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An Evaluation of Conditions That May Affect the Performance of Houseboat Exhaust Stacks in Prevention of Carbon Monoxide Poisonings from Generators

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National Institute for Occupational Safety and Health (NIOSH) researchers evaluated two exhaust stack designs for reducing carbon monoxide (CO) exposures from gasoline-powered generator exhaust on houseboats. Tests were conducted (a) after dark, (b) in high-temperature and high-humidity environments, (c) during temperature inversions, (d) under various generator loads, and (e) at different houseboat trim angles. Two different designs of houseboat exhaust stacks were evaluated and compared with the side-exhaust configuration, which is standard on many houseboats. The two designs were flagpole and vertical stack. Both exhaust stacks performed dramatically better than the standard water level, side-exhaust configuration. The highest mean CO concentrations on the upper and lower decks of the houseboat with the vertical exhaust stack were 27 ppm and 17 ppm. The highest mean CO concentrations on the upper and lower decks of the houseboat with the modified flagpole stack were 5 ppm and 2 ppm. These findings are much lower than the 67 ppm and 341 ppm for the highest mean CO concentrations found on the upper and lower decks of houseboats having the usual side-exhausted configuration. The NIOSH evaluation also indicated that high-temperature and high-humidity levels, temperature inversions, generator loading, and houseboat trim angles had little effect on the exhaust stack performance. It also demonstrated the importance of proper design and installation of exhaust stacks to ensure that all exhaust gases are released through the stack. Based on the results of this work, NIOSH investigators continue to recommend that houseboat manufacturers, rental companies, and owners retrofit their gasoline-powered generators with exhaust stacks to reduce the hazard of CO poisoning and death to individuals on or near the houseboat.

Keywords carbon monoxide, engineering control, exhaust stack, houseboats, poisoning, side exhaust

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The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

INTRODUCTION

On August 4–7, 2003, National Institute for Occupational Safety and Health (NIOSH) researchers evaluated the control of carbon monoxide (CO) emissions and exposures on houseboats at Lake Cumberland, Kentucky. This project was conducted following a request from the Houseboat Industry Association (HIA) to evaluate several parameters related to exhaust stack performance, including high temperature and humidity levels, temperature inversions, generator loading, and houseboat trim angles. Evaluations involved two houseboats that were both retrofitted with an exhaust stack connected to the gasoline-powered generator.

Initial NIOSH investigations of CO-related poisonings and deaths on houseboats at Lake Powell, Arizona, were conducted in September and October 2000 involving representatives from NIOSH, the U.S. Coast Guard, the U.S. National Park Service, Department of Interior, and Utah Parks and Recreation. These investigations measured hazardous CO concentrations on houseboats at Lake Powell and found that

- The open space under the swim platform of some houseboats could be lethal under certain circumstances because the generator and motor exhaust discharge into this area;
- Some CO concentrations near the swim platform were greater than 1200 ppm, the NIOSH immediately dangerous to life or health (IDLH) concentration;
- Measurements of personal CO exposure to workers during boat maintenance activities indicated they may be exposed to hazardous concentrations of CO.

Epidemiologic investigations revealed that from 1990 through June of 2004, 229 houseboat-related CO poisonings occurred in the United States. Nonfatal poisonings on houseboats numbered 204, and 192 were directly attributable to generator exhaust. Of the 229 houseboat-related CO poisonings, 25 resulted in death. More than 500 CO poisonings related to

recreational boating in the United States have been identified, and that number continues to increase.⁽¹⁾

Engineering control studies began in February 2001 at Lake Powell and Somerset, Kentucky.^(2,3) Results of these studies demonstrated that an exhaust stack extending 9 feet above the houseboat's upper deck dramatically reduced the CO concentrations on and near the houseboat and provided a much safer environment. NIOSH has done considerable research over the past several years to evaluate the exhaust stack and other control options to reduce the high CO concentrations on houseboats. Well-designed stacks have been shown to reduce CO concentrations on houseboats by as much as 99%.⁽⁴⁾

Although the exhaust stack as a control option has performed well in all NIOSH evaluations, the HIA requested additional testing to address questions about performance under a variety of environmental and operational conditions. This article provides background information and describes the evaluation methods, results, conclusions, and recommendations from the additional testing.

Occupational Exposure Criteria

The NIOSH recommended exposure limit (REL) for occupational exposures to CO gas in air is 35 ppm for a time-weighted average (TWA) exposure for up to a 10-hour workday, during a 40-hour workweek, and a ceiling limit of 200 ppm, which should never be exceeded.⁽⁵⁾ The NIOSH REL of 35 ppm is designed to protect workers from health effects associated with carboxyhemoglobin (COHb) levels in excess of 5%.⁽⁶⁾ NIOSH has established the IDLH concentration for CO of 1200 ppm.⁽⁷⁾ The American Conference of Governmental Industrial Hygienists (ACGIH[®]) recommends an 8-hour TWA threshold limit value (TLV[®]) for occupational exposure of 25 ppm during a workday.⁽⁸⁾ The Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for CO is 50 ppm for an 8-hour TWA exposure.⁽⁹⁾

Health Criteria Relevant to the General Public

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.⁽¹⁰⁾ The NAAQS for CO was established to protect "the most sensitive members of the general population."^(10,p.266) The World Health Organization (WHO) has recommended TWA guideline values and length of CO exposures for the general population.⁽¹²⁾ WHO guidelines are intended to ensure that COHb levels do not exceed 2.5% when a normal person engages in light or moderate exercise. Those guidelines are 87 ppm for 15 min, 52 ppm for 30 min, 26 ppm for 1 hour, and 9 ppm for 8 hours.

