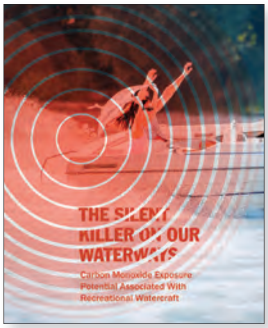

Carbon Monoxide Exposure Potential Associated With the Use of Recreational Watercraft

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Abstract **Carbon monoxide (CO) is a colorless and odorless gas generated from incomplete combustion of hydrocarbon-based fuels. Exposure to elevated CO concentrations can cause an array of health problems or even death. Of increasing concern are CO-related poisonings and fatalities associated with recreational watercraft. From 2005–2018, there were 78 known deaths of people due to CO associated with the use of recreational watercraft in the U.S. The incidence, however, is likely higher due to many CO poisoning-related deaths being inaccurately attributed to drowning instead of CO poisoning.**

To examine the significance of this public health hazard, a range of plausible exposures were characterized by measuring instantaneous CO concentrations at 17 sampling locations on or near the stern of four recreational boats. Observed CO concentrations were highest in samples proximal to the engine exhaust manifold, with maximum concentrations for the four boats being 42,600 ppm, 2,550 ppm, 6,100 ppm, and 3,700 ppm, respectively. Continuous CO monitoring was performed at a fixed location near the passenger seat in the back of each boat. Comparing our monitoring results with thresholds set by the U.S. Environmental Protection Agency, National Institute for Occupational Safety and Health, and World Health Organization demonstrates that many CO concentrations exceed or nearly exceed established exposure thresholds. Thus, environmental health and public safety professionals must remain aware of this hazard and examine administrative and engineering controls that reduce watercraft-related CO exposures and prevent injuries and drowning related to CO.

Introduction

Carbon monoxide (CO) gas is generated from the incomplete combustion of hydrocarbon-based fuels. Due to its colorless and odorless nature, combined with its potential to produce lethal health outcomes, CO is often considered a "silent killer." CO inhalation toxicity is characterized by its enhanced affinity and binding strength to hemoglobin, which leads to hypoxia (Rose et al., 2017). CO affinity for hemoglobin is 210 times greater than oxygen and CO has an even greater affinity for myoglobin, which when bound to CO can lead to myocardial depression, low blood pressure, and irregular heartbeats (Barrett et al., 2009). Symptoms and outcomes of CO poisoning can include headache, irritability, fatigue, confusion, dizziness, vomiting, disorientation, seizures, angina, and death; increasing CO concentration, length of exposure, and ventilation rates exacerbate these conditions (Blumenthal, 2001; Ramos et al., 2016).

CO-related poisonings and fatalities associated with exposure to recreational watercraft emissions occur every year in the U.S. In 2017, more than 142 million people in the U.S. (36% of the population) participated in recreational boating (National Marine Manufacturers Association [NMMA], 2017), which represents an increase from 67.5 million people in 2000 and 87.3 million in 2014 (NMMA, 2015). From 2002–2011, the number of CO-related deaths associated with recreational boating in the U.S. averaged 6.7 per year, with cabin motorboats accounting for 53.7% of these deaths (LaSala et al., 2015). From 2005–2018, there were 167 CO-related accidents, 324 CO-related injuries, and 78 CO-related deaths reported to the U.S. Coast Guard and entered into the Boating Accident Report Database (U.S. Coast Guard, 2018, 2021).

