Carbon Monoxide Exposure & Express Cruisers

Controlling CO emissions and exposures

By Alberto Garcia, Kevin H. Dunn, Bryan Beamer, G. Scott Earnest and Ronald M. Hall

EPIDEMIOLOGIC INVESTIGATIONS revealed that from 1990 to 2006, 122 fatal carbon monoxide (CO) poisoning cases and 485 nonfatal poisoning cases involving various types of boats occurred in the U.S. (U.S. Department of Interior). Initial investigations of CO exposure and poisonings on houseboats began at Lake Powell in September 2000. Since then, a substantial amount of work has been done to evaluate engineering controls for CO on houseboats, but less effort has been expended to understand the extent of CO hazards on other types of recreational boats.

In 2005, NIOSH, Ancon Marine Consultants and the U.S. Coast Guard conducted 10 evaluations of CO emissions and exposures on express cruisers with gasoline-powered drive and generator engines. Many of the evaluated boats generated hazardous CO concentrations: Peak concentrations often exceeded 1,100 ppm, while average concentrations were well over 100 ppm at the stern (rear). Three boats with a combined exhaust system (exhausting at the sides and underwater) had dramatically lower CO concentrations (about 40% lower) than any of the other boats evaluated.

Express cruisers, which are also known as cabin cruisers, are fast cruising boats with many amenities. They have full head room in the cabin, a galley, head and berths. Express cruisers also have a large open helm and aft deck area. The evaluated boats were propelled by inboard twin gasoline-powered engines with an estimated horsepower ranging between 500 and 750. The hulls of all units were made of fiberglass reinforced plastic, aluminum and wood. The evaluated boats were also equipped with gasoline-powered generators to provide electrical power for onboard appliances.

One concern with these boats is the exhaust from the propulsion engines reentering the cockpit and accommodation areas while the boat is underway. Several poisonings related to CO on express cruisers in the U.S. have been documented (U.S. Department of Interior). Most express cruisers are equipped with a canvas top consisting of panels that enclose the cockpit. Figure 1 depicts the typical canvas panel configuration offered on express cruisers. The panels are commonly misused to protect boaters from severe weather or to extend their boating season.

Several issues are associated with the use of these panels when the boat is underway. The use of the canvas top increases the station wagon effect, a phenomenon that occurs when air moves around a boat creating low pressure pockets behind the moving boat (Figure 2). This low-pressure section pulls the exhaust back into the boat, potentially exposing boaters to high levels of CO. Often, boaters leave the back panel(s) completely or partially unzipped, which will cause exhaust fumes to funnel directly into the cockpit. A similar low pressure area may be created behind the windshield or even the boat's cabin or wheelhouse.

CO Symptoms & Exposure Limits

CO is a lethal poison produced when fuels such as gasoline or propane are burned. It is one of many chemicals found in engine exhaust, which results from incomplete combustion. Because CO is a colorless, odorless and tasteless gas, it may overcome the exposed person without warning. The initial symp-

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toms of CO poisoning may include headache, dizziness, drowsiness or nausea. Symptoms may advance to vomiting, loss of consciousness and collapse if prolonged or high exposures are encountered. If the exposure level is high, loss of consciousness can occur without the initial symptoms. Coma or death can occur if high exposures continue (NIOSH, 1972, 1977, 1979). Symptoms can vary widely from one person to another, and may occur sooner in susceptible groups, such as children or older people, people with preexisting lung or heart disease, or those living at high altitudes (Proctor & Hughes, 1996; ACGIH, 1996; NIOSH, 2000).

CO exposure limits have been established by NIOSH, American Conference of Governmental Industrial Hygienists (ACGIH), OSHA and World Health Organization (WHO). CO is also a criteria pollutant for which EPA (1991) has established limits that are set to protect "the most sensitive members of the general population." These limits are shown in Table 1. While the limits recommended by EPA and WHO were set to prevent adverse effects in the general population, the limits established by NIOSH, OSHA and ACGIH are intended to protect the healthy working population (OSHA, WHO, 1999). NIOSH has established a CO concentration of 1,200 ppm as immediately dangerous to life and health (IDLH). This is the most relevant for acute CO poisoning. NIOSH (1987) currently defines an IDLH condition as one that "poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse effects or prevent escape from such an environment" (p. 22).

