AN EVALUATION OF AN ENGINEERING CONTROL TO PREVENT CARBON MONOXIDE POISONINGS OF INDIVIDUALS ON HOUSEBOATS

at

SUMERSET CUSTOM HOUSEBOATS
SOMERSET, KY

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DISCLAIMER

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

Executive Summary

During the period of 1990 to 2000, 111 carbon monoxide (CO) poisoning cases occurred on Lake Powell near the border of Arizona and Utah. Seventy-four of the poisonings occurred on houseboats, and sixty-four of the poisonings were attributable to generator exhaust alone. Nine of the 111 CO poisonings resulted in death. The National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of an engineering control installed on a houseboat generator to reduce the hazard of CO poisonings from the generator exhaust. The control consisted of a water separator and an exhaust stack outfitted onto a gasoline-powered generator that extended to just below the upper deck on the port side of the houseboat. An extension to the exhaust stack which raised the outlet to 7 feet above the top deck was retrofitted and also tested. When comparing the results of the current evaluation to previous studies, the use of an exhaust stack provides dramatically lower exposure to hazardous levels of CO to individuals on or near the houseboat. The CO concentrations on the swim platform were reduced by ten times or more when compared to boats which exhaust out of the transom underneath the swim platform. The current study found that the extension of the exhaust stack well above the upper deck further reduced CO concentrations at all locations on both the lower and upper decks. CO concentrations on the swim platform of the houseboat, an area where occupants frequently congregate, were an average of 6.05 ppm at the short stack height (exhaust stack terminating just below the upper deck) and were reduced to 0.84 ppm with the tall stack configuration (exhaust stack terminating 7 feet above the upper deck). CO concentrations were also reduced on the upper deck of the houseboat. The primary benefit of extending the exhaust stack is that the peak concentrations were reduced in all locations, in most cases by ten times or more. The peak concentration at one location on the top deck was reduced from 459 ppm to 4 ppm. Based upon the results of this and other studies, it appears that retrofitting houseboats, using gasoline powered engines, with an exhaust stack that extends well above the upper deck will greatly reduce the risk of CO poisoning and possible death to individuals on or near the houseboat.

Background

On March 1, 2001, the National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of an engineering control designed and outfitted onto a houseboat generator. The control, which consisted of a water separator and an exhaust stack, was designed to direct the generator exhaust away from individuals on or near the houseboat in order to prevent carbon monoxide (CO) poisonings from the exhaust. Many houseboat generators exhaust through the transom under the swim deck on the rear of the boat while many others exhaust to the side of boat near the waterline. The generator exhaust system design and modification was performed by Sumerset Custom Houseboats in Somerset, Kentucky. The evaluation was conducted on a small test pond at Sumerset Custom Houseboats Headquarters. This report provides background information, and describes the evaluation methods, results, conclusions, and recommendations from this survey.

Initial investigations 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 in response to CO related poisonings and deaths on houseboats at Lake Powell. The September 2000 investigation characterized CO poisonings through epidemiologic data gathering, and severely hazardous CO concentrations measured on houseboats at Lake Powell (McCammon and Radtke 2000). Incident reports provided by the National Park Service revealed 9 known boat-related CO poisoning deaths on the lake since 1994. Some of these incidents involved numerous poisonings in addition to the deaths reported (total of 15 people poisoned in the 8 incidents involving fatalities). Information regarding the fatalities is described in the previous report (McCammon and Radtke 2000). Since that report, it has been discovered that from 1990 to 2000, 111 CO poisoning cases occurred on Lake Powell near the border of Arizona and Utah. Seventy-four of the poisonings occurred on houseboats, and sixty-four of the poisonings were attributable to generator exhaust alone. Nine of the 111 CO poisonings resulted in death (McCammon, Radtke et al. 2000).

Some of the severely hazardous situations identified during the September evaluation 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.

Further investigations were conducted to gather additional CO concentration data on various types of houseboats at Lake Powell (Hall and McCammon 2000) and Lake Cumberland, Kentucky (Hall 2000). Survey results showed that when the generator is exhausted under the swim deck, hazardous concentrations of CO (greater than the IDLH) were measured in the space under and around the back of the swim platform. High concentrations were also measured at the swim platform (greater than 500 ppm) on a houseboat that exhausted the generator to the side of the boat. These concentrations were measured when in a single boat configuration and when two side exhaust boats were tied together.

In February 2001, an engineering control evaluation was conducted on a Lakeview houseboat located at the Wahweap Marina on Lake Powell, Arizona (Earnest et.al. 2001). That study looked at the effect of using an exhaust stack that extended 9 feet above the top deck of the houseboat for the generator compared to a more standard configuration of exhausting out of the transom in the space underneath the swim platform. The results indicated average reductions in CO concentrations on the swim deck of greater than 99% (607 ppm vs. 3 ppm) when the exhaust was vented through the stack versus to the airspace beneath the swim deck.

Carbon Monoxide Symptoms and Exposure Limits

Carbon monoxide (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, 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. Park Service and houseboat rental/maintenance employees should be in a state of health typical of any industrial worker. Thus, occupational criteria for CO exposure are applicable to that group. The general boating public, however, 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. The occupational exposure limits noted below should not be used for interpreting general population exposures because they would not provide the same degree of protection they do for the healthy worker population.

Exposure Criteria

The NIOSH Recommended Exposure Limit (REL) for CO is 35 ppm for full shift TWA exposure, with 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 IDLH value for CO as 1,200 ppm (NIOSH 2000). The American Conference of Governmental Industrial Hygienists' (ACGIH®) Threshold Limit Values (TLVs®) recommends an eight-hour TWA TLV of 25 ppm (ACGIH 1996), and recommends that excursions above 125 ppm be prevented. The Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PELs) for CO is 50 ppm for an 8-hour TWA exposure (CFR 1997).

The US 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 one-hour average (EPA 1991). The NAAQs for CO was established to protect "the most sensitive members of the general population".

Methods

Description of the Evaluation Equipment

Emissions from the exhaust stack and the area below the swim deck were characterized using a KAL Equip Model 5000 Four Gas Emissions Analyzer (KAL Equipment, Cleveland, Ohio). This analyzer measures CO, carbon dioxide (CO_2), hydrocarbons, and oxygen. CO and O_2 measurements are expressed as percentages. [One percent of contaminant is equivalent to 10,000 ppm.] Air contaminants in the space were determined with only the generator operating and with the generator and boat engines operating simultaneously.

CO concentrations were measured at various locations on the houseboat using ToxiUltra Atmospheric Monitors (Bacou USA, Middletown, CT) 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 30 second sampling interval. The instruments have a nominal range from 0 ppm to 999 ppm.

CO concentration data was also collected with detector tubes [Draeger CO, CH 29901– range 0.3 % (3,000 ppm) to 7 % (70,000 ppm) and CH 25601– range 5-700 ppm)] at various locations on the boat. 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 (100 miles per hour) and taking 100 measurements per second.

Description of the Evaluated Sumerset Houseboat and Engineering Control

CO samples were collected on a four bedroom, Sumerset houseboat built in 2001 (Figure 1) having the specifications listed below.

