AN EVALUATION OF FACTORS THAT MIGHT INFLUENCE EXHAUST STACK PERFORMANCE TO PREVENT CARBON MONOXIDE POISONINGS FROM HOUSEBOAT GENERATOR EXHAUST

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DISCLAIMER

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EXECUTIVE SUMMARY

In response to a request from the Houseboat Industry Association (HIA) and working under an interagency agreement with the United States Coast Guard, National Institute for Occupational Safety and Health (NIOSH) researchers continued to evaluate carbon monoxide (CO) exposures and engineering controls for gasoline-powered generator exhaust on houseboats. The current evaluation is part of a series of studies conducted by NIOSH investigators during the past several years to identify and recommend effective engineering controls to prevent CO poisonings on houseboats and other recreational marine vessels. Performance of exhaust stacks on two Sumerset houseboats was evaluated in August 2003 at Lake Cumberland, Kentucky.

In the Spring of 2003, the HIA sent a letter to NIOSH and the Coast Guard Office of Boating Safety requesting further testing of houseboats having generator exhaust stacks. HIA indicated that their members would provide the necessary houseboats and testing sites. The request was made because HIA members were concerned that previous NIOSH evaluations of houseboat generator exhaust stacks failed to include all of the appropriate environmental and operational conditions. Therefore the HIA requested that additional testing be performed under the following conditions: 1) after dark, 2) in high temperature/high humidity environments, and 3) during temperature inversions. Following further discussion, the HIA also requested additional exhaust stack testing under various generator loading conditions and at different houseboat trim angles. For comparison purposes, side exhaust was also evaluated on the houseboats provided by HIA.

During subsequent discussions between the HIA and NIOSH researchers, it was decided that NIOSH would conduct two field evaluations in August 2003. One evaluation at Lake Cumberland, Kentucky described in the current report, and another evaluation at Table Rock Lake, Missouri described separately. For the evaluations at Lake Cumberland, Sumerset Houseboats provided two model 2003 privately owned houseboats.

Exhaust stacks have been installed on the majority of Sumerset houseboats manufactured during the past several years. In addition, Fun Country Marine Industries is the other houseboat manufacturer that has installed a large number of exhaust stacks on houseboats. The evaluated Sumerset exhaust stacks were constructed from aluminum pipes and had two different designs. One stack was straight having a 1.75 inch inside diameter and extended approximately 8'3" above the houseboat's upper deck. The second stack (referred to as the flagpole design) initially had a 1.75 inch inside diameter with numerous elbows and extended approximately 7 feet above the upper deck off of the stern of the boat at approximately a 75 degree angle. Initial testing was performed on the flagpole exhaust stack, and it was found to be improperly installed causing exhaust gases to be forced out of the water outlet on the starboard side of the boat. Therefore, a temporary retrofit consisting of larger diameter, black high temperature hose was used for the evaluation. Prior to this field evaluation, most of the generator exhaust stacks evaluated by NIOSH had a larger inside diameter, fewer elbows, and typically extended 9 feet above the upper deck.

Results of this study were consistent with those of previous NIOSH exhaust stack evaluations. Both exhaust stacks performed dramatically better than side exhaust (even on the upper deck of the houseboat). The highest mean CO concentrations on the upper and lower decks of the houseboat with a straight stack were 27 ppm and 17 ppm. The highest mean CO concentrations on the upper and lower decks of the houseboat having the modified flagpole stack were 5 ppm and 2 ppm. This compares with 67 ppm and 341 ppm for the highest mean CO concentrations on the upper and lower decks for the side exhausted configuration. This survey also showed that high temperature/high humidity environments, temperature inversions, generator loading, and houseboat trim angles had relatively small effects on exhaust stack performance. It also demonstrated the importance of ensuring that all exhaust stacks are properly installed to ensure that performance is consistent with design intent.

Based upon the results of NIOSH exhaust stack studies, NIOSH investigators recommend that houseboats using gasoline-powered generators be evaluated for potential CO exposures and poisonings, especially near the lower stern deck. Houseboat manufacturers, rental companies, and owners should consider retrofitting their gasoline-powered, generators with engineering controls to reduce the potential hazard of CO poisoning and death to individuals on or near the houseboat. Properly installed exhaust stacks have performed well during all NIOSH evaluations, and they are successfully being used to prevent CO poisonings on hundreds of houseboats across the U.S. Other engineering control options such as cleaner burning engines and after treatment devices are being developed, and these options could also play an important role in preventing future poisonings.

BACKGROUND

On August 4 through 7, 2003, National Institute for Occupational Safety and Health (NIOSH) researchers evaluated control of carbon monoxide (CO) emissions and exposures on houseboats at Lee's Ford Marina on Lake Cumberland, Kentucky. This work was conducted following a request from the Houseboat Industry Association (HIA) to more closely evaluate several additional parameters related to exhaust stack performance. These parameters included high temperature/high humidity environments, temperature inversions, generator loading, and houseboat trim angles. Evaluations involved 2 houseboats, each equipped with exhaust stack systems connected to gasoline-powered generators.

Initial investigations of carbon monoxide (CO)-related poisonings and deaths on houseboats at Lake Powell were conducted in September and October 2000 involving representatives from NIOSH, U.S. Coast Guard, U.S. National Park Service, Department of Interior, and Utah Parks and Recreation. These investigations measured hazardous CO concentrations on houseboats at Lake Powell (McCammon and Radtke 2000). Some of the severely hazardous situations identified during the early studies included:

- The open space under the swim platform could be lethal under certain circumstances (i.e., generator/motor 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 1,200 parts of CO per million parts of air (ppm)].
- Measurements of personal CO exposure during boat maintenance activities indicated that employees may be exposed to hazardous concentrations of CO.

Epidemiological investigations have discovered that from 1990 through 2003, 165 boat-related CO poisonings occurred on Lake Powell near the border of Arizona and Utah. One-hundred thirteen of the poisonings occurred on houseboats, and 104 of these poisonings were attributable to generator exhaust alone. Ten of the 113 houseboat- related CO poisonings resulted in death (SMIS 2003). More than 500 CO poisonings related to recreational boats across the United States have been identified and that number continues to increase.

Engineering control studies began in February 2001 at Lake Powell and Somerset, Kentucky, (Dunn, Hall et al. 2001; Earnest, Dunn et al. 2001). Results of these studies demonstrated that an exhaust stack extending nine feet above the houseboat's upper deck dramatically reduced the CO concentrations on and near the houseboat and provided a much safer environment. A meeting was convened by the U.S. Coast Guard, Office of Boating Safety, Recreational Boating Product Assurance Division on May 3, 2001, in Lexington, Kentucky. This meeting was attended by houseboat manufacturers, marine product manufacturers, government representatives, and others interested in addressing the CO hazard. Following the meeting, NIOSH researchers were asked to evaluate the performance of a new prototype ECD and an interlocking device and to conduct further evaluations of the dry stack. These evaluations were conducted in June 2001 at Callville Bay Marina, NV. The findings of these studies indicated that although the ECD, interlock, and dry stack each performed well, longer term testing of the ECD should be conducted

(Dunn, Earnest et al. 2001; Earnest, Dunn et al. 2001). Concerns were also expressed regarding potential use of the safety interlock as a primary control option.

Following the June 2001 evaluations at Callville Bay Marina, NV, an interagency agreement was signed between the U.S. Coast Guard, Office of Boating Safety and the NIOSH, Division of Applied Research and Technology (DART) to conduct further field evaluations and computational fluid dynamics (CFD) modeling to evaluate engineering controls for carbon monoxide on houseboats and other marine vessels.

A second evaluation of the prototype ECD in October 2001 showed that performance of the prototype ECD had substantially degraded after thousands of hours of use; however, a new production ECD was developed and performed well. The prototype ECD was rapidly constructed from a combination of stainless steel and cast iron while the production ECD was constructed entirely of stainless steel to reduce corrosion. Other differences relate to the physical size and shape of the ECD housing and substrate to improve performance. Finally, a thermocouple and shut-off switch was added to new production ECDs to prevent excessive temperatures which can potentially destroy the ECD as well as presenting a potential fire hazard.

In October of 2002, an additional study was conducted at Callville Bay Marina, NV to evaluate the performance of two production ECDs that had been installed and used on gasoline-powered generators for several thousand hours and the exhaust stack. Results from the study indicated some complications with the long-term performance of the production ECD, as well as problems associated with some of the ECDs used on Marinas International houseboats. Because of the performance issues with the production and prototype ECDs, NIOSH recommended that houseboat manufacturers who use the ECD on their generators should also use an exhaust stack (Earnest, Hall, et al. 2003).

Following the October 2002 production ECD and vertical stack evaluation at Lake Mead, Nevada, NIOSH along with the U.S. Coast Guard held a carbon monoxide workshop at Annapolis Maryland. Following this workshop, the Houseboat Industry Association (HIA) requested additional testing of the exhaust stack. This report provides background information and describes the evaluation methods, results, conclusions, and recommendations from that testing.

Symptoms and Exposure Limits

CO is a lethal poison that is produced when fuels such as gasoline or propane are burned. It is one of many chemicals found in engine exhaust resulting from incomplete combustion. Because CO is a colorless, odorless, and tasteless gas, it can overcome the exposed person without warning. The initial symptoms 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 may occur without other symptoms. Coma or death may occur if high exposures continue (NIOSH 1972; NIOSH 1977; NIOSH 1979). The display of symptoms varies widely from individual to individual, and may occur sooner in susceptible individuals such as young or aged people, people with preexisting lung or heart disease, or those living at high altitudes (Proctor, Hughes et al. 1988; ACGIH 1996; NIOSH 2000).

Exposure to CO limits the ability of the blood to carry oxygen to the tissues by binding with the hemoglobin to form carboxyhemoglobin (COHb). Blood has an estimated 210-250 times greater affinity for CO than oxygen, thus the presence of CO in the blood can interfere with oxygen uptake and delivery to the body (Forbes, Sargent et al. 1945).

Although NIOSH typically focuses on occupational safety and health issues, the Institute is a public health agency, and cannot ignore the overlapping exposure concerns in this type of setting. NIOSH researchers have done a considerable amount of work related to controlling CO exposures in the past (Ehlers, McCammon et al. 1996; Earnest, Mickelsen et al. 1997; Kovein, Earnest et al. 1998). The general boating public may range from infant to aged, be in various states of health and susceptibility, and be functioning at a higher rate of metabolism because of increased physical activity.