These data account for CO-related exposures associated with auxiliary boat equipment, boat exhaust from other vessels, and exhaust of the vessel on which persons were either aboard or in close proximity at the time of the accident (U.S. Coast Guard, 2018). Overall, the incidence of CO-related accidents is likely underreported among drowning victims. Thus, physiologic testing for CO exposure needs to be requested by a

TABLE **1**

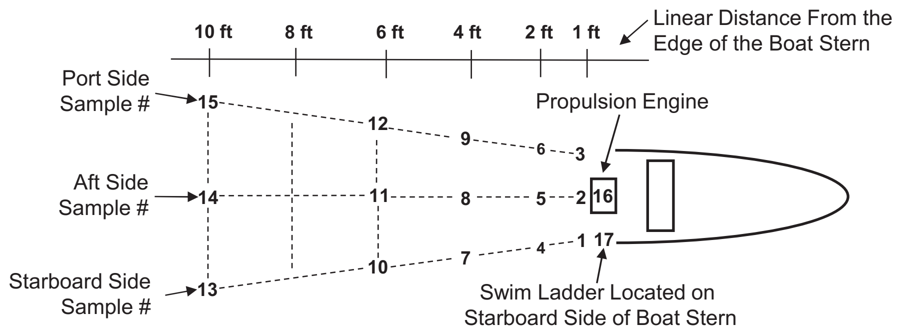
Boat Characteristics and Carbon Monoxide Monitoring Locations

Characteristic	Boat 1	Boat 2	Boat 3	Boat 4
Model and type	Bayliner, 1850 Caprice	Weldcraft, fishing	Ski Supreme, V Pro Sky	Four Winns Funship 234
Engine model	120 HP Force Outboard	Outboard Evinrude V6	Mercruiser 5.7L	Mercruiser 6.2L MX
Engine year	1999	1983	2001	2002
Site elevation	3,100 ft above MSL	2,470 ft above MSL	4,212 ft above MSL	3,100 ft above MSL
Study location	Spring Shores Marina	Private residence	Private residence	Spring Shores Marina
Water body	Lucky Peak Reservoir	Snake River	Snake River	Lucky Peak Reservoir
City and state	Boise, Idaho	Hammett, Idaho	Rupert, Idaho	Boise, Idaho

*MSL = mean sea level.

FIGURE **1**

Sampling Locations Used for Each Study Boat to Measure Carbon Monoxide



medical examiner when watercraft exhaust inhalation is expected (Armstrong & Erskine, 2018).

With regard to potential CO exposure, National Institute for Occupational Safety and Health (NIOSH) research shows that concentrations present in engine and generator exhaust emitted from houseboats often exceeded NIOSH's immediately-dangerous-to-life-or-health (IDLH) value of 1,200 ppm, a threshold that when exceeded limits one's ability to self-escape from the exposure environment (Hall et al., 2014). Research conducted by government organizations, such as NIOSH, provides a foundation for the characterization of CO emissions from recreational watercraft. Much of this research pertains to CO exposure associated with houseboats as well as the effectiveness of newly developed CO emission control features.

Significant contributors to deaths occurring outside the cabin area of recreational vessels are associated with teak surfing, sitting on the swim platform, or swimming behind an idling boat. Teak surfing is a practice now banned in many U.S. states and discouraged by the U.S. Coast Guard. This activity involves a person hanging onto the swim platform (often made of teak wood) and letting go at a time that allows them to ride (surf) the wake created by the moving boat. Teak surfing enhances the potential for greater exposure to CO because CO accumulates in the displacement wave gap created by the boat's wake. Even when the boat is moving, elevated CO exposures to those inside the vessel can exist via the "station wagon effect," an atmospheric condition created when air is displaced as a boat travels forward, creating a pocket of low pressure behind the boat that pulls exhaust gases into the boat (Garcia et al., 2006).

U.S. Coast Guard data confirm that CO poisonings and deaths continue to occur every year on U.S. waterways. Given recreational boating popularity in the U.S., studies investigating adverse CO exposure risks on and adjacent to recreational boats remain important to the safety and health of the recreating public. Thus, to better characterize CO exposures associated with the operation of non-houseboat style watercraft (e.g., ski boats, bass boats, etc.), this article describes the results of our study, which showed the dynamic nature of CO concentrations in ambient air and the potential for adverse exposure when measured at various locations on and adjacent to operating a recreational watercraft.