Methodology

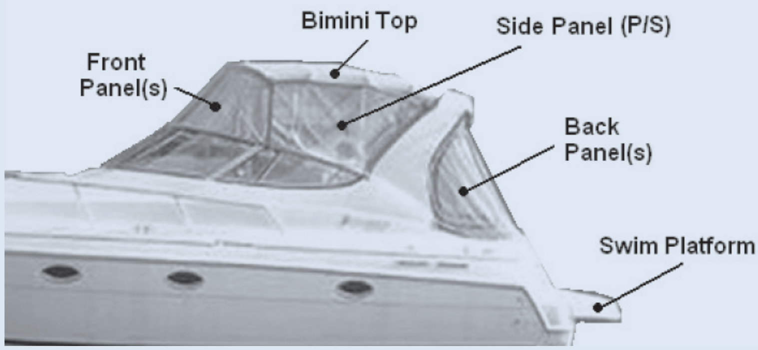
Air sampling for CO, ventilation measurements and wind-velocity measurements were conducted on 10 different express cruisers built by various manufacturers. The evaluated boats had new propulsion engines and generator sets tuned to manufacturer's specifications. Propulsion engines used on the evaluated boats were manufactured by Volvo Penta, Crusader Marine and Mercury Marine; generators were all manufactured by Kohler. Data were collected to evaluate the CO emissions of gasoline-powered engines and CO concentrations on and near the boats operating under various conditions and canvas configurations.

Table 2 provides a description of the boats, the propulsion engines and generator set. All boats were equipped with inboard engines. Most were sterndrive units with the exception of three that had straight inboard units. On an inboard engine, the engine and drive train are permanently mounted near the center of the boat's hull, and the propeller shaft penetrates beneath the hull. Stern drives are located near the back of the boat and have permanently mounted engines. However, the drive train penetrates the boat's transom (the planking that forms the stern of a square-ended boat).

Several propulsion engine exhaust configurations were evaluated:

Figure 1

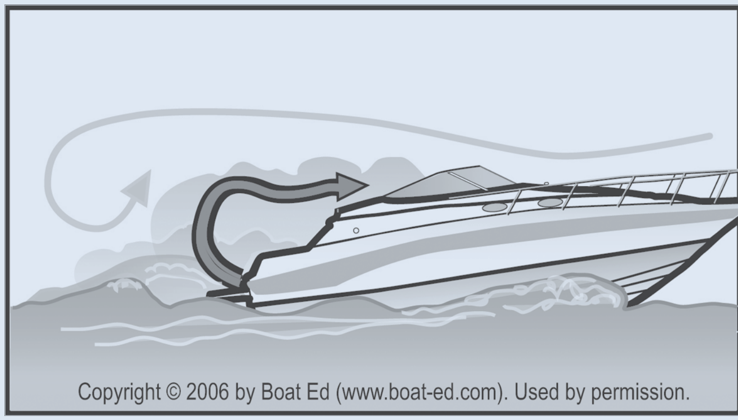
Typical Canvas Configuration



Note. *Photo courtesy U.S. Coast Guard. Used by permission.*

Figure 2

Station Wagon Effect



•Through-hub exhaust: Through-hub exhaust and over-hub exhaust propellers are used on boats where the exhaust passes through the rear of the "torpedo" on the lower unit, around the propeller shaft. Most outboards use this type of exhaust.

•Through transom exhaust: The exhaust is directed through openings located on the transom (stern) of the boat, usually above the waterline. Typically there are two exhaust openings per engine.

•Side exhaust: The exhaust is directed through openings located on the sides of the boat near the transom of the boat, usually above the waterline. There is typically one opening on each side of the boat.

•Underwater exhaust: The exhaust is directed through openings located on the transom (stern) of the boat, then released through an elbow-shaped fiberglass structure about 1.5 ft below the waterline.

•Combined exhaust through sides and underwater: This system is engineered to release all the exhaust at the surface through the sides of the boat when the engine is idling or has not exceeded 1,500 rpm. When the engine exceeds 1,500 rpm, a pressure-release mechanism is activated releasing most of the exhaust (80%) underwater, a foot inward from the transom, on the lower part of the boat hull. The remaining 20% is released through the sides above the waterline.

