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SUB-COMMITTEE ON SHIP SYSTEMS AND EQUIPMENT
7th session
Agenda item 3

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NEW REQUIREMENTS FOR VENTILATION OF SURVIVAL CRAFT

A mathematical model of lifeboat microclimates for polar regions

Submitted by Canada

SUMMARY

Executive summary:	This document provides information and a mathematical model of lifeboat microclimates for polar regions
Strategic direction, if applicable:	Other work
Output:	OW 42
Action to be taken:	Paragraph 4
Related documents:	SSE 6/18; MSC.1/Circ.1614 and SSE 7/3

Background

1 The Maritime Safety Committee (MSC), at its 101st session (5 to 14 June 2019), approved the *Interim guidelines on life-saving appliances and arrangements for ships operating in polar waters* (MSC.1/Circ.1614).

2 The sixth session of the Sub-Committee on Ships Systems and Equipment (SSE 6) re-established the Correspondence Group on Life-Saving Appliances (LSA). The LSA Correspondence Group's terms of reference included new requirements for ventilation on survival craft and the need to gather and review data on microclimate, and further consider the possible benefits of air quality monitoring for all survival crafts (SSE 6/18, paragraph 4.18).

New research on a mathematical model of lifeboat microclimates in polar regions

3 Canada acknowledges the hard work of the Coordinator and participants of the Group, and would like to provide the results of a new research to the Sub-Committee titled "A mathematical model of lifeboat microclimates in polar regions", with a view to complementing the report of the Group (SSE 7/3), as set out in the annex.

Action requested of the Sub-Committee

4 The Sub-Committee is invited to note the information set out in the annex when considering document SSE 7/3.

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ANNEX

NRC·CNRC

A MATHEMATICAL MODEL OF LIFEBOAT MICROCLIMATES IN POLAR REGIONS

Report No.: NRC-OCRE-2019-TR-045
Date: 2019/12/11

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I. Summary

This report discusses the results of a mathematical model developed in Microsoft Excel® to assess the performance of lifeboats in the Arctic and Antarctic regions. The model uses iterative calculations based on the principles of heat transfer to analyze the interior microclimate of lifeboats, including temperature and air quality. Other calculations include those relating to metabolic rate, skin temperature, and carbon dioxide concentration, in order to determine whether or not a lifeboat's environment is survivable in a variety of evacuation scenarios. The model considers a number of factors in these evacuation scenarios, including ambient temperature, occupancy, mass and height of occupants, size of lifeboat, clothing ensembles worn, wetness, and wind. Presently, the International Maritime Organization is further developing their regulations surrounding the performance of lifeboats in Polar Regions; this report, therefore, supplies further information regarding the quality of air and temperature inside lifeboats.

The results indicate that the interior environment of a lifeboat may degrade to the point where it could impact occupant survival and comfort. Therefore, lifeboat performance should be further considered by the international maritime community. The report focuses on several main areas of weakness, which include poor air quality with very high concentrations of carbon dioxide inside lifeboats when occupied as well as unstable interior air temperatures. Furthermore, the results indicate that the suggested required ventilation rate of 5.0 $m^3 \cdot hr^{-1}$ per person is insufficient, and that a per-person ventilation rate cannot be determined insofar as ventilation needs change linearly with mass rather than number of occupants. The model also finds that lifeboats without an added heater may not offer reliable thermal protection in cold regions, and that partially enclosed lifeboats, although allowed in Polar Regions, may not offer adequate interior environmental conditions for those awaiting rescue due to the increased air exchange with the exterior environment compared to the totally enclosed models.

The report therefore recommends:

1. An active ventilation system allowing the interior of the lifeboat to maintain a carbon dioxide concentration below 5,000 parts per million (ppm);
2. Sensors to be implemented within survival craft, in order to monitor the levels of carbon dioxide and therefore adjust ventilation as needed;
3. Heaters with controllable levels to be installed in survival crafts, so as to remove the dependence on human heat output;
4. That partially enclosed lifeboats undergo further testing before approval in Polar Regions;
5. Developments in testing methods for air quality inside a lifeboat, as tests are aborted at 5,000 ppm for human safety and therefore do not account for the equilibrium level of carbon dioxide, which is generally lower than the peak leading to abortion.

II. List of Tables

III. List of Figures

IV. Abbreviations/Symbols

ΔMSHF – change in mean skin heat flux, or increased heat output past resting metabolic rate ($W \cdot m^{-2}$).

ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers

cabin – the interior of the lifeboat

clo – clothing insulation value

FRP – fibre-reinforced plastic

IMO – International Maritime Organization

k-factor – thermal conductivity ($W \cdot m^{-1} \cdot °C^{-1}$)

LSA – life-saving appliances

LSA Code – Life Saving Appliance Code

MDLT – mean daily low temperature

MSHF – mean skin heat flux ($W \cdot m^{-2}$)

NRC – National Research Council of Canada

PELB – partially enclosed lifeboat

Polar Code – IMO's *International Code for Ships Operating in Polar Waters*

ppm – parts per million

PST – polar service temperature (10°C less than the MDLT)

RER – respiratory exchange ratio

SA – surface area (m^2)

SOLAS – International Convention for the Safety of Life at Sea

τ – time constant (s)

T_{sk}= mean skin temperature (°C)

TELB – totally enclosed lifeboat

TEMPSC – totally enclosed motor propelled survival craft

TWA – time weighted average

U-value – thermal transmittance ($W \cdot m^{-2} \cdot °C^{-1}$)

V. Equations

Equation 1: Heat Transfer .... $Q = U \times A \times \Delta T$

Equation 2: Heat input .... $Q_{in} = Q_{heater} + Q_{eng} + Q_{occ}$

Equation 3: Time constant .... $\tau = \frac{C}{UA}$

Equation 4: Heat capacity .... $C = c_p \times \rho \times V$

Equation 5: Newton's Law of Cooling .... $T_t = T_o + (T_i - T_o) \times e^{-t/\tau}$

Equation 6: Mean skin heat flux .... $MSHF = \frac{T_{air} - T_{sk}}{-clo}$

Equation 7: Oxygen consumption rate .... $MSHF = 281.65 + 80.65 \times RER \times \frac{\dot{V}O_2}{SA}$

Equation 8: Minimum CO_2 production .... $\dot{V}CO_{2min} = \frac{\dot{V}CO_2 base}{1000} \times m$

Equation 9: Concentration (ppm) .... $\frac{VCO_2}{V_{air}} \times 10^6 = ppm$

Equation 10: Dilution method .... $C_e = C_i \times e^{-N \times t/V}$

1.0. Introduction

Arctic-travelling ships must rely on life-saving appliances (LSA) in the event of a maritime emergency. As a response to growing marine traffic in the Arctic and Antarctic[1], the International Maritime Organization (IMO) created the *International Code for Ships Operating in Polar Waters* (the Polar Code) in order to enhance safety for ships travelling in polar waters. The Polar Code specifies that survival crafts must offer a “habitable” environment for the survivors [1]. Thus, in an emergency situation, one of the most important goals is to ensure an interior environment that allows the occupants to maintain a stable deep body temperature (~37°C) by allowing their skin to remain in the thermoneutral[2] zone, and to offer adequate ventilation for those on board the survival craft. Research based on standard lifeboats, as currently offered, often reveals gaps in lifeboat performance in these areas when utilized in polar waters.

The following report outlines the development and results of a computer model designed in Microsoft Excel® to analyze the thermal protection and ventilation of various sized lifeboats based on a number of external and internal factors. This model is not meant to provide conclusive statements about the performance of specific lifeboats, but rather to cast light on some potential issues with the use of standard lifeboats in polar environments. The model effectively illustrates the complexity of using a lifeboat in Arctic or Antarctic conditions, and illustrates concerns with air quality and internal temperature.

The variables in this model are summarized in the table below:

Table 1: Variables and resulting output of Excel model.

Input variable	Dependent/Output
Dimensions (length, width, height) (m)	Area (m^2), volume (m^3), heat transfer (W)
Percentage of canopy as canvas (%)	Area (m^2), PELB dimensions, heat transfer (W)
Outside ambient temperature (°C)	Heat transfer (W), rate of temperature change (s)
Clo value/insulation value of ensemble (clo)	MSHF ($W \cdot m^{-2}$), heat input to cabin (W), CO_2 concentration (ppm)
Wind velocity (inside, outside)	U-value ($W \cdot m^{-2} \cdot °C^{-1}$), heat transfer (W)
Initial interior temperature (°C)	Heat transfer (W), rate of temperature change (s)
Heater and engine power (W)	Heat input (W)
Ventilation rate ($m^3 \cdot s^{-1}$)	Infiltration heat loss (W), CO_2 concentration (ppm)

[1] See Appendix A for marine traffic patterns in Polar Regions.
[2] For the purposes of this model, a body with a stable deep body temperature is considered as having a skin temperature (T_{sk}) of 33°C, which is in the thermoneutral zone.

Other values which can be modified include specific heat capacity of air, density of air, average occupant mass and height, etc. These can be modified to suit a particular environmental condition; for example, the value of air density can be changed to suit a specific ambient temperature.

2.0. Development

As this is a desktop model, it is based on data from experiments previously conducted by the NRC and other researchers. No new experimental data was gathered for this model.

A heat transfer calculation was used to derive the thermal transmittance value for a lifeboat [2], using data from the SARex 2017 report [3]. This was then checked for reasonableness by using thermal conductivity values for fibre-reinforced polymer (FRP) and measurements of lifeboat wall thicknesses, and further verified with previous results obtained by Mak et al. [4].

$$Q = U \times A \times \Delta T \qquad \textit{Equation 1}$$

Where:

Q = heat transfer (W);

U = thermal transmittance ($W \cdot m^{-2} \cdot °C^{-1}$);

Where U = k/L (k = thermal conductivity ($W \cdot m^{-1} \cdot °C^{-1}$), L = thickness (m).

A = surface area (m^2);

ΔT = temperature change (T_o-T_i) (°C);

(T_o = outside temperature, T_i = inside temperature).

Once thermal transmittance was derived, the heat lost by a lifeboat of given dimensions could be determined. This was then subtracted from the sum of heat entering the lifeboat to derive net heat loss or gain, calculated from:

$$Q_{in} = Q_{heater} + Q_{eng} + Q_{occ} \qquad \textit{Equation 2}$$

Where:

Q_{in} = heat entering lifeboat (W);

Q_{heater} = heat from heater (W);

Q_{eng} = heat from engine (W);

Q_{occ} = heat output from occupants (W).

The heat output from the occupants is calculated using the number of occupants in the lifeboat and their average heat output, which is calculated using equation 7 and assuming an initial skin temperature in the thermoneutral zone (i.e. ~33.0°C) [5].

Using this net heat loss (or gain), a new thermal transmittance value was derived to describe the heat flow from a lifeboat with these conditions (i.e. occupancy, active heat input, etc.) by rearranging the heat balance equation thusly:

$$U = \frac{Q}{A \times \Delta T}$$

Using thermal transmittance, a time constant to describe the rate of heat flow from the lifeboat can be estimated using the following formula as reported by Lewis et al. [6]:

$$\tau = \frac{C}{UA}$$ *Equation 3*

Where:

τ = time constant (s);

C = heat capacity of lifeboat (J·°C^{-1})

A = area (m^2)

To calculate the heat capacity:

$$C = c_p \times \rho \times V$$ *Equation 4*

Where:

c_p = specific heat capacity of air at given temperature (J·kg^{-1}·°C^{-1});

ρ = density of air (kg·m^{-3});

V = volume of lifeboat interior (m^3).

With this time constant, and the knowledge of initial and external temperature, the model then indicates the temperature inside the lifeboat at any given time t in seconds, with the following use of Newton's Law of Cooling:

$$T(t) = T_o + (T_i - T_o) \times e^{-t/\tau}$$ *Equation 5*

Where:

t = time (s).

