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Experimental Study and Modelling of Thermal Protection in Liferafts Using a Thermal Manikin and Human Subjects

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ABSTRACT

Experiments were conducted in cold conditions (5°C water temperature and 5°C air temperature) to assess the thermal protection of a 16-person, SOLAS approved, commercially available liferaft using a thermal manikin and human subjects. The comparison tests included four 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**).

The results demonstrated equivalence in insulation between human subjects and a thermal manikin for all cases of comparison (**Idry:** Manikin 0.236 (m^2°C)/W versus Human 0.224 (m^2°C)/W; **Iwet:** Manikin 0.146 (m^2°C)/W versus Human 0.145 (m^2°C)/W; **Udry:** Manikin 0.174 (m^2°C)/W versus Human 0.185 (m^2°C)/W; **Uwet:** Manikin 0.101 (m^2°C)/W versus Human 0.116 (m^2°C)/W). The results also showed the repeatability of the thermal manikin tests (0.177 (m^2°C)/W versus 0.171 (m^2°C)/W in Udry baseline case; and 0.101 (m^2°C)/W versus 0.104 (m^2°C)/W in Uwet baseline case).

The results indicated that the insulation of a closed cell foam floor is comparable to an inflated floor (0.236 (m^2°C)/W compared to 0.221 (m^2°C)/W and 0.236 (m^2°C)/W for closed foam floor from manufacturer A and B respectively). TPA provided considerable additional insulation than all baseline cases. A test with a human subject wearing a TPA in the Uwet case showed an improved insulation of 48% over the baseline case. TPA provided more additional insulation than a wet suit in all test cases except Udry case. In Uwet case, the worst test condition, 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 liferaft occupant heat loss model was developed and integrated with Defense R&D Canada's Cold Exposure Survival Model to predict survival time. For Uwet case, the worst test condition, the survival time is 32 hours and functional time is 24 hours for the experimental conditions.

INTRODUCTION

Inflatable life rafts are currently used on almost all passenger, fishing and commercial vessels, and offshore oil installations. Worldwide, life rafts are the primary evacuation system from fishing vessels with relatively small crews to large Roll on/Roll off passenger vessels with over a thousand passengers and crew.

In a passenger ship abandonment situation in cold water, passengers may be wearing very little personal protective clothing. Therefore, life rafts provide the only significant thermal protection against the cold ocean environment while they await rescue. The survivors may need to wait for days to be rescued depending on the geographical location, search and rescue assets available, weather conditions etc. The young, old, weak and injured are particularly vulnerable. So, for vessels operating in cold bodies of water such as the frigid North Atlantic, life raft thermal protection is very important to ensure survival.

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

Experiments were conducted in mild cold (16ºC water temperature and 19ºC air temperature) and cold conditions (5ºC water temperature and 5ºC air temperature) to assess the thermal protection of a 16-person, SOLAS approved, commercially available life raft.

OBJECTIVES

The objectives of this project are to –

1. Develop thermal protection criteria for inflatable life rafts for unprotected occupants in a ferry abandonment situation.
2. Propose an objective methodology for testing inflatable life raft thermal protection performance.
3. Develop tools for Search and Rescue (SAR) planners to predict survival times of life raft occupants.
4. Provide guidance to training authorities and providers on the knowledge and skills required to optimize the thermal protection provided by life rafts.
5. Provide guidance to authorities and life rafts manufacturers on effective methods to meet the thermal protection criteria for inflatable life rafts.

DESIGN OF EXPERIMENTS

The project is composed of multiple phases of experiments, which were conducted in the controlled test environment of the Ice Tank and Towing Tank of National Research Council Canada, Institute for Ocean Technology (NRC-IOT). The differences among the various phases are summarized in Table 1.

Phase	T_{air} [ºC]	T_{water} [ºC]	Wind [m/s]	Wave Height [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

Table 1. Test Program

Phase 1 was a one-week long pilot experiment, aimed to better understand the effects of various variables, to observe the rate of occupant heat loss, to validate the proper functioning of 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 was 19ºC and 16ºC respectively.

Phases 2 and 3 were designed to assess occupant heat loss and life raft thermal protection in mild cold (19ºC air temperature and 16ºC water temperature) and cold conditions (5ºC air temperature and 5ºC water temperature) respectively. In addition to assessing the system thermal protection, the data collected was used to develop an occupant heat loss model, which interfaced with Cold Exposure Survival Model (CESM) to predict survival time (Tikuisis and Keefe, 2005). Human subjects were used in tests in Phases 1 and 2. In Phase 3, human subjects and a thermal manikin were employed.

This paper presents results of Phase 3 experiments. Mak et al. (2008), Cahill et al. (2008) and DuCharme et al. (2007) presented the results of Phase 1 and 2 experiments.

TEST PROGRAM

The objectives of Phase 3 experiments were:

- To characterize the thermal and metabolic rate responses of lightly dressed human subjects, who are exposed to cold conditions in a life raft.
- To compare the thermal insulation values measured using human subjects and thermal manikin in a range of conditions.
- To conduct special case tests that would help to address the knowledge gaps related to thermal protection of life rafts.
    - Multiple subjects (12 people) in the raft
    - Thermal protective aid (TPA)
    - Wet suit
    - Closed cell foam floor
    - Sitting on inflatable pillow
    - Sitting on lifejacket
    - 10 cm depth of water on the raft floor
- To assess the repeatability of data generated by the thermal manikin

Based on the results of Phases 1 and 2, the tests in Phase 3 were designed to assess floor insulation (inflated or uninflated) and clothing wetness (dry or wet). The tests were used to characterize human thermal and metabolic rate response and to compare thermal insulation values between human subjects and manikin in 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 human subjects (five males and three females) were exposed in pairs to the four randomly assigned conditions inside the raft. The average subject data are shown in Table 2. The test matrix of baseline and special cases using human subjects and a thermal manikin is shown in Table 3.