Exposure Criteria

Occupational criteria for CO exposures are applicable to U.S. National Park Service (USNPS) and concessionaire employees who have been shown to be at risk of boat-related CO poisoning. The occupational exposure limits noted below should not be used for interpreting general population exposures (such as visitors engaged in boating activities) because occupational standards do not provide the same degree of protection as they do for the healthy worker population. The effects of CO are more pronounced in a shorter time if the person is physically active, very young, very old, or has preexisting health conditions such as lung or heart disease. Persons at extremes of age and persons with underlying health conditions may have marked symptoms and may suffer serious complications at lower levels of carboxyhemoglobin. Standards relevant to the general population take these factors into consideration, and are listed following the occupational criteria

The NIOSH Recommended Exposure Limit (REL) for occupational exposures to CO gas in air is 35 parts per million (ppm) for full shift time-weighted average (TWA) exposure, and a ceiling limit of 200 ppm, which should never be exceeded (CDC 1988; CFR 1997). The NIOSH REL of 35 ppm is designed to protect workers from health effects associated with COHb levels in excess of 5% (Kales 1993). NIOSH has established the immediately dangerous to life and health (IDLH) value for CO of 1,200 ppm (NIOSH 2000). The American Conference of Governmental Industrial Hygienists' (ACGIH®) recommends an 8-hour TWA threshold limit value (TLV®) for occupational exposure of 25 ppm (ACGIH 1996) and discourages exposures above 125 ppm for more than 30 minutes during a workday. The Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for CO is 50 ppm for an 8-hour TWA exposure (CFR 1997).

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 (EPA 1991). The NAAQS for CO was established to protect "the most sensitive members of the general population."

The World Health Organization (WHO) has recommended guideline values and periods of time-weighted average exposures related to CO exposure in the general population [WHO 1999]. WHO guidelines are intended to ensure that COHb levels not exceed 2.5% when a normal subject engages in light or moderate exercise. Those guidelines are:

100 mg/m^3 (87 ppm) for 15 minutes
60 mg/m^3 (52 ppm) for 30 minutes
30 mg/m^3 (26 ppm) for 1 hour
10 mg/m^3 (9 ppm) for 8 hours

METHODS

Measurements of CO and other air contaminants, ventilation, and wind-velocity were collected on two 2003 model Sumerset Custom Houseboats (Somerset, KY). One of the houseboats had a straight, vertical exhaust stack on the generator (Figure 1), and the second houseboat had a stern flagpole exhaust stack on the generator (Figure 2). Data was collected to evaluate the performance of the exhaust stacks to reduce CO concentrations on the houseboats. The evaluations took place in a cove, after dark, in high temperatures and humidities, under various generator loads and houseboat trim angles. A description of the two evaluated houseboats is provided below:

Description of the Evaluated Houseboats

1. **2003 Sumerset Houseboat with Vertical Side Exhaust Stack**
   Engines: 2, 4.3L MPI V6(220hp) Mercruiser engines with Bravo II outdrive
   Generator: 15 Kw Westerbeke gas generator
   Approximate dimensions of houseboat: 68 ft. X 16 ft.
   Exhaust Configuration: 1) Centek Combo-Sep® muffler/gas/water separator to straight vertical exhaust stack 8'3" above upper deck with 25 feet of 1.75 inch inside diameter aluminum pipe for exhaust and a side water drain.

2. **2003 Sumerset Houseboat with Flag Pole Exhaust Stack**
   Engines: 2, 260 horsepower (hp) 5.0L MPI V8, engines with Bravo II outdrive
   Generator: 15kw Westerbeke gas generator
   Approximate dimensions of houseboat: 75 ft. X 17 ft.
   Original Exhaust Configuration: 1) Centek Combo-Sep® muffler/gas/water separator to exhaust stack 7 feet above upper deck with originally 31 feet of 1.75 inch inside diameter aluminum pipe for exhaust and starboard side water drain.
   Modified Exhaust Configuration: 1) Centek Combo-Sep® muffler/gas/water separator to exhaust stack 7 feet above upper deck with 2 inch inside diameter

high temperature black hose running a direct route to the 75° angle stack and a starboard side water drain.

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 near the propulsion engines. Westerbeke generators are used on nearly 75% of houseboats in the U.S. (Westerbeke 2001).

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 sets below the waterline, the water-jacketed exhaust passed through a lift muffler that further reduces noise and forces the exhaust gases and water up and out through a hole at the side of the boat. On boats with exhaust stacks, the water-jacketed exhaust passes through a muffler/gas/water separator (Figure 3) which is designed to route the exhaust gases up through the stack while the water flows out just beneath the water line near the side of the boat. Inside the water separator, exhaust gases are physically mixed with cooling water which is pumped from the flotation water. In order for a stack exhaust to be installed, the cooling water and the exhaust gases must be separated. The efficiency of the separation process is important in order to keep to a minimum, the amount of water entering the stack. Also the balance of the resistance to flow must be minimized the stack and the water drain outlet paths.

Description of the Evaluated Engineering Controls

Both houseboats had exhaust stacks retrofitted to their generator sets. An aluminum pipe, having an approximately 1.75-inch inside diameter was used as the original stack on both boats. The 1.75 inch inside diameter pipe on houseboat #2 was replaced with a larger 2" inside diameter flexible high temperature hose for the modified flagpole stack because problems were noted with the existing system prior to testing. On each houseboat, a portion of the stack extended through the boat's 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. Figure 4 shows a Combo-Sep® muffler/gas/water separator (Centek Industries, Thomasville, GA) similar to the ones used on the evaluated boats.

On houseboat #1, the exhaust stack was located on the rear, starboard side of the boat, ending at a height of approximately 8' 3.5" above the houseboat's upper deck. The stack consisted of approximately 25 feet of piping running from the water separator. On houseboat #2, the original flagpole exhaust stack was routed through the rear closet in the lower deck, through the floor board of the upper deck and out at an approximately 75 degree angle through the rear flagpole at the boat's stern. The stack ended at a height of approximately 7' 6" above the upper deck. There were two horizontal runs, four 90 degree elbows and approximately 31 feet of hose and piping running from the water separator.

Initial testing of the original flagpole stack on houseboat #2 indicated that it was improperly designed and 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 100% of the exhaust gases from flowing out of the stack. Instead, a small percentage of the exhaust gases were forced out of the water outlet on the side of the boat (Figure 5). In order to correct this problem, a temporary 2" inside diameter, shorter, flexible hose was used to reduce the static pressure in the stack and prevent exhaust gases from being forced out of the water outlet.

Description of the Evaluation Equipment

Emissions from the generator were characterized using a Ferret Instruments (Cheboygan, MI) Gaslink LT Five Gas Emissions Analyzer. This analyzer measures CO, carbon dioxide (CO_2), hydrocarbons, oxygen, and nitrogen oxides (NO_x). All measurements are expressed as percentages except hydrocarbons and NO_x which is ppm. [One percent of contaminant is equivalent to 10,000 ppm.]

CO concentrations were measured at various locations on the houseboat using ToxiUltra Atmospheric Monitors (Biometrics, Inc.) with CO sensors. ToxiUltra CO monitors were calibrated before and after use according to the manufacturer's recommendations. These monitors are direct-reading instruments with data logging capabilities. The instruments were operated in the passive diffusion mode, with a 15 - 30 second sampling interval. The instruments have a nominal range from 0 ppm to 999 ppm.

CO concentrations were also measured with detector tubes [Draeger A.G. (Lubeck, Germany) CO, CH 29901– range 0.3% (3,000 ppm) to 7% (70,000 ppm)] directly in the generator exhaust. The detector tubes are used by drawing air through the tube with a bellows–type pump. The resulting length of the stain in the tube (produced by a chemical reaction with the sorbent) is proportional to the concentration of the air contaminant.

Grab samples were collected 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 to the MSHA laboratory in Pittsburgh, Pennsylvania, where they were analyzed for CO using a HP6890 gas chromatograph equipped with dual columns (molecular sieve and porapak) and thermal conductivity detectors.

Wind velocity measurements were gathered each minute during the air sampling using an omnidirectional (Gill Instruments Ltd., Hampshire, U.K.) ultrasonic anemometer. This instrument uses a basic time-of-flight operating principle that depends upon the dimensions and geometry of an array of transducers. Transducer pairs alternately transmit and receive pulses of high frequency ultrasound. The time-of-flight of the ultrasonic waves are measured and recorded, and this time is used to calculate wind velocities in the X-, Y-, and Z-axes. This instrument is capable of measuring wind velocities of up to 45 meters per second (m/sec) and take 100 measurements per second.

Air flow from the exhaust stacks was evaluated through the use of a VelociCalc Plus Model 8360 air velocity meter (TSI Inc., St. Paul, MN). Air velocity readings were collected at the face of the exhaust stack.

Description of Procedures

The evaluation was performed over a 3-day period using 5 generator test conditions as requested by the Houseboat Industry Association (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:

1) Generator exhausting through the side exhaust terminus without a load on the generator and with no extra weight on the back of the boat.

2) Generator exhausting through the exhaust stack with a load on the generator and no extra weight on the back of the boat.

3) Generator exhausting through the exhaust stack without a load on the generator and with no extra weight on the back of the boat.

4) Generator exhausting through the exhaust stack with a load on the generator and with the extra weight of an 800 lb Sea Do water craft on the back of the boat.

5) Generator exhausting through the exhaust stack without a load on the generator and with the extra weight of an 800 lb Sea Do water craft on the back of the boat.

Sampling locations for the ToxiUltra real-time CO monitors on the lower and upper decks of the houseboats, designated with pentagons, for the side vertical exhaust stack and the modified flag pole exhaust stack are shown in Figure 6. The monitors were placed at various locations on the upper and lower decks of the houseboat to provide representative samples of occupied areas. Several monitors were placed on the boats' stern swim platforms because people commonly enter and exit the water via this structure.

RESULTS

Results of Air Sampling with ToxiUltra CO Monitors

Real-time CO monitoring results on the upper and lower deck of the houseboats are shown in Figures 7 and 8. The summary statistics for all of the ToxiUltra monitors are provided in Tables I through VIII. In Figure 7, CO concentrations near the swim platform were very low for both the vertical stack and flagpole stack while side exhaust produced hazardous concentrations. The peak CO values for side exhaust on the swim platform were beyond the instrument range for the

ToxiUltra CO monitors and indicated concentrations approaching the immediately dangerous to life and health value (IDLH) of 1,200 ppm for CO. The CO concentrations on the top deck near the stack in Figure 8 were highest for side exhaust and included two peaks near the instrument maximum range of 999 ppm. CO concentrations on the upper deck were much lower for the vertical stack and flagpole stack compared to side exhaust.