Using this model of temperature and time, an iterative calculation was performed to update the mean skin heat flux (MSHF) in relation to the internal temperature by rearranging the following equation as reported by Romet et al. [7]:

$$MSHF = \frac{Tair - Tsk}{-Clo} \qquad \textit{Equation 6}$$

Where:

T_{air} = temperature inside the lifeboat (°C);

T_{sk} = skin temperature of occupant (°C);

Clo = clothing insulation value (clo);

$MSHF$ = mean skin heat flux (W·m^{-2}).

The clo value was first multiplied by a factor of 0.155 to convert it to an SI insulation value in units of m^{2}· C·W^{-1}.

For each iteration of interior temperature and MSHF from the occupants, a new net heat transfer and thus a new time constant was derived to more accurately describe the rate of heat transfer from the lifeboat. An iterative calculation was used to account for the changing heat transfer due to changing temperature gradient between the lifeboat and the atmosphere, as well as the changing MSHF and therefore heat input from the occupants.

The following equation, reported by Peronnet and Massicotte, was then used to determine the rate of oxygen consumption based on the MSHF [8]:

$$MSHF = (281.65 + 80.65 \times RER) \times \frac{\dot{V}O_2}{SA} \qquad \textit{Equation 7}$$

Where:

RER = respiratory exchange ratio (V_{CO2}/V_{O2}) (assumed 1);

$\dot{V}O_2$ = oxygen consumption rate (L·s^{-1});

SA = surface area of average human (m^{3}).

Rearranged,

$$\dot{V}O_2 = \frac{SA \times MSHF}{362.3}$$

A RER of 1 was assumed for this model, and therefore oxygen consumption is considered equal to carbon dioxide (CO_2) production ($\dot{V}O_2 = \dot{V}CO_2$) . A baseline $\dot{V}CO_2$ of 3.16 mL·min^{-1}·kg^{-1}

was set based on experimental data from Aylward [9], and the minimum calculated per kilogram depending on occupant mass:

$$\dot{V}CO_{2min} = \frac{\dot{V}CO_{2base}}{1000} \times m \qquad \textit{Equation 8}$$

Where:

$\dot{V}CO_{2min}$= minimum CO_2 production ($L{\cdot}min^{-1}$);

$\dot{V}CO_{2base}$= measured baseline CO_2 production rate ($L{\cdot}min^{-1}{\cdot}kg^{-1}$) [9];

m = mass of occupant (kg).

Using iterative calculations, the rate of oxygen consumption was calculated for the increasing or decreasing MSHF. Since the RER was assumed as 1, the consumption of oxygen corresponded with the production of CO_2.

An estimate of the lifeboat volume was made based on lifeboat dimensions and occupancy, modelling the lifeboat as a rectangular prism. Once the interior volume was estimated (minus the volume of the occupants), the concentration of CO_2 in ppm was calculated using the following:

$$\frac{V_{CO2}}{V_{air}} \times 10^6 = ppm \qquad \textit{Equation 9}$$

Where:

V_{CO2} = volume of CO_2 (m^3);

V_{air} = total volume of air inside the lifeboat (m^3);

ppm = parts per million.

The model could then indicate when the concentration of CO_2 inside the lifeboat exceeded the safety level of 5,000 ppm. In order to determine CO_2 concentrations inside a ventilated lifeboat, the dilution equation, as reported by Mak et al [10], was rearranged and used thusly:

$$C_e = C_i e^{\left(\frac{-N \times t}{V}\right)} \qquad \textit{Equation 10}$$

Where:

C_e= diluted concentration (after ventilation) (ppm);

C_i= initial concentration (ppm);

N= number of air exchanges (h^{-1});

t= time (h);

V= volume of lifeboat (m^3).

3.0. Discussion of Results

There are many factors to consider when examining the potential performance of a lifeboat in polar waters, including but not limited to: wind speed, ambient temperature, number of occupants, lifeboat size, and clothing ensembles worn. To ensure survivability in an emergency situation in Polar Regions, all of these variables must be considered, creating a very complex survival situation. For the purpose of this report, the model was run with several variables to compare a variety of situations. All trials considered a lifeboat with dimensions of 8.6 m length, 3.35 m width, and 3.55 m height. The estimated surface area, excluding area below the waterline, is 71.23 m^2, and the volume 30.16 m^3 (before subtracting the volume occupied by persons). The lifeboats were considered as totally enclosed unless otherwise denoted as partially enclosed. The variables changed between trials included clo value of ensemble worn, occupancy, initial temperature, and other factors as noted. A general base case of 55 occupants, -10°C ambient temperature, and ensembles rated at 2.91 clo[3] is considered, with variations noted where applicable.

3.1. Temperature

The cold ambient temperature of a polar evacuation can make significant demand on the human body. In situations where the heat input to the lifeboat cannot balance with the heat transferring out, the temperature inside the lifeboat will drop, sometimes to dangerously low levels. In order to maintain a thermoneutral skin temperature in extreme temperatures, the human

[3] The chosen ensemble at 2.91 clo is based on ensembles tested by Power and Monk [26].

body will need to compensate with a significant amount of “extra” energy, beyond the resting metabolic rate heat output of approximately 58.2 W·m^{-2} [11].[4]

The model compared the MSHF (W·m^{-2}) required for occupants in different clothing ensembles to maintain a thermoneutral skin temperature. A lifeboat with occupants wearing the higher clo value suits will experience a much more rapid decrease in cabin temperature, due to the suits preservation of their body heat, thus not allowing it to escape to the cabin. However, their skin and, subsequently, deep body temperatures therefore remain stable with less energy expelled. Thus, despite the colder cabin, a well-insulated clothing ensemble can protect the individuals within the craft. As will be commented on later, these ensembles also result in a theoretical decreased rate of CO_2 production.

The necessity to produce this extra energy is a considerable demand on a human being surviving in a likely crowded survival craft with limited rations; in many circumstances, the extra heat production required is simply not feasible for a human, particularly for the long expected time of rescue[5] of a polar evacuation, or requires taxing levels of shivering. Physical activity, for example, is one way to increase the human body’s metabolic rate, but is not always possible in an emergency situation, considering space confinements, possible injuries, and the risk of exhaustion. Figure 1 shows the extra energy above baseline required to maintain a thermoneutral skin temperature at a given cabin temperature in different clothing ensembles. A clothing ensemble with lower insulation value requires the occupants to work harder to maintain a stable deep body temperature of ~37° C, by physical activity or shivering. Well-insulated ensembles improve the occupant’s ability to maintain their deep body temperature by reducing the heat required to do so, regardless of the air temperature, and thus reduce the demand on the human body, extending the possibility of survival.

[4] For this model, baseline MSHF was calculated using equation 7 as reported by Peronnet and Massicotte [8] and a constant $\dot{V}O_2$ of 0.3 L·min^{-1}, and was compared to the required MSHF (as calculated by the model) in order to determine the extent of extra heat output needed to maintain a skin temperature of 33°C.

[5] Kennedy et al. (2013) researched the estimated times of rescue in several locations in the Canadian Arctic, and found that, in several situations, the estimated time of rescue was in excess of the 5 days minimum set by the Polar Code [18].

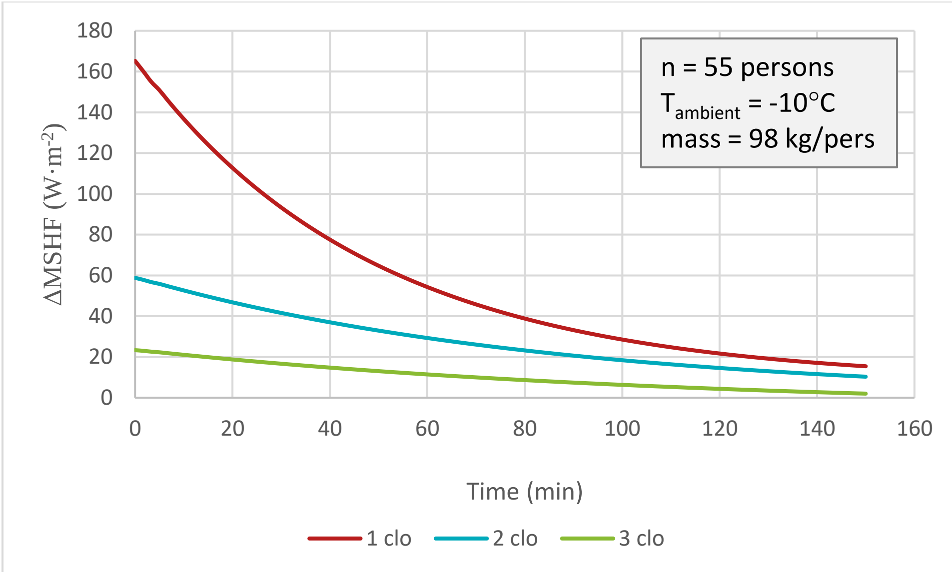

Figure 1: ΔMSHF (W·m^{-2}) over time (min) with different clo values (clo), where ΔMSHF denotes the extra energy required above a resting MSHF of ~50 W·m^{-2}.

It is evident from numerous trials ([12], [13], [14]) that the individuals within a survival craft create a significant amount of heat output, which can subsequently increase cabin temperature. An at-capacity lifeboat in particular can grow very warm; as the temperature climbs, the MSHF required of the individuals to maintain skin temperature begins to drop as the interior cabin temperature approaches skin temperature. As this happens, and as the gap narrows, the survivors' heat output decreases to the point that heat transfer in the lifeboat reaches a balance, and the interior temperature reaches an equilibrium point. As shown in Figure 2 below, a lifeboat with 20 persons at -10°C ambient temperature will eventually balance slightly above 10°C, while the same lifeboat climbs to over 20°C while at full (55-person[6]) capacity due to the extra heat output. At 3 persons, there is not enough heat output to increase the cabin temperature.

[6] The lifeboat in the model is modelled after the lifeboat used in the SARex trials, using the same dimensions; however, in the SARex trials, this boat was considered as having a capacity of 55, which is based on average mass of 98 kg. With an average mass of 75 kg, as generally held in IMO's Life Saving Appliance Code (LSA Code), the capacity is 72 persons [33].

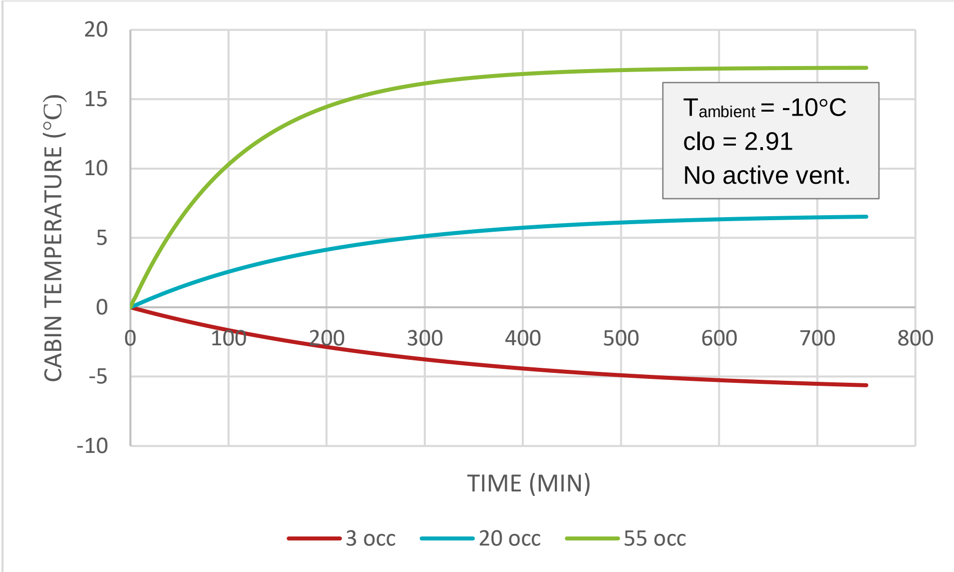

Figure 2: Cabin temperature (°C) over time as affected by the number of lifeboat occupants (occ).

