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From 1990 to 2000, a total of 111 carbon monoxide (CO) poisonings occurred on Lake Powell near the Arizona and Utah border. Seventy-four of the poisonings occurred on houseboats, and 64 were attributable to generator exhaust alone. Seven of the 74 houseboat-related CO poisonings resulted in death. Although many of the reported CO poisonings occurred to members of the general public, some poisonings involved workers performing houseboat maintenance. The National Institute for Occupational Safety and Health evaluated an engineering control retrofitted to a houseboat gasoline-powered generator to reduce the hazard of CO poisoning from the exhaust. The control consisted of a water separator and a 17-foot exhaust stack that extended 9 feet above the upper deck of the houseboat. When compared to a houseboat having no engineering controls, study results showed that the exhaust stack provides a dramatically safer environment to individuals on or near the houseboat. CO concentrations were reduced by 10 times or more at numerous locations on the houseboat. Average CO concentrations near the rear swim deck of the houseboat, an area where occupants frequently congregate, were reduced from an average of 606.6 ppm to 2.85 ppm, a reduction greater than 99%. CO concentrations were also reduced on the upper deck of the houseboat. Hazardous CO concentration in the confined area beneath the rear swim deck were eliminated. Based on the results of this study, it is clear that houseboats having gasoline-powered generators that have been outfitted from the factory or retrofitted with an exhaust stack that extends well above the upper deck of the boat will greatly reduce the hazard of CO poisoning.

Keywords: carbon monoxide, combustion, engineering control, exhaust stack, houseboats, poisoning

FIELD STUDIES AND CASE REPORTS

Mention of any company or product does not constitute endorsement by the Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

From February 6 through 8, 2001, the National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of an engineering control, retrofitted onto a gasoline-powered houseboat generator, to reduce the hazard of carbon monoxide (CO) poisoning from the exhaust. The control, which consisted of a water separator and 17-foot exhaust stack, was retrofitted on to an existing generator that exhausted under the lower rear deck of the houseboat. The stack was designed to redirect the generator emissions away from individuals on or near the houseboat to prevent CO poisonings. The evaluation was conducted at Lake Powell, Ariz., which is in the U.S. National Park Service Glen Canyon National Recreational Area.

Initial investigations were conducted in September and October 2000, involving representatives from NIOSH, the U.S. Coast Guard, U.S. National Park Service, Department of the

FIGURE 1. Photo of the evaluated Lakeview houseboat

Interior, and Utah Parks and Recreation, in response to CO-related poisonings and deaths on houseboats at Lake Powell. The September 2000 investigation characterized CO poisonings through epidemiologic data gathering and industrial hygiene air sampling. Extremely hazardous CO concentrations were measured on houseboats at Lake Powell during these surveys.[1] Incident reports provided by the National Park Service revealed seven known houseboat-related CO poisoning deaths on Lake Powell since 1994. Some of these incidents involved numerous poisonings in addition to the deaths reported. Information regarding the fatalities was provided in a previous report.[1] Since that report, it has been discovered that from 1990 to 2000, a total of 111 CO poisoning cases occurred on Lake Powell. Seventy-four of the poisonings occurred on houseboats, and 64 were attributable to generator exhaust alone. Seven of the 74 houseboat-related CO poisonings resulted in death.[2]

During the September evaluation, three severely hazardous areas and activities were identified:

- The open space under the swim platform could have lethal CO concentrations under certain circumstances (i.e., generator/drive engine exhaust discharging into this area) on some houseboats.
- Some CO concentrations above and around the swim platform were at or above the immediately dangerous to life and health (IDLH) level (greater than 1200 ppm CO).
- Measurements of personal CO exposure during boat maintenance activities indicated that employees may be exposed to hazardous concentrations of CO.

A second investigation was conducted in October 2000 to gather additional CO concentration data on various types of houseboats at Lake Powell[3] and at Lake Cumberland in Kentucky.[4]

CARBON MONOXIDE EXPOSURE LIMITS

The NIOSH recommended exposure limit (REL) for occupational exposures to CO gas in air is 35 ppm for full-shift time-weighted average (TWA) exposure, and a ceiling limit of 200 ppm, which should never be exceeded.[5,6] The NIOSH REL of 35 ppm is designed to protect workers from health effects associated with carboxyhemoglobin levels in excess of 5%.[7] NIOSH has established the IDLH value for CO as 1200 ppm.[8] The American Conference of Governmental Industrial Hygienists recommends an 8-hour TWA threshold limit value for occupational exposures of 25 ppm,[9] and discourages exposures above 125 ppm for more than 30 min during a workday. The Occupational Safety and Health Administration permissible exposure limit for CO is 50 ppm for an 8-hour TWA exposure.[10]

The U.S. Environmental Protection Agency (EPA) has promulgated a National Ambient Air Quality Standard (NAAQS) for CO. This standard requires that ambient air contain no more than 9 ppm CO for an 8-hour TWA, and 35 ppm for a 1-hour average.[11] The NAAQS for CO was established to protect the most sensitive members of the general population.