A comparison of the average CO concentrations on the starboard swim platform for the five test conditions in Figure 9 shows side exhaust averaging 341 ppm with most of the stack conditions averaging less than 7 ppm. The peak CO concentrations in Figure 10 for the five test conditions on the starboard swim platform show that side exhaust had a peak above the instrument range and greater than twelve times the peak of any stack test condition. Figure 11 shows a comparison of the average CO concentrations on the top deck near the stack for the five test conditions with side exhaust averaging approximately 63 ppm and all stack conditions averaged less than 10 ppm. Figure 12 shows a comparison of the peak CO concentrations on the top deck near the stack for the five test conditions with side exhaust reaching 929 ppm. Three stack conditions in Figure 12 show high peaks of 192 ppm, 94 ppm, and 53 ppm. The occurrence of these peaks could likely be reduced through several modifications of the stack including extending the height further above the upper deck. Table IX shows a comparison of the highest measured values for peak and average CO concentrations on the upper and lower deck of the houseboats for the vertical stack, flagpole stack, and for side exhaust. For all conditions tested, stack exhaust was much safer than side exhaust on both the upper and lower deck of the evaluated houseboats. The vertical and flagpole stack designs reduced peak CO concentrations on the swim platform by 95% and 98% respectively when compared to side exhaust. On the upper deck, the vertical and flagpole stack designs reduced CO concentrations by 81% and 90% respectively when compared to side exhaust. Well designed stacks have been shown to reduce CO concentrations on houseboats by as much as 99%.

Gas Emissions Analyzer, Detector Tubes, and Evacuated Container Results

Gas emissions analyzers, detector tubes, and glass evacuated containers were used to characterize CO concentrations in and near the exhaust stack and on the swim platform. This equipment was utilized because it is capable of reading higher CO concentrations than the ToxiUltra CO monitors which have an upper limit of approximately 1,000 ppm. Some of the data collected with the emissions analyzer is shown in Table X and Table XI. CO concentrations measured directly in the exhaust stack ranged from 5.2% to 7.49% for both houseboats.

Detector tube and evacuated container data are shown in Tables XII and XIII. The data in these tables show results for each test condition. CO concentrations measured in the exhaust stack varied more than emissions analyzer results, but the majority of the measurements were in the same range. CO concentrations measured directly in the exhaust stack ranged from less than one percent to almost nine percent. The evacuated container results were similar to the detector tube results.

Wind and Stack Velocity Measurements

Wind velocity measurements were gathered during the survey with an ultrasonic anemometer. All data was gathered while the houseboats were stationary. Most of the testing occurred at the cove where the boats were oriented in multiple different directions. When sampling in the cove, an attempt was made to position the boats in a manner such that wind was moving from the stern of the houseboat (near the CO emission sources) toward the bow of the houseboat to establish near worst case testing scenarios.

A summary of wind velocity data is shown in Table XIV. This table lists the houseboat bearing, average wind speed and direction, and standard deviations. As shown in the table, while at the marina, the houseboat was oriented at 270° W. The exception to this orientation occurred during testing in the cove on Tuesday and Wednesday. 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.

Face velocities of the exhaust stack ranged from approximately 1,400 to 1,600 fpm. The exhaust stack temperatures ranged between 100 and 110 °F while stack humidity was consistently near 100%. The modified flagpole stack with the larger diameter hose had face velocities ranging from 590 to 715 fpm. The flagpole exhaust stack temperatures ranged from 75.4 to 81.6 °F while relative humidity in the stack was 99 to 100%.

Ambient Temperature and Relative Humidity

A summary of the ambient temperature and relative humidity data is shown in Table XV. Ambient temperatures over the sampling period ranged from 76.1 to 92.8°F and humidity ranged from 47 to 82% RH. Humidity was lowest on Monday during the afternoon testing. Rain Monday night and during parts of Tuesday and Wednesday accounted for the higher humidity during those testing periods. The high temperature over the sampling period ranged from 80.4 to 92.8°F and the low temperature ranged from 76.1 to 86°F. The average temperature during each sampling period is also shown in Table XV. The lowest average temperature was 77.9°F on Wednesday evening in the cove and the highest average was 89.2°F on Monday afternoon at the marina.

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 (that releases the CO and other emissions high above the upper deck of the houseboat in non-occupied areas) allows the contaminants to diffuse and dissipate into the atmosphere away from boat occupants (Dunn, Hall et al. 2001; Earnest, Dunn et al. 2001). 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, trim angles, and in high temperatures and humidities.

Stack Exhaust

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 houseboat below hazardous levels. The highest mean CO concentration on the lower deck of a boat was 17 ppm. The highest mean concentration on the upper deck of a houseboat was 27 ppm. While these values are a dramatic improvement when compared to side exhaust, 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 can 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 could improve performance is to eliminate horizontal runs which can allow water to collect and obstruct flow, rather than draining back to the water separator. The original design of the stack on houseboat #2 had a long horizontal run through the floor of the upper deck. In order 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. These tests also indicate that uncontrolled exhaust from a gasoline-powered generator using side exhaust close to the water can result in potentially hazardous CO levels 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 seem to indicate a noticeable difference between CO concentrations on the houseboat in a cove after dark compared to CO concentrations during testing at the marina. Some of the lowest concentrations measured were in the cove with the modified flagpole stack after dark. Similar low CO concentrations were measured in the marina with the same modified flagpole stack during the day. Additionally, much higher concentrations were measured at the marina prior to making modifications to the flagpole stack. Findings from this study indicated that stack design noticeably influenced CO concentrations while environmental conditions and trim angles did not appear to impact CO concentrations on the evaluated houseboats.

Stack Design and Performance

The initial performance of the original flag pole stack raised several concerns. Rather than the hazardous exhaust gases passing through the stack to a height well above the upper deck, high static pressure in the stack forced the exhaust gases to pass out the side terminus near the water line. Modifications were then made to decrease static pressure in the stack and allow for the exhaust gases to flow through the stack. The high static pressure in the stack resulted primarily from the long distance of horizontal pipe connected from the water separator to the start of the vertical section of the stack. Increasing the number of elbows and the length that the exhaust gases must travel increases the frictional and fitting losses in the pipe system and requires a higher initial velocity pressure to accelerate the same volume of exhaust through the same diameter of pipe. Horizontal runs should be avoided while still maintaining an appropriate vertical height above the upper deck. Other factors affecting static pressure in the stack include the inside diameter of the pipe and the roughness of the inside wall of the pipe. All of these combined factors account for increased pressure in the pipe system, and if high enough can be equated to plugging or sealing the end of the stack. Since exhaust gases and fluid flow will travel the path of least resistance, careful attention should be made to determine what necessary pressure differences are required to balance out the exhaust system. In addition to proper stack design, proper design of the water outlet and water separator is necessary to prevent water from traveling up the stack.

The velocity pressure method illustrated in the Industrial Ventilation Manual (ACGIH 2001) provides a method of performing calculations using the velocity pressure. The method is based on the fact that all frictional and dynamic (fitting) losses in ducts are functions of velocity pressure and can be calculated by a loss coefficient multiplied by the velocity pressure. Figure 5-11 of the ventilation manual provides a calculation spreadsheet for performing velocity pressure calculations and sample calculations for non-standard conditions. It is important to point out that the system design considers the conditions at initial start-up and installation.

The cumulative static pressure in the exhaust stack can be found by totaling the duct losses and losses from velocity increase or any other losses. If the resulting cumulative static pressure is too high, the system parameters can be decreased by changing the parameters that create losses to balance the system with the water outlet pressure. While multiple methods can be used to increase the pressure on the water side, efforts should focus on reducing static pressure in the stack to prevent excessive backpressure on the generator.

Based on calculations using the velocity pressure method in the ACGIH Industrial Ventilation Manual, an estimated 58% reduction in static pressure was achieved through modifications to the flagpole stack. Calculations indicate that reducing the overall length of the stack by six feet and eliminating one bend, accounted for 10% of the pressure reduction while the increased diameter accounted for the remaining 48% decrease in pressure. The calculated values entered into the ACGIH Industrial Ventilation Manual Velocity Pressure (VP) Calculation Sheet are described and shown below.

In order to perform the calculations in the ACGIH VP calculation sheet, it is necessary to determine the flow rate and velocities for both stack diameters. A flow rate of 15.3 cfm was obtained by multiplying the measured velocity of 700 ft/min for the modified stack by the cross sectional area of the modified stack. Dividing the flow rate of 15.3 cfm by the original flagpole stack diameter provided a calculated value of 916 ft/min and represents what the velocity would have been if all of the exhaust was flowing through the stack.

$$Q = V_{Mod} * A_{Mod} = 700 \text{ ft/min} * [(\pi*(0.006944\text{ft})^2] = 15.3 \text{ cfm}$$

$$V_{Orig} = Q / A_{Orig} = 15.3 \text{ cfm} / [\pi*(0.0167\text{ft})^2] = 916 \text{ ft/min}$$

The duct friction factor was calculated using equation 8 in Figure 5-11 of the Industrial Ventilation Manual using the corresponding velocities with the original and modified flagpole stack.

Duct Friction Factor (Eqn 8 for Aluminum) $H_f^{(Aluminum)} = 0.0425(V^{0.465}/Q^{0.602})$

The elbow loss coefficient of 0.13 was taken from Figure 5-16 of the Ventilation Manual and assumes a stamped (smooth) round elbow and 2.00 as the R/D value for both stacks. The straight duct lengths of 31ft and 25ft for the corresponding stacks were multiplied by the duct friction factors of 0.1961 and 0.1731 to provide approximately 6.1 and 4.3 for the duct friction loss in VP. The number of 90 degree elbows multiplied by the elbow loss coefficient is 0.52 and 0.39 for the elbow loss in VP. The duct loss in VP of 6.6 and 4.7 is the sum of the special fitting coefficient, duct friction loss in VP, elbow loss in VP, and the branch entry loss in VP.

To determine the duct losses in inches of water gauge, the duct loss in VP was multiplied by the duct velocity pressure from equation 5 in Table 5-11 of the Ventilation Manual which requires the density factor from equation 2 in Table 5-11.

$df = df_e * df_p * df_t * df_m$
$df_e = [1-(6.73*10^{-6})(z)]^{5.258} = 0.975$ Assumes 700 ft msl at Lake Cumberland
$df_p = (407 + SP) / (407) = 1$
$df_t = (530) / (T+460) = 0.964$ Assume 90°F
$df_m = (1+\omega) / (1+1.607\omega) = 1$
$df = 0.9399$

Duct Velocity Pressure Equation 5: $VP = df(V/4005)^2$

The duct losses in inches of water gauge of 0.324 and 0.135 for the original and modified stacks were obtained by multiplying the duct velocity pressure by the duct loss in VP. Since it was assumed that there were not any losses from velocity increase or any other losses, the total duct pressure loss was equal to the duct loss.