METHODS

Measurements of CO and other air contaminants, ventilation, and wind velocity were collected on two 2003

model Somerset Custom Houseboats (Somerset, Ky.). One of the houseboats had a vertical exhaust stack on the generator (Figure 1); the second houseboat had a flagpole exhaust stack on the generator (Figure 2). Data were collected to evaluate the performance of the exhaust stacks to reduce CO concentrations on the houseboats. The evaluations took place in a cove, in a cove after dark, and at the marina during the daytime high temperatures and humidity levels, and under various generator loads and houseboat trim angles.

Description of the Evaluated Houseboats and Engineering Control

Houseboat 1. Vertical exhaust stack on the side of a 2003 Somerset Houseboat, 20.7 m by 4.9 m; two 4.3L MPI V6 164 kW (220 horsepower [hp]) Mercruiser engines with Bravo II outdrive; 15 kW Westerbeke gas generator; Centek Combo-Sep muffler/gas/water separator fitted with a side water drain and a straight vertical exhaust stack 2.53 m above the upper deck with 7.62 m of 4.45 cm inside diameter aluminum pipe for exhaust.

Houseboat 2. Flagpole exhaust stack on a 2003 Somerset Houseboat, 22.86 m by 5.18 m; two 194 kW (260 hp) 5.0L MPI V8 engines with Bravo II outdrive; 15 kW Westerbeke gas generator; Centek Combo-Sep muffler/gas/water separator to exhaust stack, 2.13 m above the upper deck, at a 75° angle. The exhaust system consisted of 9.45 m of 4.45 cm inside diameter aluminum pipe with a starboard water drain. The modified exhaust configuration consisted of a Centek Combo-Sep muffler/gas/water separator connected to an exhaust stack, which was 2.13 m above the upper deck and had a 5.08 cm inside diameter high-temperature hose running a direct route to an unoccupied area 2.13 m above the upper deck.

The generators on the houseboats provided electrical power for air conditioning, kitchen appliances, entertainment systems, navigation, communications equipment, etc. The 15 kW Westerbeke generators were housed in the engine compartment beneath the stern deck and near the propulsion engines. Westerbeke generators are used on nearly 75% of houseboats in the United States.

When used on houseboats, the hot exhaust gases from the generators are 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. Because the generator is 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 pipe at the side of the boat. On boats with exhaust stacks, the water-jacketed exhaust passes through a muffler/gas/water separator, which is designed to route the exhaust gases up through the stack while the water flows out the side, just beneath the waterline on the starboard stern side. Exhaust gases are physically mixed with cooling water that is pumped from the flotation water. Cooling water and exhaust gases must be separated before installation of the exhaust stack. Separation efficiency is important to minimize the amount of

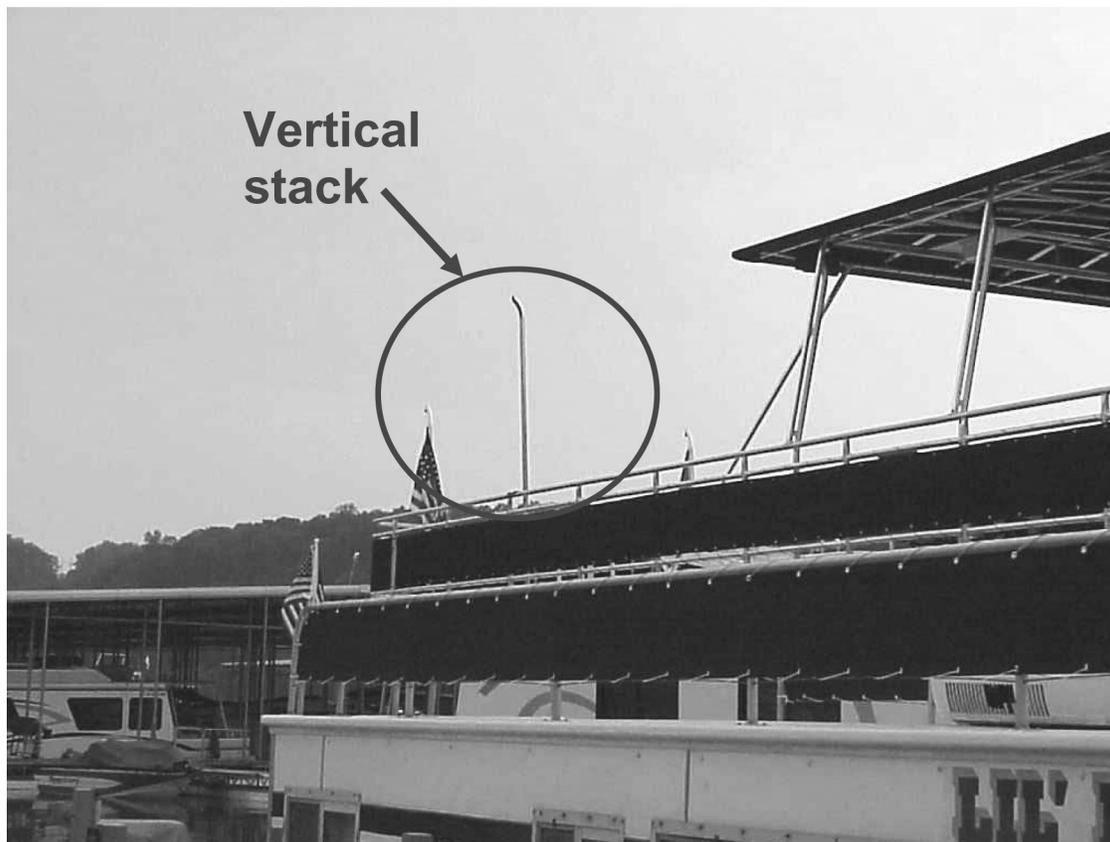


FIGURE 1. Vertical exhaust stack on the side of the evaluated Somerset Custom Houseboat

