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Thermodynamic optimization of liferaft designed for Polar regions

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ABSTRACT

The risk assessment conducted in the Polar Water Operation Manual (PWOM) defines the equipment required in the Personal Survival Kits (PSK) and Group Survival Kits (GSK) as the IMO Polar Code only mentions items that are to be considered (guideline).

According to the requirements defined in the IMO Polar Code you are to be able to survive for a minimum of 5 days (or until being rescued). This means that the life raft participants are to be able to produce the amount of energy required to compensate for the heat loss for an extended period of time (minimum 5 days). For a time, span of 5 days it is not likely that an average person is able to produce more than about 150 Watts on an average.

The cumulative energy produced by the participants in the raft is to compensate for the energy lost. The energy produced by the human body through metabolic processes is a complex study and will vary with age, weight, body surface area, fitness and physical activity level.

This study assesses the metabolic rates required for survival utilizing different types of lifesaving appliances. The assessment is conducted utilizing a theoretical approach, applying the laws of thermodynamics and heat balance calculations.

The study indicates that survival in cold climate is possible, when the correct equipment is utilized.

KEY WORDS:
IMO Polar Code; Lifesaving appliances; Survival; Heat balance; Cold climate.

INTRODUCTION

In the document "*Masterplan Svalbard mot 2025"* (Visit Svalbard/MIMIR AS, 2015), it is expected that we will see a doubling of tourist activity around the Svalbard archipelago towards 2025. Most of these tourists will be utilizing means of marine transportation.

REGULATORY RATIONALE

The International Code for Ships Operating in Polar Waters is referred to by many as the Polar Code.

The code is a supplement to existing IMO instruments, and the intention is to mitigate the additional risks present for people and environment when operating in polar waters.

A degree of discrepancy in the interpretation has been expected in the recent years.

Currently there are individuals and organizations arguing for reducing the IMO Polar Code requirement of 5 days survival, as several projects, e.g. SARex (Solberg, Knut Espen et al., 2016) (Solberg, Knut Espen et al., 2017) (Solberg K. E., Gudmestad O. T., 2018) indicate the large challenges associated with a 5 day survival scenario.

In a 5 days survival scenario in a cold climate environment, hypothermia imposes a major risk for the survivors. Based on the results from SARex (Solberg, Knut Espen et al., 2016) (Solberg, Knut Espen et al., 2017) (Solberg K. E., Gudmestad O. T., 2018) and the study presented in this paper, mitigation of the challenges in a 5 day perspective is possible.

METHODOLOGY

A system will always strive to reach a state of thermal equilibrium. Due to the first law of thermodynamics, the Law of Conservation of Energy the following is valid:

$$Q_{introduced} = Q_{lost} \quad (1)$$

Assessing a life raft floating at sea, the thermal energy introduced to the system by the participants is to be equal to the thermal energy lost to the surrounding environment to remain in thermal equilibrium. If the system loses more energy to the environment than what is introduced by the participants, the participants will experience a cooling effect. This effect can be simplified:

$$Q_{produced\ by\ participants} = Q_{lost\ to\ sea} + Q_{lost\ to\ air} + Q_{lost\ to\ ventilation} + Q_{lost\ to\ radiation} \quad (2)$$

The energy produced by the participants will have different paths before reaching the ambient air or the sea water.

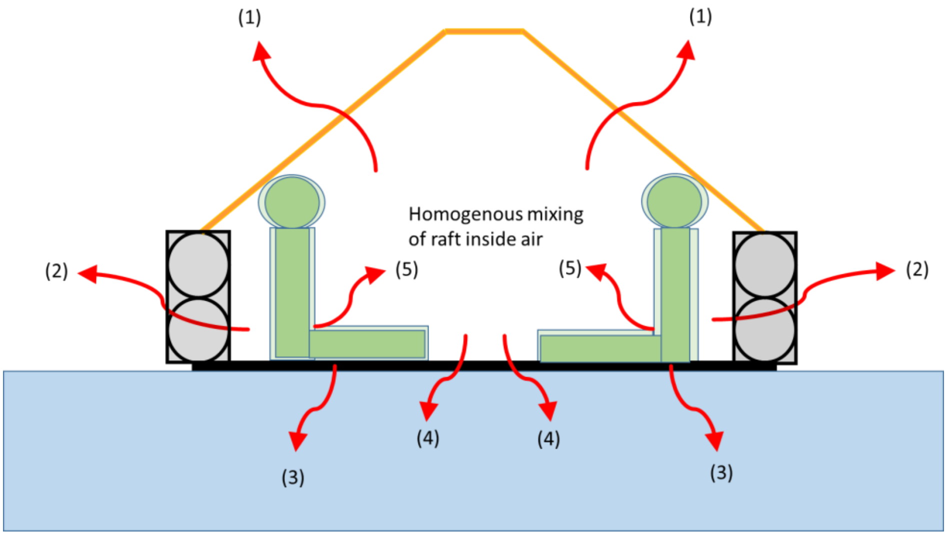

Figure 1 Heatloss mechanisms from liferaft (cross section)