One way to combat reliance on human heat output is the implementation of an active heating system inside the lifeboat. The SARex 2017 trial implemented such a system to assess how a heater would affect the temperature of a lifeboat, and found that, with the 4 kW heater running, the ambient temperature had no impact on the temperature of the lifeboat, meaning the lifeboat could maintain a comfortable temperature [3]. During the SARex 2016 trials, conversely, interior temperature could not be maintained: notably, the lifeboat was not equipped with a heater [15]. The model indicates that the inclusion of a heater (included as a static heat output) can significantly improve the temperature of a lifeboat, as shown in Figure 3 below. This is especially important in scenarios wherein heat output from the occupants is not enough to compensate for heat lost to the environment or to significantly raise the interior temperature, such as less-than-ideal scenarios where the ambient temperature is extremely low or the lifeboat is not filled to capacity. The figure below describes a scenario with an ambient temperature of -10°C, with 25 occupants in a 55-person lifeboat wearing ensembles rated at only 1.5 clo. The inclusion of a heater ensures that the cabin remains at a survivable temperature; without a heater, occupant heat output will not raise the cabin temperature to that required to maintain thermoneutral skin temperature.

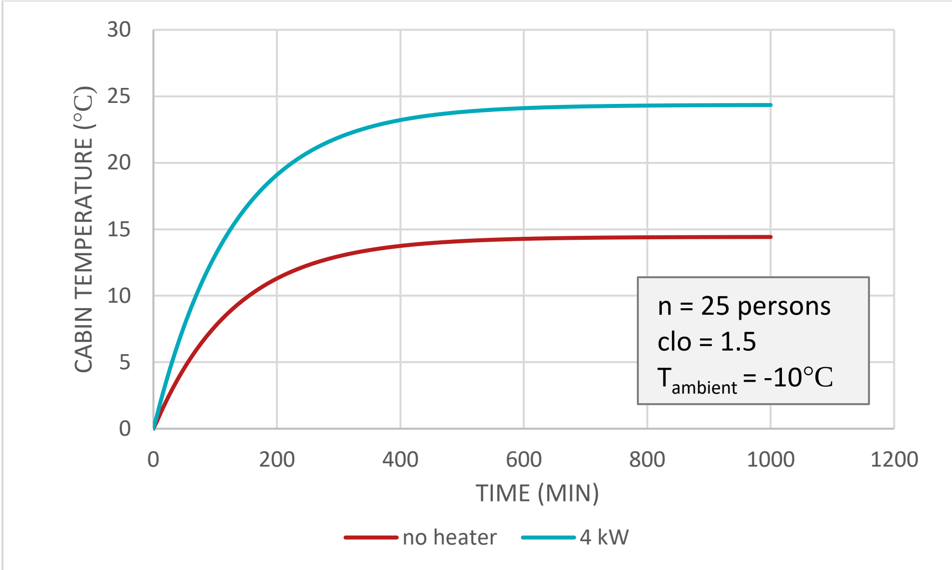

Figure 3: Effect of a 4 kW heater on lifeboat cabin temperature (°C) over time (min).

The model confirms that the risk of heat stress exists even in cold polar conditions, depending on the circumstances of the evacuation. At some temperatures, an at-capacity (or, in some scenarios, below-capacity) lifeboat can rapidly climb in temperature. This has been shown in numerous trials and tests in the past [14], [12]: however, these tests are generally conducted in non-polar conditions, i.e. warmer ambient temperatures. These tests indicate that, at these warmer temperatures, the cabin temperature of a lifeboat could result in sweating, discomfort, and eventually heat stress even with as few as 3 occupants [16] [13].

However, in warmer climates, it would likely be possible to frequently open the hatches to allow for fresh air to enter the cabin and for heat to escape more easily without compromising the thermal protection of the lifeboat. This would be more complicated in polar waters, where opening hatches would expose the occupants to uncontrolled and potentially very cold air and harsh elements; it would be very difficult to balance the temperature in this way. Considering a situation, shown in Figure 4, wherein a lifeboat with a running engine is at full capacity in -10°C weather, the lifeboat temperature, despite the below-freezing exterior air, can quickly reach almost 30°C. Without the ability to cool the cabin in a controlled way, the heat inside the craft would result in sweating, even in regular deck clothing, and thus eventually decrease the thermal protection of the clothing worn.

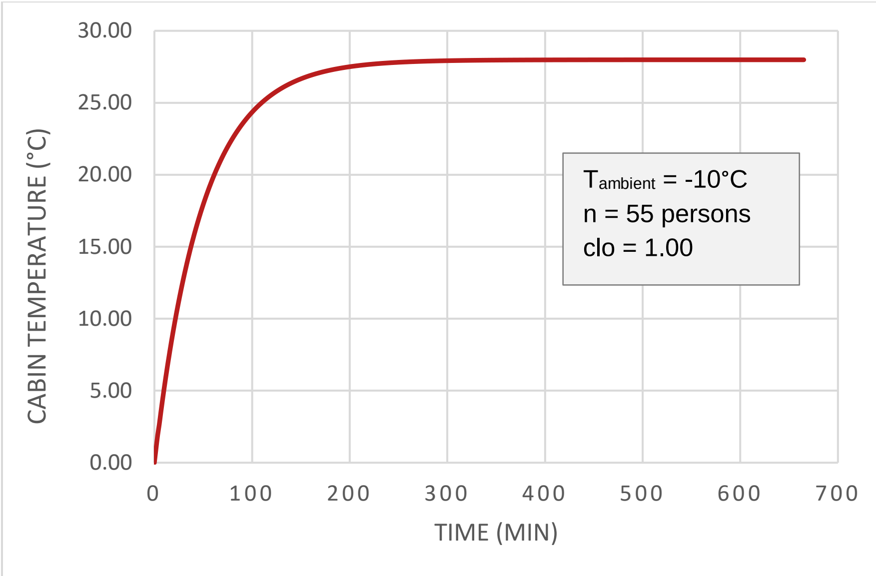

Figure 4: Lifeboat cabin temperature (°C) over time (min) when the engine is running at maximum.

It is therefore complicated to determine a minimum required temperature for a lifeboat cabin, since the needs of the occupants therein are affected by these many factors, some of which are not controllable or predictable. The quality of clothing ensemble is of particular importance, since an individual in a well-insulated ensemble can withstand much lower temperatures. Power recommends an ensemble with a clo value of 2.71 for each occupant in a lifeboat [17]; accepting this value, an interior cabin temperature of approximately 10-15°C is recommended, which allows occupants to maintain skin temperature without physical duress, i.e. at a resting metabolic rate. A lower clo value will correspond with a higher required cabin temperature; it is also important to note that this value may change dependent on mass, and should therefore be a minimum required range as well as maintained with an adjustable system to account for differences due to mass as well as changing conditions throughout the evacuation period.

Presently, lifeboat system manufacturers are developing lifeboats that are kept in covered containers to ensure the equipment is able to launch regardless of environmental conditions[7]. The model shows that the initial temperature of the lifeboat also has a great impact on the internal temperature; further development of these lifeboat containers could implement heaters to maintain an above-zero temperature inside the containers and, subsequently, inside the lifeboats. Regardless of the initial temperature, the internal temperature will eventually reach the same

[7] Threats to the launching ability of lifeboats includes mechanical failure from extreme cold or the icing of components. Heated and/or covered containers help alleviate these concerns.

approximate equilibrium value; however, a lifeboat with a warmer initial temperature offers a more consistently survivable climate. These results are expressed in Figure 5 below for a 55-person lifeboat filled to capacity with an external temperature of -10°C.

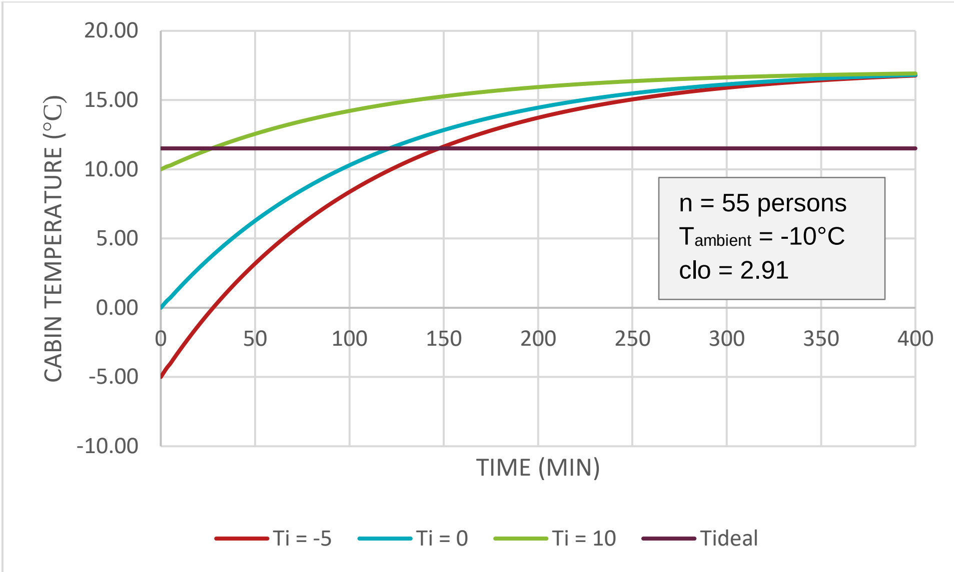

Figure 5: Effect of initial starting air temperature (°C) on interior lifeboat temperature (°C) over time (min) when it is filled to maximum capacity.

Thus, a pre-warmed lifeboat eliminates the risk of individuals sitting in a lifeboat at freezing temperatures for the initial period of the evacuation (from 0 to approximately 100 minutes in the example above) before their body heat has warmed the cabin. In the above case, all initial temperatures eventually met the equilibrium temperature of about 17°C; the pre-warmed lifeboat, however, meant that the survivors were never in a lifeboat below freezing. This is also important if the lifeboat is not filled to a capacity with significant human heat output; in this case, an initial warmer temperature means the lifeboat will be above equilibrium for at least some period. This is illustrated in Figure 6 below for a 55-person lifeboat as above, but filled to 25-person capacity:

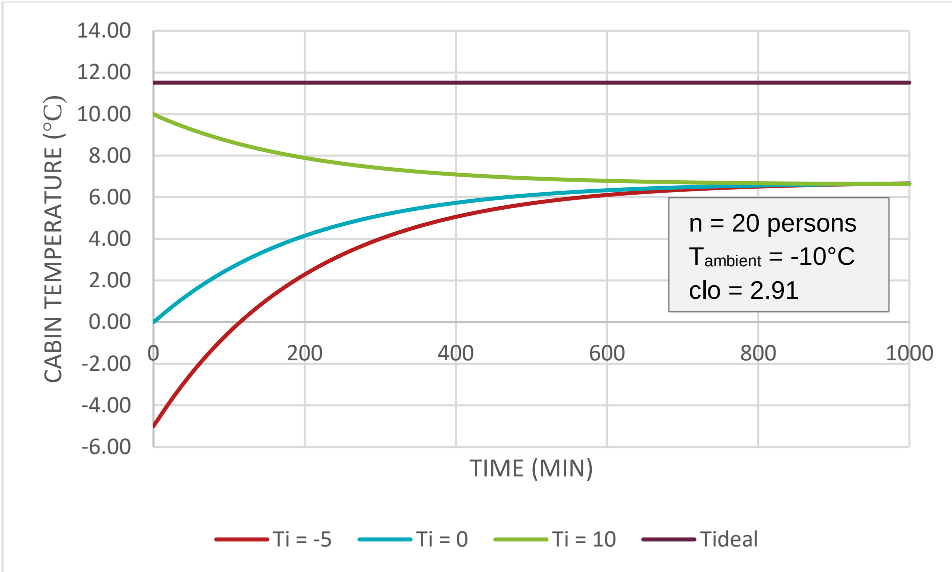

Figure 6: Effect of initial temperature (°C) on cabin temperature (°C) over time when the lifeboat is filled to approximately half capacity.