Velocity Pressure Calculation Sheet (Duct Losses Section)		
Duct Segment Identification	**Original Stack**	**Modified Stack**
Straight Duct Length	31	25
Duct Friction Factor	0.1961	0.1731
No. of 90 Degree Elbows	4	3
Elbow Loss Coefficient	0.13	0.13
Branch Entry Coefficient		
Special Fitting Coefficient		
Duct Friction Loss in VP	6.0791	4.3275
Elbow Loss in VP	0.52	0.39
Branch Entry Loss in VP		
Duct Loss in VP	6.5991	4.7175
Duct Loss “wg	0.324453	0.13545174
Other Losses “wg		
Resulting Velocity Pressure		
Loss from Velocity Increase		
Duct Pressure Loss “wg	0.324453	0.13545174

Some manufacturers have been using a trial and error approach to determine the pressure differences between the stack and water outlet by altering the input variables such as pipe diameter, number of elbows, and overall length to arrive at a balance of the exhaust system. Manufacturers should be careful to do extensive testing and verify the system is in balance at multiple generator load conditions and that exhaust gas bubbles are not present at the water outlet to the separator during operation of the generator.

RECOMMENDATIONS

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. Based on data from numerous NIOSH field surveys, we recommend that houseboats with gasoline-powered generators be evaluated for potential CO exposures and poisonings and retrofitted with control systems to reduce the potential CO hazard.

2) The vertical exhaust stack and modified flagpole stack on the evaluated Sumerset houseboats performed well during the current study. Based upon 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. Manufacturers/owners/users of houseboats that have gasoline-powered generators equipped with exhaust stacks should routinely check their systems to ensure that 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. Modifications should be made to any existing exhaust stacks that are not properly designed and/or installed. Modifications should be made to ensure that all of the exhaust gases flow through the stack. These changes to exhaust stacks should be made in consultation with the manufacturer of the water separator. Improved installation and design guidelines are also needed.

3) In multiple evaluations, properly designed exhaust stacks have been shown to be effective in reducing concentrations of carbon monoxide on all locations on houseboats by exhausting the hazardous CO high above the top deck. While concentrations on the boat remain relatively low, CO measurements taken directly at the stack outlet have been in the range of 5% to 7.5% CO (50,000 ppm to 75,000 ppm). Because this concentration is 42 to 63 times greater than the immediately dangerous to life and health value for breathing zone concentrations of CO, it would be prudent for houseboat manufacturers to clearly label and identify the exhaust outlet to notify users or anyone on the houseboat to stay clear of the exhaust gases. The label should include warnings against actions such as hanging clothing or other items that might block or restrict the outlet, making any unauthorized stack alterations, or climbing on or otherwise tampering with the exhaust stack. If the stack is damaged or exhaust flow is hindered, the exhaust gases may be forced out the side of the boat with the discharge water. Therefore, it may also be necessary to warn users to stay clear of the water discharge area by labeling the water discharge area as a potential CO discharge.

4) As new engineering control devices for reducing CO emissions and exposures are developed, independent testing is needed to ensure that these systems perform adequately. These future devices could utilize a variety of methods to reduce the hazard. Additional protection from CO poisoning could be gained by implementing multiple controls in series. For example, a cleaner burning fuel injected generator fitted with a properly functioning emission control device connected to a properly designed exhaust stack might have the potential to provide a dramatically higher level of protection against possible CO poisoning than any one of the controls acting alone. However, all of these controls need independent testing and evaluation to ensure that they will meet the needs of the boating public and do not create any additional hazards such as fire or other safety hazards.

5) A critical component of the stack system is the exhaust gas/water separator. This separator can be incorporated within the same unit with a muffler, or it can be a discreet separate unit. In order to obtain optimum performance and best possible separation of the exhaust gases and the cooling water, the flow of exhaust gases and water must be balanced. The separator unit uses gravity and centrifugal forces to obtain separation. The resistance to flow in the water drain from the separator must be adjusted to ensure that gases cannot enter that part of the system and 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 a point where it can be drawn into the exhaust gas flow. The optimum and proper performance of the separator is highly dependent on the piping sizing and arrangement, to and from the unit. The manufacturer of the separator can be very helpful with the system design and should be consulted during design of the stack and before final fitting of the unit(s) (Centek 2003).

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Table I--CO Concentrations (ppm)

Lower deck comparison of vertical stack, flag pole stack, and side exhaust with no generator load and no extra weight

Sample Location	Vertical Stack	Modified Flag Pole Stack	Side Exhaust
Stairs **#6**	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 **#2**	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 **#3**	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 **#4**	Mean = 19.0 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
Bedroom **#1**	Mean = 0.5 Std. Dev. = 0.5 Peak = 2 N = 120	Mean = 1.3 Std. Dev. = 0.6 Peak = 2 N = 38	Mean = 36 Std. Dev. = 44 Peak = 176 N = 101

N= number of data points

Table II--CO Concentrations (ppm)

Upper deck comparison of vertical stack, flag pole stack, and side exhaust with no generator load and no extra weight

Sample Location	Vertical Stack	Modified Flag Pole Stack	Side Exhaust
Top Deck Rear **#8 (Modified Flagpole Stack)** **#7 (Vertical Stack)**	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 Center **#9**	Mean = 1.0 Std. Dev. = 0.7 Peak = 4 N = 114	Mean = 1.0 Std. Dev. = 0.4 Peak = 2 N = 38	Mean = 21 Std. Dev. = 48 Peak = 318 N = 101
Top Deck Bar **#10**	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 **#7 (Modified Flagpole Stack)** **#5 (Vertical 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 **#5 (Modified Flagpole Stack)** **#8 (Vertical Stack)**	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

N= number of data points

Table III

CO Concentrations (ppm)

Lower deck concentrations for vertical stack and flag pole stack for test condition 2 (With generator load and no extra weight)

Sample Location	**Vertical Stack**	**Modified Flag Pole Stack**
Stairs **#6**	Mean = 1.1 Std. Dev. = 1.4 Peak = 4 N = 110	Mean = 0.6 Std. Dev. = 2.3 Peak = 11 N = 78
Sliding door **#2**	Mean = 1.5 Std. Dev. = 1.6 Peak = 8 N = 110	Mean = 0.4 Std. Dev. = 0.7 Peak = 3 N = 78
Starboard swim platform **#3**	Mean = 17 Std. Dev. = 13 Peak = 79 N = 110	Mean = 0.2 Std. Dev. = 0.4 Peak = 1 N = 78
Port swim platform **#4**	Mean = 11 Std. Dev. =5 Peak = 26 N = 110	Mean = 0.3 Std. Dev. = 0.5 Peak = 1 N = 78
Bedroom **#1**	Mean = 0.9 Std. Dev. = 1.6 Peak = 2 N = 110	Mean = 1.8 Std. Dev. = 1.1 Peak = 5 N = 78

N= number of data points

Table IV

CO Concentrations (ppm)

Upper deck concentrations for vertical stack and flag pole stack for test condition 2

(With generator load and no extra weight)

Sample Location	Vertical Stack	Modified Flag Pole Stack
Top Deck Rear **#8 (Modified Flagpole Stack)** **#7 (Vertical Stack)**	Mean = 0.1 Std. Dev. = 0.7 Peak = 2 N = 110	Mean = 0.4 Std. Dev. = 0.6 Peak = 3 N = 78
Top Deck Center **#9**	Mean = 0.3 Std. Dev. = 0.8 Peak = 3 N = 110	Mean = 0.9 Std. Dev. = 0.5 Peak = 2 N = 78
Top Deck Bar **#10**	Mean = 0.7 Std. Dev. = 0.6 Peak = 2 N = 110	Mean = 0.1 Std. Dev. = 0.4 Peak = 1 N = 78
Top Deck Near Stack **#7 (Modified Flagpole Stack)** **#5 (Vertical Stack)**	Mean = 8.7 Std. Dev. = 3.4 Peak = 17 N = 110	Mean = 0.1 Std. Dev. = 0.63 Peak = 2 N = 78
Starboard Top Deck **#5 (Modified Flagpole Stack)** **#8 (Vertical Stack)**	Mean = 27 Std. Dev. = 6 Peak = 46 N = 110	Mean = 1.2 Std. Dev. = 2.3 Peak = 15 N = 78

N= number of data points

Table V

CO Concentrations (ppm)

Lower deck concentrations for vertical stack and flag pole stack for test condition 4 (With generator load and extra weight)

Sample Location	Vertical Stack	Modified Flag Pole Stack
Stairs **#6**	Mean = 0.3 Std. Dev. = 0.5 Peak = 1 N = 116	Mean = 1 Std. Dev. = 0.9 Peak = 3 N = 50
Sliding door **#2**	Mean = 0.1 Std. Dev. = 1.3 Peak = 5 N = 116	Mean = 0.3 Std. Dev. = 0.5 Peak = 1 N = 50
Starboard swim platform **#3**	Mean = 3.7 Std. Dev. = 3.2 Peak = 13 N = 116	Mean = 0.3 Std. Dev. = 0.5 Peak = 1 N = 50
Port swim platform **#4**	Mean = 4 Std. Dev. = 1.3 Peak = 9 N = 116	Mean = 0.3 Std. Dev. = 0.5 Peak = 1 N = 50
Bedroom **#1**	Mean = 0.1 Std. Dev. = 0.4 Peak = 1 N = 116	Mean = 7.2 Std. Dev. = 2.4 Peak = 11 N = 50

N= number of data points

Table VI

CO Concentrations (ppm)

Upper deck concentrations for vertical stack and flag pole stack for test condition 4

(With generator load and extra weight)

Sample Location	Vertical Stack	Modified Flag Pole Stack
Top Deck Rear **#8 (Modified Flagpole Stack)** **#7 (Vertical Stack)**	Mean = 0.4 Std. Dev. = 0.5 Peak = 1 N = 116	Mean = 0.3 Std. Dev. = 0.5 Peak = 1 N = 50
Top Deck Center **#9**	Mean = 0.8 Std. Dev. = 0.5 Peak = 2 N = 116	Mean = 0.7 Std. Dev. = 0.4 Peak = 1 N = 50
Top Deck Bar **#10**	Mean = 0.7 Std. Dev. = 0.5 Peak = 2 N = 116	Mean = 0.1 Std. Dev. = 0.4 Peak = 1 N = 50
Top Deck Near Stack **#7 (Modified Flagpole Stack)** **#5 (Vertical Stack)**	Mean = 3.1 Std. Dev. = 3 Peak = 11 N = 116	Mean = 0.8 Std. Dev. = 0.4 Peak = 1 N = 50
Starboard Top Deck **#5 (Modified Flagpole Stack)** **#8 (Vertical Stack)**	Mean = 19 Std. Dev. = 1.4 Peak = 25 N = 116	Mean = 1.0 Std. Dev. = 0.3 Peak = 2 N = 50

N= number of data points

Table VII

CO Concentrations (ppm)

Lower deck concentrations for vertical stack and flag pole stack for test condition 5

(With no generator load and extra weight)