$Q_{produced\ by\ participants}$

The energy introduced by the system is equivalent to then cumulative energy produced by the humans inside the raft. At low body temperatures, the body commences muscle activity to prevent further cooling. This is visible as a cold induced shivering response.

The energy produced by the participants will be conducted through the PPE (personal protective equipment) and either to the internal air of the liferaft (Figure 1 Heatloss mechanisms from liferaft (cross section) - 5) or directly through the bottom of the liferaft to the sea (Figure 1 Heatloss mechanisms from liferaft (cross section) - 3).

$Q_{lost\ to\ sea}$

The energy lost to the sea is a function of the conductive heat transfer from the bottom and the back sides of the legs of the participants, through the clothes, PPE and raft bottom into the sea (Figure 1 Heatloss mechanisms from liferaft (cross section) - 3.

Conductive heat transfer is also taking place from the inside air of the raft, through the bottom to the sea (Figure 1 Heatloss mechanisms from liferaft (cross section) - 4).

$Q_{lost\ to\ air}$

The energy lost to the ambient air from the participants is following the path described below:

- Conductive heat transfer from the participants, through the clothes and PPE to the inside air of the raft (Figure 1 Heatloss mechanisms from liferaft (cross section) - 5).
- The inside air is assumed to mix due to convective processes, in addition to venting activities, breathing and movement of the raft participants. This is assumed to generate an evenly distributed temperature profile of the raft inside air.
- The energy in the inside air is further transported through the canopy (Figure 1 Heatloss mechanisms from liferaft (cross section) - 1) and sides (Figure 1 Heatloss mechanisms from liferaft (cross section) - 2) of the raft through conductive heat transfer processes.
- The heat conducted through the canopy/sides is transferred to the ambient air through convective heat transfer processes.

It is important to note that the energy transferred through the canopy and sides through conductive heat transfer processes is equal to the cumulative energy loss through convective processes to the ambient air and through radiation.

$Q_{lost\ to\ radiation}$

The difference in raft surface temperature and ambient temperature will define the energy lost through radiation. It is assumed that the energy lost to radiation through the bottom of the raft to the sea is negligible.

$Q_{lost\ to\ ventilation}$

The energy lost due to ventilation is proportional to the ventilation rate. The required ventilation rate depends on the oxygen consumption induced by the raft participants. In general 1 liter of oxygen is consumed for every 20,9 kJoules generated (Department of Physics and Astronomy, Georgia State University, u.d.). A person producing 100 Watts will require 360 kJoules pr hour. Burning 360 kJoules will require 17.22 liters of oxygen pr hr. Given an oxygen consumption of 20.9% in ambient air, this gives an air consumption of 82.4 liter pr hour. As the mixing is of fresh air with "used" air is not ideal, and venting of air with higher CO2 concentrations is required in a real scenario (Solberg, Knut Espen et al., 2017), a higher ventilation rate is to be expected in a real scenario, ref Thermal Protection and microclimate of SOLAS approved lifeboats (Lawrence Mak et al., 2010).

Mathematical correlations

The raft can be regarded as an enclosed system exposed to the water and the air.

Due to the first law of thermodynamics, the Law of Conservation of Energy, the following mathematical relationships are valid:

[1.] The whole system is to be in equilibrium, implying the total energy introduced to the system is equal to the energy lost.

$Q_{\text{produced by participants}} = Q_{\text{lost to sea through cond.}} + Q_{\text{lost to inside air}}$

$= Q_{\text{lost to sea through cond.}} + Q_{\text{lost to sea from inside air}} + Q_{\text{lost to ambient air through cond. canopy}} + Q_{\text{lost to air through cond. sides}} + Q_{\text{lost to ventilation}} + Q_{\text{lost to radiation}}$ (3)

[2.] The energy being conducted through the canopy is equal to the energy being transported from the canopy to the ambient air through convective heat transfer processes.

$Q_{\text{lost to air through canopy cond.}} = Q_{\text{lost to air through canopy conv.}}$ (4)

[3.] The energy being conducted through the sides of the life raft is equal to the energy being transported from the sides of the life raft to the ambient air through convective heat transfer processes.