Kennedy and colleagues estimated the expected time to rescue for survivors of a marine incident in the Canadian Arctic, with a lowest predicted value of 13 hours and with other estimates extending up to beyond five days depending on location, weather, and search and rescue (SAR) assets available [18]. Therefore, survivors will likely spend at least several hours inside a survival craft awaiting rescue: a preheated lifeboat means that survivors will not spend those first few hours in subzero temperatures, thus improving their chances of surviving long enough to be rescued. The development of this technology- containers that are not only covering but also heating the lifeboat- could have huge implications for polar LSA in terms of comfort and survivability.

3.2. Ventilation

Previous work on lifeboat air quality has indicated that CO_2 accumulation is a significant issue in the maintenance of a survivable microclimate. Prior studies have shown CO_2 concentrations increasing rapidly within totally enclosed motor propelled survival crafts (TEMPSCs, also called totally enclosed lifeboats or TELBs), and very often quickly surpassing the recommended limit[8] of 5,000 parts per million (ppm) [19]. It is therefore important for a lifeboat to be properly ventilated to avoid dangerous CO_2 concentrations. Furthermore, a properly fitted

[8] 5,000 ppm is the limit for 8-hour industrial exposure, as designated by the American Conference of Government Industrial Hygienists (ACGIH) [19]. See Appendix B for a detailed description of CO_2 limits in occupied spaces.

immersion suit with a higher clo value will result in a lower MSHF and therefore lower CO_2 production. The CO_2 production in parts per million (ppm) for three different theoretical clo values is displayed below; notably, the lower clo value corresponds with a higher CO_2 concentration.

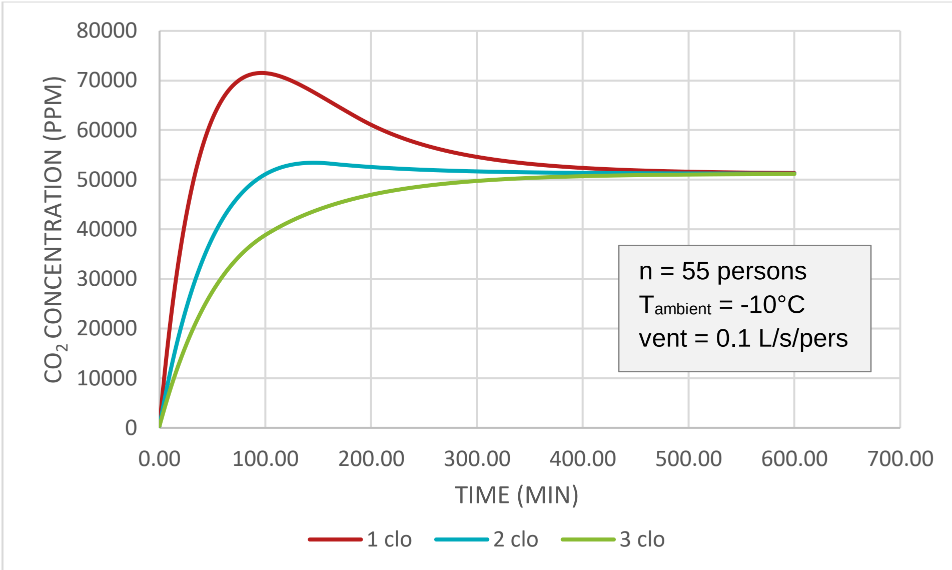

Figure 7: Effect of clo value (clo) on CO_2 concentration (ppm) in the lifeboat cabin over time (min).

Perhaps counter-intuitively, the colder temperatures of the Polar Regions could result in an increased rate of CO_2 production inside survival crafts. “Stuffiness” is often associated with hot temperatures, but as the external temperature decreases, thus increasing the temperature gradient between the interior and exterior, the MSHF per occupant tends to increase at a faster rate. As stated above, an increasing MSHF means an increasing rate of CO_2 production per occupant due to increased shivering. Thus, CO_2 accumulates at a faster rate; combined with the risk inherent in opening hatches (due to heat loss or inclement weather), the CO_2 concentrations in an enclosed lifeboat in polar waters could rise more rapidly than the same boat in a warmer climate. Figure 8 shows the increasing rate of CO_2 production in ppm with a decrease in external temperature.

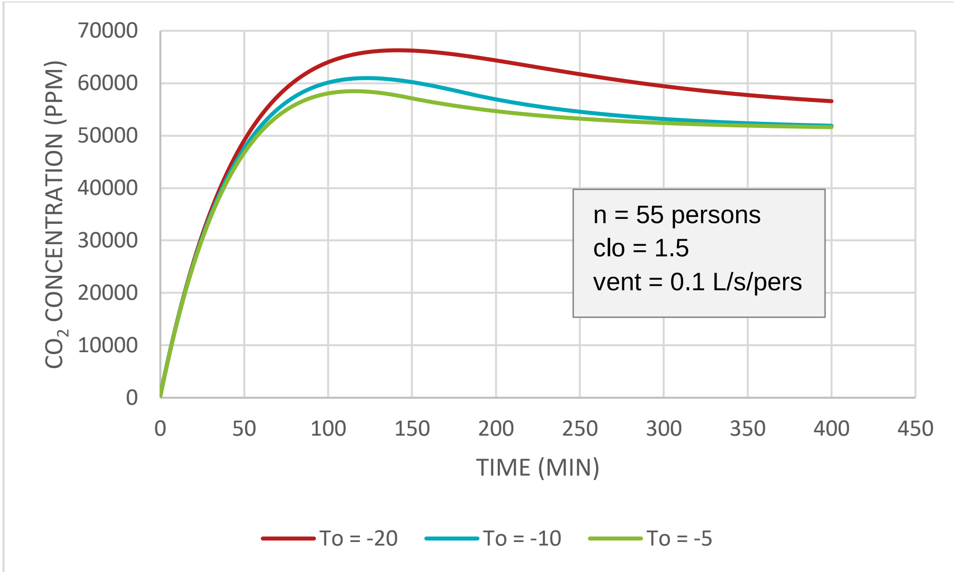

Figure 8: Effect of external temperature (To, °C) on CO_2 concentration (ppm) in the lifeboat cabin over time (min).

As shown in Figures 7 and 8, CO_2 concentration climbs very quickly above 5,000 ppm; there are very few situations wherein CO_2 does not pose a substantial risk to the occupants without active ventilation. It is therefore crucial that lifeboat cabins have active ventilation systems.

The model exposes, however, that ventilation is a delicate balance. As external temperatures decrease, the occupants expend more energy to remain thermoneutral, and CO_2 concentration rises inside the craft. At cold enough temperatures, however, the occupants will not be able to compensate for the heat loss and the temperature inside the craft will decrease as well. The lifeboat therefore is both too cold and too high in CO_2; if the hatches are opened to ventilate, the temperature will drop further; if not, the CO_2 concentration will continue to rise. Figures 9-11 demonstrate the complexity of this balance: adequate ventilation may make for a colder lifeboat, while reducing said ventilation makes the air unable to sustain human life. This series of figures describes a constant scenario with variable ventilation. It is therefore clear that lifeboats on polar-travelling ships should have a controllable active ventilation system, preferably with use of a heat exchanger to allow for fresh but warm air.

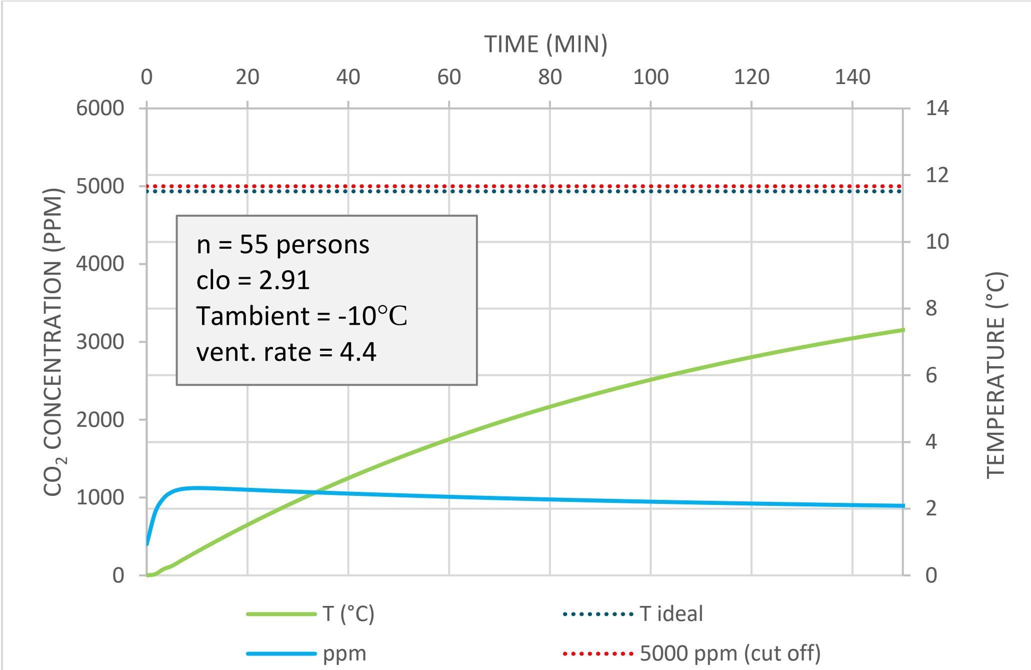

Figure 9: Effect of ventilation rate (4.4 $L \cdot s^{-1} \cdot person^{-1}$) over time (min) on CO_2 concentration in a 55 person lifeboat filled to capacity. [2].

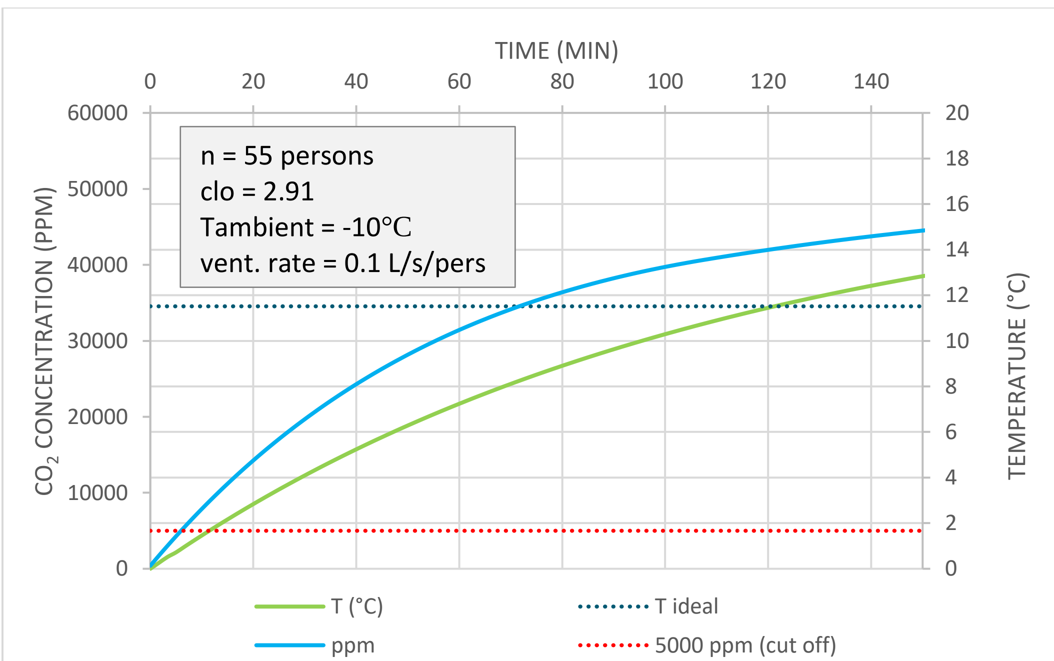

Figure 10: Effect of ventilation rate (0.1 $L \cdot s^{-1} \cdot person^{-1}$) over time (min) on CO_2 concentration in a 55 person lifeboat filled to capacity