Methods

We performed CO monitoring on and adjacent to four boats using portable CO analyzers (Monoxor II & Monoxor II H). These handheld analyzers were used to record instantaneous CO concentrations. Due to the dynamic nature of CO in ambient air, CO was instantaneously monitored at 17 fixed locations for 10-s intervals and the maximum concentration over that interval was recorded. Continuous CO levels were monitored on the back passenger seat of each boat using an indoor air quality monitor (Q-Trak). Using a 1-s logging interval, the Q-Trak provided continuous results throughout the data collection period.

Wind direction was evaluated using a wind vane (Vortex Visual Vane) that logged and digitally recorded wind speed. For boats 1 and 4, atmospheric temperature and pressure were extrapolated to the sampling site using data collected at the National Oceanic and Atmospheric Administration weather station located at Lucky Peak Dam, Idaho. Due to the absence of an adjacent weather station at study locations for boats 2 and 3, the Q-Trak monitor was used to obtain sampling site temperature and relative humidity.

CO monitoring methodologies were similar for all four boats, with the only differences being geographical location. Differences in the age, style, engine type, location, and elevation of the four boats assessed are noted in Table 1 and represent a cross-section of day-use boats on many U.S. waterways. For each boat, the wind vane and indoor air quality monitor were mounted on the back passenger seat, which is most proximal to the boat's engine.

To record CO concentrations at distances proximal and behind the boat's stern, CO analyzers were used to acquire maximum concentrations at 17 fixed locations using a researcher-operated, 7-ft Outcast pontoon boat. Monitoring distances ranged from directly behind the boat's engine to as far as 10 ft beyond the stern (Figure 1). To enable data collection at consistent distances, each monitoring location was measured using a graduated PVC pipe demarcated in 1-ft intervals. In addition to the distance-specific results obtained at engine idle, CO concentrations were recorded while the boat was in motion at engine speeds that mimicked recreational activities such as teak surfing and platform dragging.

Results

Environmental Conditions

Atmospheric data provided in Table 2 illustrate the stable, clear, sunny, and relatively warm or hot conditions observed during the three monitoring events. Wind speeds were light (<5 mph) at three of the four study locations and relative humidity variations were minor and decreasing throughout each of the four sampling periods.

Carbon Monoxide Monitoring Results at Engine Idle

Instantaneous CO results at engine idle (Table 3) show large variations at or near the engine exhaust port (locations 16 and 17). Specifically, boat 1 had CO levels ranging from 2–42,600 ppm, boat 2 had readings ranging from 45–2,550 ppm, boat 3 had readings ranging from 2–6,100 ppm, and boat 4 had readings ranging from 6–3,700 ppm. For all boats, CO concentration maximums occurred proximal to the engine.

TABLE **2**

Summary of Weather Conditions Specific to the Observation Period for Each Study Boat and Location

	Boat 1	Boat 2	Boat 3	Boat 4
Sample date	7/28/2011	8/7/2011	8/14/2011	8/21/2011
Time and duration of study	12:40–1:15 p.m.	10:16–11:03 a.m.	9:52–10:40 a.m.	8:20–11:42 a.m.
Temperature range (°F)	92–94	85–90	90–95	70–85
Relative humidity (%)	18–19	30–38	20–28	25–42
Average wind speed (mph)	1–2	1–3	0–1	8–15
Maximum wind speed (mph)	3	5	3	20

TABLE **3**

Carbon Monoxide (CO) Concentrations for the Study Boats by Sample Location and Distance

Sample Site	Distance (ft)	Carbon Monoxide Concentration (ppm)			
		Boat 1	Boat 2	Boat 3	Boat 4
1	1	270	600	35	**3,700**
2	1	320	600	**6,100**	190
3	1	80	63	**1,390**	620
4	2	800	292	27	**1,800**
5	2	500	**1,200**	1,030	**1,475**
6	2	200	24	1,030	100
7	4	90	218	20	1,100
8	4	270	270	450	6
9	4	410	45	580	8
10	6	100	–	4	42
11	6	45	–	5	30
12	6	60	–	8	14
13	10	7	350	2	75
14	10	5	120	3	80
15	10	2	24	3	10
16	0	**42,600***	**2,550***	103**	700**
17	<1	1,050	**1,850**	**5,000*****	540**

Note. Bolded numbers indicated CO concentrations at or above the National Institute for Occupational Safety and Health immediately-dangerous-to-life-or-health threshold (>1,200 ppm).