Engines: 2 Mercruiser 5.0 liter V-8, 240 horsepower (hp) Throttle Body Fuel Injection, propellor shaft exhaust
Generator: 15.0 Kw/ 25 hp Westerbeke, 4 cylinder, 4 cycle, 1800 rpm, 107.27 in^3
Approximate dimensions of houseboat: 80' X 16'
Approximate dimensions of space below deck: 8' X 16' X 1.7'
Exhaust Configuration: Engines exhaust below the rear swim deck and generator exhausted through a dry stack either: 1) extending to the base of the upper deck or 2) extending 7 feet above the upper deck.

Two stern drive Mercruiser 5.0 liter, V-8, engines are the propulsion units for this boat. These engines were housed in compartments beneath the rear swim deck of the houseboat. Access could be gained to the engines through two large doors in the floor of the rear deck. These engines exhausted through their propellor shaft beneath the water.

The generator on this houseboat (Figure 2) was manufactured by Westerbeke Corporation, (Avon, MA) to provide electrical power for air conditioning, electrical cooking, refrigeration, cabin appliances, navigation and communications equipment. The generator was housed beneath the rear swim deck and was positioned between the two Mercruiser engines. The generator is a 4-cylinder, 4-stroke, gasoline-powered engine with overhead cam, that operates at approximately 1,800 revolutions per minute (rpm) and displaces 107.27 cubic inches (in^3).

The hot exhaust gases from this generator are injected with water near the end of the exhaust manifold in a process commonly called "water-jacketing." Water-jacketing is used for cooling and noise reduction prior to exiting the discharge of the engine. The water-jacketed exhaust passes through a water separator that discharges water at the side of the boat at or below the waterline and forces the cooled exhaust gases out through the dry exhaust stack.

Beginning in 1996, all houseboats manufactured by Sumerset were designed with the generator exhaust being routed to the side of the boat. In January 2001, Sumerset issued a voluntary recall on all of its houseboats and will rework an estimated 2500 boats built from 1953-1996 to the side exhaust (Sumerset, 2001). The houseboat used in this evaluation was modified to re-route the generator from the standard side exhaust to a dry stack which terminated just below the upper deck. The exhaust outlet was angled away from the deck towards the water (Figure 3). A schedule 40 aluminum pipe, having a 2 inch outside diameter was used for the stack. An additional 9 feet of piping was added to extend the exhaust to a point 7 feet above the upper deck (Figure 4). This extension was evaluated to look at its effect on lower and upper deck CO concentrations. A Combosep® water/exhaust separator (Centek Industries, Thomasville, GA) was installed to separate the exhaust gases from the water using gravity and centrifugal force. In order to function properly, the exhaust stack must be properly sized based upon the exhaust gas, water flow rate, and the maximum back pressure permitted by the manufacturer. It is also important that the separator releases the water less than 8 inches below the water line to reduce back pressure which could force some water up the stack.

In addition to the Westerbeke generator, the evaluated houseboat had a marine inverter system (Trace Engineering, Arlington, WA) that provided AC power and DC battery charging that enabled many of the appliances on the houseboat (ceiling fans, lights, refrigerators) to be operated overnight on batteries rather than the generator. There were numerous CO warning signs located at various locations on the houseboat including an aluminum embossed plate on the rear swim deck. CO detectors were located in every sleeping compartment and were hardwired to the electrical system.

Description of Procedures

During the evaluation, the generator operated alone for approximately 60 minutes. For the first run, both engines and the generator were operated for an additional 15 minutes. Data was collected for 4 separate runs, in which half were evaluated with the generator exhausting through the exhaust stack as originally designed (short stack). The other half were evaluated with the generator exhaust stack extended to a level of 7 feet above the upper deck (tall stack). When they operated, both Mercruiser® engines exhausted beneath the rear swim deck of the houseboat.

Results

Results of Air Sampling with ToxiUltra CO monitors

Sampling locations on the lower and upper decks of the houseboat, designated with pentagons, are shown in Figures 5 and 6. The monitors were placed at various locations on both the upper and lower decks of the houseboat to provide representative samples of where people could be positioned when the generator was operating. Because people commonly enter and exit the water via the rear swim platform of the boat, two monitors were placed on either side of this structure (Figure 1).

Real-time monitoring results for CO concentrations at various locations on the houseboat are presented in Figures 7 through 12. Figures 7 through 11 provide a comparison of CO concentrations on the houseboat when the generator exhausted through the short stack and when it exhausted through the tall stack. Figure 12 provides a look at CO concentrations at multiple locations on the houseboat simultaneously, with generator only and then with generators and main engines on (in the short stack exhaust configuration only).

The ToxiUltra monitors are electrochemical type instruments which measure the electrical current generated by a reaction between the ambient CO and the electrolyte in the sensor. The electrical current generated is proportional to the amount of reactant gas present and is used to indicate gas concentration. Occasionally, negative gas concentration readings are logged generally due to two conditions: 1) zeroing the instrument in an area which is not free of CO; or 2) performing measurements in the presence of interference contaminants which cause a negative potential across the electrode. During this evaluation, a zero drift of -1 ppm occurred on several of the sensors. To account for this, a 1 ppm shift was added to the data for those monitors.

The following summarizes the reduction in CO concentrations at various locations on the houseboat by exhausting the generator through the short stack as compared to tall stack:

- CO concentration on the port side of the rear swim platform (Figure 7, Sample 2): On average, CO concentrations with the short stack and tall stack were 6.46 ppm and 1.11 ppm, respectively. The peak concentrations seen at this point was 57 ppm for the short stack and 3 ppm for the tall stack.

- CO concentration on rear deck at breathing zone level behind the slide (Figure 8, Sample 4): On average, CO concentrations with the short stack and tall stack were 4.37 ppm and 0.91 ppm, respectively. The peak concentrations seen at this point was 52 ppm for the short stack and 3 ppm for the tall stack.

- CO concentration on the upper deck near the stairs (Figure 9, Sample 8): On average, CO concentrations with the short stack and tall stack were 24.06 ppm and 0.20 ppm, respectively. The peak concentrations seen at this point was 459 ppm for the short stack and 4 ppm for the tall stack.

- CO concentration on the middle of the upper deck (Figure 10, Sample 9): On average, CO concentrations with the short stack and tall stack were 2.97 ppm and 1.33 ppm, respectively. The peak concentrations seen at this point was 31 ppm for the short stack and 9 ppm for the tall stack.

Area Samples on the Lower Level, Rear Deck oj Boat
The results of all samples collected on the lower level rear deck are shown in Table I. The CO monitor placed at the port side of the rear swim platform, nearest to the exhaust stack, indicated an average CO concentration of 1.11 ppm and a peak of 3 ppm with the generator operating and the stack extended to 7 feet above the top deck (tall stack). This same sample indicated an average of 6.46 ppm with a peak of 57 ppm when the generator exhausted through the short stack under the upper deck. These results are shown in Figure 7. Similarly, the monitor located behind the slide at breathing zone height (Figure 8, sample 4) indicated an average CO concentration of 0.91 ppm and a peak of 3 ppm with the generator operating and the tall stack connected. This same sample indicated an average of 4.37 ppm and a peak of 52 ppm when the generator exhausted through the short stack. In all samples evaluated during the initial run, concentrations were dramatically worse when the main engines were started, and the houseboat remained stationary. This is shown in Figure 12. On the port side of the swim platform, concentrations reached levels greater than 1000 ppm when the main engines and generator were both operating.