Automobile engines and marine engines used on recreational boats differ in several ways. The cooling

Abstract: *In 2005, NIOSH, Ancon Marine Consultants and the U.S. Coast Guard conducted 10 evaluations of carbon monoxide (CO) emissions and exposures on express cruisers with gasoline-powered drive and generator engines. This article discusses the results of these evaluations and provides a description of the environmental sampling performed, along with information to develop engineering controls that can reduce CO exposures on express cruisers.*

Table 1
CO Exposure Limits

Organization	TWA[a] exposure limit	Short-term exposure limit	Notes
ACGIH	25 ppm		8-hr TWA
NIOSH	35 ppm	200 ppm ceiling 1,200 ppm IDLH	8-hr TWA
OSHA	50 ppm		
EPA	9 ppm	 35 ppm	8-hr TWA 1-hr average
WHO	9 ppm	 87 ppm 52 ppm 26 ppm	8 hr 15 min 30 min 60 min

[a]TWA: time weighted average

Table 2
Description of Evaluated Boats

Boat	Length	Engine	Exhaust[a]	Generator set[b]
1	33 ft	Twin Volvo Penta 5.7 L	H	5.0 kW Kohler
2	30 ft	Twin Mercruisers 5.0 L	H	5.0 kW Kohler
3	31 ft	Twin Volvo Penta 8.1 L	H	7.3 kW Kohler
4[c]	37 ft	Twin Mercruisers 8.1 L	T	7.3 kW Kohler
5	36 ft	Twin Mercruisers 8.1 L	S/U	7.3 kW Kohler
6	40 ft	Twin Mercruisers 8.1 L	S/U	7.3 kW Kohler
7	41 ft	Twin Mercruisers 8.1 L	S/U	7.3 kW Kohler
8	34 ft	Twin Mercruisers 8.1 L	S	7.3 kW Kohler
9	38 ft	Twin Crusaders 8.1 L	U	8.0 kW Kohler
10	35 ft	Twin Crusaders 8.1 L	U	8.0 kW Kohler

[a]Exhaust types: H = through hub; T = through transom; S/U = sides and underwater; S = side; U = underwater. [b]Generators in this study exhausted on one side of the boat, close to the transom of the boat above the waterline. [c]Boat 4 was equipped with a selectable exhaust configuration through hub or through transom.

system in an auto engine is closed-loop, having air-to-coolant radiators. In contrast, marine engines are open-loop, drawing sea or lake water into the engine's water pump. A second difference is that marine engines use water-cooled exhaust manifolds to mix water (from sea-water pump supply) with exhaust gases for cooling. The objective is to keep all surface temperatures within the boat below 200 °F. Automobile engines do not add water into the engine exhaust.

A third difference relates to the treatment of the exhaust gases before releasing them to the atmosphere. In automobile engines, the exhaust passes through a catalytic converter that removes many of the air pollutants, including CO. In contrast, most marine engine exhausts are directly released into the environment without passing through a catalyst. New catalyst-based technologies are being developed and released for both propulsion engines and generators to reduce contaminants from the exhaust including CO. However, none of the evaluated cruisers had such engines.

The hot exhaust gases produced by the generators were injected with water, near the end of the exhaust manifold, in a process commonly called "water-jacketing." Water-jacketing is used for exhaust cooling and noise reduction.

Description of Evaluation Equipment

CO concentrations were measured at various locations on the boat using ToxiUltra atmospheric monitors (Biosystems, Middletown, CT) equipped with CO sensors. The monitors were calibrated before and after use, according to the manufacturer's recommendations. These monitors are direct-reading instruments with datalogging capabilities. The instruments were operated in the passive diffusion mode with the datalogging feature enabled and having a 30-second sampling interval. The nominal range of these instruments is from 0 ppm to approximately 1,000 ppm. The monitors were partially wrapped in plastic, leaving the sensor portion exposed, to protect them from water spray.

CO concentration data were also collected with colorimetric detector tubes (Draeger Safety Inc., Pittsburgh, PA) in the areas near the swim deck. In addition, grab samples were collected using MSHA 50-ml glass evacuated containers. These samples were collected by snapping open the top of the glass container, allowing air to enter and sealing the tubes with wax impregnated caps. The containers were sent to the laboratory and analyzed for CO. These additional methods were used to spot-check the data collected by using the ToxiUltra.

