight the importance of having a shelter as a windbreak.

The thermal resistance and drying time of wet Ensembles 1, 3 and 8 at 5°C in still air and 7 m/s wind, are shown in Tables 5 and 6. These values were taken from NEMO thermal manikin. Unlike other ensembles, these ensembles do not have a water vapour impermeable layer of clothing, so they will dry given sufficient time.

Table 5. Thermal resistance of wet clothing ensembles in 5°C, 0 m/s wind

Ensemble	R_{wtd}(parallel) Dry [(m^2 °K) / W]	Initial wet R_{wtd}(parallel) [(m^2 °K) / W]	Drying time [hours]
1 (CW)	0.21	0.09	25
3 (EW1)	0.48	0.18	60
8 (MAJ1)	0.48	0.19	45

Table 6. Thermal resistance of wet clothing ensembles in 5°C, 7 m/s wind

Ensemble	R_{wtd}(parallel) Dry [(m^2 °K) / W]	Initial wet R_{wtd}(parallel) [(m^2 °K) / W]	Drying time [hours]
1 (CW)	0.06	0.03	3.5
3 (EW1)	0.22	0.11	45
8 (MAJ1)	0.19	0.09	13

The thermal resistance and drying time of wet Ensembles 1, 3 and 8 in 0 m/s at -15°C are shown in Table 7. In comparison to Table 5, the drying times are longer as expected due to lower rate of evaporation.

Curves of thermal resistance versus time were extrapolated until the resistance values from the dry tests were reached. Generally the initial wet thermal resistance was 2 to 2.5 times lower than the dry value, and drying times ranged up to 60 hours. This highlights the importance of staying dry. Drying times were shorter in the wind corresponding to the much higher rate of evaporation and accompanying low thermal resistance (high heat loss).

Table 7. Thermal resistance of wet clothing ensembles in 15°C, 0 m/s wind

Ensemble	R_{wtd}(parallel) Dry [(m^2 °K) / W]	Initial wet R_{wtd}(parallel) [(m^2 °K) / W]	Drying time [hours]
1 (CW)	0.21	0.09	55
3 (EW1)	0.48	0.19	70
8 (MAJ1)	0.48	0.19	60

8.2 Simulation Results

Application of the human thermal model is illustrated for two plausible scenarios for the first 24 hours following an accident in which passengers abandon a cruise ship when the air temperature is 0°C and the wind speed is 25 km/hr (or 7 m/s). Passengers are assumed to be wearing Ensemble 3 (Expedition Wear) wet below the waist due to a wet floor when they are in an enclosed liferaft. 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 $m^{2\circ}K/W$), 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 10 and 11. Filled and open circles identify the first and second scenarios, respectively. Passengers are mildly hypothermic and strongly dependent on shivering metabolism to prevent the development of more severe hypothermia. The metabolic rate when victims are protected by a tent is roughly twice the resting rate. Without protection afforded by the tent and sleeping bag, bodily temperatures decrease and shivering increases until the metabolic rate becomes approximately three times the resting rate. Although a steady-state can in principle be established for either scenario, there have been no studies that establish the feasibility of such behaviour for prolonged cold exposure. The duration of typical cold exposure studies has been only two hours (for example, Bittel et al., 1988, and Tikuisis et al. 1991), although a few studies have lasted as long as five hours (Thompson and Hayward, 1996, and Tikuisis et al., 1999). It is worth noting that several subjects were unable to complete the longer trials. Whether one’s ability to shiver vigorously for a long time is limited by loosely-defined fatigue remains an open question (Tikuisis et al. 2002).

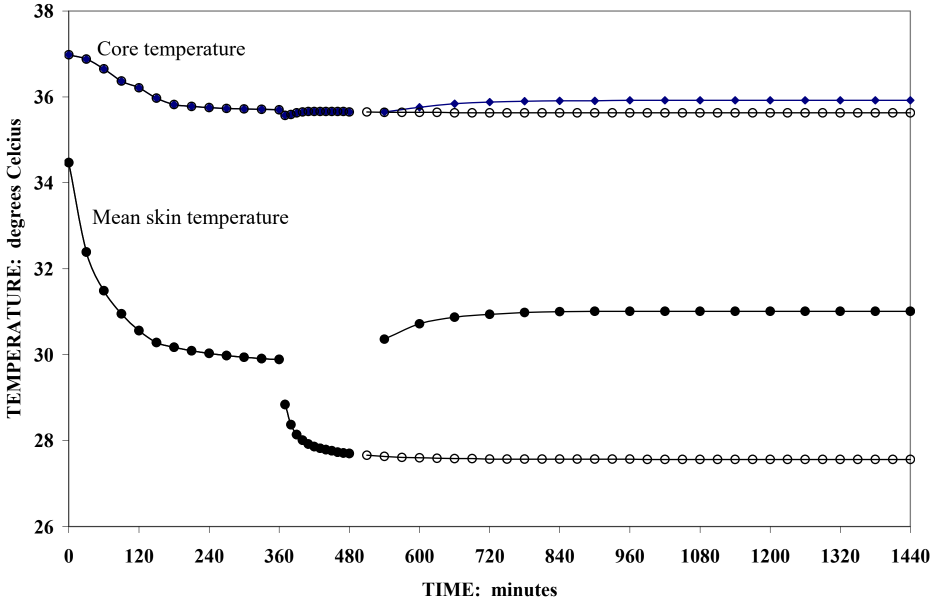

Figure 10. Core and mean skin temperatures for two different 24-hour scenarios. Closed circles identify use of a sleeping bag in a tent during the last 16 hours, and open circles identify continuous exposure without a tent or sleeping bag.