Area Samples on Upper Deck of Boat
The results of all samples collected on the upper deck are shown in Table II. The CO monitor placed on the upper deck near the stairs indicated an average CO concentration of 0.20 ppm and a peak of 4 ppm with the generator operating and the stack extended to 7 feet above the top deck (tall stack). This same sample indicated an average of 24.06 ppm with a peak of 459 ppm when the generator exhausted through the short stack under the upper deck. These results are shown in Figure 9. The monitor located on the middle of the upper deck on the port side of the boat indicated an average CO concentration of 1.33 ppm and a peak of 9 ppm with the generator operating and the tall stack connected. This same sample indicated an average of 2.97 ppm and a peak of 31 ppm when the generator exhausted through the short stack. These results are shown in Figure 10.

Figure 11 shows the CO concentration in the airspace beneath the rear deck while only the generator was running. The ToxiUltra monitor was removed from that area before the main engines were started due to concern that the sensor would be damaged from high CO concentrations. The monitor indicated an average CO concentration of 0.88 ppm and a peak of 2 ppm with the generator operating and the tall stack connected. This same sample indicated an average of 4.68 ppm and a peak of 10 ppm when the generator exhausted through the short stack. These CO concentrations are well below those documented in the airspace underneath the rear deck in previous surveys at Lake Powell and Lake Cumberland (McCammon and Radtke 2000, Hall and McCammon 2000, Hall 2000).

Figure 12 provides data showing how CO concentrations at various locations changed with time as the generator (exhausting through the short stack) and later both the generator (exhausting through the short stack) and main engines (exhausting through the propellor shaft) were operated.

This graph clearly shows that the most hazardous location is the rear swim platform near the water; however, it shows that the stack dramatically reduces CO concentrations in that area when only the generator is operating.

Wind Velocity Measurements

Wind velocity measurements were taken with an ultrasonic anemometer while the CO sampling data was gathered. The anemometer was mounted on the surface of the top deck to measure prevailing wind conditions. During this study, the bow of the boat was oriented to the Northeast on an azimuth of approximately 40 degrees with respect to magnetic North, and the boat was stationary. Wind speeds were relatively low with an average wind speed of approximately 0.92 m/sec (181.1 ft/min) and a standard deviation of 0.44 m/sec (Figure 13). Although wind direction changed periodically, on average, it was in a Northeastern direction (217 degrees with respect to magnetic North: where magnetic North = 360 degrees). Based upon boat orientation, the wind direction was likely to move CO away from the stern of the boat after it was exhausted.

Gas Emissions Analyzer, Detector Tubes, and Evacuated Container Results

The gas emissions analyzer, detector tubes, and glass evacuated containers were used to characterize CO concentrations near the exhaust stack and under the lower, rear deck. These instruments were utilized because they are capable of reading higher CO concentrations than the Toxiultra CO monitors which has an upper limit of around 1,000 ppm. When measuring exhaust from the stack, the probe of the emissions analyzer was placed directly in the exhaust pipe and approximately six inches beyond the terminus of the exhaust stack.

Measurement taken with the gas emissions analyzer directly in the exhaust stack of the generator indicated CO concentrations in the range of 3.6 % (36,000 ppm) to 3.8 % (38,000 ppm). At a distance of 6 inches from the exhaust terminus, the CO concentrations ranged from 0.00% to 0.76% (7,600 ppm).

Measurements were also taken in the space below the lower, rear deck with the gas emissions analyzer while both the generator and both main engines were operating (during the initial run only). CO concentrations in the range of 0.79 % (7,900 ppm) to 2.39 % (23,900 ppm) were found. A Draeger detector tube sample taken in this space indicated a CO concentration of 0.3 % (3,000 ppm). The gas emissions analyzer also indicated that the area under the swim platform was oxygen deficient (15.9 % O_2) during the time period when the generator and motors were running. The rate of decay of CO concentration found in this space following shut-off of the generator and main engines was also measured (during the initial trial only). The CO concentration decayed to 0.0% (as measured by the gas emissions analyzer) after a period of approximately 8 minutes. Instantaneous spot measurements taken with Draeger colorimetric detector tubes and evacuated containers correlated well with readings of ToxiUltra and emissions analyzer at several sampling points.

Discussion and Recommendations

Previous NIOSH investigations on houseboats that exhaust generator combustion gases beneath or near the rear deck have shown that extremely hazardous CO concentrations accumulate in the space beneath the rear deck and near the rear swim platform when the generator is operated. The evaluated houseboat had a gasoline-powered, Westerbeke generator that provided electrical power for the on-board appliances. When this generator operates as designed (having no catalytic converter or other pollution control devices) dangerously high CO concentrations will be emitted into the atmosphere. Exhaust gases released from a gasoline engine may contain from 0.1 to 10 percent CO (1,000 to 100,000 ppm) (Heywood 1988). This evaluation indicates that the stack exhaust greatly reduces this hazard under the conditions studied. When the exhaust stack was extended to a height of 7 feet above the top deck, average and peak CO concentrations were well below OSHA occupational and NIOSH recommended exposure limits.

However, if the propulsion engines are operating, the hazardous conditions will still be encountered. CO concentrations in the area underneath the swim deck indicated concentrations well above the NIOSH IDLH value of 1,200 ppm with the propulsion engines on at idle. Individuals swimming or working in the area under the swim platform, or around the area directly behind the swim platform (near the water level), with the generator or motors in operation could quickly experience CO poisoning or death. When the generator or motors are in operation, the area around the lower, rear deck of the houseboats can be hazardous under certain conditions (i.e., lack of air movement).

This investigation confirms that the CO hazard to swimmers and occupants on houseboats can be greatly reduced by running the generator exhaust through a stack that releases the CO and other emission components well above the swim platform of the houseboat. This survey also showed that increasing the stack height to a level of at least 7 feet above the upper deck reduces exposure to dangerous peak concentrations. With the short stack in place, one location exceeded the NIOSH ceiling of 200 ppm. Exhausting the generator high above the upper deck, allows the contaminants to diffuse and dissipate into the atmosphere away from boat occupants. One concern about terminating the exhaust near the base of the upper deck is the possibility of contaminating adjacent boats that have been tied together for recreational purposes. This is a common activity and although the exhaust is directed away from one boat, it may be inadvertently directed towards an adjoining boat.

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

1) All manufacturers/owners/users of U.S. houseboats that use gasoline-powered generators should be aware of and concerned about the location of the exhaust terminus. The data collected in this and previous evaluations show that an exhaust stack, vented well above the upper deck of the houseboat, moves CO away from the airspace below the rear deck, and dramatically reduces CO concentrations on the rear deck, swim platform, and top deck. A comparison of data

collected on houseboats with rear-directed, side-directed, and dry stack exhaust configurations (McCammon, Radtke et al. 2001) demonstrates that the dry stack is the most effective control evaluated to date. Based on these data, we recommend that houseboats with gasoline-powered, generators be retrofitted with an exhaust stack that extends well above the upper deck of the houseboat in order to reduce the hazard of CO poisoning and death to individuals on or near the houseboat.

2) Additional work should be performed to develop the optimum design for the exhaust configuration. Use of the tall stack exhaust configuration reduced both average and peak CO concentrations to levels well below OSHA occupational and NIOSH recommended exposure limits at all locations. Houseboat manufacturers, however, need to do some development work to determine the optimum stack height and size as well as selecting the appropriate water separator. Factors which should be considered include stack location, exhaust exit velocity and temperature as well as the effect of wind and other environmental conditions (such as ambient temperature) on dispersion characteristics. The use of analytical tools such as computational fluid dynamics modeling should be employed to evaluate a range of variables which may effect CO dispersion.