water entering the stack. Resistance to the water flow and exhaust exiting the generator should be minimized to prevent excessive backpressure. The exhaust stack and water outlet to the separator must be designed properly to prevent either exhaust from exiting the water outlet or water from going through the stack.

Houseboats 1 and 2 had exhaust stacks connected to the generator. Aluminum pipes having 4.45 cm inside diameters were used for the original stacks on both boats. Because of the static pressure problems on Houseboat 2, NIOSH evaluators replaced the 4.45 cm inside diameter pipe with a larger 5.08 cm inside diameter flexible, high-temperature hose, which is referred to as the modified flagpole stack. On each houseboat, a portion of the stack extended through the lower stern deck and was clamped to a high-temperature exhaust hose. A water separator was used on both houseboats to separate the exhaust gases from the water using gravity and centrifugal force.

On Houseboat 1, the exhaust stack was located on the starboard stern, ending at a height of approximately 2.53 m above the upper deck. The stack consisted of approximately 7.62 m of piping, which ran from the water separator. On Houseboat 2, the original flagpole exhaust stack was routed through the rear closet in the lower deck, through a floor board of the upper deck, and out at approximately a 75° angle through

the rear flagpole at the stern. The stack ended at a height of approximately 2.29 m above the upper deck. There were two horizontal runs, four 90° elbows, and approximately 9.45 m of hose and pipe running from the water separator.

Description of the Evaluation Equipment

The evaluation equipment for this investigation included the following:

- Ferret Instruments 14 Gaslink LT Five Gas Emissions Analyzer (Cheboygan, Mich.)
- ToxiUltra Atmospheric Monitors model 54-07-01 (Biosystems, Inc., Middletown, Conn.)
- Draeger detector tubes, CO, (Draeger Safety Inc., Pittsburgh, Pa.)
- Mine Safety and Health Administration (MSHA) 50-mL glass evacuated containers
- Omnidirectional ultrasonic anemometer model 1390 (Gill Instruments Ltd., Hampshire, England)
- VelociCalc Plus Model 8360 air velocity meter (TSI Inc., St. Paul, Minn.)

A detailed description of this equipment is provided elsewhere.⁽⁴⁾

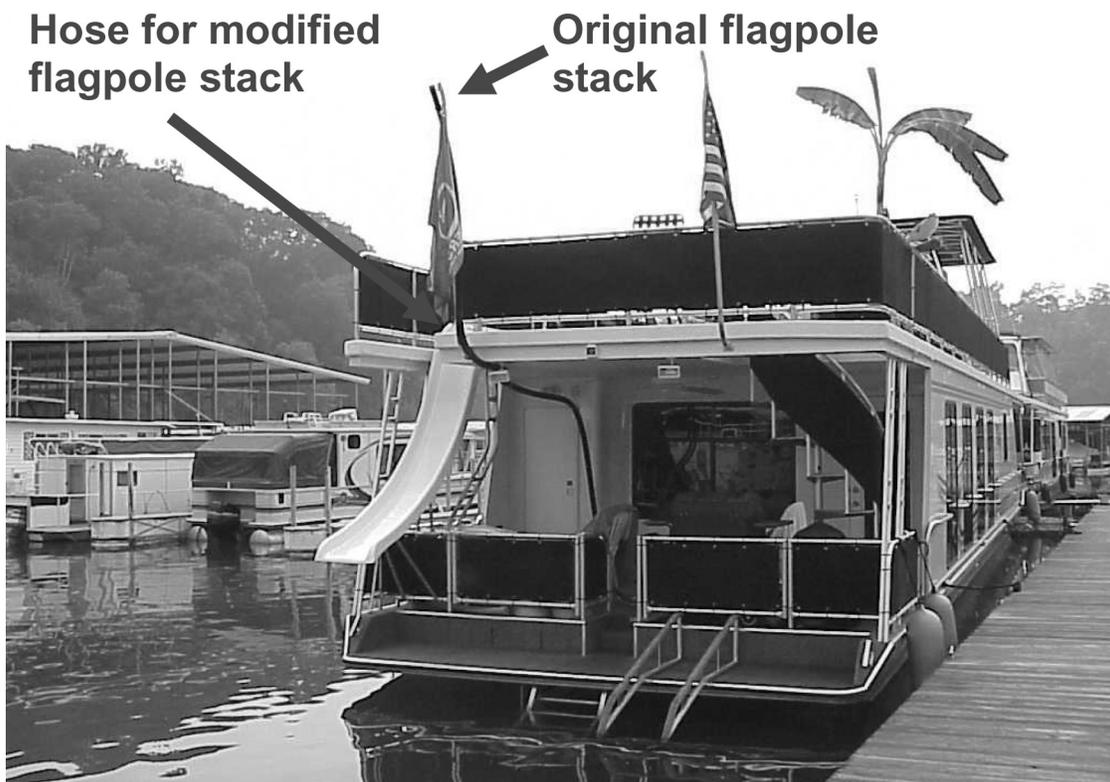


FIGURE 2. Modified flagpole exhaust stack on an evaluated Somerset Custom Houseboat

Description of Procedures

The evaluation was performed over a 3-day period using five generator test conditions, as requested by HIA. Each test condition was performed in a cove on Lake Cumberland, and Test Conditions 4 and 5 were also performed at the marina. Details concerning the test conditions are summarized below.