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 2. Subject data

EXPERIMENTAL SETUP

Phases 3 experiments were conducted in the ice tank of National Research Council Canada, Institute for Ocean Technology (NRC-IOT) (Figure 1). The ice tank is 90 m long, 12 m wide and 4 m deep.

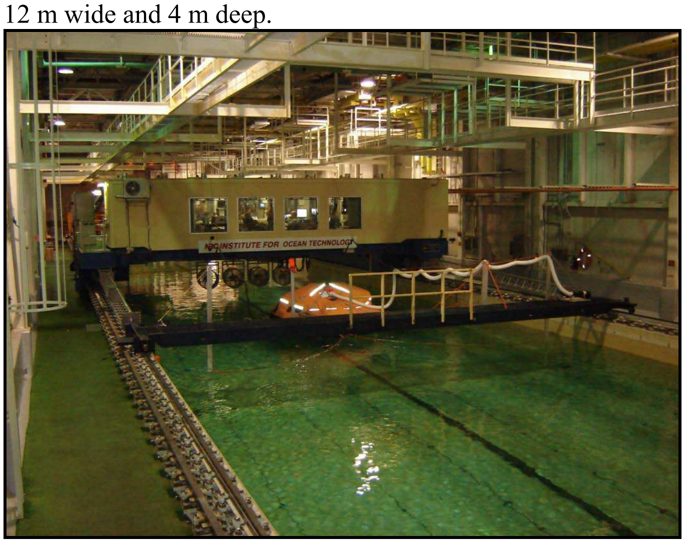


Figure 1. Life raft setup between the towing carriage and the service carriage

In the experiments, the towing carriage was connected to the service carriage via two aluminum truss-like structures, which allowed the two carriages to move as a unit. The service carriage was placed at the back of the towing carriage. The life raft was set up between the towing carriage and the service carriage. Two towlines were extended from the fore and aft tow points of the life raft to two towing posts on the service carriage and the towing carriage respectively. During the experiments, the carriages towed the life raft in calm water, up and down the tank, to simulate leeway (speed of life raft over water). The life raft was free to surge, sway, heave, yaw, pitch and roll. The electrical cables for the various sensors were overhung using an umbilical cord, so they did not influence the life raft motion.

A SOLAS approved, commercially available, 16-person life raft was used in the test program. The life raft has two separate

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[1]	✓	✓	✓	✓
Manikin with TPA from manufacturer 2[2]				✓
Manikin sitting on an inflatable pillow	✓			
Manikin sitting on his own lifejacket	✓			✓
Manikin with lifejacket sitting on a second lifejacket			✓	
Manikin sitting on closed foam floor from manufacturer A. The closed cell foam floor is placed on top of the inflatable raft floor, either inflated or uninflated as indicated.	✓		✓	✓
Manikin sitting on closed foam floor from manufacturer B. The closed cell foam floor 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		✓		

Table 3. Test Matrix

[1] Manufacturer 1 = TYCO Manufacturing, B.C., Canada; meets Chapter III SOLAS 2002; DOT-Canadian Coast Guard Approved #T.C. 079.069.001

[2] Manufacturer 2 = ASCON AB, Scandinavia; EUROTHERM; DNV 0575/05

inflatable floatation tubes, a lower and an upper floatation tube. The upper floatation tube is connected to the canopy arch inflation chamber. The floatation tubes are made of heavy butyl rubber. The raft is 3.3 m in diameter and is 1.7 m high. It has one boarding platform and two entrances. The raft is equipped with an inflatable floor, to insulate the occupants from direct contact with the cold ocean when seated.

The manufacturer's tow points were not used. Instead, two new tow points were made at the two entrances. These tow points enabled fans installed on the towing carriage to blow wind directly at the life raft entrances.

In Phase 3 experiment, there were tests with
- 2 primary human subjects;
- 1 primary human subject and 11 secondary human subjects; and
- A thermal manikin alone

Primary subjects are those instrumented to provide the necessary data for the study. Secondary subjects represent the other occupants who are there to create the microclimate inside the raft.

Figures 2 show the seating arrangements for Phase 3. The primary human subjects always sat in RT4 and LF4 positions, either by themselves or surrounded by secondary human subjects on both sides. During human subject tests, a researcher stayed in the raft to periodically clean the face mask of the metabolic system, to spray the subjects each hour in wet clothing tests, to assess the thermal comfort of the subjects and to log subject postures and other events. The thermal manikin sat alone in RT1 position. The seating positions at the entrances of the raft were left empty as emergency exits.