METHODS

Air sampling for CO, ventilation, and wind-velocity measurements were collected on a five-bedroom Lakeview houseboat, built in 1999 (Figure 1). These data were collected in an effort to evaluate the performance of an engineering control that had been retrofitted on to a gasoline-powered generator on the houseboat. A description of the houseboat and engineering control follow.

FIGURE 2. Photo of the generator exhaust stack near the upper deck of the houseboat

Field Studies and Case Reports

Description of the Evaluated Houseboat and Engineering Control

- Drive engines: two inboard, Mercury Mercruiser 4.3 L, V-6, 190 hp, carburated, gasoline-powered engines, propeller shaft exhaust
- Generator: 1 Westerbeke, 4 cylinder, 4 stroke, 27 hp, carburated, gasoline-powered engine, 1800 rpm, 79.1 cubic inches (in^3)
- Approximate dimensions of houseboat: 75 × 16 ft
- Approximate dimensions of space below lower rear deck: 4 × 16 × 1.5 ft
- Exhaust configuration: (1) drive engines exhausted below the rear swim deck and (2) generator exhausted either below the rear swim deck (referred to in this report as "without the stack") or through a stack, exhausting 9 ft above the upper deck

Two inboard Mercruiser drive engines provided propulsion for the houseboat. These engines were housed in compartments beneath the rear swim deck of the houseboat. Access could be gained to the engines through two large door openings in the floor of the rear deck. The drive engines exhausted through their propeller shafts beneath the water.

The generator on this houseboat, manufactured by Westerbeke Corp. (Avon, Mass.), provided electrical power for air conditioning, electrical cooking, refrigeration, cabin appliances, navigation, and communications equipment. The generator was housed beneath the rear swim deck, between the two Mercruiser engines. The generator was a 4-cylinder, 4-stroke, gasoline-powered engine, having an overhead cam. This generator is similar in size to engines found in small cars. Westerbeke generators are used on nearly 75% of houseboats manufactured in the United States.[12]

The hot exhaust gases from the generator are injected with water near the end of the exhaust manifold in a process called "water-jacketing." Water-jacketing is used for cooling and noise reduction prior to discharge from the engine. Because the generator is located below the waterline, the water-jacketed exhaust passes through a lift muffler that further reduces noise and forces the exhaust gases and water up and out through a hole beneath the swim platform.

The original exhaust system was modified to reroute the generator exhaust approximately 9 ft above the upper deck of the houseboat and nearly 20 ft above the water level to prevent the buildup of hazardous concentrations of CO near the boat's lower rear deck. An 18-ft, schedule-40 aluminum pipe, having a 2-inch outside diameter and 1.5-inch inside diameter, was used for the stack (Figure 2). NIOSH researchers were informed that this relatively thick and heavy pipe was the only suitable conduit available in Page, Ariz., at the time of construction. To allow the pipe to pass from beneath the lower swim deck to 9 ft above the upper deck, a hole had been made in the rear corner of the transom through which the 2-inch pipe passed. A Gensep™ water/exhaust separator (Centek Industries, Thomasville, Ga.) was installed between the muffler and the stack to separate the exhaust gases from the water by using the force of gravity. This separator is commonly used on some houseboats and other types of boats to further reduce noise related to water surges from the lift muffler. A diagram of this system is shown in Figure 3.

To function properly, the exhaust stack must be correctly sized based on the exhaust gas volume, water flow rate, and the maximum pressure differential permitted by the manufacturer. Also important, the separator must release the water less than 8 inches below the water line to reduce back pressure, which could force some water up the stack. The evaluated system, designed and installed by Lake-Time Houseboats (Page, Ariz.) and Larry's Marine (Page, Ariz.), released generator effluent from the stack at a velocity of approximately 1100 ft/min and a temperature of approximately 58°F.