- Test 1.* Generator exhausting through the side-exhaust configuration without a load on the generator or extra weight on the back of the boat.
- Test 2.* Generator exhausting through the exhaust stack with a load on the generator but no extra weight on the back of the boat.
- Test 3.* Generator exhausting through the exhaust stack without a load on the generator or extra weight on the back of the boat.
- Test 4.* Generator exhausting through the exhaust stack with a load on the generator and with the extra weight of an 363 kg personal water craft (PWC) on the swim platform, which altered the trim angle by lowering the back of the boat about 1 inch.
- Test 5.* Generator exhausting through the exhaust stack without a load on the generator and with the extra weight of an 363 kg personal water craft (PWC) on

the swim platform, which altered the trim angle by lowering the back of the boat about 1 inch.

The ToxiUltra real-time CO monitors (Biometrics Inc.; Middletown, Conn.) were placed in 10 sampling locations on the lower and upper decks of the houseboats, as described in Tables I and II. The monitors were placed at various locations on the upper and lower decks to provide representative samples of occupied areas. Several monitors were placed on the stern swim platforms because people commonly enter and exit the water via this structure.

Additional Testing on Stack Diameter, Length, and Number of Bends

Following the evaluations of the generator exhaust stacks at Lake Cumberland, NIOSH funded a senior design project with mechanical engineering students from the University of Cincinnati to collect additional data concerning generator stack design.⁽¹³⁾ The students collected static pressure and velocity measurements in exhaust systems and calculated how pressure and velocity relate to stack diameter, length, and number of elbows for a 20 kW Westerbeke generator exhaust system. The pressure measurements and calculations can be applied to a variety of generator sizes using the basic methods and equations of industrial ventilation.

TABLE I. Lower Deck CO Samples

| Sample Location | Vertical Stack (ppm) | Modified Flagpole Stack (ppm) | Side-Exhaust Configuration (ppm) |
|-------------------------|--|---|---|
| Stairs | Mean = 0.6 Std. Dev. = 1.2 Peak = 7 N = 120 | Mean = 0.8 Std. Dev. = 1.4 Peak = 4 N = 38 | Mean = 82 Std. Dev. = 65 Peak = 245 N = 101 |
| Sliding door | Mean = 0.9 Std. Dev. = 1.3 Peak = 6 N = 120 | Mean = 0.6 Std. Dev. = 0.5 Peak = 2 N = 38 | Mean = 151 Std. Dev. = 111 Peak = 626 N = 101 |
| Starboard swim platform | Mean = 0.4 Std. Dev. = 1.8 Peak = 14 N = 120 | Mean = 0.4 Std. Dev. = 0.5 Peak = 1 N = 38 | Mean = 341 Std. Dev. = 308 Peak = 1069 N = 101 |
| Port swim platform | Mean = 17.0 Std. Dev. = 1.9 Peak = 30 N = 120 | Mean = 0.2 Std. Dev. = 0.4 Peak = 1 N = 38 | Mean = 121 Std. Dev. = 102 Peak = 415 N = 101 |

Note: N= number of data points.

RESULTS

Results of Air Sampling with ToxiUltra CO Monitors

Summary statistics for the ToxiUltra monitors are provided in Tables I and II. CO concentrations near the swim platform were considered low for both the vertical stack and flagpole

stack, but the side-exhaust condition produced hazardous concentrations. The peak CO concentrations for side exhaust on the swim platform were beyond the instrument range for the ToxiUltra CO monitors and indicated concentrations approaching the 1200 ppm IDLH. The CO concentrations on the top deck near the stack were highest for the side-exhaust condition

TABLE II. Upper Deck CO Samples

| Sample Location | Vertical Stack (ppm) | Modified Flagpole Stack (ppm) | Side-Exhaust Configuration (ppm) |
|---------------------|---|---|---|
| Top deck back | Mean = 0.9 Std. Dev. = 1.0 Peak = 5 N = 114 | Mean = 0.4 Std. Dev. = 0.8 Peak = 3 N = 38 | Mean = 66 Std. Dev. = 54 Peak = 209 N = 101 |
| Top deck bar | Mean = 0.7 Std. Dev. = 0.6 Peak = 2 N = 114 | Mean = 0.1 Std. Dev. = 0.5 Peak = 1 N = 38 | Mean = 15 Std. Dev. = 29 Peak = 114 N = 101 |
| Top deck near stack | Mean = 9.8 Std. Dev. = 29 Peak = 192 N = 114 | Mean = 0.9 Std. Dev. = 0.3 Peak = 1 N = 38 | Mean = 63 Std. Dev. = 144 Peak = 929 N = 101 |
| Starboard top deck | Mean = 22 Std. Dev. = 5 Peak = 44 N = 114 | Mean = 0.6 Std. Dev. = 0.7 Peak = 2 N = 38 | Mean = 30 Std. Dev. = 78 Peak = 496 N = 101 |

Note: N = number of data points.