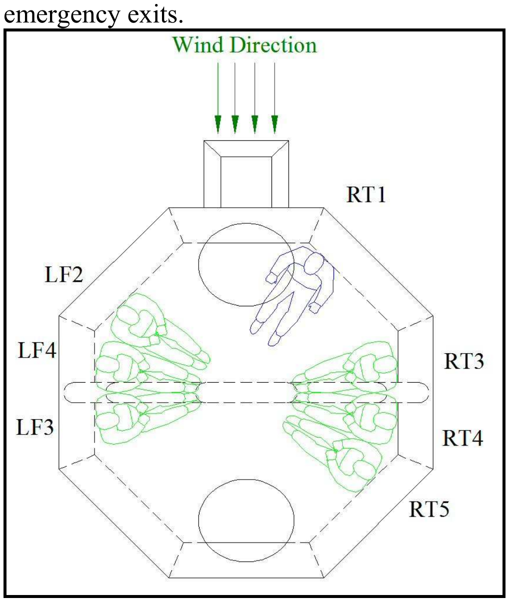


Figure 2. Phase 2 Seating Arrangements

In all the tests, the human subjects and the thermal manikin were wearing cotton T-shirts, cotton briefs, one-piece cotton coveralls (model Big Bill 414; Codet Inc., Magog, QC) and SOLAS life jackets (model MD8000; Mustang Survival Ltd., Richmond, BC). Neoprene foam gloves and boots protected their extremities. All the occupants were in a sitting position, with their buttocks in direct contact with the raft floor and their backs leaning against the floatation chambers of the raft, though generally the life jacket prevented direct contact between the subjects' backs and the floatation chambers. The raft canopy was fully closed in all the tests.

INSTRUMENTATION

The Ice Tank is equipped with a VMS and Windows based distributed client/server data acquisition system. An external overhead camera pointing towards the aft of the raft recorded the raft motions. Inside the life raft, two infrared cameras recorded the occupant motions.

Two data acquisition systems were used, one system was used to acquire signals from the human subjects and the life raft, and another system was used to acquire signals on the towing carriage. A bundle of cables, overhung in an umbilical cord, was used to carry the human subject and life raft signals back to the carriage. On the carriage, all the signals, except for heart rate data, from both acquisition systems were acquired by GDAC (GEDAP Data Acquisition and Control) client-server acquisition system, developed by National Research Council Canada, Institute for Ocean Technology. Data from all other sensors, except the heart rate monitors, was acquired at 1 Hz.

The heart rate of the primary human subjects was collected with a heart rate monitor (Model S-810i; PolarElectro, Kempele, Finland). The monitor was fastened to the chest of the human subject using a plastic elastic band that came with the device. It acquired data every 5 seconds and transmitted them to a wrist logger wirelessly.

Thirteen heat flow sensors (model FR-025-TH44033-F6; Concept Engineering, Old Saybrook, CT) were used on each of the primary human subjects (Figure 3). Each heat flow sensor has two channels, measuring the heat flow and temperature at the installation point on the human subject. Researchers used 3M Transpore tape to attach heat flow sensors to the subjects.

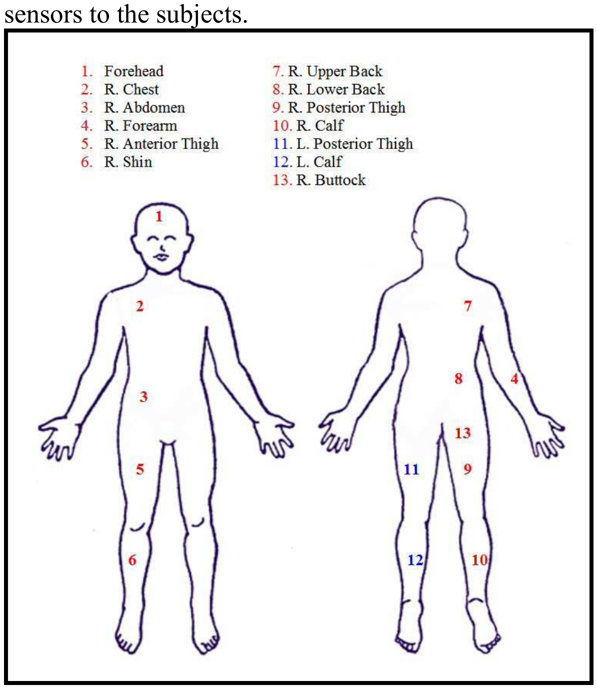


Figure 3. Heat flow sensor locations on primary human subject

Oxygen consumption, dioxide output, minute ventilation, and respiratory exchange ratio were continuously recorded with two automated breath-by-breath systems (K_4B_2, Cosmed, Rome, Italie and Cortex Metamax, Leipzig, Germany) using a Nafion filter tube and a turbine flow meter (opto-electric) (Figure 4). Prior to the experimental sessions, gas analyzers and volume were calibrated with medically certified calibration gases (15% O_2 and 5% CO_2) and with a 3-liter calibration syringe, respectively. Both systems used the same technology, that is, electrochemical cells as O_2 sensors and infrared technique for CO_2.

Core body temperatures of the primary and secondary human subjects were recorded using tympanic probes (Mon-a-therm 400 series thermistor, model 90058, Mallinckrodt Medical, inc., St. Louis, MO) and (rectal probes (Model 21090A, Philips). The tympanic probe was inserted into the external ear, positioned as close to the tympanic membrane as possible (Figure 5). The insertion depth for rectal probes was 15 cm.

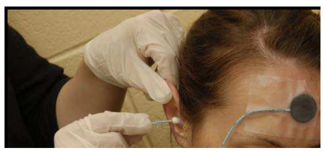


Figure 5. Researcher inserting tympanic probe into the subject's ear and heat flow sensor mounted on subject forehead using 3M Transpore tape

Figure 4. Primary subject dressed in clothing ensemble and wearing an automated breathe-by-breathe metabolic system

Instrumentation inside the raft included:

- Five heat flow sensors on the floor (Model F-025-TH44033-F10; Concept Engineering, Old Saybrook, CT);
- Four heat flow sensors on the chambers (Model F-025-TH44033-F10; Concept Engineering, Old Saybrook, CT),
- Four heat flow sensors on the canopy (F-002-4-TH44033-F20; Concept Engineering, Old Saybrook, CT),
- A carbon dioxide sensor (T-1047 CO2 Transmitter 4-20mA, Comspec, Toronto, ON),
- Two wind sensors (Model 1405-PK-040; Gill Instruments Ltd., Lymington, Hampshire),
- Two air temperature sensors (Model ON-401-PP; OMEGA Engineering, inc., Stamford, CT),
- A floor inflation system,
- Pressure sensors for raft floatation tube and floor,
- A humidity sensor, and
- Two infrared video cameras

This raft floor design secures the inflatable floor with button-like fasteners that create depressions (dimples) in the raft floor and allow water to collect. Heat flow sensors were installed in raft floor areas with depression and without depression. The raft has two independent floatation chambers.