During air sampling, wind velocity was measured when the boat was stationary and underway using a TSI Velocicalc Plus model 8360 air velocity meter (TSI Inc., Shoreview, MN). The same instrument was also used to measure pressure differential between the engine compartment and adjacent cabin space. If the pressure within the engine compartment is positive with respect to the cabin, the potential exists for flow from the engine compartment to the cabin. Additional measurements using real-time CO detectors and smoke generators were used to track the flow of CO from the engine compartment to the adjacent cabin area. Boat speed was estimated with a marine global positioning system (Magellan, Santa Clara, CA).

Description of Evaluation Procedures

CO concentrations were collected for multiple test runs on each boat. Each test run typically lasted for 5 to 7 minutes. During some runs, the boats were stationary; during others, the boats were underway. Table 3 shows a sample test matrix. During the stationary evaluation, the generator alone was operated for approximately 15 minutes. CO concentrations were measured during engine cold starts, at the slip and while the boat was on the water.

Data were also collected with boats underway at four different speeds: 5, 10, 15 and 25 mph. Tests for each speed were conducted both with and without the canvas panels installed. For each test speed, data were collected while the boat was operating at several different headings to compensate for prevailing winds. Wind velocity was recorded each time a new run was initiated.

Air samples were collected and analyzed for CO concentrations in areas where boaters are likely to sit or congregate. Examples include spaces above deck—cockpit, helm, swim platform, aft deck—and spaces below deck—cabin and accommodation areas. Particular attention was paid to CO concentrations near the stern (emission source). Figure 3 illustrates the typical sampling locations on an express cruiser.

Table 3

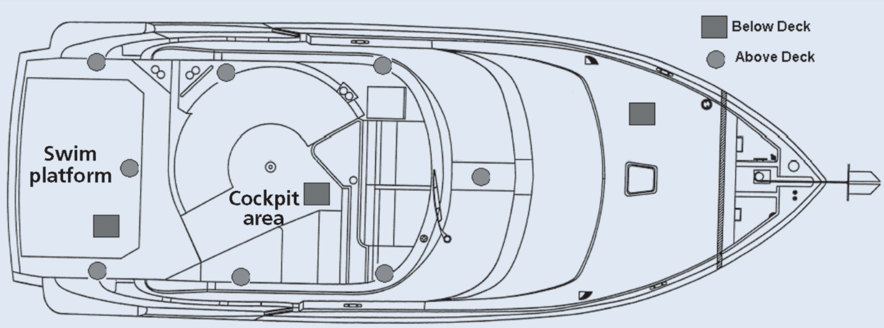
Test Matrix

Stationary or underway	Condition
Stationary (at slip)	1) Generator on 2) Generator and propulsion engines on
Stationary (on water)	1) Generator on 2) Generator and propulsion engines on
Idle speed	1) Full canvas configurations 2) Partial canvas configurations 3) Bimini top configurations Generator and propulsion engines on at all times
Two mid-range speeds	1) Full canvas configurations 2) Partial canvas configurations 3) Bimini top configurations Generator and propulsion engines on at all times
Open throttle	1) Full canvas configurations 2) Partial canvas configurations 3) Bimini top configurations Generator and propulsion engines on at all times

Note. *Full canvas configuration includes the bimini top, front and two side panels, with back panel(s) removed. Partial canvas configuration includes the bimini top and front panel(s), with two side panels and back panel(s) removed. Bimini top configuration includes only the bimini top.*

Figure 3

Typical Sampling Locations



Note. *Not to scale. Photo courtesy U.S. Coast Guard. Used by permission.*

Tests to Isolate & Track CO Emission within the Cabin

Tests were conducted to establish how CO flows into an express cruiser cabin. First, measurements were made to determine the presence of CO within the engine compartment. Potential sources of CO contamination could result from an engine propulsion leak or induction of exhaust gases into the engine compartment via the blower system. For positive results, additional tests were conducted to determine whether leakage from the engine compartment was making its way to the cabin (e.g., unsealed firewall).