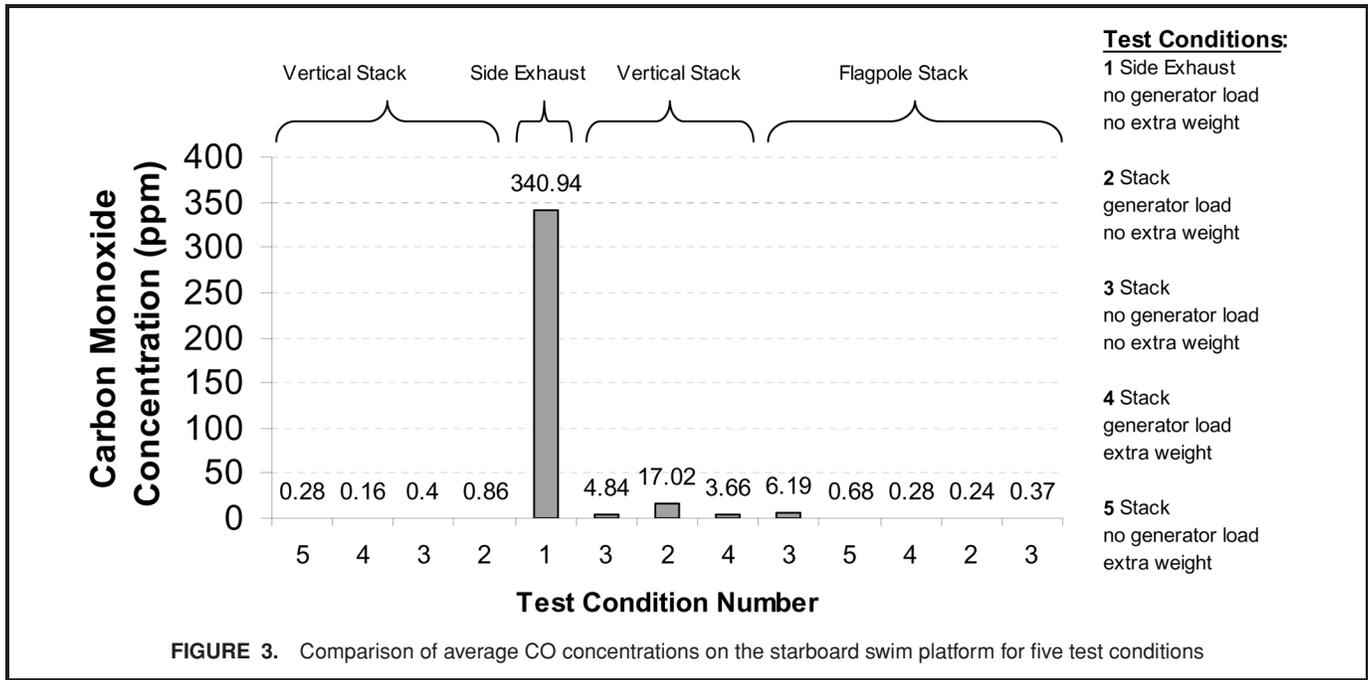


FIGURE 3. Comparison of average CO concentrations on the starboard swim platform for five test conditions

and included two peaks near the instrument's maximum range of 999 ppm. CO concentrations on the upper deck were much lower for the vertical stack and flagpole stack when compared with the side-exhaust condition.

A comparison of the average CO concentrations on the starboard swim platform for the five test conditions in Figure 3 shows the side-exhaust condition averaged 341 ppm, whereas most of the stack conditions averaged less than 7 ppm. Figure 4 shows that the peak CO concentrations from the side-exhaust condition, for the five test conditions, on the starboard swim platform were above the instrument range and greater than 12

times the peak of any stack test condition. Figure 5 shows a comparison of the average CO concentrations on the top deck near the stack for the five test conditions. Side exhaust averaged approximately 63 ppm, and all evaluated stack conditions averaged less than 10 ppm. Figure 6 is a comparison of the peak CO concentrations on the top deck near the stack for the five test conditions and shows that side exhaust reached a peak of 929 ppm. Three stack conditions in Figure 6 show high peaks of 192 ppm, 94 ppm, and 53 ppm. The occurrence of these peaks could likely be reduced by several modifications of the stack, including extending its height above the upper deck.

