CARBON DIOXIDE ACCUMULATION WITHIN A TOTALLY ENCLOSED MOTOR PROPELLED SURVIVAL CRAFT

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ABSTRACT - **Exposure to high levels of carbon dioxide (CO_2) may have adverse effects on human health and performance, and the likelihood of such an event may be increased when situated in a confined space like a fully loaded totally enclosed motor propelled survival craft (TEMPSC). The goal of this research was to quantify the occupant complement to CO_2 concentration relationship in order to provide guidance regarding TEMPSC ventilation strategies. A pool of 15 subjects was loaded systematically into a IMO-SOLAS TEMPSC in group sizes ranging from 1 to 15 persons. Repeated measures were taken, and in special cases subjects donned SOLAS-approved survival suits. Results showed that increasing the number of occupants greatly increased the amount and rate of CO_2 accumulation, thereby increasing the frequency at which the TEMPSC must be ventilated to mitigate the risk of CO_2 exposure.**

KEYWORDS

Carbon dioxide, TEMPSC, lifeboat, habitability

INTRODUCTION

Commercial and industrial operations continue to push further north as shipping lanes open up and oil and gas exploration expands. As a result, the safety equipment and regulations that accompany these operations must also adapt to the harsh Arctic environments. It is important to consider the impact of climatic conditions such as cold and snow, as well as the remoteness of the work since search and rescue stations may be located hundreds of miles away. A good example of a safety modification to marine safety equipment in northern waters is the development of totally enclosed motor propelled survival craft (TEMPSC). Survival crafts were originally designed to be propelled by either oar or sail, and were completely open to the elements, the goal being to move the occupants to safety while awaiting rescue. However, this type of survival craft does not lend itself to the frigid conditions and relative isolation of Arctic waters. Therefore, the need for a totally enclosed survival craft, with a propulsion system capable of travelling greater distances, has become both apparent and crucial.

A great deal of research has been focused on how best to shield TEMPSC occupants from external environmental conditions such as wind and waves. However, it may be suggested that it is just as important to consider the environmental conditions within the survival craft when trying to maintain occupant safety and improve upon habitability, since necessary evacuation, escape, and rescue (EER) tasks such as communication, maneuvering, and decision-making, may be hindered by factors such as noise levels and poor air quality. An environmental factor that should be of primary concern within a TEMPSC is the level of carbon dioxide (CO_2) accumulation.

Under normal atmospheric conditions, CO_2 is a trace gas that comprises roughly 0.03% of the air we breathe, and plays a major role in metabolism within the human body (Scott *et al*. 2009). However, when CO_2 is inhaled at relatively high levels it can prove to be harmful to human life. Xu *et al.* (2011) showed that inhalation of high levels of CO_2 may have a suppressive affect on brain function in the form of a reduction in metabolic activity within the brain, as well a decrease in spontaneous brain connectivity. Moreover, Scott *et al.* (2009) indicated that increased levels of inspired CO_2 produces an increase in hydrogen and bicarbonate ions in the blood (i.e. hypercapnia), potentially leading to respiratory acidosis. It is also noteworthy that the potential for an increase in CO_2 levels is especially dangerous in confined spaces, such as a TEMPSC. Since CO_2 is heavier than air, it will displace oxygen within a confined space and result in a greater relative increase in CO_2 levels (Scott *et al*. 2009). In

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fact, Taber *et al.* (2010) suggested that the SOLAS guidelines regarding waterproofing and internal air-tightness of a TEMPSC might, inadvertently, contribute to gas concentrations (i.e. CO_2) reaching levels that are dangerous to humans according to Canadian health and safety standards.

The current standard ventilation system onboard TEMPSC is a passive system that depends on the movement of the vessel to provide circulation and exchange of air. Consequently, if the lifeboat were to become relatively stationary due to entrapment in ice floes or a lack of fuel, all passive ventilation within the craft would essentially stop, leading to a potential build up of dangerous gases such as CO_2. Therefore, it is critical that TEMPSC be ventilated in order to provide an exchange of air between the cabin and its surrounding external environment. Currently, when in a stationary state, a TEMPSC can only be ventilated by opening one or more of its watertight hatches and exposing its occupants to the external weather conditions. Ideally, occupants would be exposed to these potentially harsh conditions as infrequently as possible; however, without an understanding of the potential for CO_2 accumulation within TEMPSC it is very difficult to speculate as to how often ventilation would have to take place.