3) The main engines of the houseboat should never be operated in idle while persons are in the water or on or near the rear deck of the houseboat.

4) Additional research and development work should be performed by marine engine manufacturers to evaluate the efficacy of using catalytic converters, afterburners or other pollution control devices on generators that are used on houseboats. NIOSH will be working with manufacturers to evaluate one of these systems.

5) Public education efforts must also be utilized to immediately inform and warn all individuals (including boat owners, renters, and workers) potentially exposed to CO hazards. The U.S. NPS has launched an awareness program to inform boaters on their lake about boat-related CO hazards. This Alert included press releases, flyers distributed to boat and dock-space renters, and verbal information included in the boat check-out training provided for users of concessionaire rental boats. These and other educational materials are available at the following web site: http://safetynet.smis.doi.gov/COhouseboats.htm. Training about the specific boat-related CO hazards provided for houseboat renters, who may be completely unaware of this deadly hazard, should be enhanced to include specific information about the circumstances and number of poisonings and deaths. The training should specifically warn against entering air spaces under the boat (such as the cavity below the swim platform), or immediately behind the swim platform, that may contain a lethal atmosphere.

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Table I. CO Samples (ppm) taken on the Lower, Rear Deck of the Houseboat with Generator Operating.

Sample Location (Sample #)	Generator Operating with Short Stack	Generator Operating with Extended Stack
Rear Swim Platform-Starboard (#1)	Mean= 5.64 S.D. = 5.77 Peak = 53 N = 266	Mean=0.68 S.D. = 0.48 Peak = 2 N = 206
Rear Swim Platform-Port (#2)	Mean= 6.46 S.D. = 5.32 Peak = 57 N = 269	Mean= 1.11 S.D. = 0.59 Peak = 3 N = 119
On Stairs Near Breathing Zone (#3)	Mean= 3.85 S.D. = 3.39 Peak = 27 N = 267	Mean= 0.82 S.D. = 0.48 Peak = 2 N = 205
Behind Slide Near Breathing Zone (#4)	Mean= 4.37 S.D. = 5.35 Peak = 52 N = 268	Mean= 0.91 S.D. = 0.35 Peak = 3 N = 208
In Airspace Below Rear Deck (#5)	Mean= 4.68 S.D. = 2.15 Peak = 10 N = 267	Mean= 0.88 S.D. = 0.34 Peak = 2 N = 210
Inside Cabin, lower level (#6)	Mean= 5.04 S.D. = 1.96 Peak = 10 N = 266	Mean= 0.44 S.D. = 0.55 Peak = 3 N = 182

Table II. CO Samples (ppm) taken on the Upper Deck of the Houseboat with Generator Operating.

Sample Location (Sample #)	Generator Operating with Stack	Generator Operating with Extended Stack
Near Top of Slide (#7)	Mean= 4.92 S.D. = 9.45 Peak = 88 N = 269	Mean= 1.15 S.D. = 1.33 Peak = 12 N = 212
On Rail Near the Top of Stairs (#8)	Mean=24.06 S.D. = 53.39 Peak = 459 N = 268	Mean= 0.20 S.D. = 0.48 Peak = 4 N = 211
Middle of Top Deck (right) (#9)	Mean= 2.97 S.D. = 3.81 Peak = 31 N = 270	Mean= 1.33 S.D. = 0.97 Peak = 9 N = 212
Front of Boat, Bridge (#10)	Mean= 4.36 S.D. = 2.03 Peak = 11 N = 269	Mean= 0.83 S.D. = 1.46 Peak = 11 N = 212

Figure 1. Photo of evaluated Sumerset houseboat.

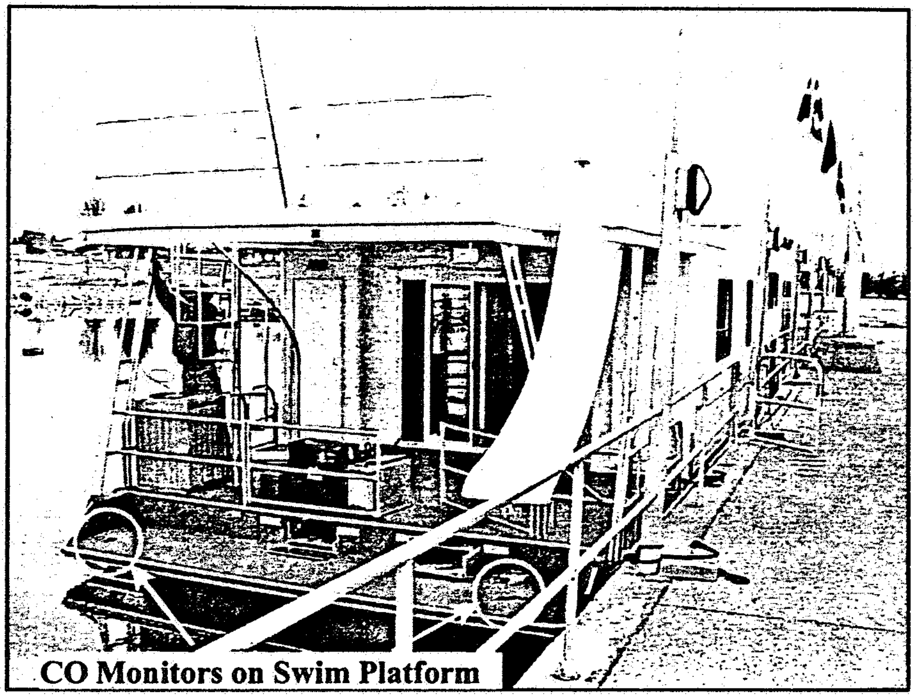


Figure 2. Photo of Westerbeke 15 kW, 4-cylinder generator.

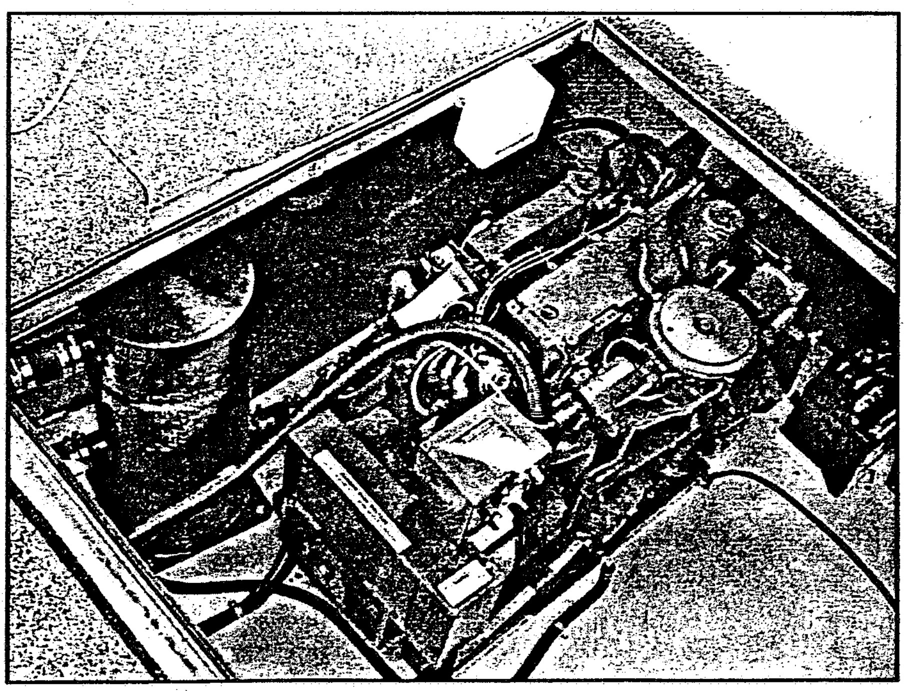


Figure 3. Photo of short exhaust stack terminating just below upper deck.