There was one wind sensor outside the raft (Model 1405-PK-040; Gill Instruments Ltd., Lymington, Hampshire) and two water temperature sensors on the carriage (Model ON-401-PP; OMEGA Engineering, inc., Stamford, CT). Detail information regarding the raft internal and external environment was collected throughout the tests. Layouts of the instrumentation are shown in Figures 6 to 8.

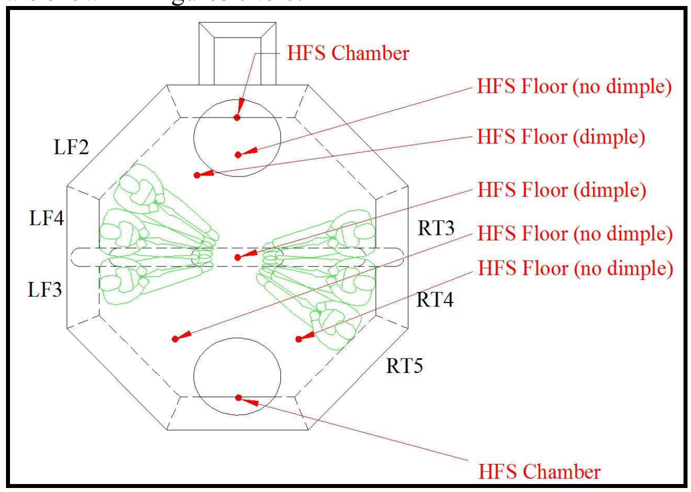


Figure 6. Heat flow sensors on raft floor and chambers

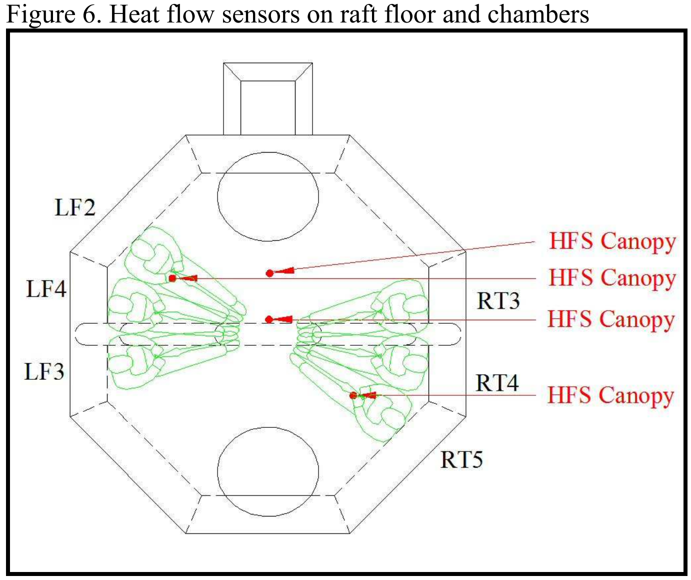


Figure 7. Heat flow sensors on raft canopy

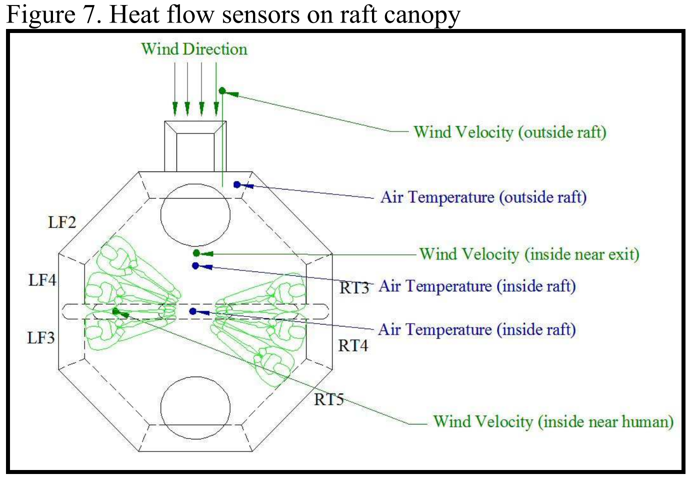


Figure 8. Wind and air temperature sensors inside raft

THERMAL MANIKIN

A Measurement Technology Northwest (Seattle, Washington, USA) NEMO 23-zone submersible thermal manikin was used in this study (Figure 9). Its stature represents a 50th percentile adult North American male, weighting 71 kg. The manikin shell is made of aluminium. The 23 independently heated thermal zones are shown in Figure 10. Each thermal zone is equipped with heaters to generate uniform heating of the aluminium shell and two precision thermistors to measure skin temperature.