The National Research Council of Canada Institute for Ocean Technology (NRC-IOT) and Memorial University of Newfoundland (MUN) investigated the effects of occupancy during normal operations on TEMPSC habitability, as well as the implementation of an active ventilation system within these vessels. Although it may be suggested that there are many variables that may impact occupant habitability within a TEMPSC, this paper will focus on air quality, and specifically the accumulation of CO_2.

METHODS

Location & Conditions*:*

Trials were conducted in January and February 2011 at the NRC-IOT facility in St. John's, Newfoundland, Canada. These trials were carried out with the engine off, hatches closed, and the TEMPSC sitting on a trailer located within an indoor loading bay (see Figure 1). Condition 1 involved participants being loaded systematically into the TEMPSC wearing street clothes in experimental group sizes ranging from 3 to 15 persons. This condition was repeated using a different complement of participants, again repeating group sizes of 3 to 15. Condition 2 involved participants being loaded into the TEMPSC wearing survival suits in group sizes ranging from 3 to 11 persons (see Figure 2).

Figure 1. An exterior view of the TEMPSC located within the test site.


Figure 2. An interior view of the TEMPSC cabin with occupants in survival suits.

Equipment & Instrumentation:

Trials were conducted using an International Maritime Organization Safety of Life at Sea (IMO-SOLAS) TEMPSC built in accordance with the requirements put forth by the SOLAS Convention (IMO, 1997) and the International Lifesaving Appliance (LSA) Code (IMO, 2003) and rated for 20 occupants. The TEMPSC has been retrofitted as a research craft, and is instrumented to collect pertinent interior cabin information via a custom-built data acquisition system. To ensure participant safety, alarms were configured to sound when CO_2 levels reached 4800ppm, below the 5000ppm 8-Hour Exposure Limit set by the Health and Safety Executive (HSE, 2007). Trials ended when the CO_2 alarms sounded. During trials involving survival suits, participants donned White's Marine Abandonment Suits (White's Manufacturing, Victoria, BC, Canada), which are Transport Canada certified immersion suits.

Participants and Ethics:

28 participants volunteered to participate in the study, with an age range of 19 to 53 years. The Memorial University Human Investigation Committee (MUN-HIC) and NRC's Research Ethics

Board approved this study. All participants gave their written informed consent prior to testing.

RESULTS

Un-suited trials simulate an EER scenario in which passengers without proper thermal protection (e.g. cruise ship passengers) have abandoned to a TEMPSC. The suited trials would be more representative of an evacuation of professional mariners to a TEMPSC (e.g. commercial shipping or offshore oil workers).

Since the trials were carried out in an indoor loading bay, variables such as temperature were kept relatively constant between trials (~18°C). In un-suited trials, incremental loading of participants in groups of 3, 5, 7, 9, 11, 13, and 15 showed expected increases in the rate of CO_2 accumulation within the TEMPSC. In turn, this led to a decrease in the time required to reach the 8-hour CO_2 exposure limit. Figure 3 presents data showing the time required to reach the exposure limit for the respective un-suited trials. A third order polynomial was fitted to the dataset (R^2 = 0.99). Suited trials, with occupants loaded in groups of 3, 5, 7, 9, and 11, also showed significant increases in the rate of CO_2 accumulation within the TEMPSC, and decreases in time to the 8-hour exposure limit. Figure 4 presents data showing the time required to reach the exposure limit for each of the respective suited trials. Again, a third order polynomial was fit to the dataset (R^2 = 0.99). Raw data for both the un-suited and suited datasets are shown in Table 1.

DISCUSSION

The results of this study suggest that recommended air quality conditions within a TEMPSC may be compromised due to accumulation of CO_2 gas with increased occupant numbers unless scheduled or monitored ventilation strategies are implemented. It took approximately 10 minutes for 15 occupants to produce CO_2 levels that exceeded the 8-hour exposure limit (Health and Safety Executive, 2007). As is reported in previous work (Power & Simões Ré, 2010; Taber *et al*. 2010), having the lifeboat hatches closed decreases the functionality of the passive ventilation system. Given that the occupants of the lifeboat were the source of CO_2 production, increasing their number from 15 occupants to 20 (the maximum rated capacity of the TEMPSC used in this study) would only serve to increase the amount of CO_2 accumulation and decrease the time taken to approach the 8-hour exposure limit. In addition, a regression equation predicts that CO_2 accumulation would occur at an even greater rate if the occupants were wearing survival suits.