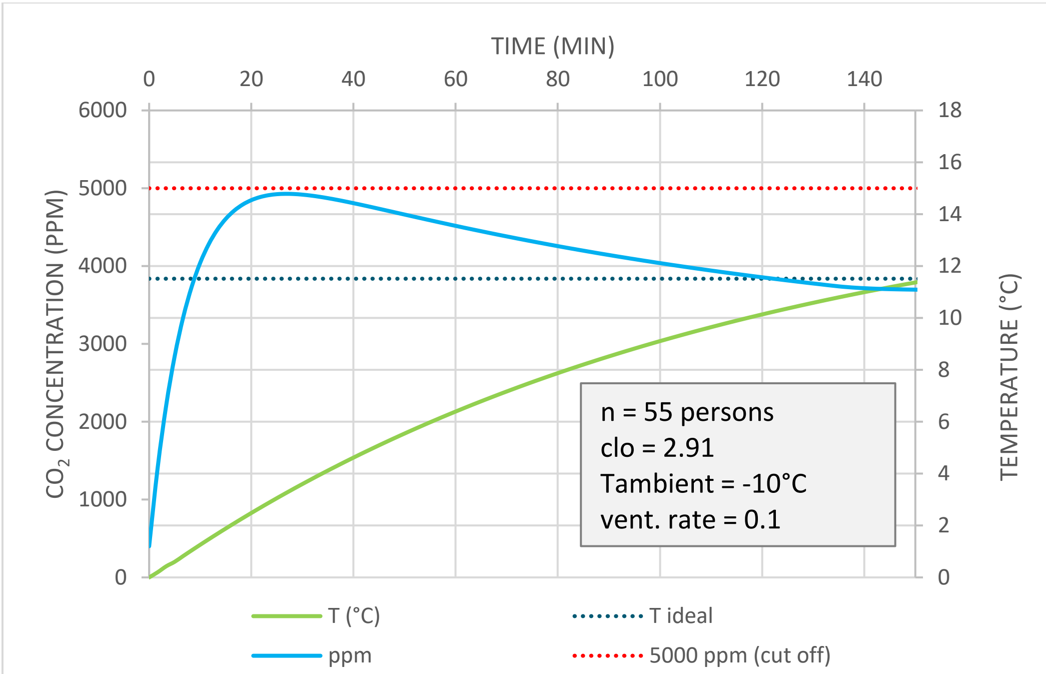

Figure 11: Effect of ventilation rate (1.25 $L{\cdot}s^{-1}{\cdot}person^{-1}$) over time (min) on CO_2 concentration in a 55 person lifeboat filled to capacity

The complexity of ventilation is especially demonstrated in situations where the conditions are considerably less than ideal[9]. Consider a scenario wherein the occupants were unable to remain dry while evacuating, and, due to wetness, are wearing ensembles now rated at 1 clo[10]; furthermore, the lifeboat is filled only to half capacity, and the ambient temperature is -10°C. If cold and wet, the occupants in the lifeboat will eventually begin shivering if not warmed, and will produce significant amounts of CO_2. In this situation, neither the temperature nor the level of CO_2 is suitable for survival. Since ideal conditions cannot be guaranteed in an emergency, the lifeboat must be able to compensate in both areas.

Previous tests and studies ([12] [20]) have explored the idea of a minimum ventilation rate per person in order to maintain a CO_2 concentration below 5,000 ppm. One suggested rate is 5.0 $m^3 \cdot h^{-1}$, or 1.4 $L{\cdot}s^{-1}$, per person. The model suggests, however, that a minimum recommended rate may be difficult to determine. To illustrate this, several scenarios with a constant ventilation rate of 1.4 $L{\cdot}s^{-1}$ (5.0 $m^3{\cdot}h^{-1}$) per person were compared. While this ventilation rate was sufficient in some specific cases, in others it was too high or too low. Several scenarios are compared below

[9] The "ideal" conditions for a Polar evacuation could involve meeting criteria such as calm water, low wind speed, relatively mild ambient temperature, a dry evacuation i.e. no wet occupants, and well insulated clothing ensembles.
[10] A study by Power et al found that an ensemble rated at 2.2 clo was reduced to 1 clo due to wetness [26].

in Figure 12, demonstrating that a static rate is unreliable. The details for each scenario are given in Table 2. Erring on the side of caution and opting for a higher-than-needed ventilation rate may actually reduce the survivability of the lifeboat microclimate by allowing for too much cold air to enter the craft[11]. Conversely, a too-low ventilation rate has the obvious ramifications of a high CO_2 concentration. The model suggests that 5.0 $m^3 \cdot h^{-1}$ per person cannot reliably and confidently assure that this balance is achieved.

Table 2: The scenarios depicted in Figure 12: All scenarios used a lifeboat with dimensions 8.6 m × 3.25 m × 3.55 m, an initial temperature of 0°C, all occupants were considered dry, and a static ventilation rate of 5.0 $m^3 \cdot h^{-1}$ (1.4 $L \cdot s^{-1}$) per person was applied.

SCENARIO	Ambient temperature (°C)	Occupancy	Mass (kg)	Insulation value (clo)
A	-9	18	90	2.3
B	-9	18	90	1.5
C	-5	55	85	2.3
D	-5	55	100	3.0
E	-5	55	100	1.5

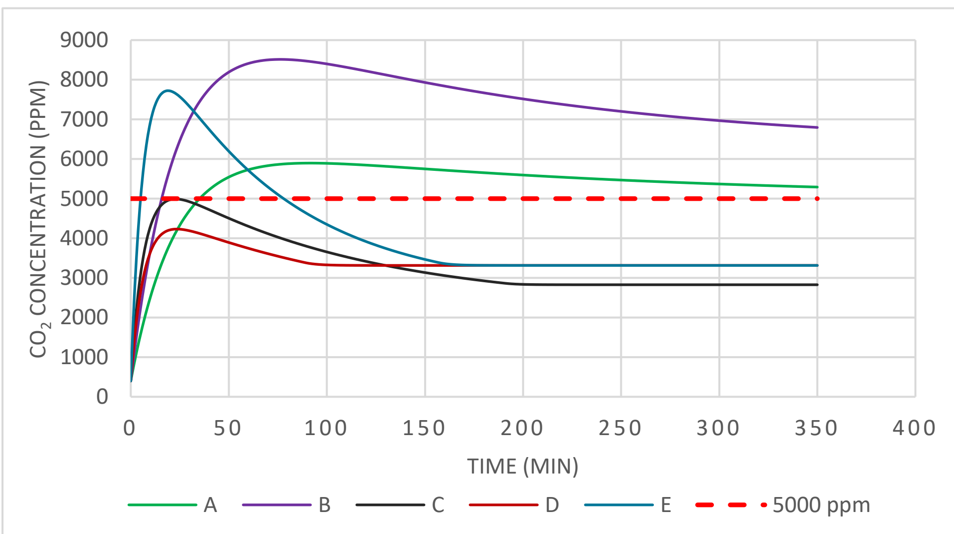

Figure 12: The effect of different variables (described in Table 2), with a static ventilation rate of 5.0 $m^3 \cdot h^{-1} \cdot person^{-1}$ on CO_2 concentration over time.

[11] A way to rectify this issue of too-cold air entering the lifeboat would be a ventilation system consisting of a heat exchanger, thus allowing fresh air to enter the craft without sacrificing temperature.

Furthermore, there is a fundamental issue with considering a ventilation rate per person: each individual is of different mass. Baker et al demonstrated experimentally that CO_2 production increases linearly with mass [21]; therefore, two separate lifeboats filled with the same number of individuals may have substantially different ventilation needs if the population inside each boat is different in terms of mass. Figure 13 shows the changing CO_2 concentration at three different average masses in kilograms, with a static ventilation rate of 5.0 $m^3 \cdot h^{-1}$ per person and an occupancy of 20 persons in a lifeboat in -5°C ambient temperature. Previous studies have used different average masses and heights, with some using masses as low as 75 kg [12]. The size of occupants considered in future studies should be significantly higher than this value. Workers on western cargo ships are generally significantly larger than this, with an average mass and height of ~91 kg and 1.79 m in the United Kingdom (UK) [24]; Kozey et al also found that 85% of marine workers in Atlantic Canada had a body mass greater than 75 kg [25]. Therefore, in assessing the ventilation needs of lifeboats on a specific ship, one must consider the demographic for which said ship is intended: a cargo ship, for example, generally has a complement of individuals who are larger than average [24], and therefore a lifeboat on such a ship is likely to require a higher ventilation rate. Thus, real-time monitoring and adjustable ventilation are recommended, to ensure the needs of the specific individuals inside the lifeboat are met. Establishing a ventilation rate based on the average mass of all individuals travelling in these regions will potentially give a rate that is insufficient for those of larger size.

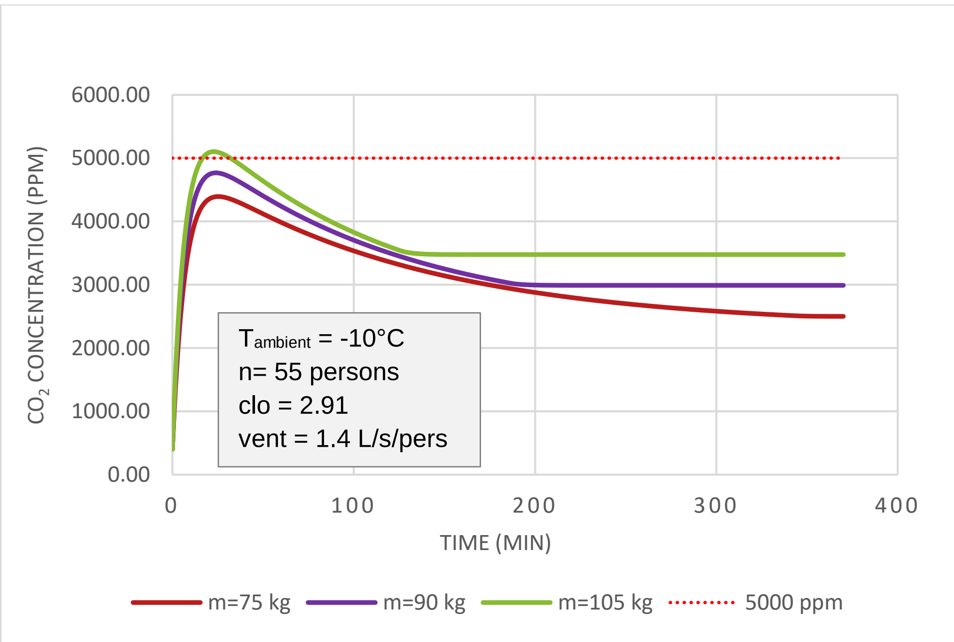

Figure 13: Effect of mass (kg) on CO_2 concentration (ppm) over time.

However, efforts to determine a per-kilogram-mass ventilation rate struck a similar issue, in that these needs also differ based on other factors such as occupancy, clothing ensemble, and lifeboat volume. This is illustrated in Figure 14 below, where only changing the insulation value of the ensemble worn significantly changes the sufficiency of the ventilation rate. It is therefore preferable that the Polar Code specify that the lifeboat be equipped to maintain a CO_2 concentration below 5,000 ppm through the implementation of an adjustable ventilation system, since it is very difficult to predict the ideal ventilation rate without being able to control these other parameters. The lifeboat should therefore also be equipped with sensors in order to allow the occupants of the lifeboat to monitor the levels of CO_2 inside the lifeboat, and to increase ventilation as needed. With this method, ventilation and temperature can both be maximized.