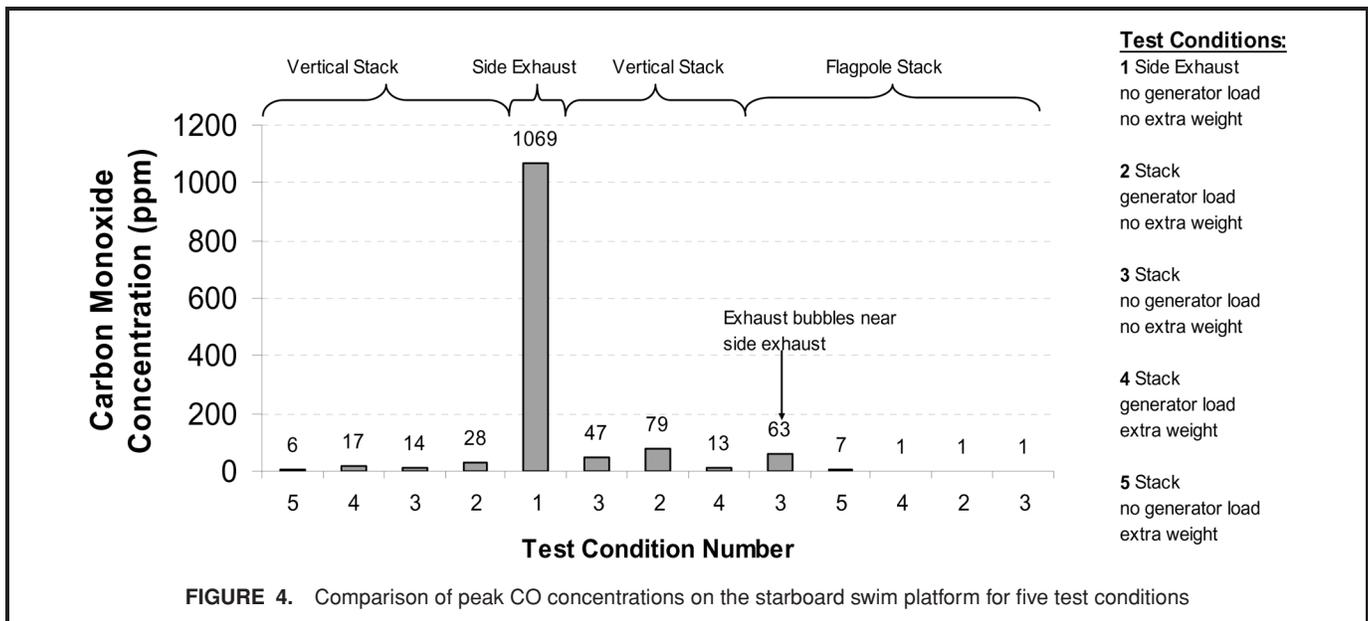
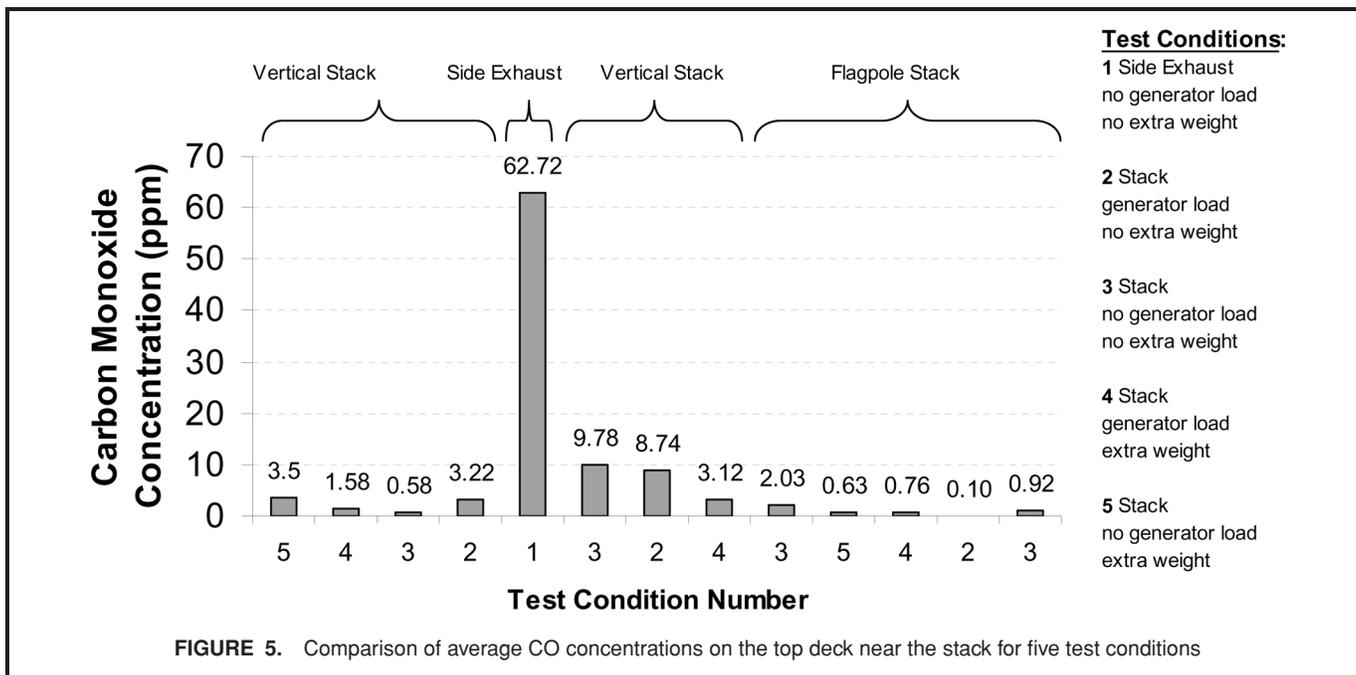


FIGURE 4. Comparison of peak CO concentrations on the starboard swim platform for five test conditions