Results

Table 4 presents the sampling results when testing the boats underway with various canvas configurations. Ten samples, or the equivalent of 5 min (30 s sampling interval), were collected for each run. Geometric mean and geometric standard deviation for CO concentrations are shown for the 10 evaluated boats at the center of the stern near the swim platform.

Boat Underway, Full Canvas Configuration

The term *full canvas* refers to the configuration for the installation of the bimini top, front and two side panels, with back panel(s) removed. Concentrations tended to be higher at lower speeds (5 and 10 mph) and decreased as the boats gained speed. The average CO concentration for almost all boats reached or exceeded the NIOSH ceiling limit of 200 ppm when at speeds of 5 and 10 mph.

CO concentrations were different when comparing one boat to another. The evaluated boats were equipped with different propulsion engine exhaust configurations, which played an important role in how CO concentrations are distributed in and around the boat. For boats exhausting above the waterline, CO concentrations tended to be higher at all locations around the boat. For boats using the combined exhaust system that exhausted through the sides and underwater, CO concentrations seemed to be consistently lower at all sampling locations when compared to the other boats. Figure 4 illustrates the average CO concentration of the 10 boats on the center of the stern when tested underway in the full canvas configuration.

Boat 2 exhibited much higher CO concentrations than the other boats throughout the sampled speed range. It is noted that the nominal range of the instrument was exceeded when traveling 15 mph. Once the nominal range of the instrument is exceeded, the response is uncertain, and it often requires a few minutes for return to normal operation. As noted, measurements were collected with several instruments. The data collected with other methods

Table 4

CO Concentrations on Express Cruisers

Boat (exhaust[a])	Canvas configuration	Geometric mean (ppm) 5 mph	10 mph	15 mph	25 mph
1 (H)	Full canvas	280 (1.5)	420 (1.1)	115 (2.9)	53 (1.8)
	Partial canvas	18 (2.2)	286 (2)	280 (1.5)	21 (2.7)
	Bimini top	24 (2.4)	21 (1.3)	261 (1.7)	172 (1.3)
2 (H)	Full canvas	666 (1.3)	489 (1.2)	1083 (1)	743 (1.6)
	Partial canvas	566 (1.4)	483 (1.1)	1076 (1)	744 (1.6)
	Bimini top	627 (1.5)	119 (1.2)	264 (2.6)	130 (1.8)
3 (H)	Full canvas	420 (1.3)	275 (1.1)	108 (2.1)	107 (2.4)
	Partial canvas	331 (1.3)	314 (1.3)	50 (1.6)	55 (1.6)
	Bimini top	59 (1.3)	41 (1.3)	11 (1.3)	5 (1.2)
4 (T)	Full canvas	474 (1.3)	333 (1.6)	333 (1.4)	118 (1.6)
	Partial canvas	358 (1.7)	101 (2.9)	218 (1.9)	42 (1.7)
	Bimini top	116 (1.6)	164 (2.6)	20 (1.3)	46 (1.5)
5 (S/U)	Full canvas	55 (1.2)	51 (1.6)	40 (1.4)	3 (2.7)
	Partial canvas	42 (1.9)	26 (1.2)	11 (1.4)	4 (1.8)
	Bimini top	7 (1.5)	5 (1.2)	0 (3.3)	2 (1.9)
6 (S/U)	Full canvas	171 (1.6)	194 (1.9)	67 (2.2)	1 (3)
	Partial canvas	5 (1.6)	49 (3.8)	11 (2.5)	2 (24)
	Bimini top	8 (2.2)	7 (1.9)	1 (1.4)	1 (8.1)
7 (S/U)	Full canvas	226 (1.4)	260 (1.3)	236 (1.6)	158 (1.6)
	Partial canvas	21 (1.6)	11 (1)	9 (1.1)	7 (1.1)
	Bimini top	186 (1.4)	163 (1.3)	243 (1.2)	107 (1.5)
8 (S)	Full canvas	276 (1.1)	345 (1.5)	38 (1.4)	77 (1.8)
	Partial canvas	149 (1.2)	206 (1.3)	18 (2)	3 (2)
	Bimini top	1 (1.4)	13 (3.1)	4 (2.1)	3 (2)
9 (U)	Full canvas	205 (1.8)	400 (1.2)	40 (2.3)	5 (8.2)
	Partial canvas	150 (1.5)	201 (1.5)	72 (1.9)	4 (6.1)
	Bimini top	242 (1.3)	186 (1.5)	—	—
10 (U)	Full canvas	189 (2.5)	368 (1.2)	199 (1.3)	68 (4.8)
	Partial canvas	59 (5.3)	532 (1.2)	162 (1.2)	11 (2.1)
	Bimini top	965 (1.2)	754 (1.1)	—	—