$Q_{\text{lost to air through cond. sides}} = Q_{\text{lost to air through conv. sides}}$ (5)

The following parameters are known:

- Properties of ambient air
- Properties of sea water
- Properties of insulation barriers:
  - PPE
  - Life raft bottom
  - Life raft sides
  - Life raft canopy
- Temperature, surface area and energy produced by the human body
- Rate of ventilation

There are 3 unknown parameters important for the calculation of the heat loss. The unknown parameters are:

- $T_{\text{internal air}}$ – the temperature of the internal air inside the liferaft
- $T_{\text{surface canopy}}$ – the surface temperature of the canopy
- $T_{\text{surface side}}$ – the surface temperature of the sides

Solving the 3 above equations reveals the following relationships:

Based on (4):

$$t_{canopy} = \frac{U_{canopy}}{h+U_{canopy}} * t_{int} + \frac{h}{h+U_{canopy}} * t_{amb} \quad (6)$$

Based on (5):

$$t_{tube} = \frac{U_{tube}}{h+U_{tube}} * t_{int} + \frac{h}{h+U_{tube}} * t_{amb} \quad (7)$$

Inserting (6) and (7) into (3) and solving for t_{int} reveals the following relationship:

$$t_{int} =$$

$$\frac{U_{ppe} * A_{ppeAir} * t_{body} - U_{ppe+floor} * A_{ppefloor} * (t_{body} - t_{water}) + U_{floor} * A_{floorExpAir} * t_{water}}{U_{floor} * A_{floorExpAir} + U_{canopy} * A_{canopy} - \frac{U_{canopy}^2 * A_{canopy}}{h+U_{canopy}} + U_{tube} * A_{tube} - \frac{U_{tube}^2 * A_{tube}}{h + U_{tube}} + U_{ppe} * A_{ppeExpAir} + C_{pAir} * \rho * air_{vol} * t_{amb}}$$

$$+$$

$$\frac{\frac{U_{canopy} * A_{canopy} * h}{h + U_{canopy}} * t_{amb} + \frac{U_{tube} * A_{tube} * h}{h + U_{tube}} * t_{amb} + C_{pAir} * \rho * air_{vol} * t_{amb}}{U_{floor} * A_{floorExpAir} + U_{canopy} * A_{canopy} - \frac{U_{canopy}^2 * A_{canopy}}{h+U_{canopy}} + U_{tube} * A_{tube} - \frac{U_{tube}^2 * A_{tube}}{h + U_{tube}} + U_{ppe} * A_{ppeAir} + C_{pAir} * \rho * air_{vol} * t_{amb}}$$

(8)

The total energy lost by the life raft is given by the following equation:

$$Q_{total} =$$

$$Q_{cond\ lost\ to\ water} + Q_{conv\ lost\ air\ tubes} + Q_{conv\ lost\ air\ canopy} + Q_{ventilation} =$$

$$U_{ppe+floor} * A_{ppefloor} * (t_{body} - t_{water}) + U_{floor} * A_{floorExpAir} * (t_{int} - t_{water}) +$$

$$h * A_{tube} * (t_{tube} - t_{amb}) + h * A_{canopy} * (t_{canopy} - t_{amb}) + c_p * \rho * q_v * (t_{int} - t_{amb}) \quad (9)$$

Abbreviations:

Abbreviation	Description	Denomination
U_{ppe}	Heat transfer coefficient personal protective equipment	Watt/KelvinMeter^2
U_{floor}	Heat transfer coefficient liferaft floor	Watt/KelvinMeter^2
$U_{ppe+floor}$	Heat transfer coefficient personal protective equipment and	Watt/KelvinMeter^2
U_{canopy}	Heat transfer coefficient life raft canopy	Watt/KelvinMeter^2
U_{tubes}	Heat transfer coefficient life raft tubes	Watt/KelvinMeter^2
A_{ppeAir}	Area of personal protective equipment exposed to air	meter^2
$A_{ppeFloor}$	Area of personal protective equipment exposed to life raft	meter^2
$A_{floorExpAir}$	Area of life raft floor exposed to air	meter^2
A_{canopy}	Area canopy	meter^2
A_{tube}	Area tubes	meter^2
h	Convective heat transfer coefficient	Watt/KelvinMeter^2
$Q_{ventilation}$	Energy lost due to ventilation	Watt
$Q_{radiation}$	Energy lost due to radiation	Watt
$Q_{cond\ lost\ to\ water}$	Heat loss to water through conduction	Watt