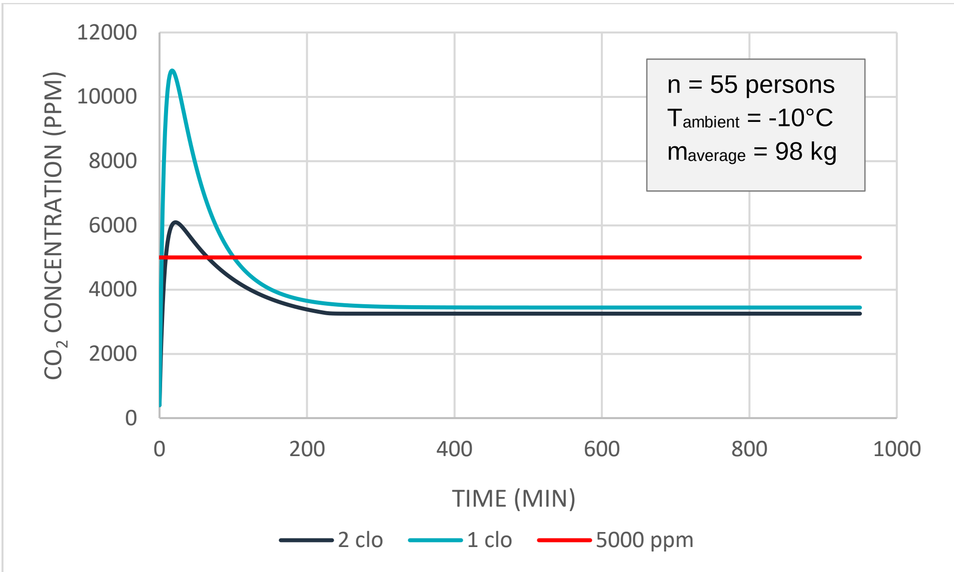

Figure 14: Effect of insulation (clo) on CO_2 concentration (ppm) over time, with a constant ventilation rate of 0.01 $L \cdot s^{-1} \cdot kg^{-1}$ (approximately 1.4 $L \cdot s^{-1} \cdot person^{-1}$).

The model also shows that CO_2 concentration in a ventilated lifeboat will, in many scenarios, rise to a value where it peaks before dropping to a lower value, which is in some cases below 5,000 ppm. This is likely to occur in a lifeboat with an increasing cabin temperature since, as the cabin warms, the rate of CO_2 production decreases until it is eventually less than the rate of ventilation[12]. Thus, new testing methods should be considered for testing ventilation in lifeboats. Presently, ventilation is largely tested in lifeboats by monitoring the environment in an occupied lifeboat and aborting the test once the concentration reaches a level near 5,000 ppm. This is done for the safety of the participants, who disembark before 5,000 ppm is reached. However, these procedures may lead to skewed results, as the test may suggest that a certain ventilation rate is not adequate. In reality, however, that ventilation rate may peak slightly about 5,000 ppm for a

[12] Starting the engine in the lifeboat may also contribute to this peak in CO_2; further research is required.

short period before dropping to an acceptable level. This is demonstrated in Figure 15 below, with a static ventilation rate of 66 L·s^{-1}. In a test situation, this ventilation rate would be deemed too low, with test abortion around approximately 30 minutes; however, the concentration would drop below 5,000 ppm in a little over an hour, which is considered acceptable by most workplace standards [19]. This test method therefore potentially overestimates the ventilation needed, depending on the actual CO_2 limit set by IMO.

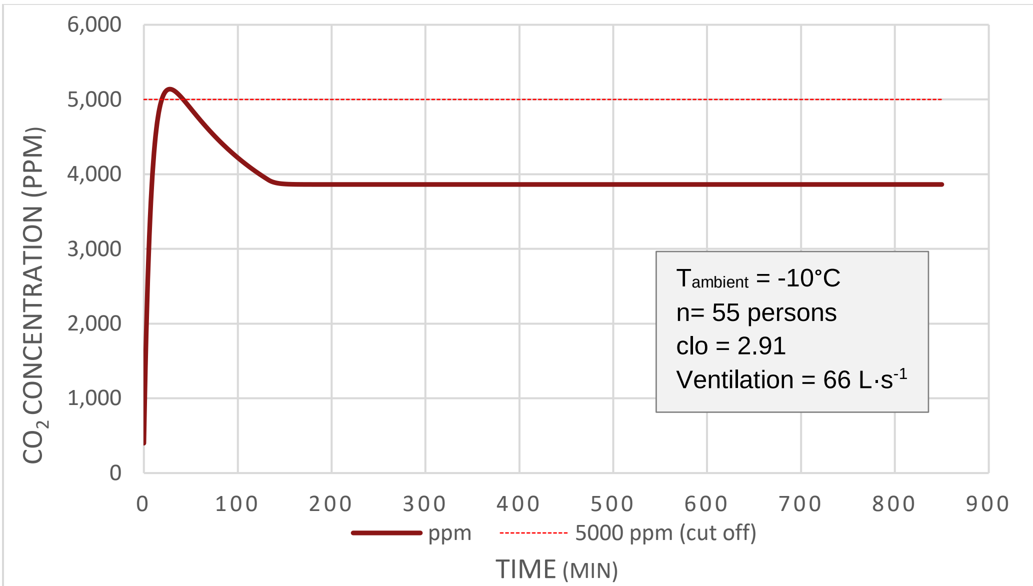

Figure 15: CO_2 concentration (ppm) over time (min) in a 55 person lifeboat.

This peak can be explained by the increasing cabin temperature, leading to a decreasing rate of CO_2 production from the occupants; as well, the boarding process will likely contribute to higher rates of CO_2 production for the initial period, which will then decrease once individuals are settled, as will the initial use of the engine. As the rate of production decreases, it is eventually produced at a rate less than that of ventilation, and the concentration begins to drop as it is diluted more and more. Eventually, equilibrium is reached with thermal equilibrium of the occupants.

To confront the issue created by the peak and subsequent decrease of CO_2 concentration, the CO_2 limit must be more clearly defined. If it is established that a concentration of 5,000 ppm is acceptable for short periods of time, the ventilation rate needed may be reduced to preserve temperature inside the lifeboat. If the 5,000 ppm limit is established as absolute, i.e. the air inside the lifeboat must never reach 5,000 ppm, the ventilation rate may need to be increased to meet this level of air quality. As CO_2 concentrations between 5,000 and 10,000 ppm are generally considered acceptable for a time weighted average of 8 hours, it is recommended that a CO_2 level in this range be allowable for a period of time not exceeding a defined limit as set by regulatory bodies. This limit must be adopted in conjunction with sensors inside the survival craft in order to monitor the levels of CO_2 and increase ventilation as needed.

3.3. Partially Enclosed Lifeboats

Partially enclosed lifeboats (PELBs) have not been the subject of much analysis to date, likely due to the prevalence of TEMPSCs on commercial ships. However, as cruise ships increasingly take to Arctic and Antarctic waters, it is worth noting that they may employ PELBs on board[13]. This begs the question: do PELBs offer sufficient protection?

Using the model described above, and modifying it to account for the canvas covered openings, the interior temperature of a PELB was assessed. The results of this model indicate that the effect of infiltration and the insulation of the canvas material both decrease the thermal resistivity of the survival craft. When comparing the results of the analysis of the TEMPSC with that of the PELB, it is clear that the temperature inside the PELB decreases at a much faster rate; the MSHF therefore increases much more rapidly, leading to an increased CO_2 output and lower skin temperature. Figure 16 shows the internal temperature of a TEMPSC compared to that of a PELB in the same circumstances; it is worth noting that the performance gap between a TEMPSC and a PELB grows as ambient temperature decreases or the size of the canvas-covered opening on a PELB increases.

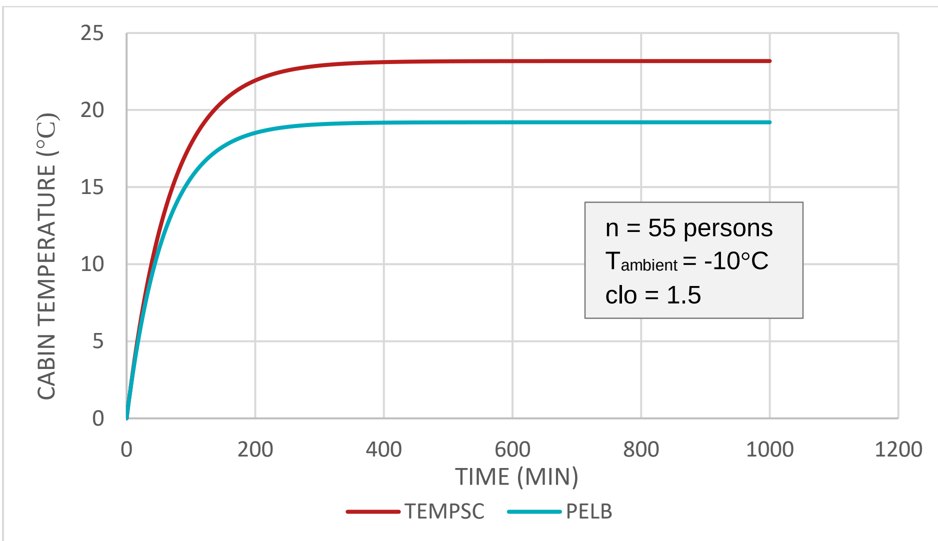

Figure 16: TELB versus PELB performance. The temperature gap grows with a decrease in ambient temperature or an increase in the size of the canvas covered opening; both boats have a 55-person capacity.

[13] Under paragraph 8.3.3.3.1 of the Polar Code, lifeboats are restricted to being of either partially or totally enclosed type [1].

However, it is also worth noting that the canvas covering, which is not perfectly airtight, allows for increased passive ventilation. Mak et al. estimated the passive ventilation of a partially enclosed lifeboat to be 95 $L \cdot s^{-1}$ by using a TEMPSC with the hatches open to simulate a PELB with the canvas covering rolled up [10]. The estimated rate of ventilation for a partially enclosed lifeboat with the canvas covering rolled down is much lower, based on the ASHRAE crack method [22]. With this lower ventilation rate based on the crack method, the PELB does offer extra passive ventilation, but not always substantially so, and the rate is dependent on factors such as wind speed; furthermore, this passive ventilation through the covering is not controllable and therefore not reliable.

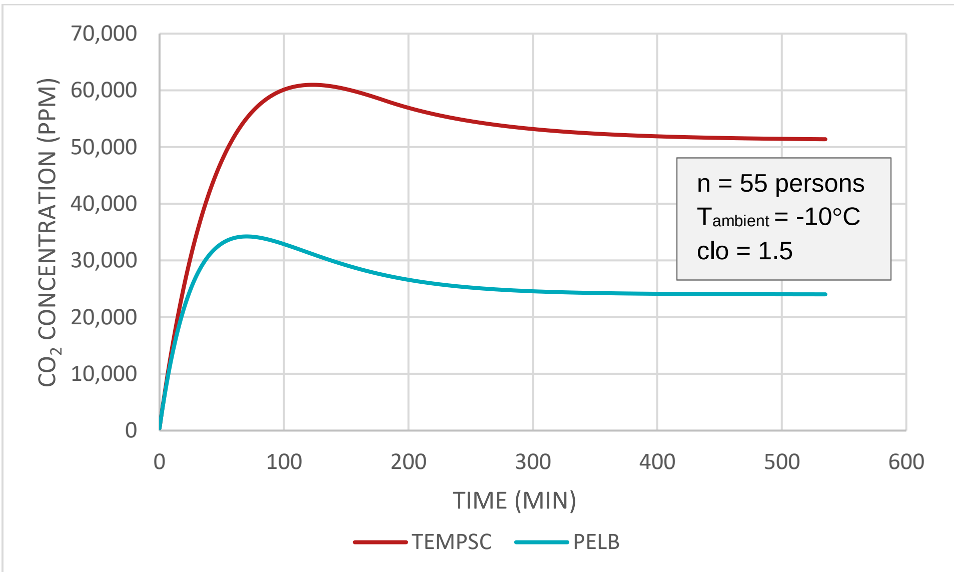

Figure 17: Effect of lifeboat type (totally (TEMPSC) or partially enclosed (PELB)) on CO_2 concentration (ppm) over time (min).