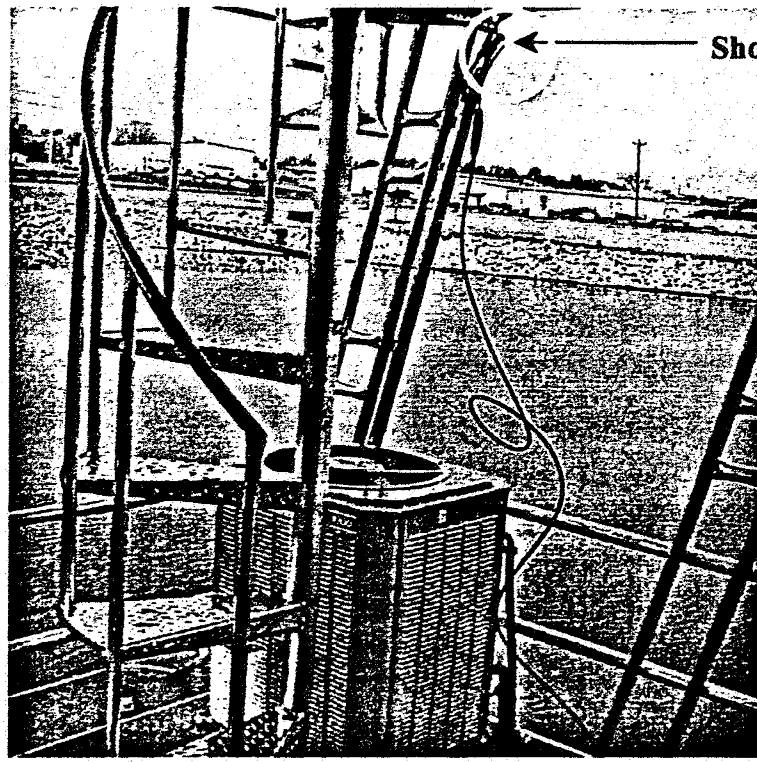


Figure 4. Photo of tall exhaust stack terminating 7 feet above upper deck.

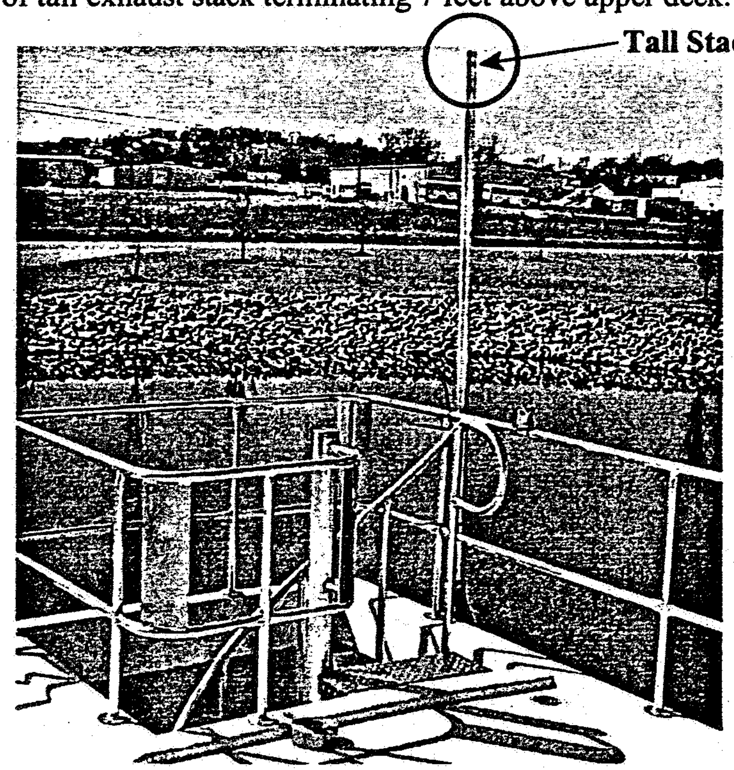


Figure 5. Sampling locations on the lower rear deck of the houseboat.