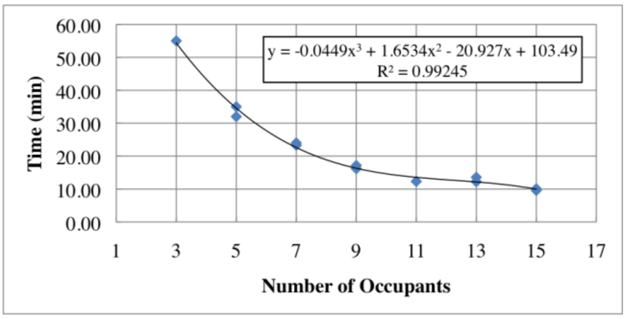

Figure 3. Time to maximum allowable carbon dioxide accumulation relative to occupant loading (without survival suits).

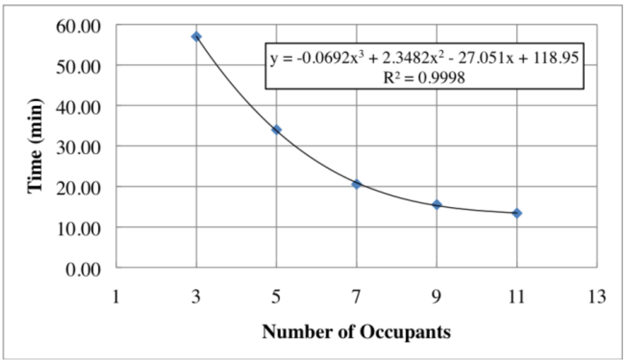

Figure 4. Time to maximum allowable carbon dioxide accumulation relative to occupant loading (with survival suits).

	Un-Suited Trials	Suited Trials
Number of Occupants	Time to Limit (min:sec)	Time to Limit (min:sec)
3	55:00	57:00
5	35:00	34:00
	32:00	
7	24:00	20:56
	23:30	
9	17:15	15:52
	16:19	
11	12:30	13:40
	12:34	
13	12:23	N/A
	13:57	
15	10:07	N/A
	09:57	

Table 1. Data summary of trial durations as determined by the various occupant complements within the TEMPSC.

It may seem obvious to suggest that operating the TEMPSC with the hatches open would be an effective mitigating step to prevent CO_2 build-up, and although this may be true, it may not always be possible or safe to do so. Operating with the hatches open compromises the watertight integrity of the TEMPSC, and doing so in a high sea state would greatly increase the risk of taking on water. Also, if the TEMPSC were forced to navigate through fires or clouds of sour gas, having the hatches open would directly expose the occupants to these dangers. Also, it should be noted that unpredictable factors such as wind speed or direction may not always work in favor of quickly and efficiently ventilating the TEMPSC. In light of this, ventilation may have to occur more frequently than the proposed minimum of once every ten minutes.

EER events are often very fast-paced and stressful situations that involve many cognitive tasks, such as decision-making and navigation. It would be very difficult to effectively carry out EER protocols and operate the TEMPSC while undergoing the respiratory distress and central nervous system effects that can be brought on by exposure to high levels of CO_2 (Xu *et al.* 2011; Scott *et al.* 2009). Ironically, the TEMPSC, a safety appliance that has been designed to increase safety in harsh climates, is capable of creating an internal environment that is harmful to human life.

It may prove fruitful to conduct further testing on TEMPSC operation in various conditions with the hatches closed in order to investigate the potential for further effects on CO_2 accumulation. These conditions could include ice navigation, high sea states, and different complements of occupants, to name a few. Moreover, testing could also be conducted using different TEMPSC models, including those that are rated for many more occupants.

In conclusion, it is proposed that a TEMPSC trapped in a stationary state at sea would have to ventilate its cabin at least once every ten minutes. It is not unrealistic to expect that the occupants of a TEMPSC located in Arctic waters may have to wait 24 hours, or more, for rescue vessels to arrive due to the relative inaccessibility of many regions thereby straining fuel resources, or that they may become stuck in constantly shifting ice floes. While in these stationary states, the passive ventilation system within the TEMPSC is rendered ineffective, and thus it is highly probable that CO_2 levels will climb to levels that are dangerous to human health. However, if an active ventilation system were implemented that constantly exchanged air between the internal and external environment of the vessel, the need for ventilation via an opening of one or more of the TEMPSC's hatches, thereby exposing its occupants to potentially harmful external environmental conditions, would be effectively negated. In turn, occupant habitability within the TEMPSC would be greatly improved, along with the likelihood of a successful EER event.

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