Figure 9. NEMO 23-zone submersible thermal manikin

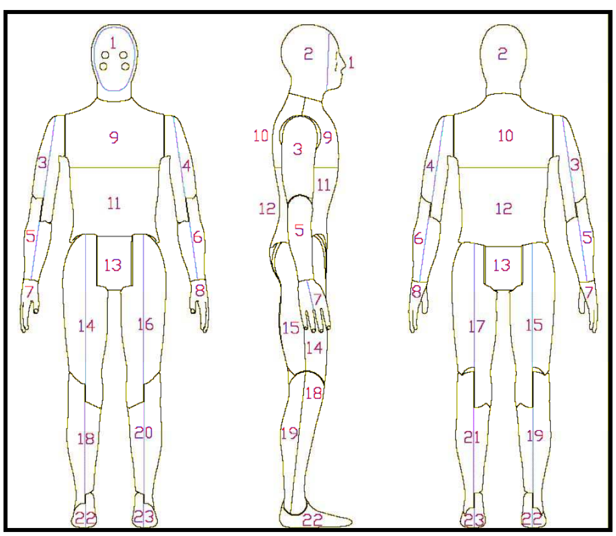


Figure 10. NEMO submersible thermal manikin zones

The main components of the thermal manikin are shown in Figure 11 and include:

- Thermal manikin with heaters, sensors and internal controllers for regulation and monitoring
- Power supply enclosure including air pressure regulator
- Ambient sensors (2 temperature, 1 relative humidity and 1 wind speed)
- Interconnect cabling and air pressure supply hose
- Laptop with ThermDAC control software.

The NEMO thermal manikin operates on 60Hz AC electrical power, 200-250 VAC with a maximum current of 20 Amps.

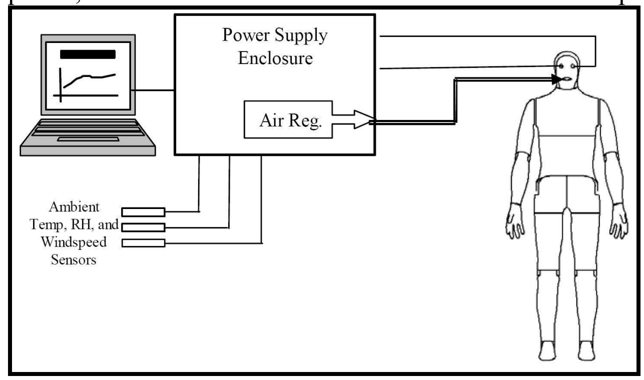


Figure 11. Thermal Manikin Block Diagram

The ThermDAC control software is a 32-bit Windows based program that controls, records and displays real-time zone information numerically and graphically. Each thermal zone is individually controlled using either a temperature control, constant heat flux or comfort equation output.

ThermDAC is a fully automated data acquisition and control program. It has two independent methods of data logging. Full data logging provides a complete data set of the entire run, at user selectable intervals. Steady State logging will write steady state average values to the file once the system has stabilized. These logging methods can be used individually or together. ThermDAC also includes an automatic steady state detection, which can initiate data logging.

Tests generate comma delimited (*.CSV) data files suitable for direct importing into Excel or any other Windows compatible spreadsheet program. The data file contains a header with the data file name, test date, comments entered at test start, setpoint, and logging interval. The data consists of a time stamp, followed by, in order, all zone temperatures, all zone heat fluxes, area weighted average temperature, area weighted heat flux, area weighted thermal resistance, ambient temperature, and relative humidity.

EXPERIMENTAL METHOD

Human subject tests in Phase 3 varied from 4 to 8 hours in duration depending on how long the subjects was able to stay in the cold environment inside the raft. Each human subject baseline test was repeated eight times and the average insulation values were compared to those from the thermal manikin. The order of conditions was randomized for each pair of subjects.

Prior to entering the raft, researchers conducted anthropometric measurements on the human subjects. The human subjects put on test clothing and with assistance from the researchers install the core temperature probes, heat flow sensors and heart rate monitors. Baseline core body temperatures of all human subjects were recorded on the carriage. Then, the primary subjects were wetted if it was a wet clothing test. Lastly, researchers put the portable metabolic system on the human subjects before they stepped into the raft.

Inside the liferaft, a researcher re-wetted the subjects' clothing each hour, periodically cleaned the mask and sample tube of the metabolic system, enquired about the subjects condition and documented the subjects sitting posture and when shivering started. After a test was finished, researchers and lifeguards assisted the human subjects to exit the liferaft, put them on stretchers and carried them to a re-warming room. In there, researchers connected a second data acquisition system to the subjects to record and monitor their re-warming.

The thermal manikin tests were about 1 hour 15 min each. Researchers dressed the thermal manikin the same as the human subjects. Then, they put the manikin inside the lifeboat, positioned him to sit upright with legs flat on the floor, connected up the power and communication cables, exited the liferaft and started testing. The constant temperature control mode of the manikin was used, where the set point temperature of each zone was specified at 20ºC. The thermal manikin test was terminated when it reached steady state, with surface temperatures of each zone steady around their set points and constant average heat flux.

DATA ANALYSIS

Thermal insulation (or resistance) values were computed offline using IGORpro commercial data analysis software. For consistency with the human tests, who wore insulated boots and gloves to prevent cold injury, the manikin hands and feet (zones 7, 8, 22, 23) were not included in the calculation of the thermal insulation value. To allow for this the total surface area (A_{tot}) was scaled using the appropriate ratio.

In all tests the manikin was seated in the raft with both legs in contact with the floor. The ambient temperatures for zones 15, 17, 19, 21 were taken as the water temperature. For all other zones the ambient was taken as the air temperature. The thermal resistance for each zone was calculated using the following formula:

$$R_{ct} = (T_{skin} - T_{amb}) / (Q/A)$$

Where:

R_{ct} = Thermal resistance (m^2°C)/W
T_{skin} = Zone average temperature (°C)
T_{amb} = Ambient temperature (°C)
Q/A = Area weighted Heat Flux (W/m^2)

The overall thermal insulation (R_{wtd}) was then calculated using the parallel method formula for both the manikin and the human:

$$R_{wtd}\ (\text{parallel}) = 1 / \Sigma (A_i / (A_{tot} * R_i))$$

Where:

R_i = Zone resistance
A_i = Zone surface area
A_{tot} = Total surface area

To facilitate direct comparison between human subject and thermal manikin data, two corrections were made.