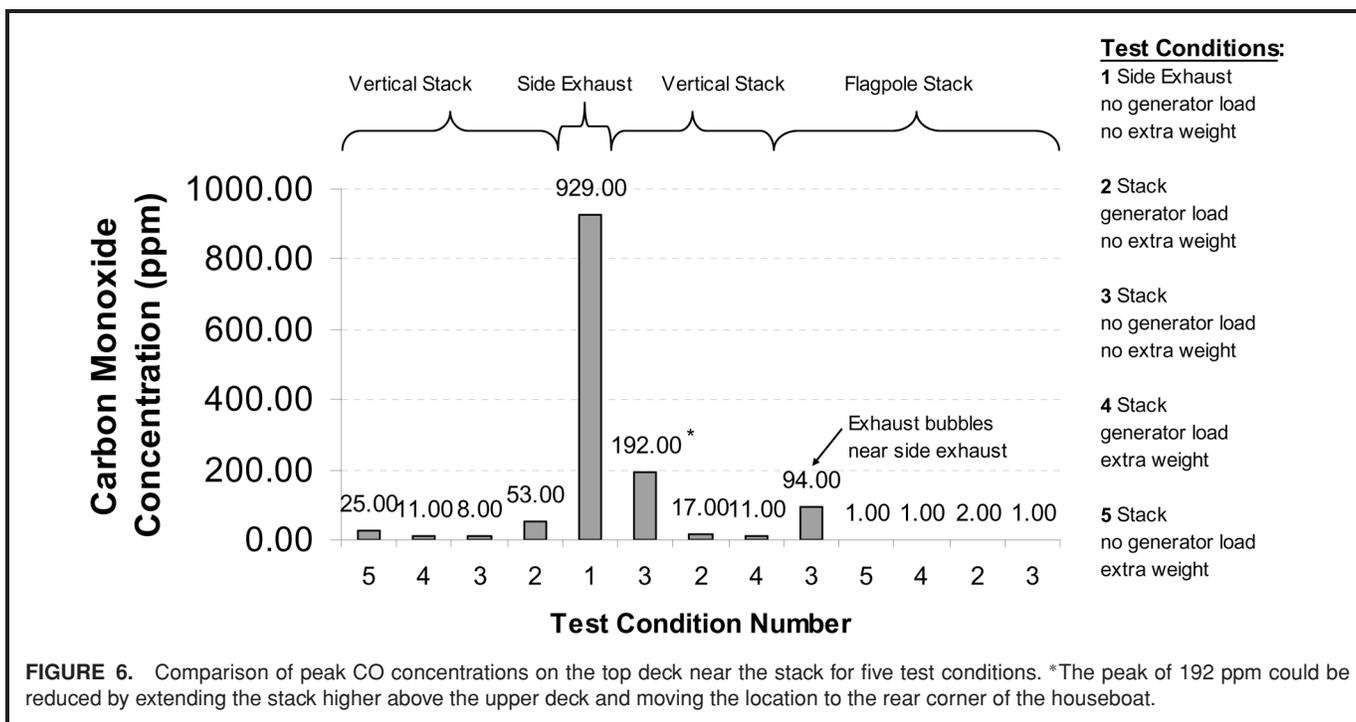


For all conditions tested, the data indicated that both stack exhaust designs were much safer than the side-exhaust condition on both the upper and lower decks of the evaluated houseboats. The vertical and flagpole stack designs reduced peak CO concentrations on the swim platform by a minimum of 95% and 98%, respectively, when compared with the side-exhaust condition. On the upper deck, the vertical and flagpole stack designs reduced CO concentrations by a minimum of

81% and 90%, respectively, when compared with the side-exhaust condition.

Statistical Analysis of Air Sampling Results

Both stacks significantly reduced CO concentrations on the lower and upper decks of the evaluated houseboats when compared with the side-exhaust condition. The air sampling data did not fit the normality assumptions for a parametric test



either before or after performing a log transform. Therefore, air sampling data collected for the five different generator conditions were compared using a one-way nonparametric analysis with Kruskal-Wallis scores test, followed by a nonparametric multiple comparison based on Kruskal-wallis Rank Sums. For sampling locations on the upper and lower deck of the evaluated houseboat, CO concentrations from the generator when exhausting at the side of the boat were statistically significantly higher than any stack condition with a p-value <0.0001.

Wind, Ambient Temperature, and Relative Humidity

Wind velocity measurements were gathered while the two houseboats were stationary. During sampling in the cove, an attempt was made to position the houseboats so that the wind moved from the stern, near the CO emission sources, toward the bow for a near worst-case testing scenario. When at the marina, the houseboats were oriented at 270° W. Average wind direction ranged from 256.3° SW to 62.9° NE. Average wind speeds ranged from 0.5 m/sec to 1.9 m/sec.

Ambient temperatures over the sampling period ranged from 24.5°C to 33.8°C and humidity ranged from 47% to 82% RH. Humidity was lowest on the first day of testing during the afternoon. Rain during parts of second and third days accounted for the higher humidity during those testing periods. The high temperature over the sampling period ranged from 26.9°C to 33.8°C and the low temperature ranged from 24.5°C to 30°C. The highest average temperature was 31.8°C at the marina the afternoon of the first day of testing; the lowest average temperature was 25.5°C in the cove the evening of the third day of testing.