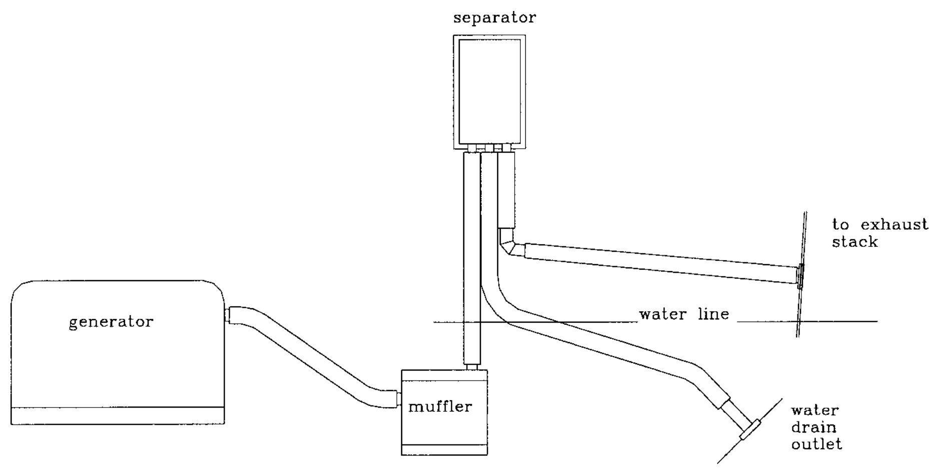

FIGURE 3. Configuration of the generator exhaust system

Representatives from Lake-Time Houseboats estimated that the evaluated system would cost between $500 and $1000 to retrofit to the houseboat while in the water and between $1000 and $1500 if it was necessary to remove the boat from the water to perform the installation. The evaluated houseboat's original purchase price was between $200,000 and $250,000.

Also, the evaluated houseboat had a Freedom marine inverter system (Heart Interface Corp., Kent, Wash.). This system provided AC power and DC battery charging, which allowed for 8 hours of battery operation of many of the appliances on the houseboat (except the air conditioner). Numerous CO warning signs and CO detectors were placed at various locations on the houseboat. One CO detector manufactured by Xintex Corp. (Grand Rapids, Mich.) was hardwired into the houseboat's electrical system. Other detectors, manufactured by Nighthawk Corp., were plugged into various electrical outlets.

Description of the Evaluation Equipment

Emissions from the exhaust stack and in the area below the swim deck were characterized using a KAL Equipment (Otsego, Mich.), model 5000, Four Gas Emissions Analyzer. This analyzer measured CO, carbon dioxide (CO_2), hydrocarbons, and oxygen. All measurements were expressed as percentages, except hydrocarbons, which were in parts per million. (One percent of contaminant is equivalent to 10,000 ppm.) Air contaminants in the space were first determined when only the generator was operating and then while the generator and drive engines operated simultaneously. When measuring exhaust from the stack, the probe of the emissions analyzer was placed approximately 4 inches beyond the terminus of the exhaust stack to reduce back pressure within the stack.

CO concentrations were measured at various locations on the houseboat, using ToxiUltra Atmospheric Monitors (Biometrics Inc.) and CO sensors. ToxiUltra CO monitors were calibrated before and after use, according to the manufacturer's recommendations. These monitors are direct-reading instruments, having data logging capabilities. The instruments were operated in the passive diffusion mode, with a 15- to 30-sec sampling interval. These monitors have a nominal range from 0 to 500 ppm, having the capability of measuring peak concentrations approximately between 1000 and 1200 ppm.

Because the upper limit of the ToxiUltra CO monitors was sometimes exceeded, additional air sampling equipment, capable of measuring higher CO concentrations, was also used. CO concentration data was collected with detector tubes (Draeger A.G. [Lubeck, Germany] CO, CH 29901, range 0.3% [3000 ppm] to 7% [70,000 ppm]) in the areas below and near the rear swim deck. The detector tubes draw air through the tube with a Draeger bellows-type pump. The resulting length of the stain in the tube (produced by a chemical reaction between the specific air contaminant and a reagent on the sorbent) is proportional to the concentration of the air contaminant.

"Grab"-type air samples were collected near the generator exhaust and under the rear swim platform using Mine Safety and Health Administration (MSHA) 50-mL glass evacuated containers. These samples were collected by snapping open the top of the glass container and allowing the air to enter. The containers were sealed with wax-impregnated MSHA caps. The samples were then sent by overnight delivery to the MSHA laboratory in Pittsburgh, Pa., where they were analyzed for CO using an HP 6890 gas chromatograph equipped with dual columns (molecular sieve and porapak) and thermal conductivity detectors.

Wind-velocity measurements were gathered each minute during the sampling period using an omnidirectional (Gill Instruments Ltd., Hampshire, U.K.) ultrasonic anemometer. This instrument was located on the upper deck of the houseboat. Airflow to the boat's drive-engine/generator compartment was evaluated by visual inspection and with a VelociCalc Plus Model 8360 air velocity meter (TSI, St. Paul, Minn.).