(A) Contact Area Correction

In the normal sitting position, the posterior zones of the thermal manikin are subjected to two different thermal paths, which resulted in non-uniform cooling. The two thermal paths are from:

- Areas of the posterior zones losing heat to the water through direct contact with the raft floor
- Areas of the posterior zones losing heat to the air in the raft

To account for the different heat loss to water and to air from the same thermal manikin zone, a contact area correction was made. A measurement of the actual contact area was made and compared to the thigh/calf segment areas. It was determined that approximately 33% of the thermal manikin posterior calf and thigh areas were in direct contact with the raft floor.

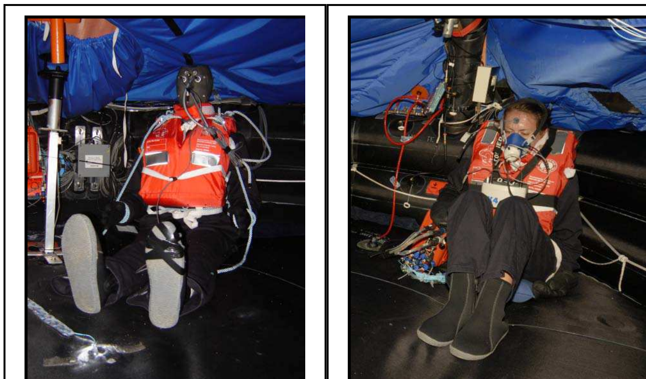
The contact area correction was applied to all manikin test cases, except for the wet suit, sitting on a pillow/lifejacket and sitting in 10cm of water. In these cases the differences in the physical arrangement and/or thermal regime were outside the scope of the algorithm used.

For tests where an adjustment for contact surface area was made, the algorithm used in place of the formula above to calculate the adjusted overall system insulation value is shown in Table 4.

(B) Behaviour Correction

The thermal manikin was placed in a sitting position, with its legs in direct contact with the raft floor and its back leaning against the floatation chambers of the raft. The life jacket collar prevented direct contact between the manikin's back and the floatation chambers. This is the same as for the human subjects.

The two legs of the thermal manikin lay flat and maintain constant contact with the raft floor. The manikin was positioned this way because there is limited rotational flexibility at the hip joints to bring the knees up. Human subjects, on the other hand, did not generally put their legs flat on the floor. They tended to sit with knees up and change sitting positions periodically throughout the experiment, to stay comfortable and keep warm. A comparison of the thermal manikin sitting posture to a typical human subject sitting posture is shown in Figures 12 and 13.



Figures 12 and 13. Thermal manikin and typical human sitting postures

Human subjects typically sit with knees up and change positions periodically throughout the experiment, while the thermal manikin sat with both legs flat on the floor. In the uninflated floor cases, to facilitate direct comparison of thermal insulation values between human subjects and thermal manikin, the insulation value was derived only with sections of data from a human subject where all five posterior heat flow sensors were in contact with the uninflated raft floor.

INPUT:
Arrays:
Zone areas (A : [m^2])
Area weighted Heat Flux (Q/A : [W/m^2])
Manikin Zone Temperature (T_{skin} : [°C])
Variables:
Measured Air/Water Temperatures (T_{amb} : [°C])
OUTPUT:
Variables:
Adjusted overall system insulation [(m^2°C)/W]

BEGIN
Calculate Zone Power (Q : [W]) as (Area weighted Heat Flux)* (zone area) for all zones
Create list of zones for normal processing
Create list of anterior leg zones (i.e. those in contact with the air)
Create list of posterior leg zones (i.e. those in contact with the floor)

FOR (Items in list normal)
$R_{ct} = (T_{skin} - T_{amb(air)}) / (Q/A)$
(Weighted R_{ct}) = $A_i / R_{ct} / A_{tot}$
END FOR

FOR (Items in list anterior & posterior)
Posterior:
Calculate Area in contact with floor (A_{floor}) as posterior zone area * 0.33
Define Area in contact with air (A_{air}) as the remainder
Power into floor Q_{floor} = Q – (Typical Heat flow into air * A_{air})

Calculate Adjusted Heat Flow (Q/A) into floor as Q_{floor} / A_{floor}
$R_{ct} = (T_{skin} - T_{amb(water)})$ / Adjusted (Q/A)
(Weighted R_{ct}) = $A_{floor} / R_{ct} / A_{tot}$

Anterior:
$R_{ct} = (T_{skin} - T_{amb(air)}) / (Q/A)$
[Adjusted area = $A_i + A_{air}$]
(Weighted R_{ct})= $(A_i + A_{air}) / R_{ct} / A_{tot}$
END FOR

Calculate system insulation R_{wtd} (parallel) = 1/ Σ (Weighted R_{ct})
END

Table 4. Algorithm to adjust for contact area

Factorial ANOVA tests were conducted to determine statistical significance in thermal responses of the primary subjects ($p \leq 0.05$).

RESULTS AND DISCUSSION

The thermal manikin overall thermal insulation values for various tests are shown in Table 5.