Note. *CO concentrations (ppm) on express cruisers under various operating conditions at center of swim deck.*
[a]*Exhaust types: H = through hub; T = through transom; S/U = sides and underwater; S = side; U = underwater.*

confirmed that the instrument was working correctly up to the speed of 15 mph. Grab samples indicated concentrations of 1,516 ppm when the boat was traveling at 15 mph. Although the reason for the high CO concentrations from this boat is unknown, several factors could have influenced the behavior of the gases in this particular boat. These factors include wind velocity and direction (back winds), exhaust generation rate, working load and various weather conditions.

Boat Underway, Partial Canvas Configuration

Partial canvas configuration refers to back and side panels removed. Only the front panels and the bimini top were installed when testing the boats. Figure 5 illustrates average CO concentrations for the partial canvas configuration on the 10 evaluated boats at the center of the stern.

Results show that CO concentrations tended to be lower for the partial canvas scenario than for the full canvas scenario. CO concentrations tended to be higher at 5 and 10 mph than at increased speeds. At 10 mph, the average concentration ranged between 11 and 540 ppm depending on the boat.

When comparing the 10 boats, the boats exhausting underwater exhibited lower CO concentrations than those exhausting above the waterline. For these express cruisers, 10 mph seems to be a problematic speed, since most of them displayed the higher concentration when traveling at this speed. Having fewer panels installed seemed to reduce the CO concentrations somewhat but not as much as expected.

Boat Underway, Bimini Top Configuration

CO concentrations were consistently lower under the bimini top configuration than when compared with full canvas or partial canvas configurations. Fresh air circulation helped clear the back of the boat as well as the cockpit and cabin areas. Even with no canvas panels installed, the CO concentration reached and sometimes exceeded the NIOSH ceiling limit of 200 ppm.

A different trend was observed in Figure 6, which represents a comparison of the 10 evaluated boats. The speed that created an increased CO concentration on the stern of the boat shifted from 10 to 15 mph. It is important to address the fact that CO seems to be an issue even without canvas panels installed and a bigger problem when the canvas panels are installed.

Boat Stationary

Air sampling data were collected while the boats were stationary (with propulsion engines running), resulting in generally higher concentrations than while the boats were underway. When the propulsion engines were shut off, concentrations tended to range between single-digit concentrations to a peak of 370 ppm. All the evaluated express cruisers had gasoline-powered generators, which create an additional source of CO. Samples were not collected at the generator exhaust terminus, which was usually on one side of the boat. Previous boat

Figure 4

Boat Comparison: Full Canvas

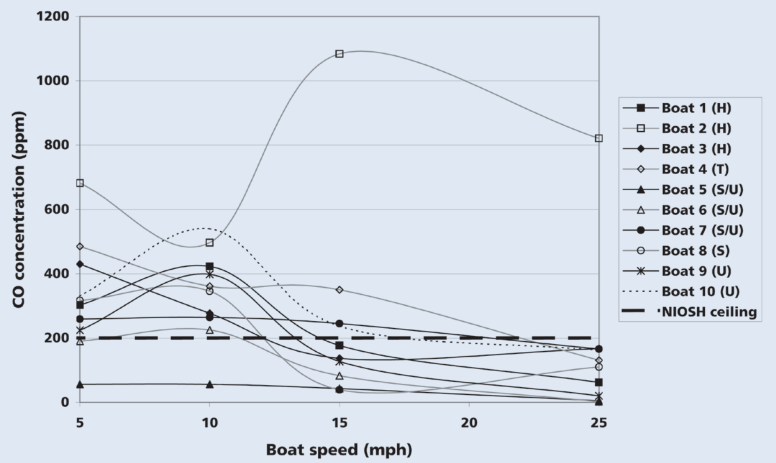
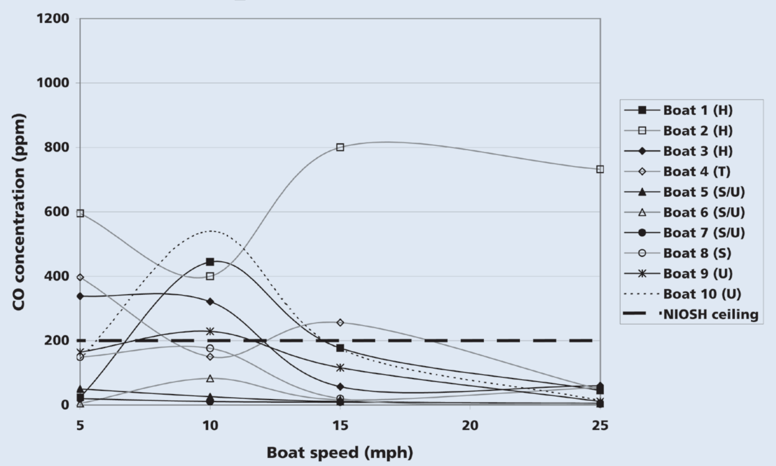