Description of Procedures

During the evaluation, the generator and drive engines were operated. The generator operated for approximately 30 min followed by the drive engines and the generator operating together for another 15 min. This 45-min sequence constituted one complete run. Data was collected for six separate runs, half of which were evaluated while the generator exhausted through the stack 9 ft above the upper deck. The other half were evaluated while the generator exhausted under the rear swim deck, in the original generator-exhaust location for this houseboat. When they were operated, both Mercruiser drive engines exhausted, from the center of the propeller hub, under water, beneath the lower rear deck.

Sampling locations on the lower and upper decks of the houseboat are designated by pentagons in Figures 4 and 5. To provide

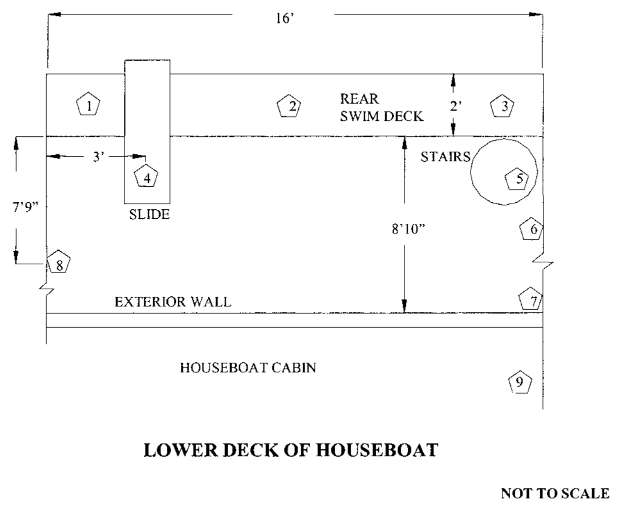

FIGURE 4. Sampling locations on the lower, rear deck of houseboat

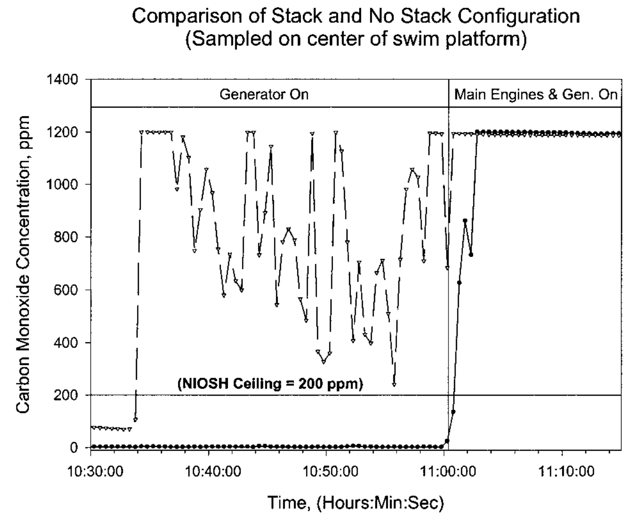

FIGURE 6. Comparison of stack/no stack configuration (center of swim platform—Sample 2)

representative CO area air samples, the monitors were placed in likely passenger locations on the upper and lower decks of the houseboat, where people could be during generator operation. Because passengers commonly enter and exit the water via the rear swim platform of the boat, three monitors were evenly spaced across this structure.

RESULTS

Results of Air Sampling with ToxiUltra CO Monitors

Real-time monitoring results for CO concentrations at various locations on the houseboat are presented in Figures 6 through 10. Figures 6 through 8 provide a comparison of CO concentrations on the houseboat when the generator exhausted through the stack to when it exhausted under the rear swim deck. Figures 9 and 10 provide a comparison of CO concentrations at multiple locations on the houseboat simultaneously, with and without the stack.

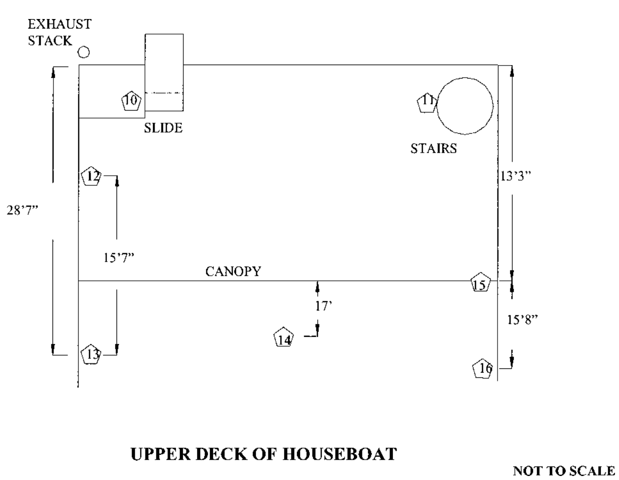

FIGURE 5. Sampling locations on the upper deck of the houseboat

The following compares the reduction in CO concentrations at various locations on the houseboat when the generator exhausted through the stack to when it exhausted under the rear swim deck. (The drive engines were not operating under either condition.)