$Q_{conv\ air\ tubes}$	Heat loss to air through conductive processes on the air tubes	Watt
$Q_{conv\ canopy}$	Heat loss to air through conductive processes on the canopy	Watt
σ	Stefan-Boltzmann Constant = 5.6703 10^{-8}	Watt/Kelvin^{4}Meter2
c_p	Specific heat air	Joules/kgKelvin
ρ	Density of air	Kg/m^3
q_v	Air volume flow	M^3/Sec

Figure 2 Abbreviations used in formulaes

The above approach takes into account that only parts of the floor is covered by the life raft participants. The area covered is dependent on the number of people onboard the life raft. There will be a conductive heat loss from the participants directly through the personal protective equipment and through the floor into the sea, see Figure 1 Heatloss mechanisms from liferaft (cross section) the remaining area of the floor will be exposed to the internal air, a conductive heat loss through the floor is considered for this area.

The heat loss caused by the need for ventilation is dependent on the participants oxygen consumption, which again is dependent on the metabolic rate/activity intensity. It is however assumed that from a practical perspective venting a minimum, replacing only the used oxygen is difficult to achieve. A ventilation rate is defined, which is equivalent to an oxygen consumption induced by a metabolic rate of 150 Watts per person.

Assumptions and simplifications

To be able to model a life raft, several assumptions and simplifications have been made. These assumptions and simplifications will influence the results, but are not believed to affect the results to a high degree as the natural variations within a group of people represent the biggest uncertainty:

- There is a high variability within the metabolic rate of a population. During extreme events when the body can produce several hundred watts (Xiaojiang Xua et al., 2004).
- There is a high variability within a population to with regards physical (and psychological) endurance. This is highly correlated to physical fitness and age.
- The effect of only 430mm breadth (SOLAS requirement) will not only restrict ability to move limbs and generate heat, but also enable conductive heat transfer between the different participants.
- The effect of wet evacuation/water being present inside (on the floor) the raft is not considered.
- Lack of food/water reduces the ability to carry out activities with a high metabolic rate

The mathematical methodology described is based on the following assumptions:

- Ideal and homogeneous thermal conditions within the air trapped inside the raft
- No heat lost to sea/water due to water spray
- No accumulation of an insulating ice/snow barrier on the canopy
- Homogenous design of the raft with no major thermal bridges from the inside to the ambient air/water
- Ideal conductive heat transfer is taking place through the life raft bottom to the sea water
- Temperature of air at exhalation is defined to 30 degrees Celsius

The above-mentioned mechanisms are expected to represent a larger uncertainty/variability than the uncertainty resulting from the simplification represented in the mathematical modelling.

It can be expected that the model represents a "best case" compared with a real survival situation. The model only considers the thermal challenges and none of the additional challenges present when conducting a prolonged stay in a life raft are addressed.

VERIFICATION OF MODEL

Verification of model results was carried out at the training facilities of Falck Nutec at Nesodden. One of their modules in the survival training program is a stay (about 15 minutes) in a life raft. During a one of these stays the raft and the raft and two of the survival suites were fitted with temperature recording devices. Due to the participants being part of an ongoing course, the measurements were conducted in a way that fitted into the course schedule.

Figure 3 Falck Nutec training facilities at Nesodden, Norway

The following conditions were present:

Parameter	**Value**
MetOcean Parameters	
Wind	Average 2.5 m/s
Ambient air temperature	0.9 C
Sea water temperature	2.9 C
Precipitation	Light snow
Equipment	
Life Raft	Viking-Life 20 person life raft, floor not inflated
Survival suits	Hansen Protection helicopter suits
Undergarment	One layer of wool underwear
Participants	
Gender	Male
Age	20 to 60 years
Number of participants	Test Run1: 16, Test Run2: 7

Figure 4 Conditions present during trials

Internal air Temperature

The air temperature inside the raft was measured at 3 different levels inside the raft. There was observed little difference between the 3 different measurement points due to mixing processes taking place inside the raft.

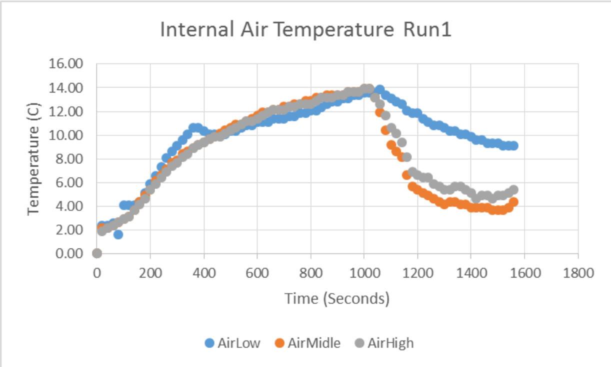

Figure 5 The internal air temperature (measured at different vertical locations) in the life raft, Run1, 16 People onboard.