Sample Location	Vertical Stack	Modified Flag Pole Stack
Stairs **#6**	Mean = 0.6 Std. Dev. = 1 Peak = 6 N = 194	Mean = 0.4 Std. Dev. = 2.3 Peak = 16 N = 82
Sliding door **#2**	Mean = 1.3 Std. Dev. = 0.7 Peak = 5 N = 194	Mean = 0.6 Std. Dev. = 0.7 Peak = 2 N = 82
Starboard swim platform **#3**	Mean = 0.3 Std. Dev. = 1.1 Peak = 6 N = 194	Mean = 0.7 Std. Dev. = 1.2 Peak = 7 N = 82
Port swim platform **#4**	Mean = 0.6 Std. Dev. = 1.2 Peak = 7 N = 194	Mean = 0.4 Std. Dev. = 0.5 Peak = 1 N = 82
Bedroom **#1**	Mean = 1.5 Std. Dev. = 0.5 Peak = 2 N = 194	Mean = 12.5 Std. Dev. = 1 Peak = 14 N = 82

N= number of data points

Table VIII

CO Concentrations (ppm)

Upper deck concentrations for vertical stack and flag pole stack for test condition 5 (With no generator load and extra weight)

Sample Location	Vertical Stack	Modified Flag Pole Stack
Top Deck Rear **#8 (Modified Flagpole Stack)** **#7 (Vertical Stack)**	Mean = 1.3 Std. Dev. = 5.3 Peak = 53 N = 194	Mean = 0.4 Std. Dev. = 0.7 Peak = 4 N = 82
Top Deck Center **#9**	Mean = 1.4 Std. Dev. = 4.3 Peak = 41 N = 194	Mean = 0.6 Std. Dev. = 0.5 Peak = 1 N = 82
Top Deck Bar **#10**	Mean = 0.9 Std. Dev. = 3.9 Peak = 40 N = 194	Mean = 0.1 Std. Dev. = 0.4 Peak = 1 N = 82
Top Deck Near Stack **#7 (Modified Flagpole Stack)** **#5 (Vertical Stack)**	Mean = 3.5 Std. Dev. = 2.9 Peak = 25 N = 194	Mean = 0.6 Std. Dev. = 0.5 Peak = 1 N = 82
Starboard Top Deck **#5 (Modified Flagpole Stack)** **#8 (Vertical Stack)**	Mean = 4.7 Std. Dev. = 14.3 Peak = 178 N = 194	Mean = 0.9 Std. Dev. = 0.7 Peak = 6 N = 82

N= number of data points

Table IX

Highest CO concentrations for all conditions.

		Vertical Stack	Flag Pole Stack	Side Exhaust
Swim Platform	Average CO Concentrations	5 ppm	2 ppm	341 ppm
	Peak CO Concentrations	50 ppm	20 ppm	1000 ppm
Top Deck	Average CO Concentrations	27 ppm	5 ppm	67 ppm
	Peak CO Concentrations	192 ppm *	94 ppm *	929 ppm

* These numbers can be further reduced by increasing the stack height and moving the location to the rear corner of the houseboat.

Table X

Vertical Exhaust Stack Emissions Test Data.

	No Load Extra Weight	Load Extra Weight	No load No Extra Weight	Load No Extra Weight
HC (ppm)	205	150	192	258
CO %	6.4	5.2	6.25	5.41
CO2 %	10.8	11.6	11	11.3
02 %	0.2	0.1	0.1	0.3
Nox ppm	40	48	25	45
AFR	12.15	12.65	12.27	12.7
λ	0.83	0.86	0.84	0.86

Table XI

Modified Flagpole Exhaust Stack Emissions Test Data.

	No Load Extra Weight	Load Extra Weight	Load No Extra Weight
HC (ppm)	211	223	292
CO %	7.49	5.48	7.48
CO2 %	9.9	11.2	10.6
O2 %	0.2	0.3	0.7
Nox ppm	52	86	59
AFR	11.8	12.57	12.53
λ	0.8	0.86	0.85

Table XII

Detector Tube Results.

Boat and Condition	**Detector Tube Location and Results**
Vertical Side Stack	No generator load, extra weight, sample in stack = 7% No generator load, extra weight, sample in stack = 6.75% Load on generator, extra weight, sample in stack = 7% Load on generator, extra weight, sample in stack = 6.2% Load on gen, no extra weight, sample in stack = 5% No gen load, no extra weight, sample in stack = 6% Load on gen, no extra weight, sample in stack = 6% Load on gen, extra weight, sample in stack = 6%
Side Exhaust	Generator on with side exhaust, sample on top deck near the stack = 4,000 ppm
Modified Flag Pole Stack	No gen load, no extra weight, sample in stack = 6% No gen load, extra weight, sample in stack = 7% No gen load, extra weight, sample in stack = 6% Load on gen, extra weight, sample in stack = 6.5% Load on gen, no extra weight, sample in stack = 6.8%

Table XIII

Evacuated Container Results.

Boat and Condition	**Evacuated Container Location and Results**
Vertical Side Stack	No generator load, extra weight, sample in stack = 61,795 ppm No generator load, extra weight, sample in stack = 4,657 ppm Load on generator, extra weight, sample in stack = 88,227 ppm Load on generator, extra weight, sample in stack = 3,913 ppm Load on gen, no extra weight, sample in stack = 51,789 ppm No gen load, no extra weight, sample in stack = 37,405 ppm Load on gen, no extra weight, sample in stack = 48,466 ppm Load on gen, extra weight, sample in stack = 27,725 ppm
Side Exhaust	Generator on with side exhaust, sample on center of boat upper deck = 93 ppm Generator on with side exhaust, sample on lower deck side near exhaust terminus = 50 ppm (Could not collect samples close to exhaust discharge because of water in the exhaust) Generator on with side exhaust, sample on top deck near the stack = 1 ppm
Modified Flag Pole Stack	No gen load, no extra weight, sample in stack = 62,230 ppm Load on gen, no extra weight, sample in stack = 52,604 ppm

Table XIV

Boat Heading and Wind Velocity Data.

Day	Houseboat Bearing	Average Wind direction	Average Wind Speed	Std. Dev. Wind Speed
Monday afternoon (marina)	270°	256.3°	1.9 m/sec	1.0 m/sec
Tuesday, morning (cove)	330°	236.1°	1.0 m/sec	0.6 m/sec
Tuesday, evening (cove)	330°	104.8°	0.5 m/sec	0.25 m/sec
Wednesday, afternoon (marina)	270°	148.0°	1.0 m/sec	0.5 m/sec
Wednesday, evening (cove)	180°	62.9°	0.8 m/sec	0.3 m/sec

Table XV

Ambient Temperature and Relative Humidity Data.

Day	Temp Range	Temp Avg.	Temp Std. Dev.	Humidity Range	Humidity Average	Humidity Std. Dev.	Number of Data Points
Monday afternoon (marina)	86 – 91.4°F	89.2°F	1.0	51 – 58 %RH	54% RH	2.3	230
Tuesday, morning (cove)	81.1 – 89.8°F	84.2°F	1.6	49 – 63 %RH	57% RH	4.3	185
Tuesday, evening (cove)	78.8 – 92.8°F	84.4°F	2.5	47 – 71 %RH	61% RH	7.3	170
Wednesday, afternoon (marina)	78.4 – 84.2°F	80.6°F	0.8	58 – 68 %RH	64% RH	2.5	62
Wednesday, evening (cove)	76.1 – 80.4°F	77.9°F	0.6	76 – 82 %RH	79% RH	1.4	141

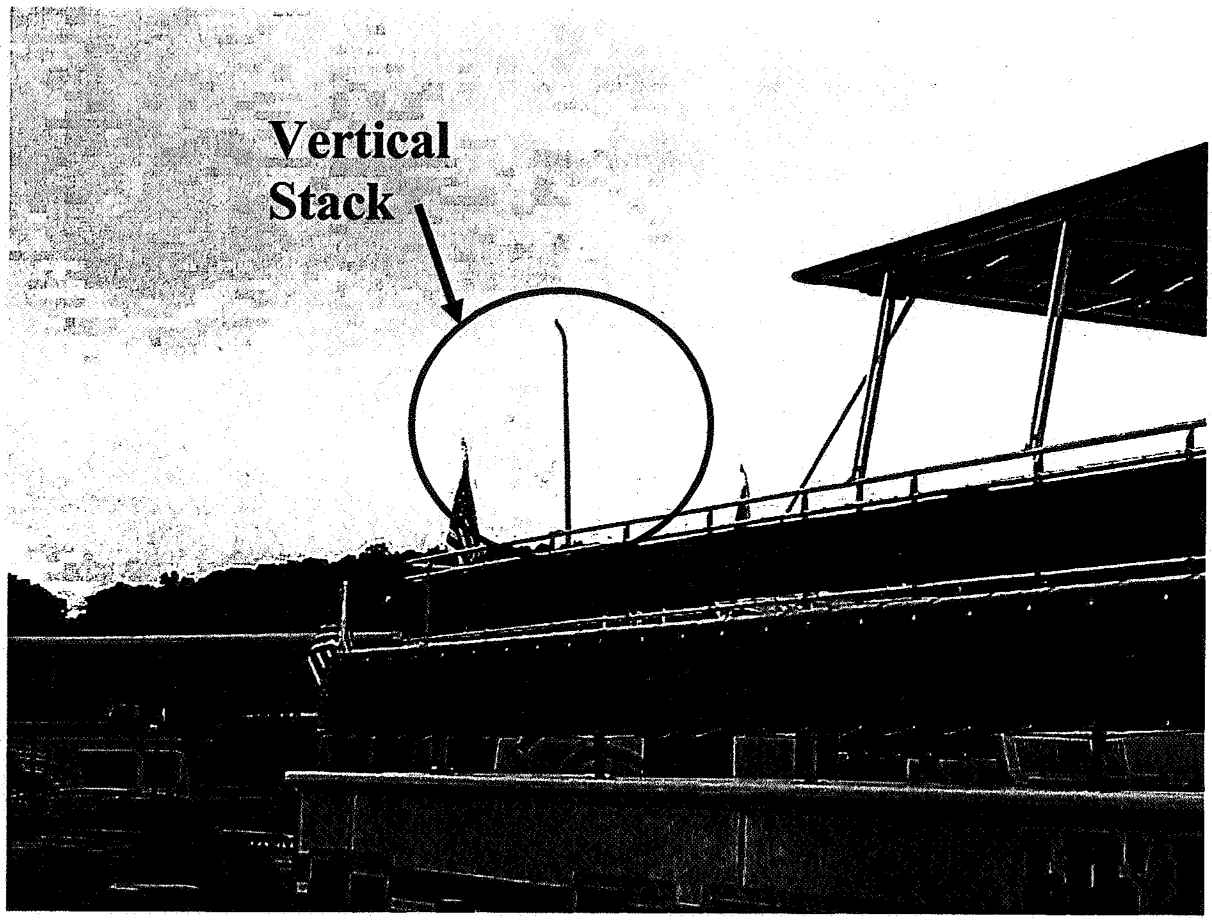


Figure 1: Vertical Exhaust Stack on the side of the evaluated Sumerset Custom Houseboat.