Area Samples on the Lower Level, Rear Deck of Boat

The CO monitor placed at the center of the rear swim platform (Figure 4, Sample 2) indicated an average CO concentration of 606.6 ppm and a peak greater than 1200 ppm when the generator exhausted under the rear swim deck. This same sample indicated an average of 2.9 ppm and a peak of 13.0 ppm when the generator was operating and the stack connected. This is an average reduction of approximately 99.5%. These results are shown in Figure 6.

Similarly, the monitor located near the wall that separated the rear deck from the cabin (Figure 4, Sample 7) indicated an average

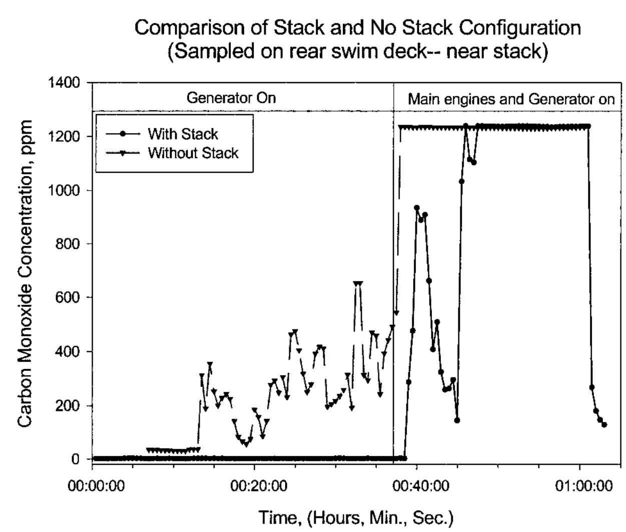

FIGURE 7. Comparison of stack/no stack configuration (rear swim platform, near stack—Sample 1)

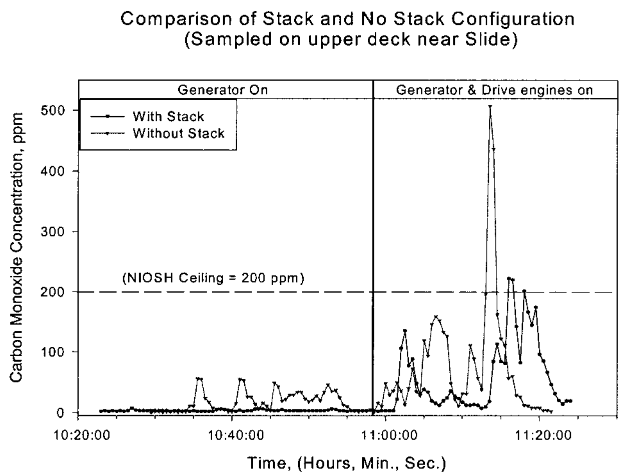

FIGURE 8. Comparison of stack/no stack configuration (upper deck near slide—Sample 10)

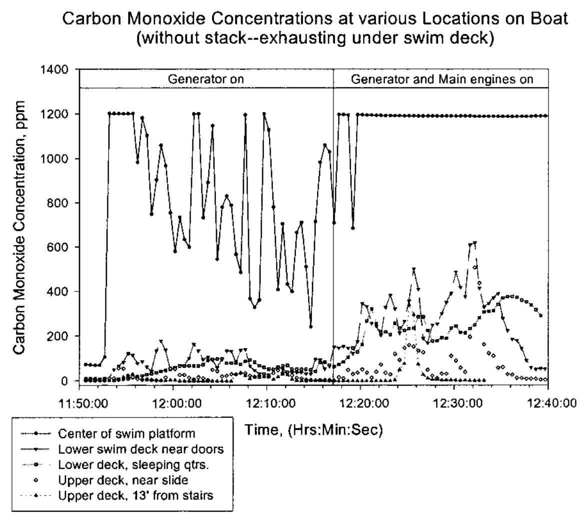

FIGURE 10. Comparison of air samples at various locations (without stack)

CO concentration of 62.6 ppm and a peak of more than 281 ppm when the generator exhausted under the rear deck. This same sample (Figure 4, Sample 7) indicated an average of 5.4 ppm and a peak of 15.0 ppm while the generator was operating and the stack connected. This is an average reduction of approximately 91.4%. Figure 7 shows results of the monitor located on the rear swim platform near the stack (Figure 4, Sample 3). In this case as in most others, the CO concentrations were dramatically different: peak concentrations were near baseline when the generator exhausted through the stack versus the highest peak concentrations of between 400 and 1000 ppm when it exhausted under the rear deck. In virtually all samples evaluated on the lower rear deck, concentrations were dramatically worse when the drive engines were started, but the houseboat remained stationary. This condition is illustrated on the right side of each graph (Figures 6, 7). On the rear lower deck, concentrations rapidly exceeded the NIOSH IDLH concentration of 1200 ppm. The results of other samples collected on the lower level rear deck are shown in Table I.