*Sample collected directly in front of outboard engine exhaust port.

**Sample collected directly behind swim platform at level of head height when holding onto platform.

***Sample collected directly behind the swim platform at platform level.

Distribution analyses of instantaneous CO results using the Shapiro–Wilk test demonstrated that data were not normally distributed and thus, all data were log-transformed. Overall, *t*-test analyses showed no difference in the average of $\log_{10}$ CO levels between the four boats. For all boats, there was a significant negative correlation between CO concentrations and distance from the boat stern (Figure 2). Spearman's ρ was -.81, -.61, -.83, and -.56 for boats 1, 2, 3, and 4, respectively.

Carbon Monoxide Results for Each Boat in Motion

CO concentrations acquired for each boat in motion were monitored under conditions mimicking platform dragging and teak surfing. The observed CO concentrations mimicking platform dragging at varying speeds and at distances of 5- and 10-ft behind moving boats ranged from 50–390 ppm (Table 4). Table 4 shows CO concentrations ranging from 155–700 ppm when using boats 3 and 4 to simulate teak surfing at speeds of 5, 7, and 10 mph.

We performed continuous CO monitoring over the duration of the sampling period at the rear seat location of boats 2 and 3. Figure 3 shows 60-s peak concentrations of 302 ppm and 1,000 ppm for boats 2 and 3, respectively. Additionally, Table 5 provides 15-, 30-, and 60-min time-weighted average (TWA) CO concentrations computed from the logged data. Acquired 15-min TWA concentrations for boats 2 and 3 were 56 ppm and 13 ppm, respectively. The 30-min averages for boats 2 and 3 were lower at 38 ppm and 7 ppm, respectively. The 60-min average CO levels were lowest at 25 ppm and 4 ppm for boats 2 and 3, respectively.

FIGURE **2**

Scatterplot Demonstrating the Negative Relationship Between Carbon Monoxide (CO) Concentration and Distance From the Stern of Each Study Boat

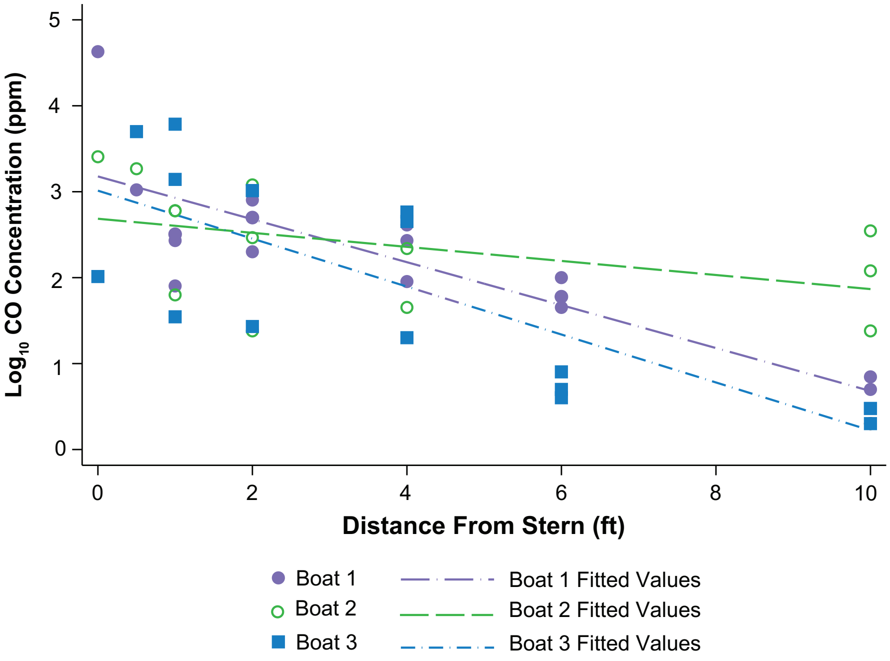


TABLE **4**

Carbon Monoxide (CO) Concentrations Measured During Simulated Recreational Activities