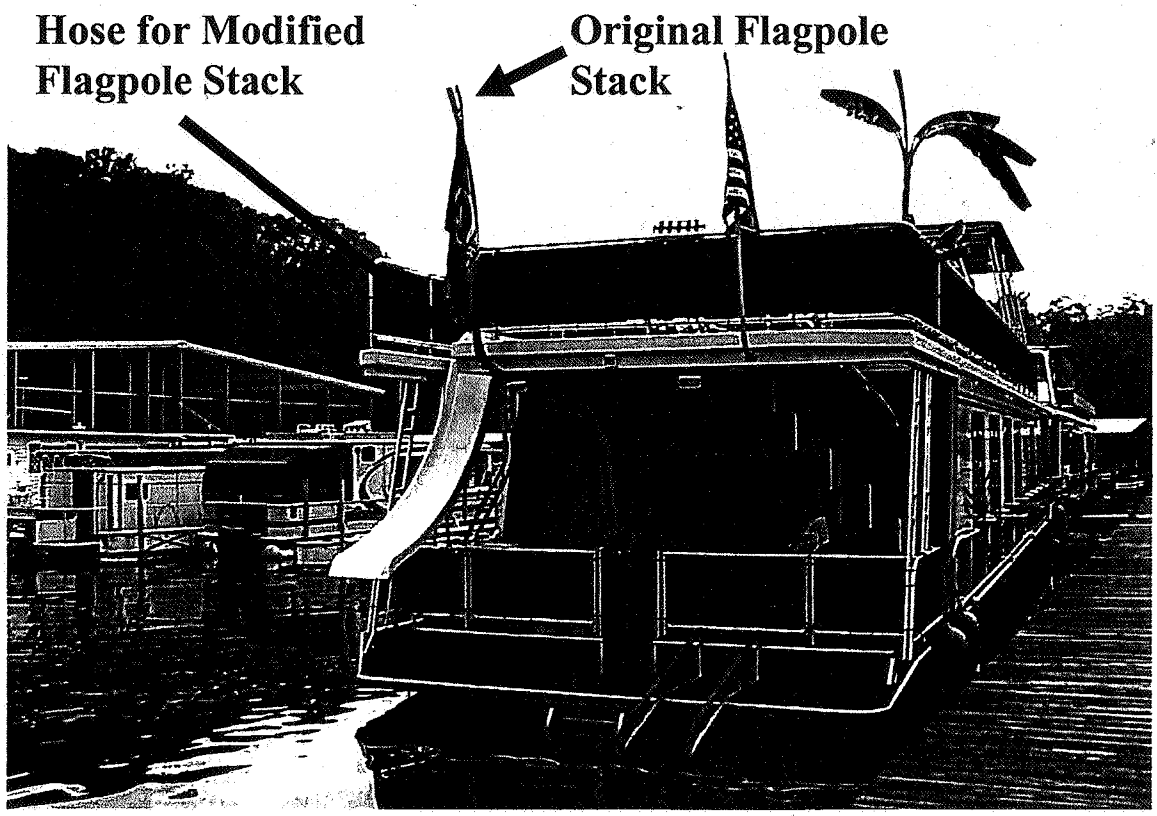


Figure 2: Modified flagpole exhaust stack on an evaluated Sumerset Custom Houseboat.

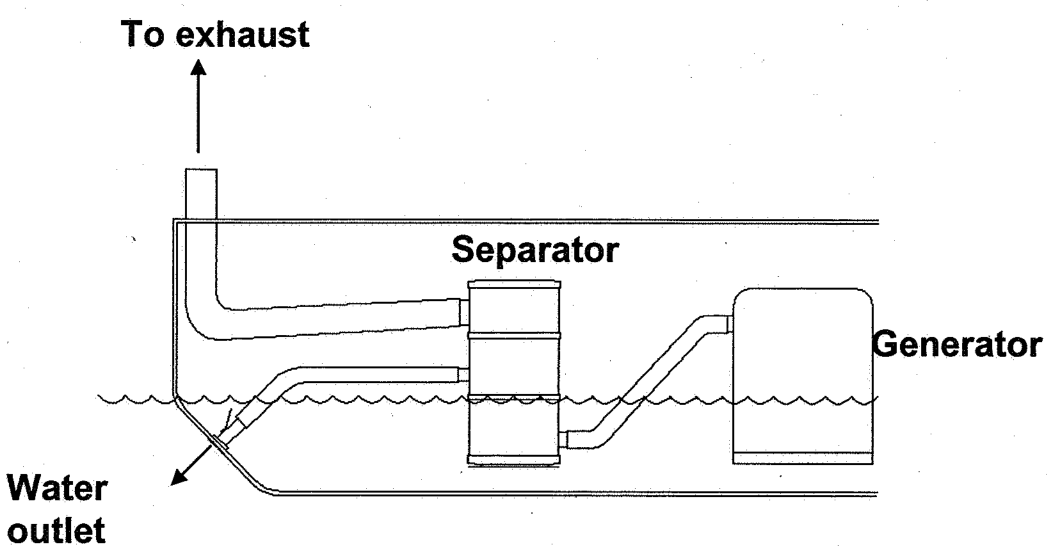


Figure 3: Simplified gas water separator configuration.

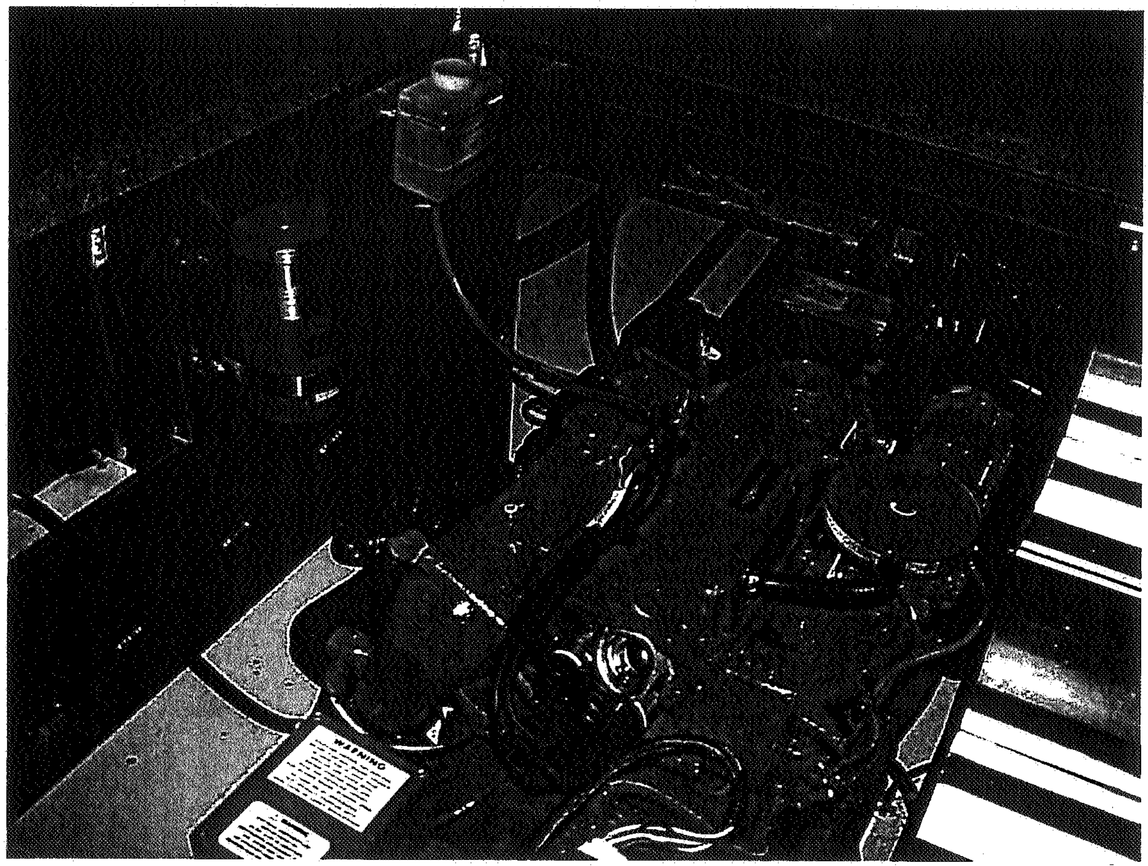


Figure 4: Combo-Sep® muffler/gas/water separator and Westerbeke 15 Kw generator.

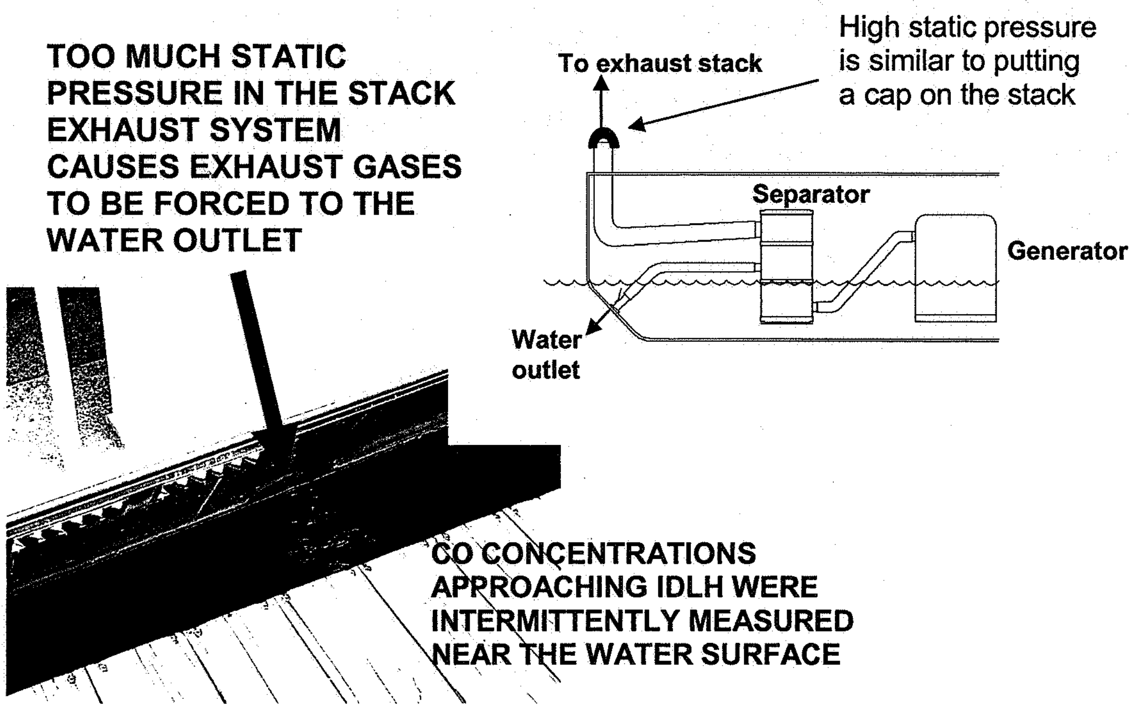


Figure 5: Visible bubbling near water outlet from high static pressure in the stack.