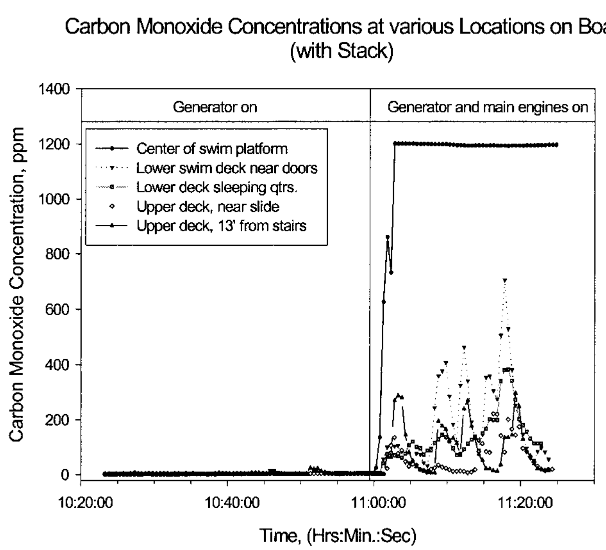

FIGURE 9. Comparison of air samples at various locations (with stack)

Area Samples on Upper Deck of Boat

The CO monitor placed on the upper deck near the slide (Figure 5, Sample 10) indicated an average CO concentration of 13.8 ppm and a peak of 93.0 ppm when the generator exhausted under the rear deck. This same sample indicated an average of 2.2 ppm and a peak of 7.0 ppm with the generator operating and the stack

TABLE I. CO Samples (ppm) Taken on the Lower Rear Deck of the Houseboat With Generator Operating (Drive Engines Off)

Sample Location[A] (Sample No.)	Generator Operating With Stack	Generator Operating Without Stack
Rear swim platform (1)	mean = 9.4	mean = 456.9
	SD = 7.5	SD = 368.8
	peak = 41.0	peak = 1200.0
	N = 186	N = 111
Midrear swim platform (2)	mean = 2.9	mean = 606.6
	SD = 1.9	SD = 449.3
	peak = 13.0	peak = 1200.0
	N = 216	N = 116
Rear swim platform (3)	mean = 1.3	mean = 242.9
	SD = 0.5	SD = 153.7
	peak = 3.0	peak = 653.0
	N = 71	N = 54.0
Beneath slide (4)	mean = 4.8	mean = 41.6
	SD = 2.7	SD = 45.0
	peak = 21.0	peak = 304.0
	N = 123	N = 181
Near exterior wall (7)	mean = 5.5	mean = 62.6
	SD = 2.4	SD = 59.1
	peak = 15.0	peak = 281.0
	N = 194	N = 178
Inside cabin, lower level (9)	mean = 8.2	mean = 44.5
	SD = 6.5	SD = 28.8
	peak = 35.0	peak = 99.0
	N = 190	N = 178

[A] Sample locations shown in Figure 4.

TABLE II. CO Samples (ppm) Taken on the Upper Deck of the Houseboat With Generator Operating (Drive Engines Off)

Sample Location[A] (Sample No.)	Generator Operating With Stack	Generator Operating Without Stack
Near slide	mean = 2.2	mean = 13.8
(10)	SD = 2.1	SD = 17.8
	peak = 7.0	peak = 93.0
	N = 192	N = 178
Near stairs	mean = 1.8	mean = 14.4
(11)	SD = 1.9	SD = 15.5
	peak = 16.0	peak = 72.0
	N = 195	N = 178
13 Feet from slide	mean = 2.3	mean = 8.6
(12)	SD = 3.6	SD = 24.6
	peak = 20.0	peak = 183.0
	N = 182	N = 167
Near canopy	mean = 2.6	mean = 8.4
(15)	SD = 4.0	SD = 10.9
	peak = 25.0	peak = 43.0
	N = 99	N = 97

[A]Sample locations shown in Figure 5.

connected, an average reduction of approximately 83.9%. These results are presented in Figure 8. The monitor located on the upper deck near the stairs (Figure 5, Sample 11) indicated an average CO concentration of 14.4 ppm and a peak of 72.0 ppm when the generator exhausted under the lower rear deck. This same sample indicated an average of 1.8 ppm and a peak of 16.0 ppm with the generator operating and the stack connected, an average reduction of approximately 87.5%. Although the upper deck was closer to the stack exhaust than the lower deck, interestingly, the CO concentrations were still lower on the upper deck when the generator exhausted through the stack than when it did not. The results of other samples collected on the upper deck are shown in Table II.