Tests	Inflated Floor; Dry Clothing (Idry) [(m^2°C)/W]	Inflated Floor; Wet Clothing (Iwet) [(m^2°C)/W]	Uninflated Floor; Dry Clothing (Udry) [(m^2°C)/W]	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[1]	0.334	0.235	0.204	0.158
Manikin with TPA from manufacturer 2[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 closed foam floor from manufacturer A. The closed cell foam floor is placed on top of the inflatable raft floor, either inflated or uninflated as indicated.	0.225		0.221	0.124
Manikin sitting on closed foam floor from manufacturer B. The closed cell foam floor 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. Manikin system thermal insulation values

The results show that –

- The two repeatability tests demonstrated that the thermal manikin results are repeatable (0.177 (m^2°C)/W versus 0.171 (m^2°C)/W in Udry baseline case; and 0.101 (m^2°C)/W versus 0.104 (m^2°C)/W in Uwet baseline case).
- Closed foam floor insulation is comparable to inflated floor insulation. The Idry baseline case has an insulation value of 0.236 (m^2°C)/W compared to 0.221 (m^2°C)/W and 0.236 (m^2°C)/W for closed foam floor from manufacturer A and B respectively, installed on uninflated floor with dry clothing.

- TPA provided considerable additional insulation compared to all baseline cases. The insulation increased most considerably in wet clothing cases (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. The contact area and behaviour are not corrected for the human data.[3]
- TPA provided more additional insulation than the wet suit in all cases except the dry clothing uninflated floor.
- In 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 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.[3]

DuCharme et al. (2008) compared the insulation value between human subjects and thermal manikin, shown in Table 6. Each human subject baseline test was repeated eight times and the average system insulation value was reported in the table.

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 0.171	0.101 0.104
Human subjects average (baseline cases)	0.224 ±0.023	0.145 ±0.017	0.185 ±0.022	0.116 ±0.006

Table 6. System insulation values derived from manikin and human subject experiments.

Farnworth (2009) described the development of a numerical model of the transport of heat from the subjects through the clothing to the raft and hence to the external air and water. The various heat transfer coefficients were derived from measurements of heat flow with heat flow transducers on the body, on the raft canopy, chambers and floor, and from manikin results. The model 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 4 hours 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 14. 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. The four points from left to right represents the four cases, Uwet, Udry, Iwet and Idry, respectively.

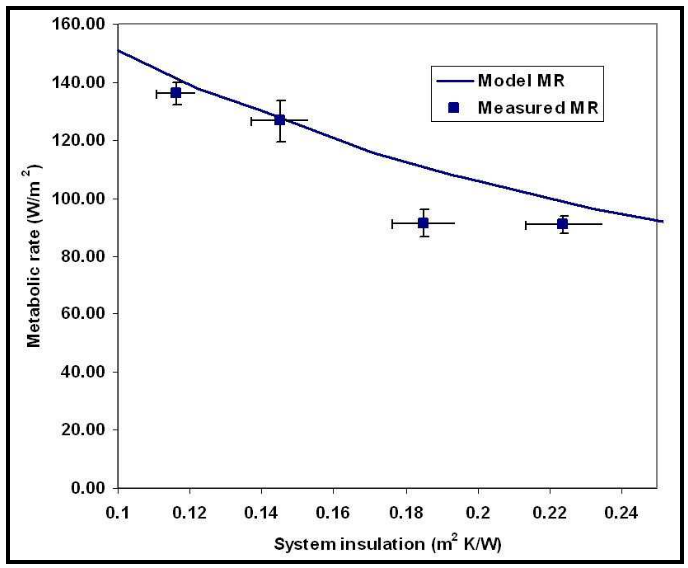


Figure 14. Comparison of the metabolic rates (MR) estimated from the experimental data and predicted by the model as a function of system thermal insulation

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 36 hours since the uncertainties become too great at longer times. Therefore, the data is presented in Figure 15 as the combination of environmental temperature and system thermal insulation that will give ST for FT of at least 36 hours.

[3] 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.