The lack of ventilation and temperature control suggests that PELBs need further assessment to be deemed Polar-ready. In particular, they must be assessed for the conditions in which they are intended to be used, and thus must be tested in harsh environmental conditions as well as for the demographics with which they are likely to be used: that of a cruise ship population, which may include retirees, children, and people who are less fit than a cargo ship worker, thus impacting the average mass of potential occupants.

3.4. Other Factors

Developments during an emergency situation can dangerously affect the survivability of the occupants, such as decreasing external temperature, wetness, high motion, injury, or loss of life. SARex 2016's results showed the impact of an individual leaving the boat. Once the engine was shut off, the temperature began to decline with approximately 18 individuals on board. As people began to regularly leave, the temperature continued to decline until it reached nearly 0°C inside the lifeboat [15]. Had these individuals stayed inside the lifeboat, the model predicts that the temperature inside the lifeboat would have stabilized at around 8-9°C; occupant heat production is therefore not a reliable source of heat and can be compromised in the case of loss of life.

There are other factors that play a role in survivability which are not controllable by the lifeboat occupants. As indicated, the total mass of the occupants influences the temperature inside the lifeboat, the amount of CO_2 produced, and other areas such as comfort at full or partial capacity. Using the body surface area (SA) equation from Gehan and George [23] and substituting the SA value into equation 8, the model shows that a larger individual (based on mass and height) produces more heat, thus contributing more to warming of the temperature inside the lifeboat. While this factor is not controllable, it suggests that fitting lifeboats with monitoring systems and controllable heaters would allow for a maintainable ideal cabin temperature.

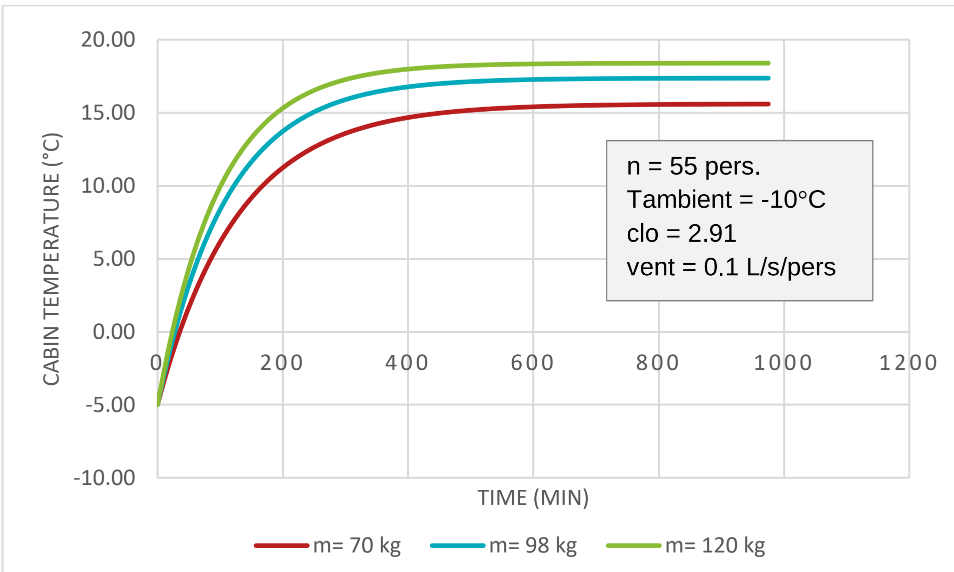

Figure 18: Effect of mass (kg) on lifeboat temperature (°C) over time (min).

The external temperature, as described in the sections prior to this one, is hugely influential to the microclimate of the lifeboat. Lifeboats on ships travelling in polar waters must be able to support survivability in temperatures ranging from 0°C to -35°C. Figures in Appendix A indicate the mean daily low temperature (MDLT) as well as the Polar Service Temperature (PST) for different regions in the Arctic and Antarctic. Note that the Polar Code specifies that all LSA must be functional at the specified PST for a region, which is defined as ten degrees less than the MDLT. Severe and changing weather further influences the microclimate of the lifeboat. In developing this model, wind velocity was considered as an influence in the thermal transmittance value of the lifeboat; higher winds wick heat away more quickly. In general, full-scale tests of lifeboats in cold waters have been conducted on calm days, but winds in Polar Regions can quickly become severe. This possibility must also be considered; a report by Aylward indicated an increased rate of CO_2 production in high motion scenarios, suggesting that harsh weather during a maritime evacuation could cause a faster accumulation of CO_2 [9]. Furthermore, changeable weather means that temperatures outside could decrease quickly, creating a heavier strain on lifeboat occupants.

Wetness is another serious risk, and often uncontrollable. A previous study by Power and Monk indicates that the effectiveness of an immersion suit is significantly decreased when wet [26]; however, it is difficult to ensure that, in a maritime emergency, all occupants will remain dry. Therefore, wetness can greatly impact the heat flux of the individuals who are wet, and they will succumb to heat loss and cold stress far more quickly.

It is therefore important to consider that a survival situation cannot be considered as a static event with one set of conditions and responses; the situation can change at any moment. Thus, the lifeboat microclimate must be able to adapt to accommodate these changes: for example, a controllable heater to compensate for plummeting temperatures or the loss of an occupant, or monitors to keep track of air quality and allow for ventilation adjustment as needed. By giving occupants the ability to control their situation in real time, they will be able to adapt systems to their needs as they change.

4.0. Limitations

As previously described, this is a desktop heat transfer analysis and is not a thermoregulatory model. It is therefore not intended to describe lifeboat microclimate with precise data, but rather to describe and examine trends and potential issues among lifeboats in Polar Regions.

A future model could be improved through the following:

1. Further full-scale testing could determine a more precise thermal transmittance values for different lifeboats in thermal balance based on temperature and area. Assumptions were instead made in the development of this model to accept the calculated value as universal to all lifeboats.
2. This model does not take into account the heat lost due to respiration, which can be accounted for in a future version.
3. The model does not account for the effects of sweating, and therefore does not account for change in body temperature due to this thermal response and the resulting wetness.
4. The lifeboat was modelled as a rectangular prism due to precise measurements being beyond the scope of this report. A future model could be made based on more accurate measurements accounting for specific shape and thicknesses. This is a simplification, as lifeboats also have air gaps and buoyancy foam at different locations.

It also does not account specifically for the space occupied by equipment inside. Therefore, the total volume was calculated from the dimensions given, and the volume used was taken as ~30% of this volume to calculate an interior volume that did not include the space below the deck or the equipment inside the boat.

5. A full-scale trial of partially enclosed lifeboats was beyond the scope of this report; therefore, the results suggest that PELBs should undergo testing in the conditions in which they are intended to be used.

5.0. Conclusion

The model indicates that there are several potential issues with the use of conventional lifeboats, both totally and partially enclosed, in Polar Regions. The extreme temperatures and weather encountered in these regions, combined with the long expected time of rescue, culminate in additional and harsher demands on LSA, and lifeboats not specially designed for these regions do not necessarily offer adequate protection for survivors. The model indicates that lifeboats used in warmer climates are considerably more predictable and dependable; the ability to open the hatches to ventilate, for example, may be hugely beneficial to those inside the craft if the ambient temperature is warm. Because polar waters are a relatively new avenue of transit, LSA have not yet developed enough to fully meet the new needs.

Due to this complexity, lifeboat performance in any given situation in Polar Regions depends on many factors; this means that current off-the-shelf LSA may not provide adequate protection in polar waters because they cannot account for these many variables. In order to ensure survivability, LSA must be equipped to deal with a wide range of possibilities.

5.1. Recommendations

The following recommendations are made based on the results of the model:

1. Lifeboats should be equipped with cabin heaters capable of maintaining an interior temperature of 10-15°C. The power needed to maintain this temperature will depend on the circumstances, i.e. occupancy, external temperature, wind, etc.

2. A highly-rated immersion suit reduces the loss of human heat to the environment, and therefore reduces human CO_2 output; it is therefore recommended that highly-rated immersion suits be provided on ships travelling to Polar Regions. The recommended clo rating is 2.71, as reported by Power et al [17]. According to equation 6, this clo

value would support a suitable internal cabin temperature of approximately 10-15°C[14], based on a resting metabolic rate of approximately 58.2 W·m^{-2} [11].

3. Further consideration should be given to using PELBs on polar travelling ships without further assessment, insofar as they cannot presently be confirmed to offer an adequate microclimate. Presently, the model suggests that the interior temperature and ventilation of PELBs is inadequate to ensure human survival in Polar Regions, and therefore PELBs should be tested under the appropriate conditions, i.e. cold ambient temperatures and considering the demographic likely to use said LSA.

4. LSA should be tested at temperatures down to the MDLT and PST for the regions in which the ship will be travelling. As indicated by the model, polar climates offer a significant issue for the performance of survival crafts, yet most tests and full-scale trials have examined lifeboat temperatures at more moderate temperatures.

5. Lifeboats must also be equipped with an adequate ventilation system capable of maintaining a CO_2 concentration below 5,000 ppm without compromising temperature. The use of a heat exchanger will help achieve this.

6. A minimum ventilation rate of 5.0 m^3·h^{-1} (~1.4 L·min^{-1}) per person, while suitable for some scenarios, is questionable in others. There are situations wherein this minimum value is actually excessive and thus compromises the temperature of the lifeboat. Thus, a requirement as described in 5 above in conjunction with monitors (see point 8) will allow for better microclimate protection in any situation.

7. A more stringently defined CO_2 limit must be determined; the 5,000 ppm level generally tested for is not defined by IMO but rather by several regulatory bodies as a workplace limit. A clearer definition of what the limit is as prescribed by IMO will clarify ventilation needs. Furthermore, the type of limit must be established: an absolute limit will mean that lifeboat ventilation must be able to maintain a CO_2 level that never rises above the determined limit, whereas a limit based on an 8 hour time-weighted average (TWA) will allow for CO_2 to peak beyond this limit for short periods, thus decreasing the ventilation needed.

8. Lifeboats, prior to use, should be kept in protected containers, and ideally ones that are warmed and allow for an initial internal cabin temperature of above zero upon launching.

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[14] This value is approximate because individual need changes with occupant size; however, 10°C would be maintainable.

9. The interior microclimate of the lifeboat should be monitored in real time. Reports from the SARex exercise indicated that those inside the lifeboat had a difficult time describing their own state of being [3]; therefore, microclimate monitoring will ensure that cabin temperature and ventilation remain stable and do not reach dangerous levels.

5.2. Recommendations for Future Research

The following are recommendations for future research or versions of the model:

1. A full-scale trial of PELBs in polar conditions will help solidify understanding of the effectiveness of these PELBs in low temperatures. A trial similar to those conducted by the SARex exercises will help establish whether or not PELBs are adequate LSA for Arctic or Antarctic travelling ships.
2. Heat lost due to occupant's respiration should be included in a future model.
3. Life rafts are commonly used on ships, including polar-travelling ships. However, there has been little work done on the effectiveness of life rafts in these conditions, despite the fact that life rafts must supply protection similar to that of a lifeboat. Therefore, applying this model to a life raft could expose some of the potential risks of using a life raft in polar waters.
4. Ventilation tests should be redesigned to account for the peak in CO_2 concentration, thus avoiding aborting a test too early due to a falsely assumed equilibrium concentration. This risks over-ventilating a lifeboat and thus causing unneeded heat loss. Tests should therefore allow individuals to remain in the craft regardless of CO_2 concentration, perhaps equipped with oxygen tanks for inhalation.
5. Carbon monoxide (CO) has been detected inside TEMPSCs, and is dangerous at very small concentrations. Therefore, future research and testing on the accumulation of CO inside TEMPSCs would be valuable.
6. Humidity levels have also shown to be an issue inside survival crafts [3], and a future version of the model could account for the effect of humidity on skin temperature.