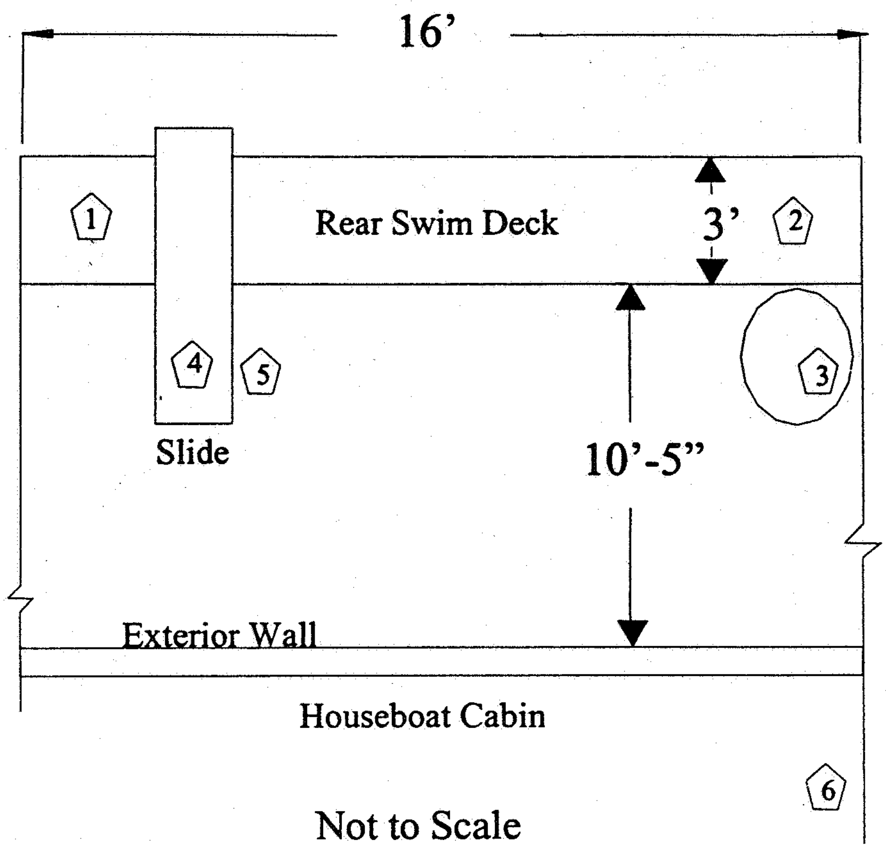
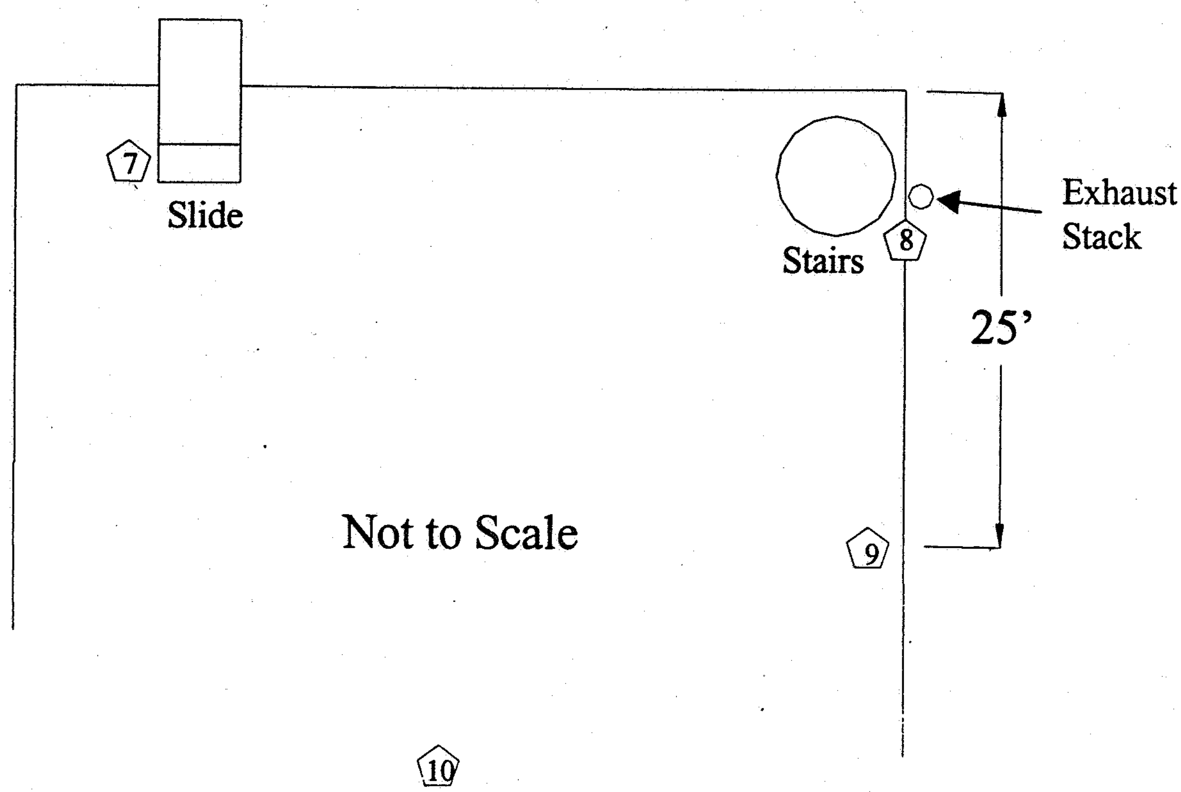


Figure 6. Sampling Locations on the upper deck of the houseboat.



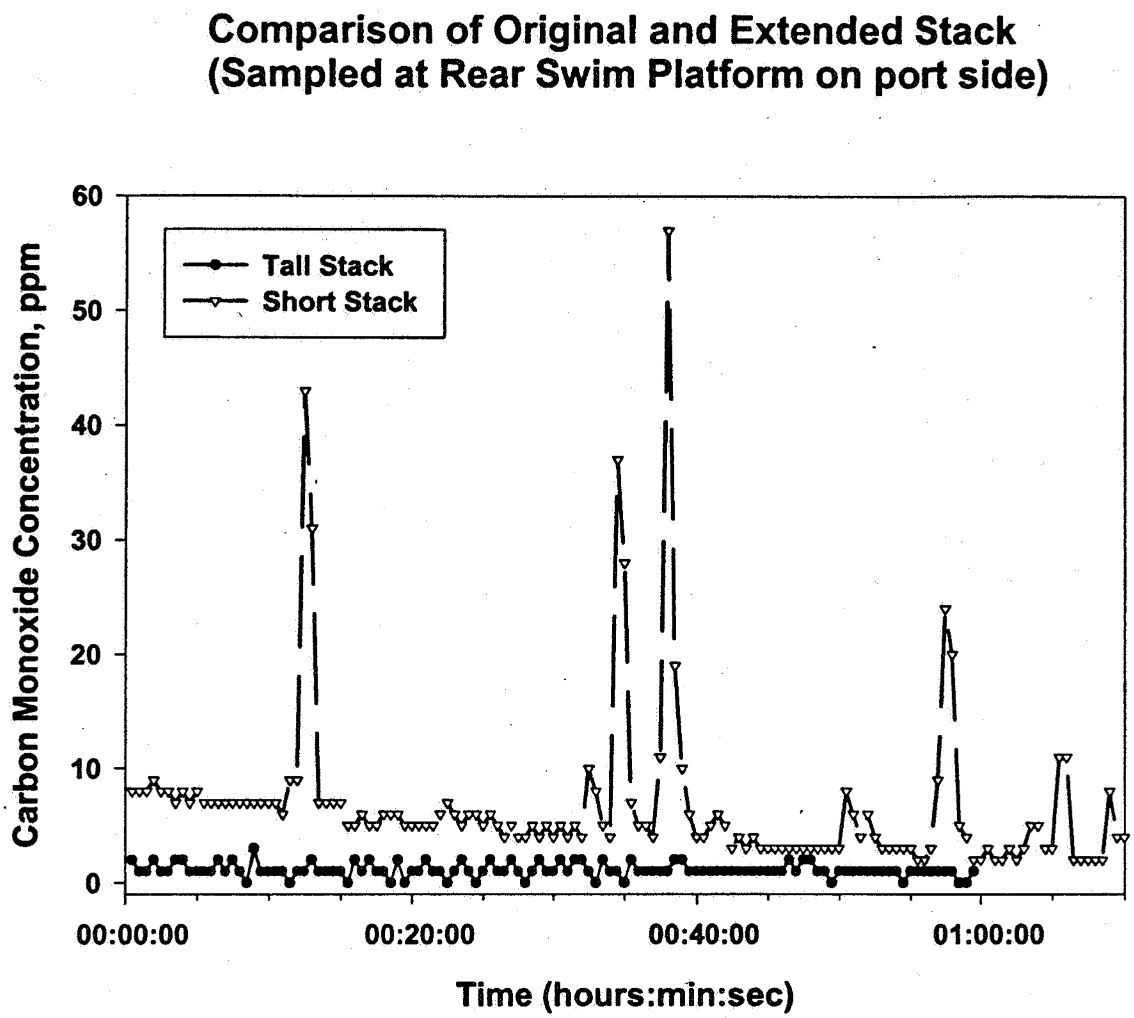


Figure 7. Comparison of short and tall stack exhaust configuration (on rear swim platform--Sample # 2).