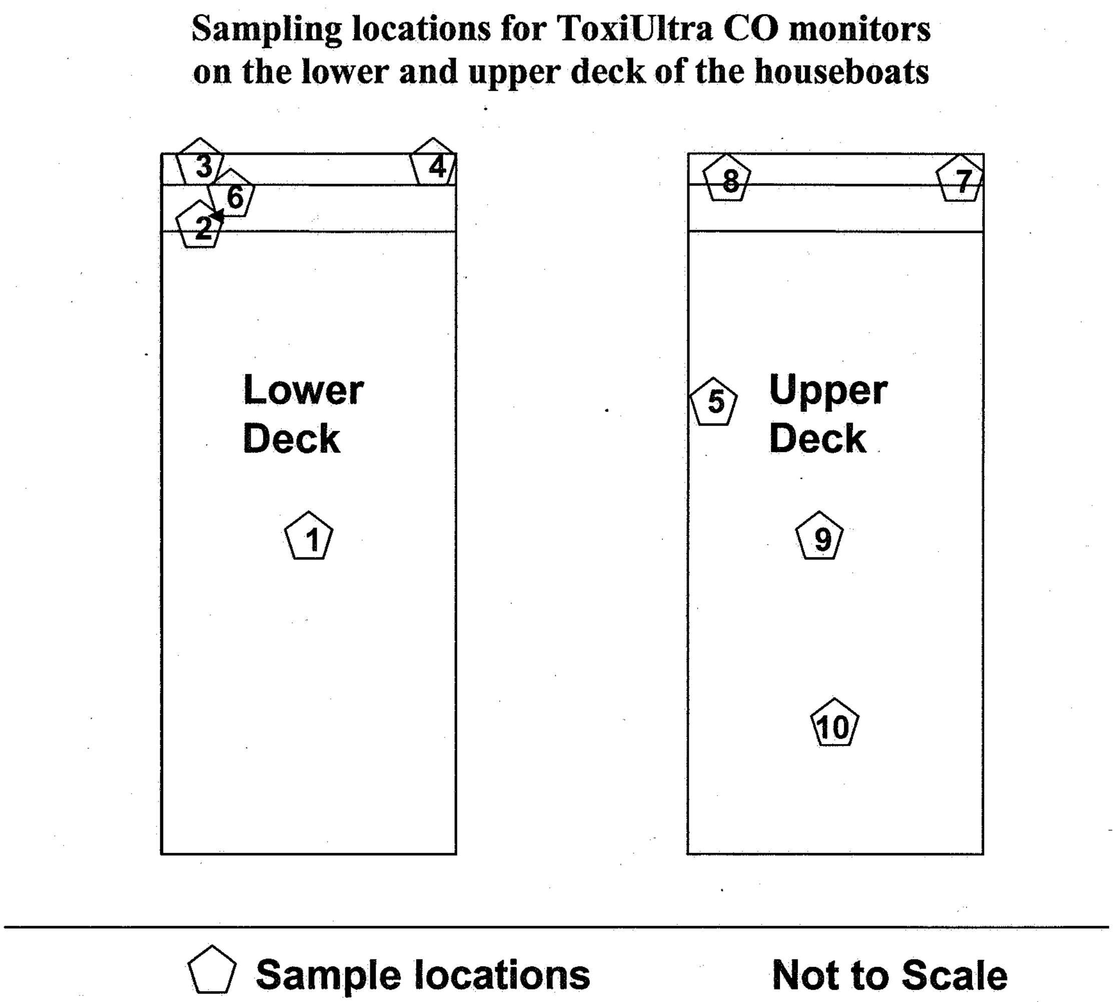


Figure 6: Sampling locations on the vertical stack and flagpole stack houseboats.

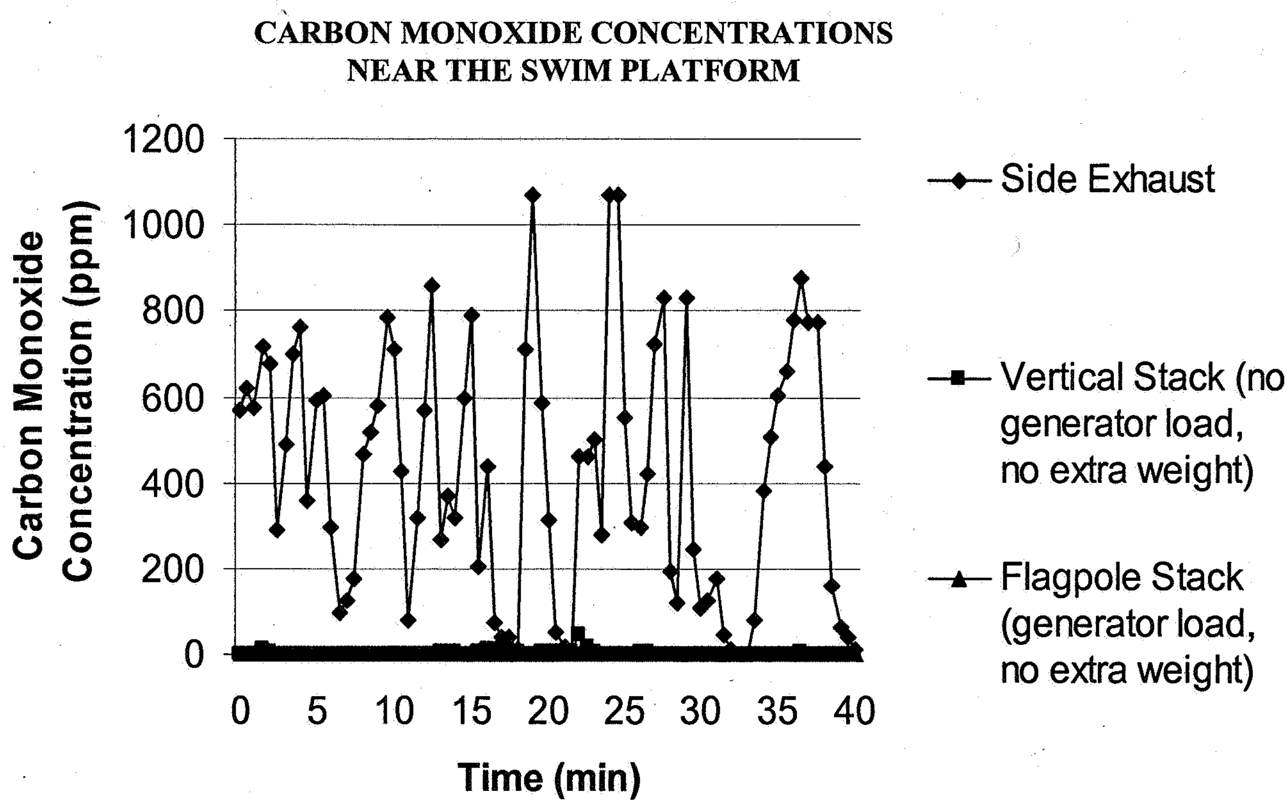


Figure 7: Comparison of CO concentrations on the houseboats lower deck for three different exhaust configurations.

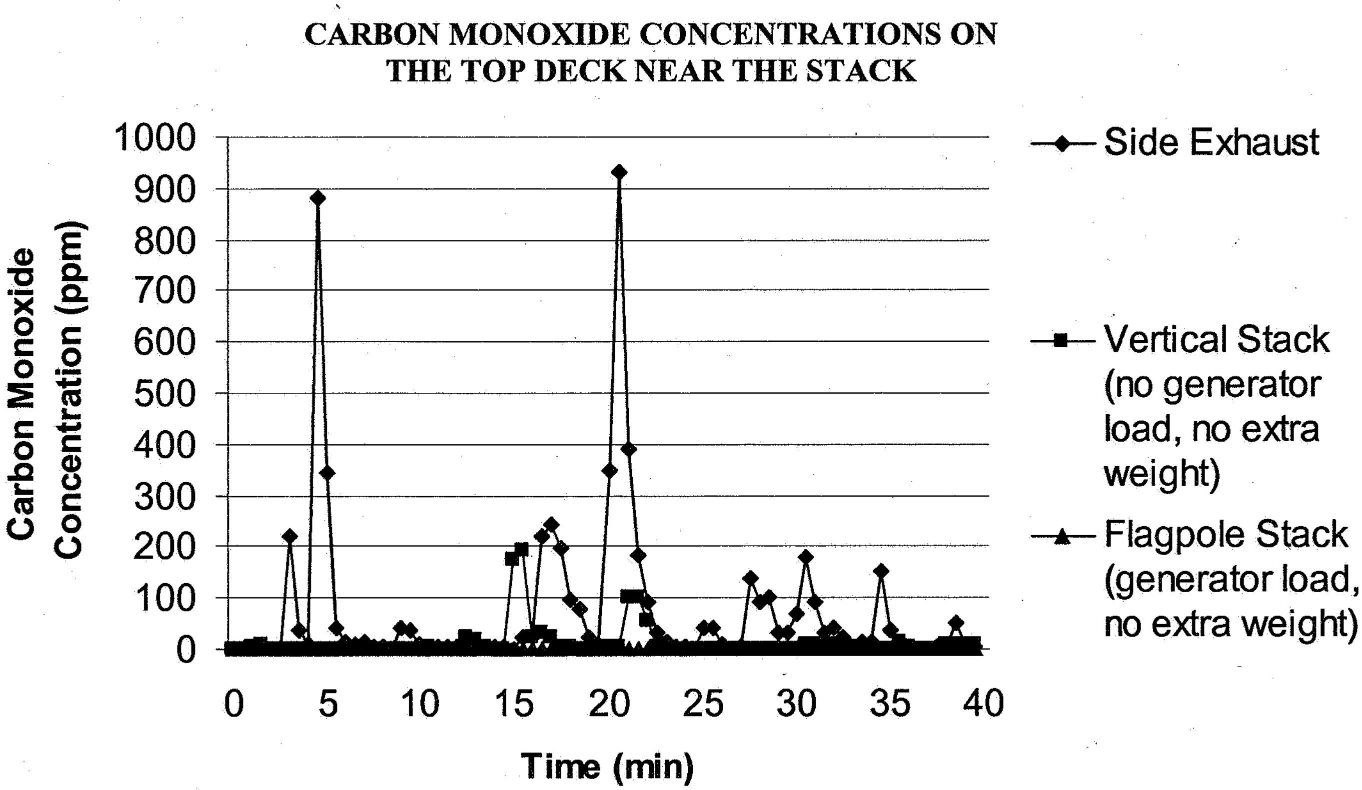


Figure 8: Comparison of CO concentrations on the houseboats upper deck near the stack for three different exhaust configurations.