Results from Additional Testing Performed by University of Cincinnati Students

For a Westerbeke 20 kW generator, the pressure drop increased approximately 24.9 Pa (0.1 inches of water) for every 1.9 m of pipe length and only 12.5 Pa (0.05 inches of water) for every three 90° bends. The pressure drop increased dramatically for inside diameters smaller than 5.08 cm. By using the information available in the University of Cincinnati Report,⁽¹²⁾ one example of a well-designed stack with the sum of the three pressure drops equaling less than 1 inch of water gauge, with a load on a 20 kW generator, could be a stack with three elbows, 9.5 meters of length, and a 5.72 cm inside diameter pipe. Other combinations also exist.

DISCUSSION AND CONCLUSIONS

The CO hazard to swimmers and occupants on houseboats that have gasoline-powered generators can be greatly reduced by retrofitting engineering control systems to the generators. Previous NIOSH studies have shown that an exhaust stack, which releases the CO and other emissions high above the upper deck of the houseboat in nonoccupied areas, allows the contaminants to diffuse and dissipate into the

atmosphere away from boat occupants.^(2,3) The present study, requested by the HIA, evaluated the exhaust stacks on two houseboats in a cove at night, under a variety of generator load conditions, with different trim angles, and in high temperatures and humidity.

Stack Exhaust and Design Performance

Data gathered when the houseboats were in the cove and in the marina indicated that the exhaust stack performed well and kept CO concentrations on both decks of the houseboats below hazardous concentrations. The data collected from the stacks show a dramatic improvement over the side-exhaust configuration. However, further reductions in CO concentrations could be achieved by extending the stack height and ensuring that static pressure in the stack does not force any exhaust gases out through the water outlet. This retrofit could be accomplished by increasing stack diameter, reducing the length of the total stack run from the water separator, and eliminating unnecessary elbows. Another modification that would improve performance is elimination of horizontal runs, which allow water in the system to collect and obstruct flow rather than draining back to the water separator.

Initial testing of the original flagpole stack on Houseboat 2 indicated that it was improperly designed and thus not functioning properly. The inside diameter of the stack was too small, the horizontal pipe runs were too long, and there were numerous elbows in the system. This design created excessive static pressure that prevented all the exhaust gases from flowing out of the stack. Instead, some of the exhaust gases were forced through the water outlet at the side of the boat. Modifications were made to decrease the static pressure in the stack, which allowed the exhaust gases to flow up through the stack and out. To achieve lower CO concentrations on a houseboat, it is important that the exhaust stack, water separator, and associated piping and hoses be designed and installed properly.

This study demonstrated that uncontrolled exhaust from a gasoline-powered generator using the side exhaust configuration close to the water can result in potentially hazardous CO concentrations on both the upper and lower decks.

Effect of the Cove, Darkness, Load, High Temperature and Humidity, and Trim Angle on Stack Performance

Results from the stack testing did not indicate a noticeable difference between CO concentrations on the houseboat in a cove after dark and those at the marina during the day. Some of the lowest concentrations measured were from the modified flagpole stack in the cove, after dark. Similar low CO concentrations were measured in the marina from the same modified flagpole stack during the day. Additionally, much higher concentrations were measured in the marina before modifications to the flagpole stack were made. Findings from this study indicated that a houseboat's

stack design noticeably influences CO concentrations, but environmental conditions and trim angles do not impact CO concentrations.

RECOMMENDATIONS

NIOSH technical reports and journal articles on CO and exhaust stacks available at (<http://safetynet.smis.doi.gov/COhouseboats.htm>) contain valuable recommendations on reducing CO concentrations near houseboats and providing a safer and healthier environment. The following are additional recommendations related to the safe design and operation of a generator stack exhaust system:

- Based on collaborative testing with students from the University of Cincinnati, it was determined that stack diameters should be between 5.08–5.72 cm (2–2.25 inches) inside diameter. Pressure drop through the exhaust stack should not exceed approximately 0.25 kilopascal (1 inch of water gauge) under a full load condition for the 20 kW Westerbeke generator and water separator configuration tested. These specifications seem to work well for generator sizes 20 kW and smaller.
- Reinforced marine exhaust hose should be used for any runs that require flexible hosing to ensure that the true inner diameter of the exhaust is maintained through any bends in the system.
- The vertical exhaust stack and modified flagpole stack on the evaluated houseboats performed well during the current study. Based on the results of this and previous NIOSH evaluations, NIOSH researchers believe that when properly designed and installed, the exhaust stack is a viable, low-cost engineering control that can dramatically improve the safety of houseboat users and maintenance personnel.
- Manufacturers, owners, users, and maintenance personnel of houseboats that have gasoline-powered generators equipped with exhaust stacks should routinely check their systems to ensure that (a) they do not present any additional safety hazards, and (b) they are properly installed and operating. If static pressure in the stack is too high, exhaust gases can be forced out of the water outlet on the side of the boat. If the water outlet is below the water line, bubbles will be visible near the water outlet, indicating that CO and other exhaust gases are being released. A critical component of the stack system is the water separator. The flow of exhaust gases and water must be balanced to obtain optimum separation. The separator unit relies on gravity and centrifugal forces to obtain separation. The resistance to flow in the water drain from the separator must be adjusted to prevent gases

from entering. The resistance to flow in the exhaust gas piping (stack) must be designed to prevent the water level within the separator compartment from rising to the point of being drawn into the exhaust gas flow. The optimum performance of the separator is highly dependent on the size and arrangement of the pipe to and from the unit. The manufacturer of the separator can provide invaluable help with the system design and should be consulted during design of the stack and before the final fitting of the unit(s).

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