6.0. References

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Appendix A: Description of Polar Regions

Polar Regions include the area within the Arctic Circle and the area surrounding Antarctica as indicated by the following figures taken from the IMO's Polar Code [1].

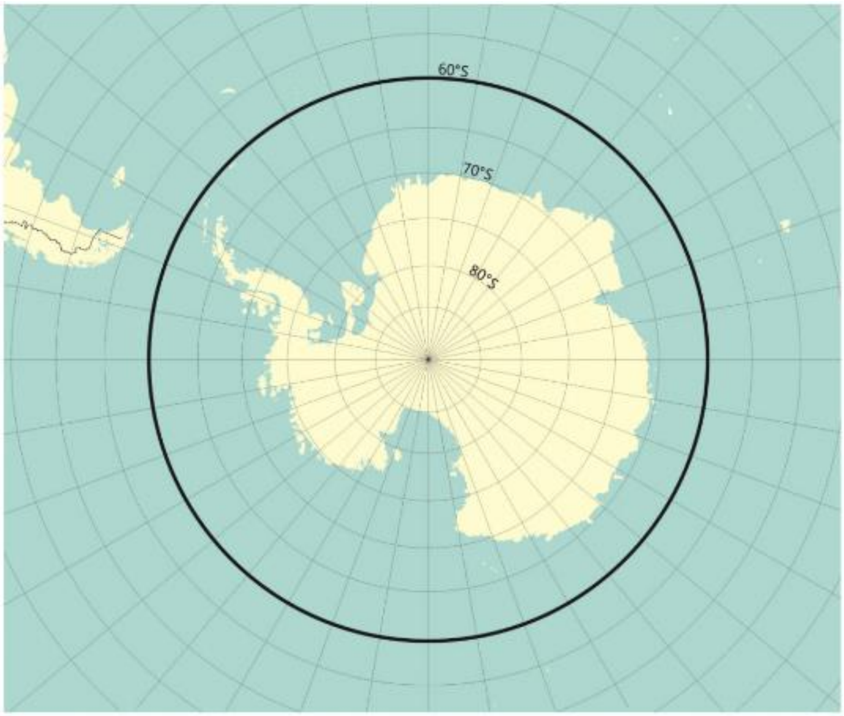

Figure 19: The Antarctic [1].

Figure 20: The Arctic Circle [1].

The MDLT and PST for specified locations within these regions is displayed below:

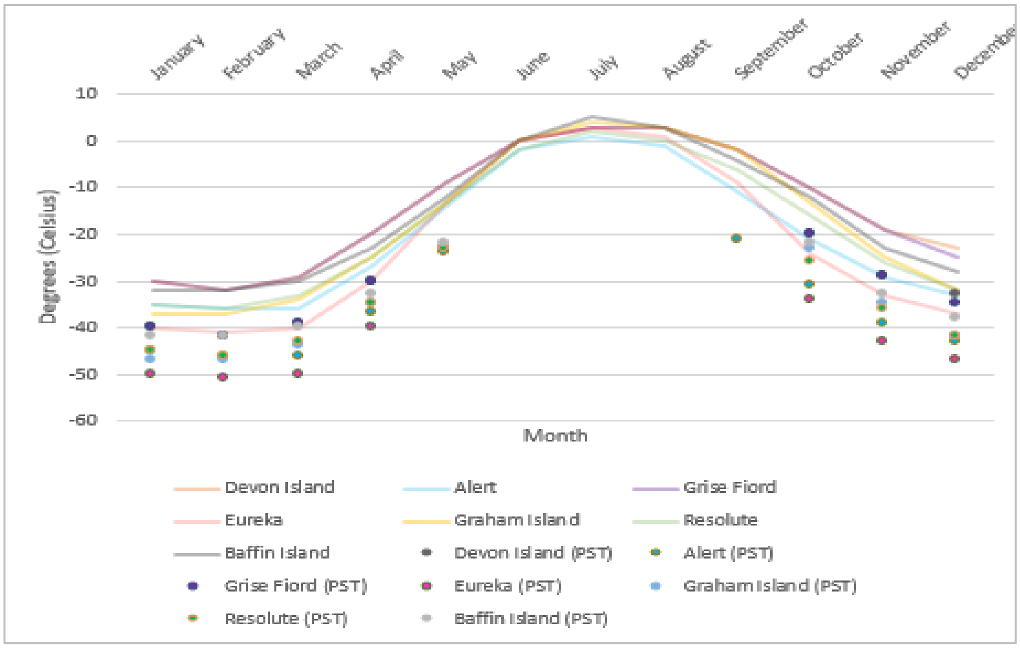

Figure 21: MDLT and PST for locations in the Canadian Arctic. Data from Environment Canada. [27].

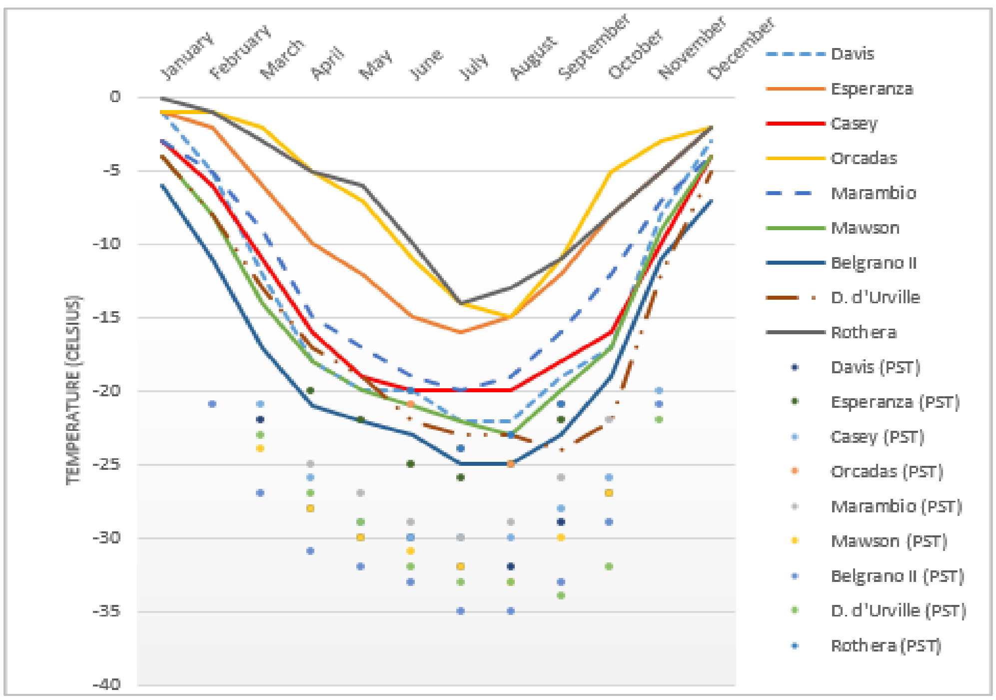

Figure 22: MDLT and PST for selected locations in Antarctica (coastal or marine). Data from Australian Bureau of Meteorology. [28]

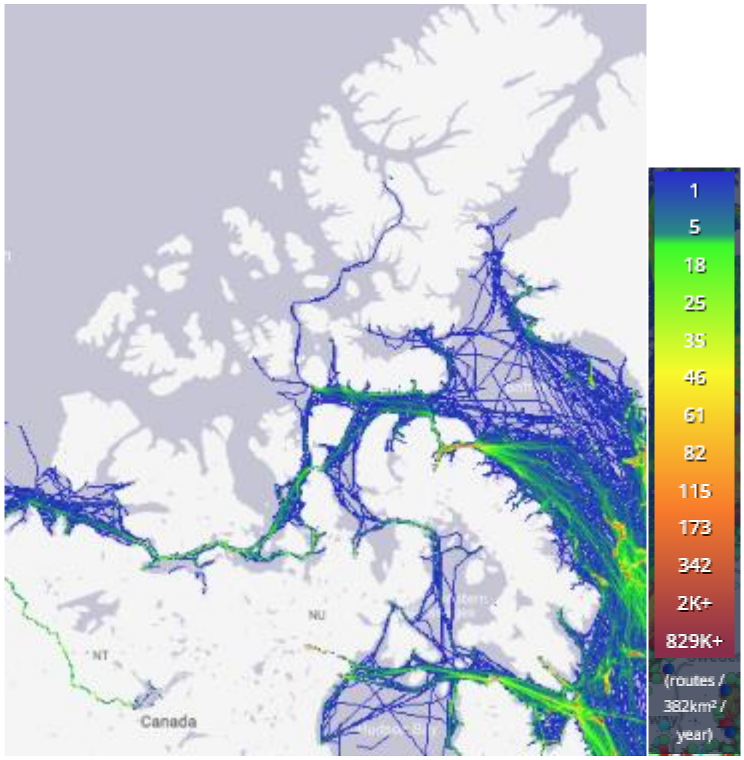

Figure 23: A 2017 density map showing marine traffic in the Canadian Arctic. Taken from marinetraffic.com. [29]

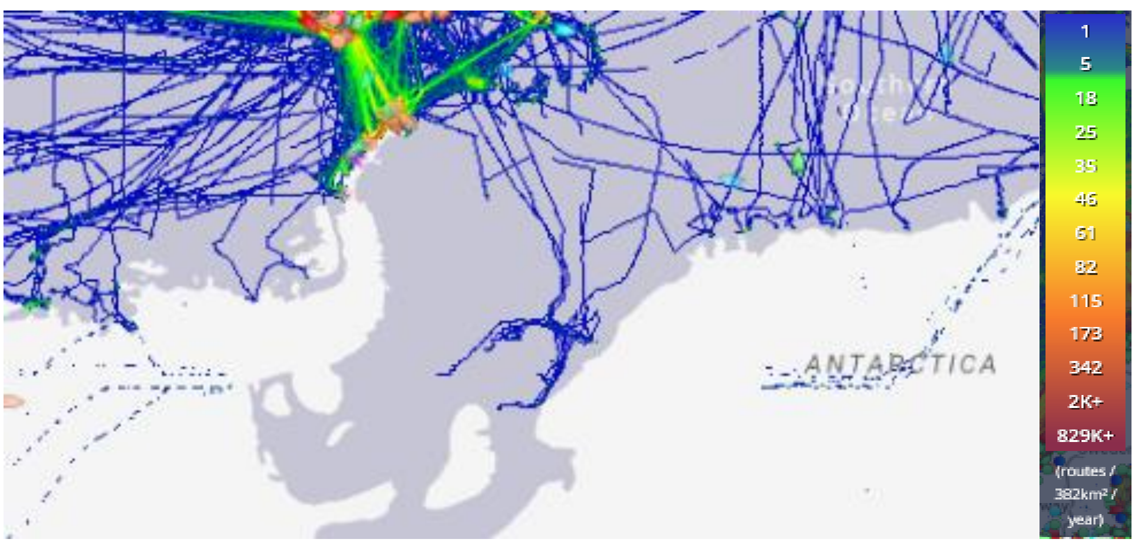

Figure 24: A density map showing marine traffic near the Antarctic Peninsula. Taken from marinetraffic.com. [29]

Appendix B: Carbon Dioxide Limits

Table 3: Levels of CO_2 concentration and the result/hazard; human discomfort, notably, begins around 1000 ppm yet this is still considered by some regulatory bodies to be an acceptable level, indicating the lack of clarity regarding acceptable concentrations.

CONCENTRATION (PPM)	IMPACT ACCORDING TO SOURCE	SOURCE
650	Maximum recommended	OSHA & U.S. Air Force Standard [2]
800-1,000	Human discomfort begins	[2]
1,000-1,200	Acceptable indoor levels	ASHRAE 62.1 [2]
>5,000	8-hour industrial exposure limit	American Conference of Government Industrial Hygienists (ACGIH) [19]
>12,000	Long term health effects may occur	[2]
>30,000	Brain function deteriorates	[19]