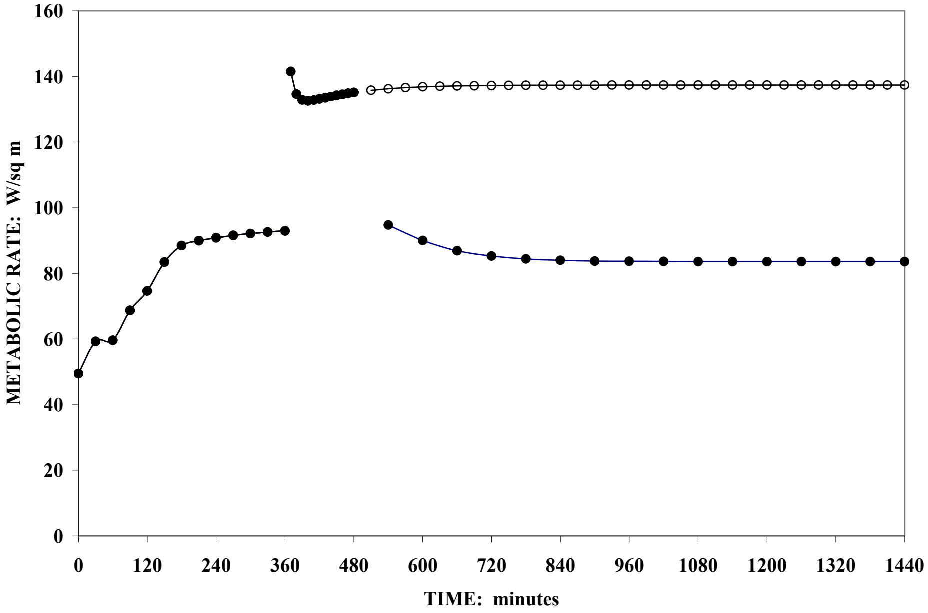

Figure 11. Metabolic rates for two different 24-hour scenarios. Closed circles identify use of a sleeping bag in a tent during the last 16 hours, and open circles identify continuous exposure without a tent or sleeping bag.

Another important factor that should be taken into consideration is individual variability (Buskirk et al., 1963, and Eyolfson et al. 2001). The mathematical model employed for these simulations represents reasonably well the mean behaviour of the young, fit, male subjects usually employed in experimental studies. However, cruise ship passengers include men and women who are considerably older and less fit than typical subjects of cold exposure studies. Women and men have different physiological responses to cold. The elderly also have different response compared to young adults.

Moreover, examination of data for individual subjects published in several papers clearly shows that there is considerable individual variation even among young subjects, some of whom were unable to complete the trial and would almost certainly fare less well than those represented in Figures 10 and 11. Although the random behaviour of individuals has not been well defined, several studies clearly establish that the elderly as a group fare less well than the young during cold exposure (DeGroot et al., 2006).

Given the uncertainty associated with such simulations, how should the results shown in Figures 10 and 11 be interpreted? The simple answer seems to be that equipment and procedures are required to prevent exposures as severe as those represented in these scenarios. Although some victims would probably survive under those conditions, there would almost certainly be fatalities owing to hypothermia. Given significant gaps in our knowledge about the behaviour of a very diverse group of victims, it is only prudent to provide sufficient protection to avoid exposures as severe as those represented by these simulations.

9.0 Conclusions

1. There is very good agreement between the thermal resistances measured by the two manikins. The differences in thermal resistances observed are likely caused by variations in fit, and wrinkles and folds in the ensembles from dressing.

2. With no wind, the thermal resistance is lowest with Ensemble 1 (Cabin Wear) and highest with Ensemble 9 (Major Air Disaster Kit clothing with down-filled casualty bag). The Expedition Wear, Abandonment Wear and the Major Air Disaster Kit clothing alone (Ensembles 3-8) have about the same thermal resistance.

3. With 7 m/s wind, the thermal resistance of all ensembles decreased significantly by 30% to 70%. The thermal resistance of Ensemble 9 (Major Air Disaster Kit clothing with down-filled casualty bag) is the best but its effectiveness is reduced by 60% with wind. These highlight the importance of having a windbreak (e.g. a tent).

4. For wet clothing ensembles at 5°C, the initial wet thermal resistance was 2 to 2.5 times lower than the dry value, and drying times ranged up to 60 hours. This highlights the importance of staying dry. Drying times were shorter in 7 m/s wind corresponding to the much higher rate of evaporation and accompanying low thermal resistance (high heat loss).

5. Preliminary 24-hour survival simulation predicts that the survivors are mildly hypothermic and depend strongly on shivering (3 times the resting metabolic rate) to maintain thermal balance. It is still unknown if such level of shivering could be maintained for 24 hours.

The numerical model predicts that a sleeping bag and tent provide considerable protection for survivors. The predicted metabolic rate with shelter is roughly double the resting rate. It is triple the resting rate without protection from the wind. Although steady-state can in principle be established in the short-term, it is not known if this is possible for prolonged cold exposure.

10.0 Recommendations

1. Shivering fatigue could have serious consequences since survivors are dependent on shivering metabolism to maintain thermal balance. There is a need to further investigate the nature of shivering fatigue and long-term sustainable metabolic rate through research.

2. The model represents the mean behaviour of the generally young, fit, male subjects of several experimental studies. Cruise ships typically have older and less fit passengers of both gender. There is also considerable individual variation even among young subjects. Therefore, it is prudent to provide sufficient protection. It is also important to assess the effect of age. Research should also include subjects from both genders.

3. It is known that exercising is an effective means to create body heat to supplement heat generated from shivering. Research should assess using exercises as a survival strategy.

11.0 Acknowledgments

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