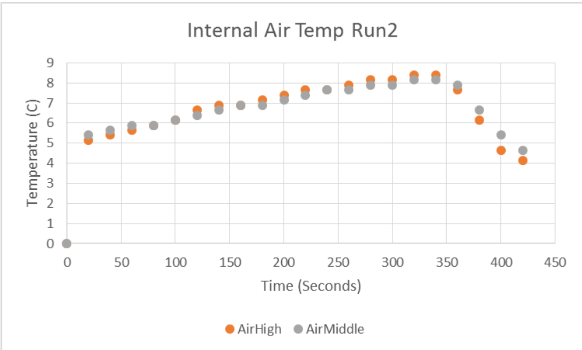

Figure 6 The internal air temperature in the life raft, Run2, 7 People.

In Test Run 1, the system had reached a relatively steady state equilibrium after about 1100 seconds. In Test Run 2 the system had stabilized after about 340 seconds. Ideally there should have been more time allocated to let the system stabilize, but due to the progression of the safety course, the measurements had to be aborted. The temperatures recorded at about 1100 seconds (Test Run 1) and 340 seconds (Test Run 02) into the test was extracted and utilized for further analysis.

Canopy outside surface temperature

The canopy surface temperature was measured by attaching sensors to the outside of the canopy. This proved difficult due to snow, water and ice and some sensors were attached by sticking them underneath a reflector strip. See images below.

Figure 7 Liferaft logging system

Measuring the canopy temperature with an ir-thermometer revealed local differences of more than 2 degrees C. This is assumed to originate from several different mechanisms at play:

- Distance from personnel inside life raft to the inside canopy surface.
- Uneven temperature distribution inside life raft
- Insulation induced by inflatable canopy beam
- Flapping of canopy due to people inside touching the canopy and wind induced movement, reducing and generating movement of the insulating air gap enclosed in the double canopy.
- Different degree of stretching of the material, depending on wind and pressure in inflated tubes.

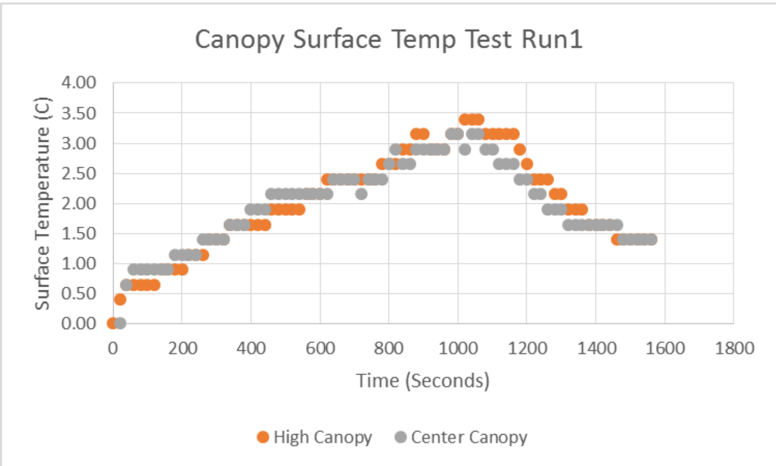

Figure 8 The surface temperature of the life raft canopy Test Run 1

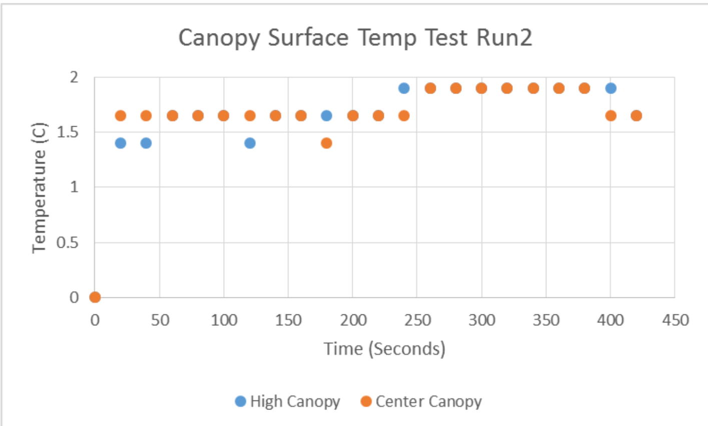

Figure 9 The surface temperature of the life raft canopy Test Run 2

During Test Run 2 the canopy temperature was also measured with an IR-thermometer. The measurements revealed the following distributions:

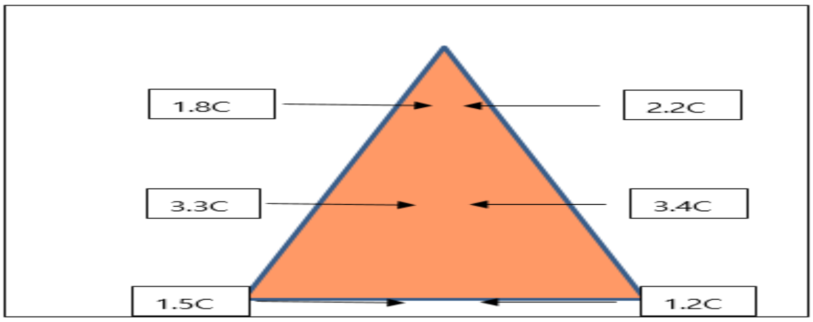

Figure 10 Canopy temperature distribution

It is evident that there are thermal bridges and fluctuations in the surface temperature of the canopy.

In Test Run 1, 3.4 degrees Celsius was assumed to be representative of the canopy outside surface temperature, while in Test Run 2 1.8 degrees Celsius was assumed to be representative of the canopy outside surface temperature.

Tubes outside surface temperature

The temperature was measured utilizing an IR-thermometer. It was evident that being partly submerged, the outside surface temperatures of the tubes were greatly affected by the water temperature. Based on readings from the IR-thermometer 2.2 degrees Celsius was assumed to be the tube outside surface temperature in Test Run 1 and 1.9 degrees Celsius was assumed to be the tube outside surface temperature in Test Run 2.

Survival suit outside surface temperature

The outside air temperatures of the survival suits were also measured. A sensor was attached to the pocket that was supposed to contain the “buddy lines”. These pockets are located on the chest of the suit. There were significant variations with regards to the measured temperatures. This was due to the effects of the following parameters:

- Participant movement
- Contact area between the sensor and the suit
- Location of participant (e.g. facing a cold area)
- Amount of air trapped inside survival suit

Based on the assumption that the participants had a surface area of 1.9 m^2 and a metabolic rate of 130 Watts per person. This harmonizes with the findings in Assessment of Thermal Protection of Life rafts in Passenger Vessel Abandonment Situations (Lawrence Mak, Andrew Kuczora et al., 2008) The thermal resistance values for PPE (Personal Protective Equipment), including underwear were calculated.

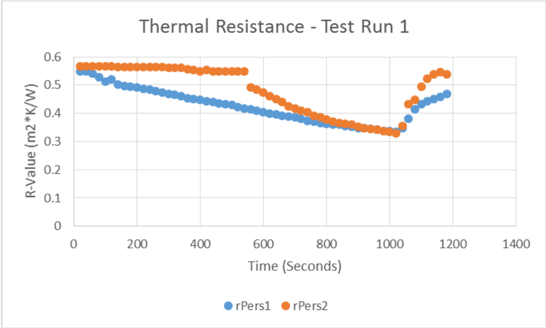

Figure 11 Thermal resistance for underwear and PPE, Test Run1

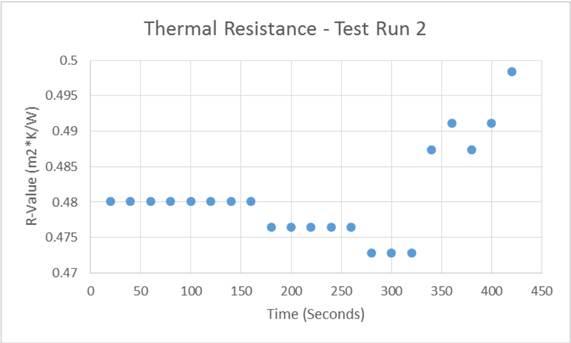

Figure 12 Thermal resistance for underwear and PPE, Test Run2

The rapid increase/variation in calculated values at the right end of the plots is due to experiment abortion and should be disregarded. Based on the measured parameters a thermal resistance value of 0.5 m^2Kelvin/Watt was chosen.

Implementation of recorded values in model

The main measured parameters measured on the raft were implemented in the model. The recorded temperature values were used to adjust the model to represent a real scenario.