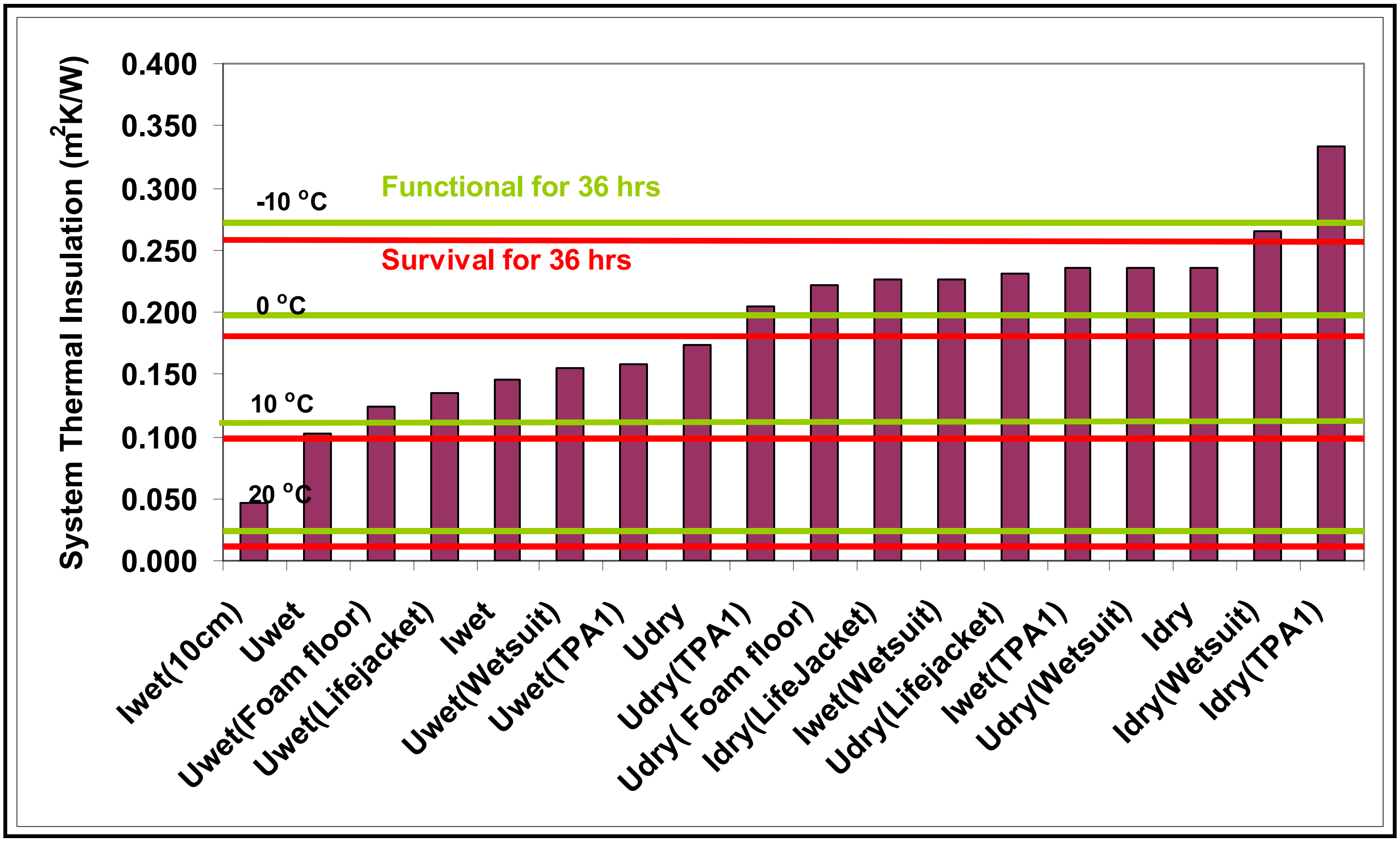


Figure 15. System thermal insulation required for ST or FT of 36 h at various temperatures (horizontal lines) compared to values measured with a thermal manikin (vertical bars).

Keys to the labels on the graph:

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 (TYCO Manufacturing, B.C., Canada; meets Chapter III SOLAS 2002; DOT-Canadian Coast Guard Approved #T.C. 079.069.001)
Udry	Uninflated floor; dry clothing
Udry (TPA1)	Uninflated floor; dry clothing and TPA (TYCO Manufacturing, B.C. Canada; meets Chapter III SOLAS 2002; DOT-Canadian Coast Guard Approved #T.C. 079.069.001)
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 (TYCO Manufacturing, B.C., Canada; meets Chapter III SOLAS 2002; DOT-Canadian Coast Guard Approved #T.C. 079.069.001)
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 (TYCO Manufacturing, B.C., Canada; meets Chapter III SOLAS 2002; DOT-Canadian Coast Guard Approved #T.C. 079.069.001)

In Figure 15, the horizontal lines represent the system insulation values required for ST or FT of 36 hour 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 inflated raft floor up to dry clothing plus a thermal protective aid (TPA) and an inflated floor. Where the top of a bar is higher than a line, then it can be expected that the ST or FT will be longer than 36 hours at the temperature corresponding to that line. The results showed the importance to keep dry, the value of TPA and the value of floor insulation.

In addition, model predictions were made of the effect of the number of occupants and ventilation rate on ST. In Figure 16, the minimum ambient temperature for 36 hours 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.

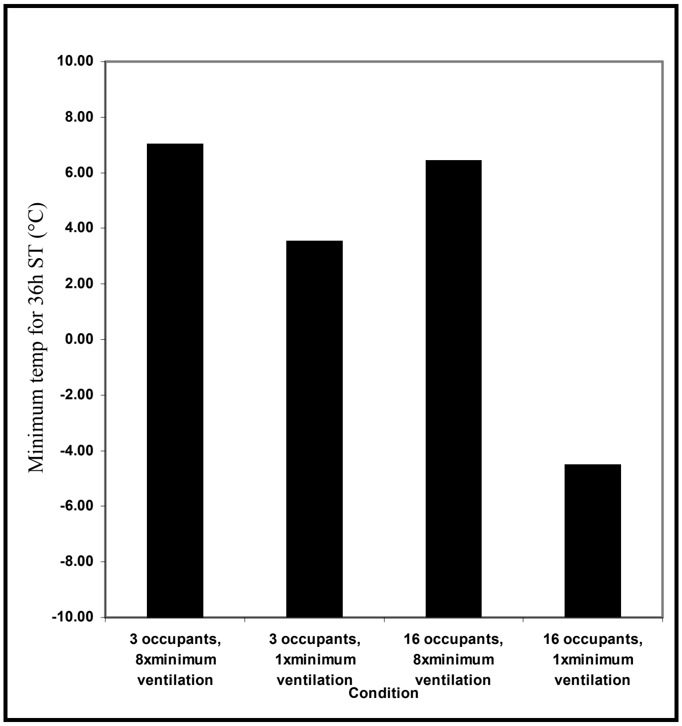


Figure 16. Ventilation comparion

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. Factors which substantially affect the survival time are:
    - Wearing of a TPA
    - Clothing wetness
    - Raft floor insulation
    - Raft ventilation rate

The recommendations for liferaft standards or design are:

1. Rafts should include a TPA for every occupant
2. 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.
3. Raft floors should be insulated or every occupant should be able to sit on an insulated surface.
4. 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.

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