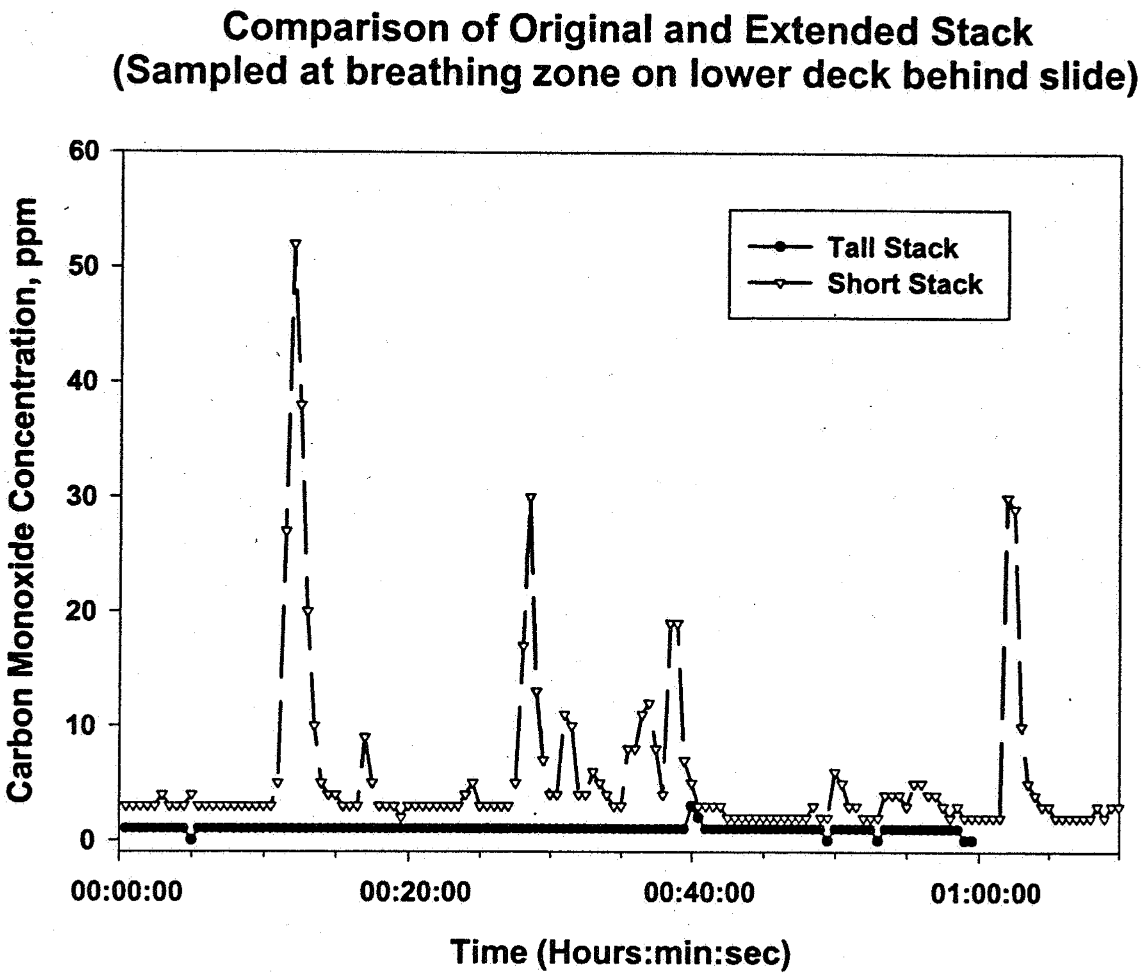


Figure 8. Comparison of short and tall stack exhaust configuration (at BZ height on lower deck behind slide-- Sample # 4).

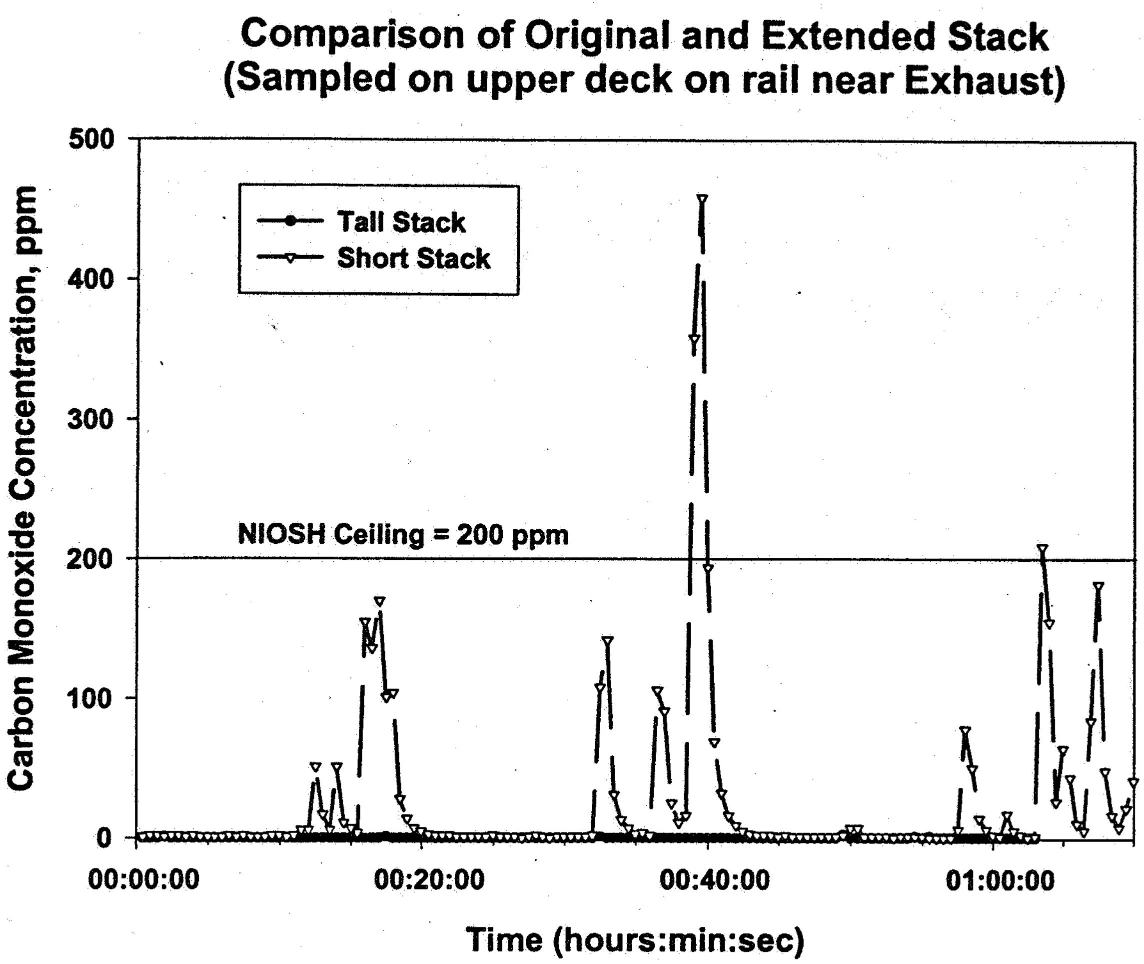


Figure 9. Comparison of short and tall stack exhaust configuration (on upper deck near stairs--Sample # 8).