Activity	Boat #	Speed (mph)	CO Concentration (ppm)
Platform dragging (5 ft from stern)	1	2	160
	2	2	90
	3	5	55
	3	7	150
	3	10	75
	4	5	390
Platform dragging (10 ft from stern)	1	2	140
	2	2	50
Teak (wake) surfing	3	10	155
	3	10	520
	4	10	700
	4	10	540
	4	10	250
	4	10	448

Discussion

The four study boats, with variable engines, usage hours per engine, and exhaust systems, provided an opportunity to investigate a range of CO exposure scenarios. Additionally, for each boat, we examined the potential for near-engine exhaust concentrations to exceed health-relevant standards. The results of this study suggest CO exposures can occur at concentrations that encroach upon and exceed exposure thresholds established by government and nongovernmental organizations.

Comparing Results to Occupational Standards

Upon reviewing boat-related CO poisoning case reports (National Institute for Occupational Safety and Health, 2006), it is apparent to us that CO poisoning happens to persons of all ages; however, children and adolescents could be at increased risk for CO-related accidents. The World Health Organization

(WHO, 1999) has always considered children a high-risk group for CO poisoning. Children presumably have higher received and inhaled doses due to differences in their respiratory rates and body mass.

For working adults, NIOSH designates occupational exposures to CO concentrations that are at or above 1,200 ppm to be immediately-dangerous-to-life-or-health (IDLH). Thus, given their enhanced risk, children would theoretically need a level more protective than 1,200 ppm. For all four boats, our study showed that persons using the swim ladder or hanging from the stern or swim platform could be exposed to CO levels that exceeded the IDLH level (Table 3). For boat 2, even at a distance of 2 ft beyond the stern, CO concentrations were observed at or above 1,200 ppm. These results corroborate findings from Hall et al. (2014), who observed CO levels above the NIOSH IDLH concentration proximal to houseboat exhaust.

The Q-Trak continuous sampling for boats 2 and 3 mounted on a passenger seat nearest the stern showed peaks ranging from 300–1,000 ppm (Figures 3 and 4). On boat 3, the boat started and stopped several times, mimicking typical recreational skiing or surfing, where a boat starts and stops numerous times to collect fallen recreationalists. The air current during this time was dragged into the back of the boat and concentration spikes reached upwards of 300 ppm inside the boat. Although these levels when averaged over 8 hr might not result in exceedances of 8-hr TWA limit values for working adults in occupational environments, it is plausible that the TWA could be exceeded depending on the different watercraft involved, variations in engine performance, and activity use patterns on the water. The 8-hr TWA values from NIOSH, American Conference of Governmental Industrial Hygienists (ACGIH), and Occupational Safety and Health Administration are 35, 25, and 50 ppm, respectively (ACGIH, 2013; Air Contaminants, 1997; NIOSH, 2007). Boat 3 had 15-min, 30-min, and 60-min values of 55, 38, and 25 ppm, respectively. Boat 3, if used for skiing all day theoretically could have exceeded the 8-hr TWA values.

Comparing Results to Indoor and Ambient Air Guidelines

In comparison to WHO indoor air guidelines, our results suggest that under conditions that closely mimic skiing activities (after 10:45 a.m. in boat 3, Figure 3), the potential for passengers to be exposed to levels exceeding WHO established standards is plausible. The WHO guidelines indicate persons should not be exposed to levels exceeding 87 ppm for 15 min, 52 ppm for 30 min, 26 ppm for 60 min, and 9 ppm for 8 hr. The 60-min result observed inside boat 3 was 25 ppm, which was just below the 60-min level of 26 ppm set by WHO.