Figure 5

Boat Comparison: Partial Canvas



surveys suggest that swimmers near the generator exhaust area can be exposed to high levels of CO.

Emissions from Engine Compartment

All boats, except those with the engine access cover inside the cabin area, were tested for potential leakage in the engine compartment. An evaluation of how a leak would potentially cause CO to migrate to adjacent cabins was also performed. All tested units performed well, demonstrating a proper sealing between the engine compartment and adjacent compartments. In the past, improper sealing of the engine bulkhead along with a leaky exhaust have led to CO poisoning, and even death, to individuals aboard cabin cruisers.

Pressure differential tests revealed that when the boat is underway with the cabin door closed and the air conditioning running, the cabin is under a slightly negative pressure. This condition can lead to CO being drawn into the cabin.

The cabin door was kept closed for the duration of these evaluations. Usually CO levels inside the cabin ranged from 17 to 170 ppm. Higher concentrations were reported during continuous opening and closing of the cabin sliding door. CO levels varied within the boat even at similar locations.

Discussion

In terms of reducing onboard CO concentrations, the results demonstrate that boats equipped with underwater exhaust exhibited lower CO concentrations than boats equipped with other exhaust designs. For underwater exhaust systems, the rise of gases through the water is governed by bubble size and depth of injection. The propeller wash (turbulent churning of water by the boat's propeller) may also affect the rate of release of gas into the atmosphere by 1) breaking large bubbles into smaller ones; 2) causing bubbles to coalesce; or 3) propelling bubbles deeper into the water (NIOSH, 2004).

Regarding the behavior of individual bubbles, small bubbles (less than 1 millimeter in diameter) have a low rise velocity and, as a result, are likely to be spherical and rise in a straight path. As bubbles grow larger, their rise velocity increases, resulting in a less stable ellipsoidal bubble shape. The propeller may cause some of the larger bubbles to break up and become smaller, thereby reaching the surface more slowly and further reducing CO concentrations close to the boat. By implementing underwater exhaust configurations that entrain exhaust through the propeller wash, the potential for CO from the exhaust to be reentrained into the boat is greatly reduced (NIOSH, 2004).

A significant station wagon effect was documented for many of the experiments conducted. This effect is produced when negative pressures at the rear of the boat and cockpit areas (which are generated when the boat is underway) draw exhaust gases, including CO, from behind the boat into occupied areas. This effect was maximized when the boat was traveling at low speeds into the wind with the full canvas configuration and no forward hatches, windows or front panels opened. This stands to reason since the protection of the canvas and windows while underway creates a pocket of negative pressure relative to the outside. Conversely, when the canvas was removed not only was a negative pressure pocket less likely to be created, but air being drawn directly into the cockpit tended to ventilate the area.

Another interesting trend was observed regarding the station wagon effect. With the full canvas configuration, CO concentrations did not always change at higher speeds as much as expected. Rather, areas of high onboard CO concentrations merely shifted. At lower speeds of 5 to 10 mph, exhaust air was reentrained into the cockpit up to 4 ft from the cockpit floor. However, at 15 and 25 mph, higher CO levels were found closer to the cockpit floor (as low as 2 ft).