The following raft dimension parameters were utilized in the calculation:

- Raft external diameter = 3.75
- Raft height of canopy= 1.65
- Area raft canopy = 20.8 m^2
- Area bottom of raft =16.9 m^2
- Surface area of tubes = 11.43 m^2

The following thermal resistance values were utilized in the calculations:

- Thermal resistance PPE (incl underwear) = 0.5 m^2Kelvin/Watt
- Thermal resistance contact area PPE (incl underwear) and bottom when sitting (compressing insulation layer) = .35 m^2Kelvin/Watt
- Thermal resistance raft bottom = 0.15 m^2Kelvin/Watt
- Thermal resistance raft tube = 0.68 m^2Kelvin/Watt
- Thermal resistance raft canopy = 0.6 m^2Kelvin/Watt

The following metocean parameters were utilized in the calculations:

- Ambient Air Temperature = 273.9 Kelvin

- Ambient Water Temperature = 275.9 Kelvin
- Windspeed = 2.5 meter/second

Implementation of the above values in the model revealed the following results:

	Measured Values	**Modelled Values**
Run2 -7 people onboard		
Internal air temp (C)	8.40	7.47
tempTube (C)	1.90	2.22
tempCanopy (C)	1.80	2.35
qTotal/Person	121.37	125.57
Run1 -16 people onboard		
Internal air temp (C)	13.90	14.22
tempTube (C)	2.20	3.57
tempCanopy (C)	3.40	3.85
qTotal/Person	100.42	106.75

Figure 13 Measured Values vs Modelled values

As seen above there is a margin of error of 4.7% for Test Run1 and an margin of error of 3.5% for Test Run2 with regards to the total energy loss from the life raft. This figure does not take into account the potential margin of error associated with the conductive heat loss from the participants, through the bottom of the life raft to the sea or the heat loss arising as a result of ventilation (ventilation rate = 0).

DISCUSSION

Interpretation of results

The cumulative energy produced by the participants in the raft is to compensate for the energy lost. The energy produced by the human body through metabolic processes is a complex study and will vary with age, weight, body surface area, fitness and physical activity level. The following table indicates general metabolic rates for different activities.

Activity Description	W/m^2	W (body
Sleeping	46	83
Standing	70	126
Walking (2km/hour, level ground)	110	198
Walking (5km/hour, level ground)	200	360
Swimming	348	624
Running (15km/hour)	550	990

Figure 14 Metabolic rate for different level of activities (Engineering ToolBox , 2004)

According to the requirements defined in the IMO Polar Code you are to be able to survive for a minimum of 5 days (or until being rescued). Based on the "Activity Description" in the figure above it is evident that the human body is able to produce up to 1000 Watts, but few people are able to produce this for an extended period of time. For a time span of 5 days it is not likely that a person is able to produce more than about 150 watt on an average.

Utilizing the above-mentioned model, the results have been plotted for an arbitrary date (01.01.2018) in the North Atlantic. The metocean data is was downloaded (European Centre for Medium-Range Weather Forecasts, 2012) and plotted in a GIS format. The model results reveal that obtaining an adequate cumulative thermal protection, reducing the heat loss per person to a significant degree is possible, if the right measures are implemented, e.g. the importance of floor insulation to reduce the heat loss to the sea. This harmonizes with the results found in “Effect of wetness and floor insulation on thermal responses during cold exposure in a life raft” (Michel B. DuCharme et al.)

It is important to note that there are many sources of uncertainty associated with the calculation. However, there is also a large natural variation among the participants in a survival scenario with regards to body weight, body surface area, metabolism, life raft ergonometric and movement. As long as there are no definitions with regards to the human abilities and survival strategies present in a real-time survival scenario, the uncertainty associated with the above-mentioned parameters is believed to outweigh the uncertainty associated with the model.

The results are to be found in Appendix 1.

CONCLUSIONS

Calculating heat loss per person in a real-time survival scenario is dependent on many uncontrollable variables. Isolating and assessing these variables individually is a challenging task. Obtaining full scale data describing the cumulative effect of these variables on survival rates is extremely challenging.

It is clear that a theoretical approach can reveal the significance of simple measures with regards to reduction of the heat loss per person. Utilizing a theoretical approach when optimizing a survival packet will help to gain an understanding of the impact caused by the different types of equipment or different combinations of equipment packages utilized to produce a cumulative insulation effect.