Figure 9 provides data that illustrates how CO concentrations at various locations changed with time as the generator (exhausting through the stack) and later both the generator (exhausting through the stack) and drive engines (exhausting through the propeller shafts) were operated. In contrast, Figure 10 provides data showing how CO concentrations at various locations changed over time as the generator (exhausting under the lower rear deck) and later both the generator (exhausting under the lower rear deck) and drive engines (exhausting through the propeller shafts) were operated. These two graphs clearly show that the most hazardous location was the rear swim platform near the water; however, Figure 9 shows that the stack dramatically reduced CO concentrations in that area when only the generator was operating.

Wind Velocity Measurements

Wind velocity measurements were taken with an ultrasonic anemometer while the CO sampling data was gathered. During this study, the rear of the boat was oriented at 260° W, and the boat was stationary. Wind speeds were relatively low, having an average speed of approximately 0.60 m/sec (118.1 ft/min) and a standard deviation of 0.26 m/sec. On average, wind direction was at 338.05° NE. Because of the boat orientation, the wind direction was likely to move CO in the direction of the boat after it was exhausted.

Statistical Analysis of Air Sampling Results

The retrofitted water separator and exhaust stack significantly reduced CO concentrations at various locations on the houseboat when compared with samples of exhausting under the lower rear deck. Air sampling data, collected when the generator operated with and without the stack (with the drive engines off), were compared using a t-test. Statistical analysis of the data was performed using Statgraphics Plus 4.1 (Manugistics Inc., Rockville, Md.).

Details concerning the results for four different locations (middle of the lower swim platform; lower rear deck near wall; upper deck, near slide; and upper deck, near stairs) on the houseboat are shown in Table I. In all four locations the CO concentrations when exhausting through the stack were statistically significantly lower than the CO concentrations sampled when exhausting under the swim platform. The p-values for the t-test were less than 0.0001 when comparing concentrations at all four locations.

Gas Emissions Analyzer, Detector Tubes, and Evacuated Container Results

The gas emissions analyzer, detector tubes, and glass evacuated containers were used to characterize CO concentrations near the exhaust stack and under the lower rear deck. These instruments were used because they are capable of reading higher CO concentrations than the ToxiUltra CO monitors, which have an upper limit of between 1000 and 1200 ppm. Gas emissions analyzer measurements collected 4 inches above the stack when the generator was operating and exhausting through the stack indicated CO concentrations in the range of 1.68% (16,800 ppm) to 5.53% (55,300 ppm). Measurements taken in the space below the lower rear deck with the gas emissions analyzer indicated CO concentrations in the range of 0.27% (2700 ppm) to 0.49% (4900 ppm) while the generator was running and exhausting under the deck (drive engines off). A detector tube sample taken in this space indicated a CO concentration of 0.3% (3000 ppm).

When the generator and drive engines both were in operation, the gas emissions analyzer indicated CO concentrations in the range of 0.28% (2800 ppm) to 3.85% (38,500 ppm) in the space below the swim platform. The gas emissions analyzer also indicated that the area under the swim platform was oxygen deficient (14.4% O_2) while the generator and engines were operating.

Evacuated container grab samples also were taken in the area under the swim platform when the generator was operating and when both the generator and drive engines were operating. Multiple evacuated container samples obtained in the opening to the area below the swim platform (when only the generator was running) indicated CO concentrations similar to that shown with the gas analyzer and detector tubes.

DISCUSSION AND RECOMMENDATIONS

This investigation confirms that the CO hazard to swimmers and passengers on and around houseboats can be greatly reduced by passing the generator exhaust through a stack that releases the CO and other emission components high above the upper deck of the houseboat. Exhausting the generator in this location eliminates hazardous CO concentrations in the area beneath the rear swim deck, dramatically lowers concentrations on both decks of the houseboat, and allows convective air currents to diffuse and dissipate the contaminants into the atmosphere, away from boat occupants.

The evaluated houseboat had a gasoline-powered Westerbeke generator that provided electrical power for the on-board appliances. When this generator operated as designed, having no catalytic converter or other pollution control devices, CO concentrations well above 10,000 ppm were emitted into the atmosphere.