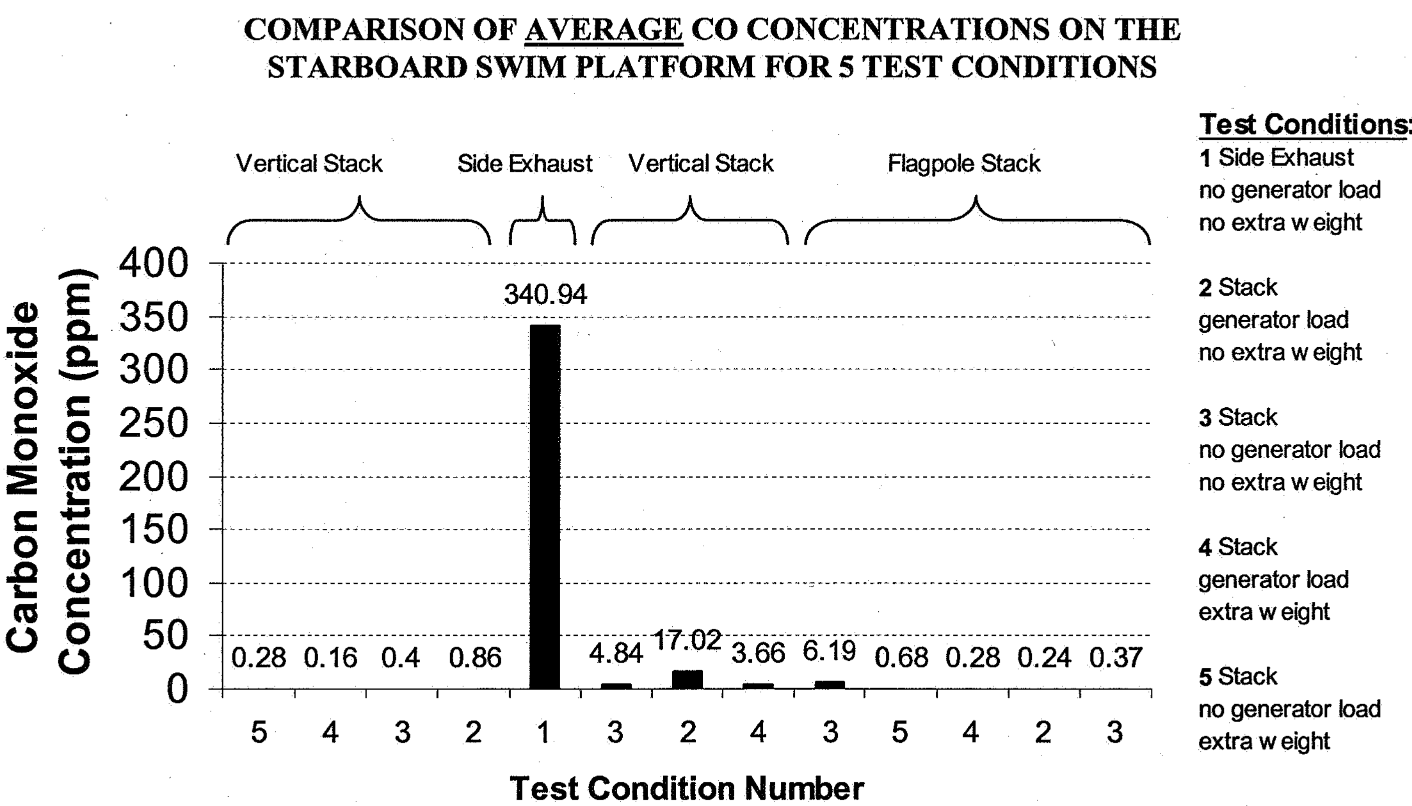


Figure 9: Comparison of average CO concentrations on the starboard swim platform for 5 test conditions.

COMPARISON OF PEAK CO CONCENTRATIONS ON THE STARBOARD SWIM PLATFORM FOR 5 TEST CONDITIONS

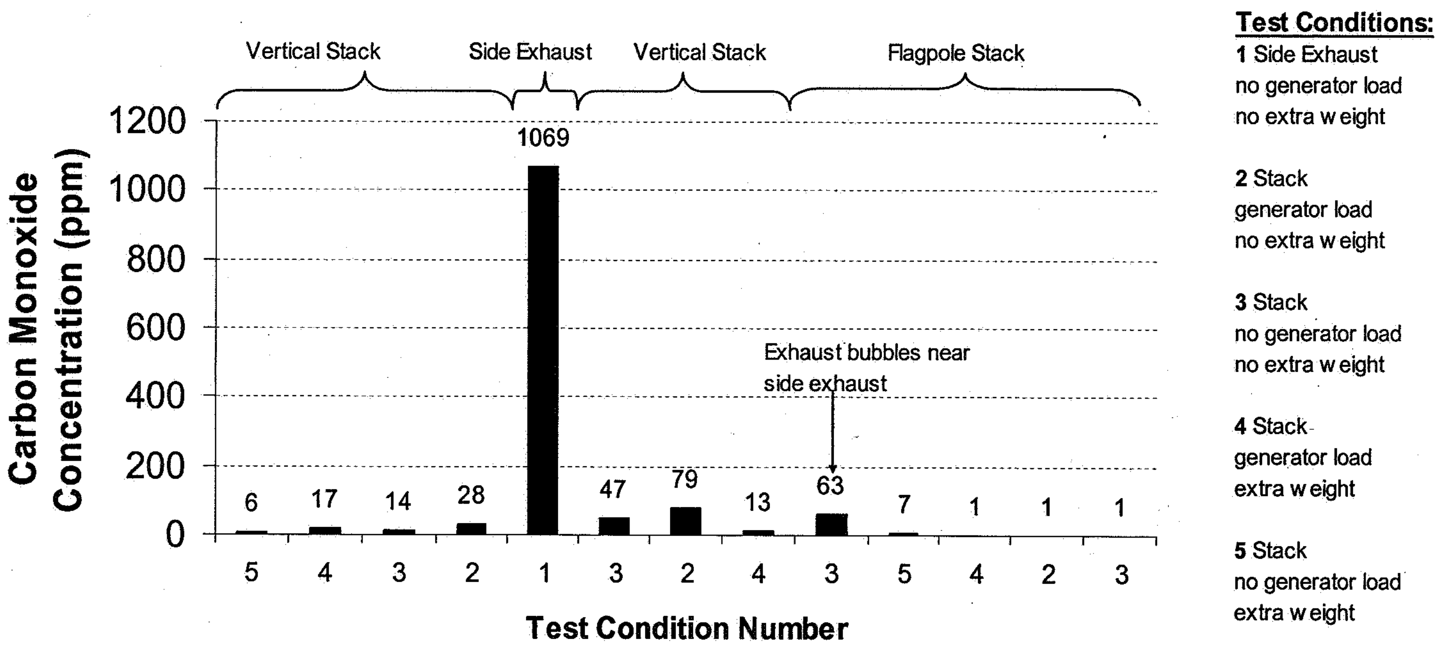
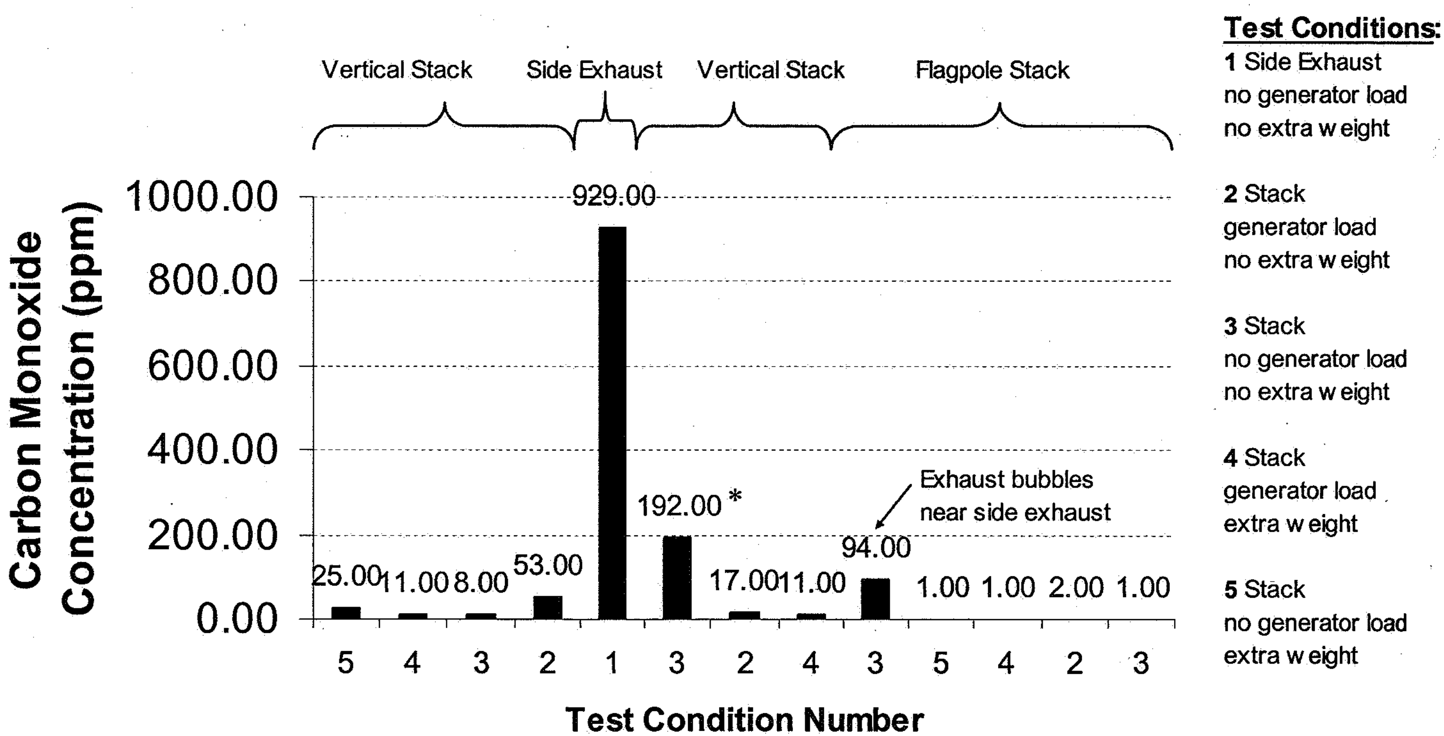


Figure 10: Comparison of peak CO concentrations on the starboard swim platform for 5 test conditions.

COMPARISON OF PEAK CO CONCENTRATIONS ON THE TOP DECK NEAR THE STACK FOR 5 TEST CONDITIONS



*The peak of 192 ppm could be reduced by extending the stack higher above the upper deck and moving the location to the rear corner of the houseboat.