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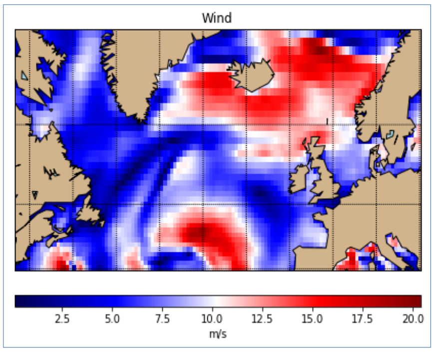
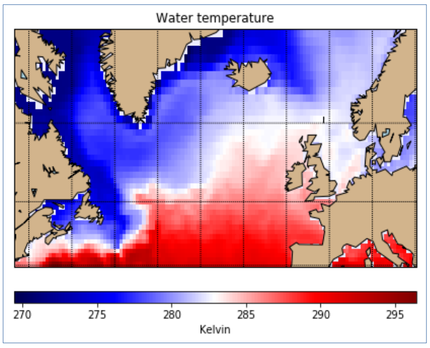
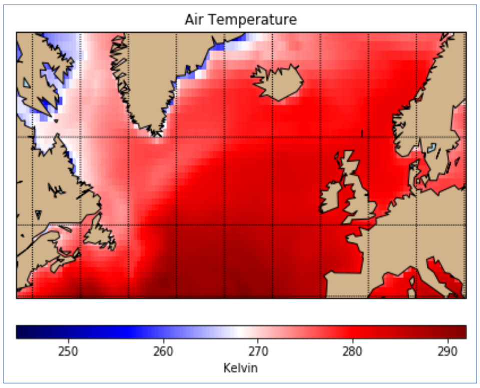
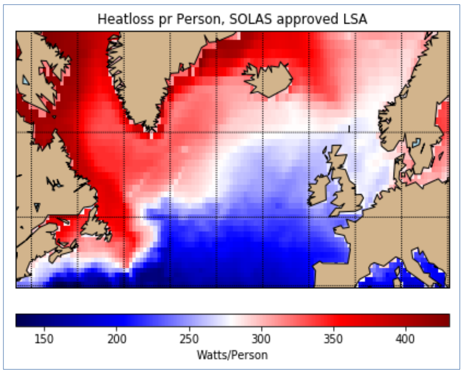
APPENDIX 1 – EXAMPLE CALCULATION

The heatloss pr. Person from a 20-person liferaft filled with 10 persons (excluding last plot where the life raft is filled with 15 persons) calculated for the North Atlantic on 31.12.2017. The metocean data has been obtained from NCAR hindcast models (European Centre for Medium-Range Weather Forecasts, 2012). Each person inside the raft is assumed to wear normal jacket/shirt under the required SOLAS equipment.

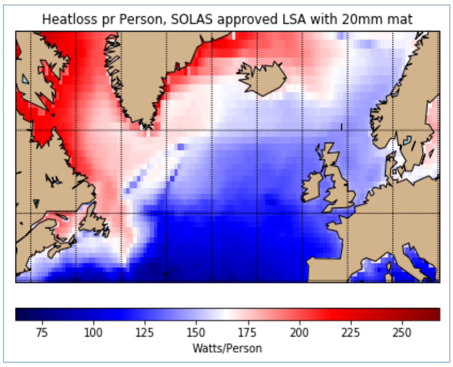




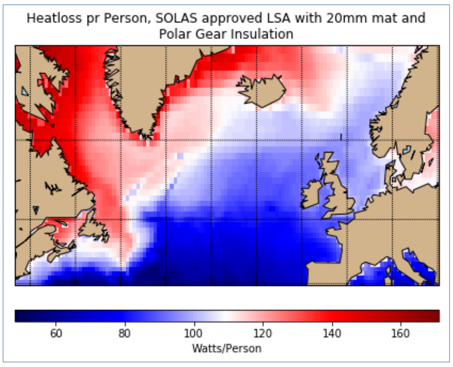




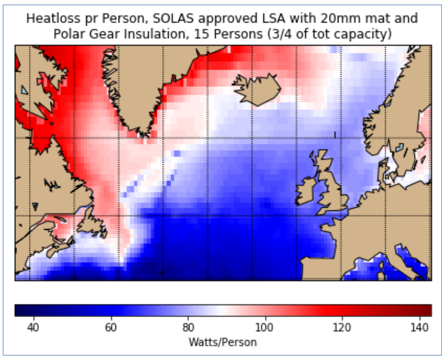
The individuals are wearing normal clothes under standard LSA equipment. The life raft is filled at 50% capacity.



The individuals are seated on a 20mm closed foam insulation mat. The life raft is filled at 50% capacity.



The individuals are seated on a 20mm closed foam insulation mat and are wearing polar gear insulation layers (4 clo). The life raft is filled with 50% capacity.



The individuals are seated on a 20mm closed foam insulation mat and are wearing polar gear insulation layers (4 clo). The life raft is filled at 75% capacity.