The significance of these observations is that depending on the various boat designs and ambient factors operating the boat at higher speeds is no guarantee of adequately ventilating occupied areas of the boat when the canvas is installed. Figure 7 illustrates the observed recirculation patterns when the boat was traveling at 5 to 10 mph, with the full canvas configuration and the rear panel opened.

Figure 6

Boat Comparison: Bimini Top

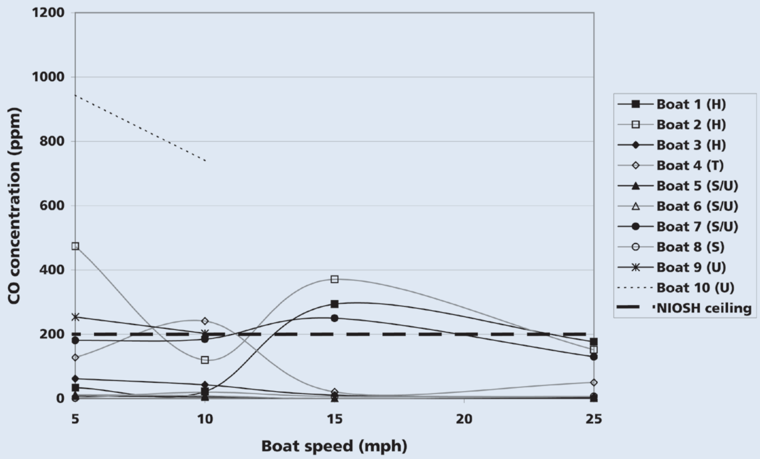
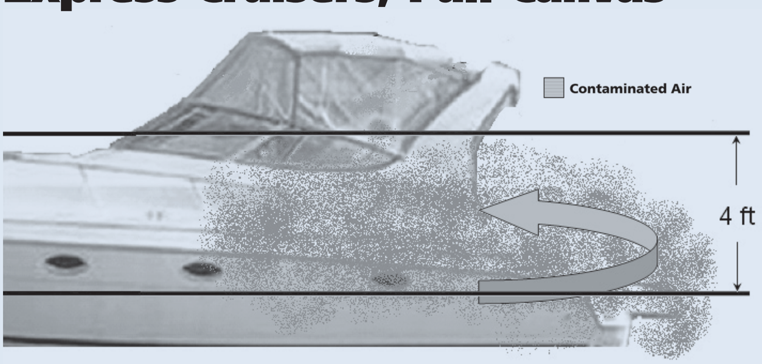


Figure 7

Recirculation Patterns on Express Cruisers, Full Canvas



Note. *Modified from Figure 1, courtesy U.S. Coast Guard. Used by permission.*

Conclusion

Analysis of the results made several trends apparent. With the full canvas configuration, CO concentrations reached instantaneous levels above 1,000 ppm (close to the NIOSH IDLH) near the swim platform for some of the evaluated boats. As noted, the full canvas configuration increases the negative pressure behind the boat, which tends to draw the exhaust gases into occupied areas. Therefore, it is appropriate to conclude that the full canvas configuration significantly affects CO concentrations in the cockpit area.

Different exhaust configurations have a major impact on how CO concentrations are entrained into the cockpit and other occupied areas. Boats equipped with underwater exhaust exhibited significantly lower CO concentrations than boats equipped with other exhaust designs.

CO concentrations are typically higher at the stern of the boat and become gradually lower toward the front of the boat. This is not surprising, as the emission source is located at the rear of the boats. Recirculation patterns varied with boat speed. At lower speeds the recirculation was observed to be as high as 4 ft measured from the cockpit floor. This height was reduced to 2 ft at 25 mph.

Low-emission generators that employ a catalytic converter are available. Although none of the units tested was equipped with this technology, it has been shown that these generators greatly reduce CO exposures. New technologies that employ catalytic converters on propulsion engines are being investigated to assess the impact which these developments may have on CO reduction for recreational boats.

All manufacturers/owners/users of express cruisers that use gasoline-powered engines/generators should be aware of the hazards of CO poisoning. Further research is planned to evaluate the impact of exhaust configuration and emission-control devices on propulsion engines as well as to determine whether forced air ventilation into the cockpit and helm areas can significantly reduce the negative pressure and thus reduce the station wagon effect. ■

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