Exhaust gases released from a gasoline engine may contain from 0.1 to 10% CO (1000 to 100,000 ppm). Gasoline engines operating at full-rated horsepower will produce exhaust gases of approximately 0.3% CO (3000 ppm).[13]

Relative amounts of CO produced from gasoline-powered engines depend on engine design, operating conditions, and, most important, the fuel/air equivalence ratio.[14] The fuel/air equivalence ratio is the actual fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio. The Department of Transportation predicted CO concentrations exhausted from marine engines as a function of air inlet and several other parameters.[15] Because so many factors influence the CO concentration exhausting from the engine, the location of the exhaust is critical to prevent persons on or near the houseboat from being poisoned.

EPA is currently phasing in emissions standards between 1998 and 2006 to reduce hazardous emissions from gasoline and diesel marine engines; however, these changes will only help to reduce, but not eliminate this problem.[16] Incremental reductions in CO emissions obtained by modifying engine design or operating parameters may slow the CO generation rate. However, these measures will not eliminate CO exposure and poisonings. Likewise, CO is also produced from engines operating on alternative fuels, such as diesel and liquified petroleum gas. If engines running on alternative fuels are not properly adjusted, hazardous CO concentrations can be produced.

This and previous NIOSH investigations on houseboats that exhaust generator combustion gases beneath or near the rear deck have shown that extremely hazardous CO concentrations accumulate in the space beneath and around the rear deck. These hazardous conditions are exacerbated when the drive engines are operating. CO concentrations in this area measured by three separate methods (i.e., real-time instruments, evacuated containers, and detector tubes) indicated concentrations well above the NIOSH IDLH value of 1200 ppm. Individuals swimming or working in the area under the swim deck, or around it (near the water level), could experience CO poisoning or death within a short period of time if the generator and/or drive engines were operating.

When the generator or drive engines are in operation, the area around the lower rear deck of the houseboat can also be hazardous under certain conditions (i.e., lack of air movement). This is substantiated by the CO poisonings and deaths that have been reported in this area of the boat. During the NIOSH evaluation, CO measurements obtained in this area indicated that CO concentrations could reach or exceed 1200 ppm, particularly when the drive engines were idling. CO measurements obtained on the top deck of the houseboat, peaks at 183 ppm, and were a concern; however, these concentrations were considerably less than those sampled on the lower rear deck.

The following recommendations are provided to reduce CO concentrations near houseboats and provide a safer and healthier environment.

(1) All manufacturers/owners/users of U.S. houseboats that use gasoline-powered generators should be aware of and concerned about the location of the exhaust terminus. The data collected in this evaluation show that an exhaust stack, vented several feet above the breathing zone of people on the upper deck of the houseboat, moves CO away from the airspace below the rear deck and dramatically reduces CO concentrations on the rear deck, swim platform, and top deck. A previous comparison of data collected on houseboats with rear-directed, side-directed, and stack exhaust configurations[2] demonstrates that the stack exhaust is the most effective control evaluated to date. Based on these data, it is clear that houseboats having gasoline-powered generators that have been retrofitted with an exhaust stack that extends well above the upper deck of the boat will greatly reduce the hazard of CO poisoning and death to passengers or those nearby.

(2) All manufacturers of U.S. houseboats should work on developing the optimum design for the exhaust configuration. The system used during the NIOSH survey was very effective at reducing CO concentrations on the boat; however, houseboat manufacturers need to determine the optimum stack height and diameter, as well as to select the appropriate water separator. The evaluated system consisted of schedule-40 pipe, which is unnecessarily thick, but was the only material available in Page, Ariz., at the time of construction. The stack diameter and height may change slightly based on the size of the generator and configuration of the houseboat.

(3) The cavity beneath the swim platform should be eliminated through design changes, and if this is not possible, ventilation should be used to prevent the buildup of hazardous CO concentrations from the drive engines.

(4) The drive engines of the houseboat should never be operated in idle while persons are in the water, on, or near the rear deck of the houseboat.

(5) Additional research and developmental work should be performed by marine engine manufacturers to evaluate the efficacy of installing catalytic converters or other pollution control devices on houseboat generators.

(6) All individuals (including boat owners, renters, and workers) who might be exposed to CO boating hazards must be immediately informed and warned. The U.S. National Park Service has launched an awareness campaign to inform boaters on their lake about boat-related CO hazards. This campaign has included press releases, flyers distributed to boat and dock-space renters, and verbal information included in the boat checkout training provided for users of concessionaire rental boats. These and other educational materials are available at the following web site: http://safetynet.smis.doi.gov/CO-houseboats.htm. Specific boat-related CO hazard training for houseboat renters, who may be completely unaware of this deadly hazard, should be enhanced to include specific information about the circumstances and number of poisonings and deaths. The training should specifically target warnings against entering air spaces under the boat (such as the cavity below the swim platform), or the area immediately behind the swim platform, which may contain a lethal atmosphere.

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