It should be noted that a full 60 min of skiing was not simulated, and only 20 min were recorded by the Q-Trak. The 60-min average obtained from the Q-Trak included approximately 40 min of idling time. If the study occurred for a period of time only focusing on the boat in operation for skiing, wakeboarding, etc., it is apparent over 60 min that boat 3 would likely have exceeded one or more WHO guidelines. Furthermore, it is plausible that over 60 min, the passenger seat of boat 3 could have experienced an exceedance of the U.S. Environmental Protection Agency (U.S. EPA, 2021a) ambient air quality standard of 35 ppm for a 60-min average.

TABLE **5**

Maximum Time Weighted Average of Carbon Monoxide (CO) Concentrations Measured During the Sampling Period

Time (min)	CO Concentration (ppm)	
	Boat 2	Boat 3
15	56	13
30	38	7
60	25	4

Comparing Results to Acute Exposure Guideline Levels

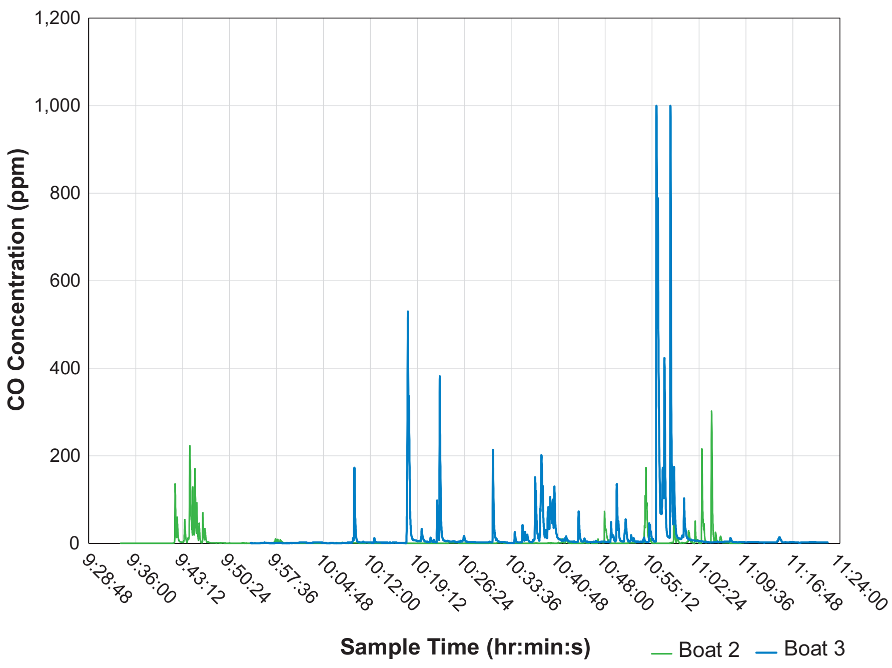
U.S. EPA identifies CO as an extremely hazardous substance. For assisting communities with planning for potentially harmful emergency exposures to extremely hazardous substances, the National Research Council (2010) developed acute exposure guideline levels (AEGLs). The two AEGL values applicable to life safety (AEGL-2 and AEGL-3) are applicable to the general population, which includes susceptible individuals. AEGL-2 is the concentration that could result in irreversible or other serious long-lasting health effects, or impair the ability to escape. AEGL-3 is the level that could result in life-threatening adverse health effects or death. Values for AEGL-2 and AEGL-3 exist for exposures ranging from 10 min to 8 hr.

AEGL-2 indicates that 10 min of 420 ppm or 30 min of 150 ppm exposure would be disabling and could result in an inability to escape. AEGL-3 indicates that 10 min of exposure at 1,700 ppm could be lethal. The AEGL values were developed by the National Research Council (2010) as "emergency exposure limits for exposures at high levels but of short duration, usually less than 1 hour, and only once in a lifetime for the general population, which includes infants (from birth to 3 years of age), children, the elderly, and persons with diseases, such as asthma or heart disease."

The CO concentrations observed for the teak surfing scenario for boats 3 and 4 (Table 4) would exceed AEGL-2 if 10 min of sustained teak surfing occurred. Individuals who are exposed might be unable to escape, which could result in injury or drowning if the person is not wearing a face-up personal flotation device. Sustained platform dragging with a distance of 5 ft could also exceed AEGL-2 (Table 4).

Overall, the variability observed here in CO concentrations likely pertains to engine type, engine performance, and wind variability. A larger study of more engine types would likely demonstrate more health-favorable as well as more concerning measures of CO. The TWA values used in this study are inclusive of the time periods with idle operation of the watercraft. The TWA values would be higher for sustained activities involving operation of the watercraft at speeds used for skiing, wakeboarding, etc. The engines and watercraft involved in our study were all operational with no known defects. Improper fuel mixtures, engine malfunctions, exhaust system damage, FIGURE **3**

Maximum Carbon Monoxide (CO) Concentrations Measured at the Rear Seat of Study Boats 2 and 3



Note. This time-series plot is inclusive of CO concentrations obtained at idle and moving speeds during 60-s measurement periods.

and other factors could create conditions that would be of greater concern for public health than the results observed in our study.

Health Implications and Recommendations

Recreational watercraft continue to be linked to preventable CO-related injuries and deaths (U.S. Coast Guard, 2018, 2021). Since 1995, there has been clear documentation in the medical literature of this danger (Silvers & Hampson, 1995). In this study, the CO observations show opportunities for exposed persons to experience loss of consciousness, neurologic damage, physical injury, and accidental death. Furthermore, even passengers in open-air watercraft can be exposed to CO levels that are detrimental to health. Also of concern would be pregnant passengers, as increasing CO exposure has been linked to adverse impacts on fetal growth and birth-related health outcomes (Liu et al., 2007; Stieb et al., 2012)

It is presumed many recreational boaters remain unaware of CO dangers present on and around boats. Along with existing private and government efforts, increasing awareness through state-mandated boating education courses could further reduce CO-related accidents. Signage, decals, and greater use of regulations regarding the dangers of teak surfing—as well as emphasizing the unique concept of the “death zone” could be considered as intervention opportunities. Interventions aimed at reducing CO-related injuries and mortality could fit into the National Association of State Boating Law Administrators (NASBLA) public health advocacy work related to the *National Recreational Boating Safety Program 2017–2021 Strategic Plan* that emphasizes a public health approach for increasing safer recreational boating practices (NASBLA, 2016; U.S. Coast Guard, 2016).

For houseboats, NIOSH recommended a variety of engineering controls such as exhaust stacks (Dunn et al., 2001). Research demonstrates that well-designed stacks can reduce houseboat CO concentrations by 90% (Dunn et al., 2003). Continued efforts at engineering controls for reducing CO emissions would improve boater safety. Newer engines (post-2010) should have lower emissions due to regulations pertaining to marine spark-ignition engines established by U.S. EPA (2021b); however, older engines will continue to remain on the water. In the absence of engineering controls and as a precautionary measure, people of all ages should avoid danger areas and always wear a life vest, as drowning events from CO-related loss of consciousness are plausible.

For legislation, several states including California, Nevada, Oregon, Pennsylvania, and Washington prohibit teak surfing, while some jurisdictions consider it reckless or careless operation of a vessel. In addition, several states including California, Minnesota, and Washington require decals, CO monitors, or both to warn boaters of the dangers of CO; however, the laws vary regarding vessel types and whether the vessel has any enclosed spaces. Few states mandate CO-related decals to be placed on watercraft, which can be an affordable intervention. Lastly, NASBLA (2019) reports that an overwhelming majority of U.S. states and territories require some form of boater education, which affords an opportunity to educate boaters on CO dangers. Many states already include CO-related education; however, education should not be limited to cabin-only vessels.

Conclusion

Recreational boater exposure to CO, on both idling and operational watercraft, has the potential to encroach and often exceed government exposure thresholds. Our study results validate the potential for poisonings and fatalities that have been documented by the U.S. Coast Guard. We anticipate that these findings will promote awareness of this health hazard among environmental health practitioners. Results from this study can promote continued progress in enhancing education as well as administrative and engineering controls for minimizing dangerous and potentially fatal CO exposures.

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