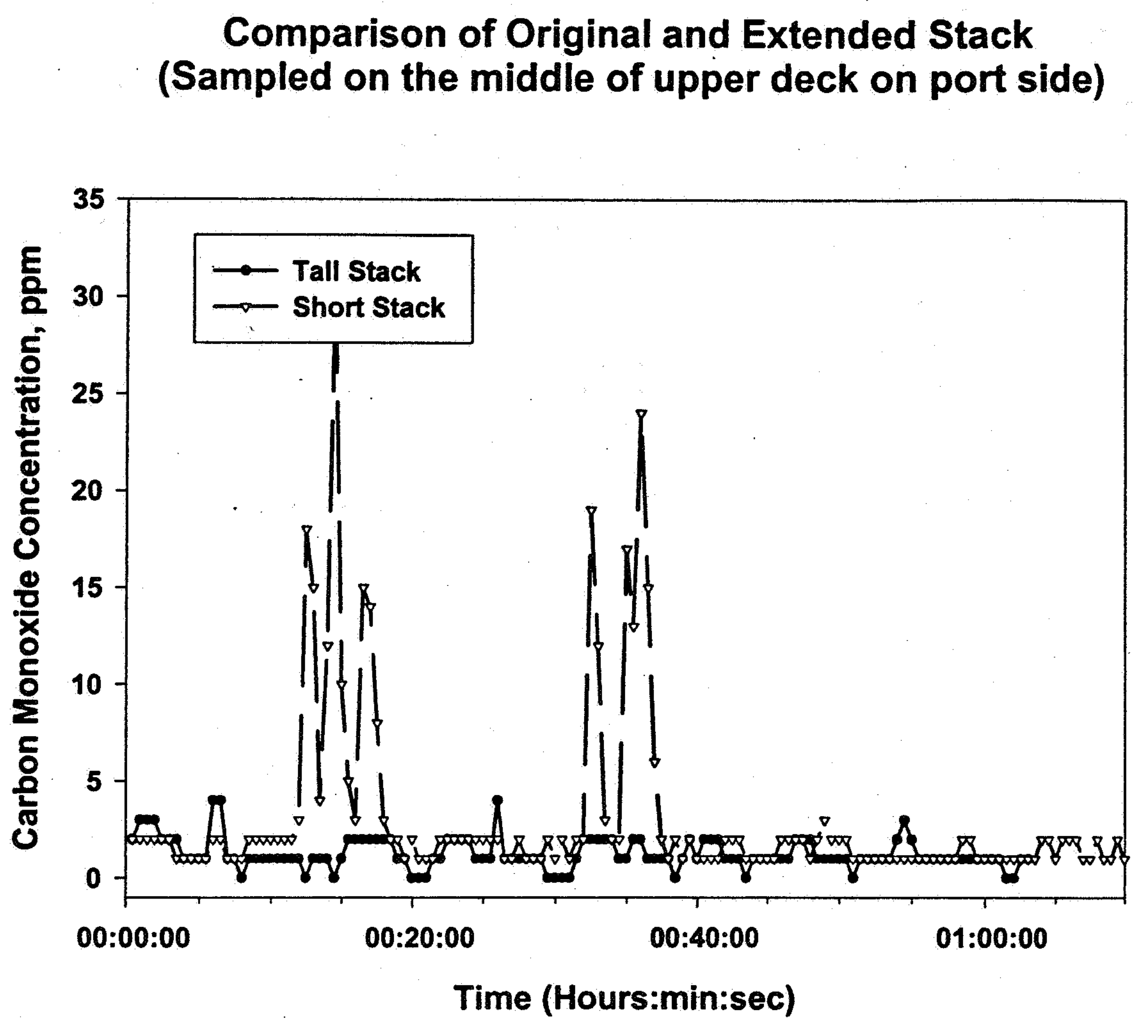


Figure 10. Comparison of short and tall stack exhaust configuration (on middle of upper deck-- Sample # 9).

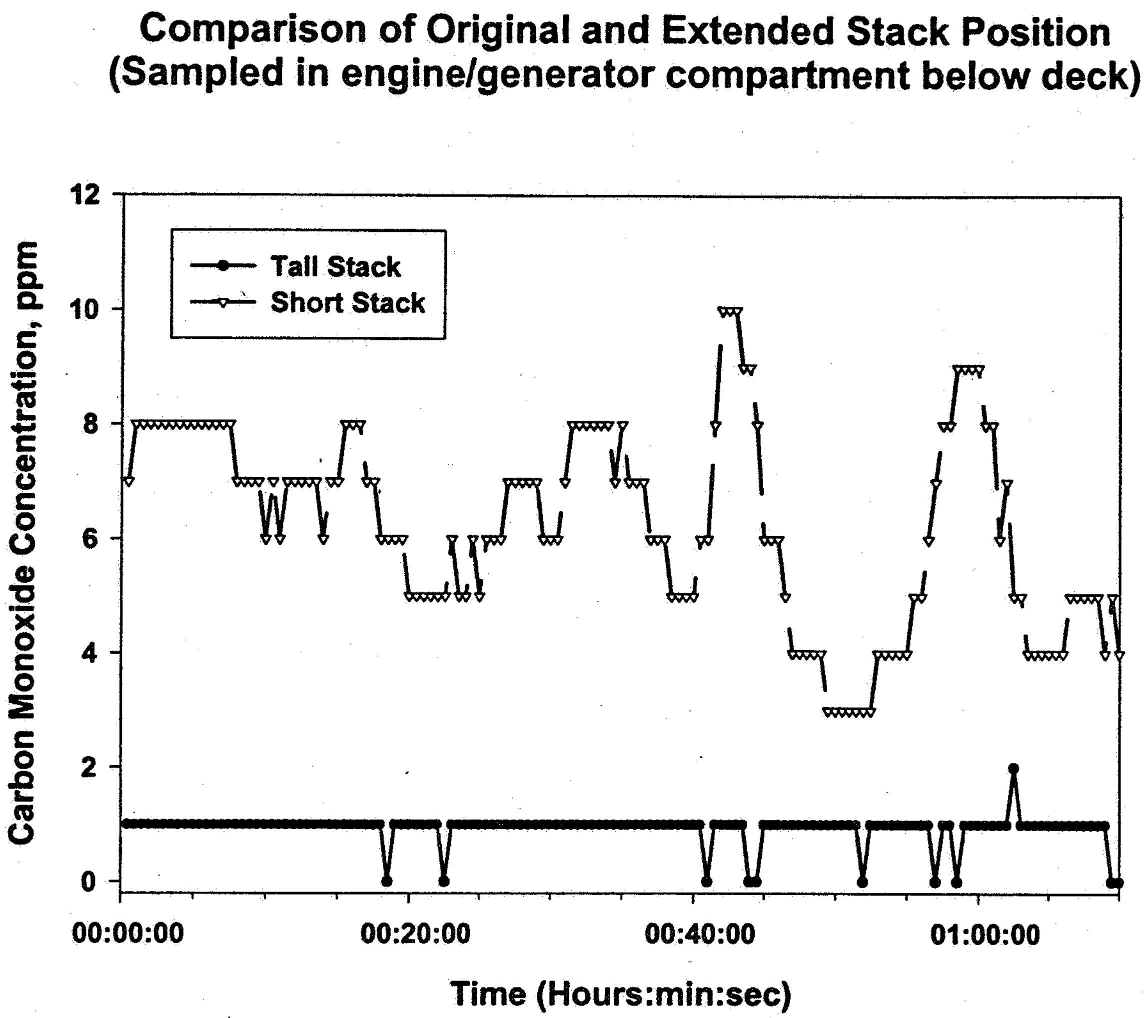


Figure 11. Comparison of short and tall stack exhaust configuration (in airspace beneath the rear deck–Sample #5).

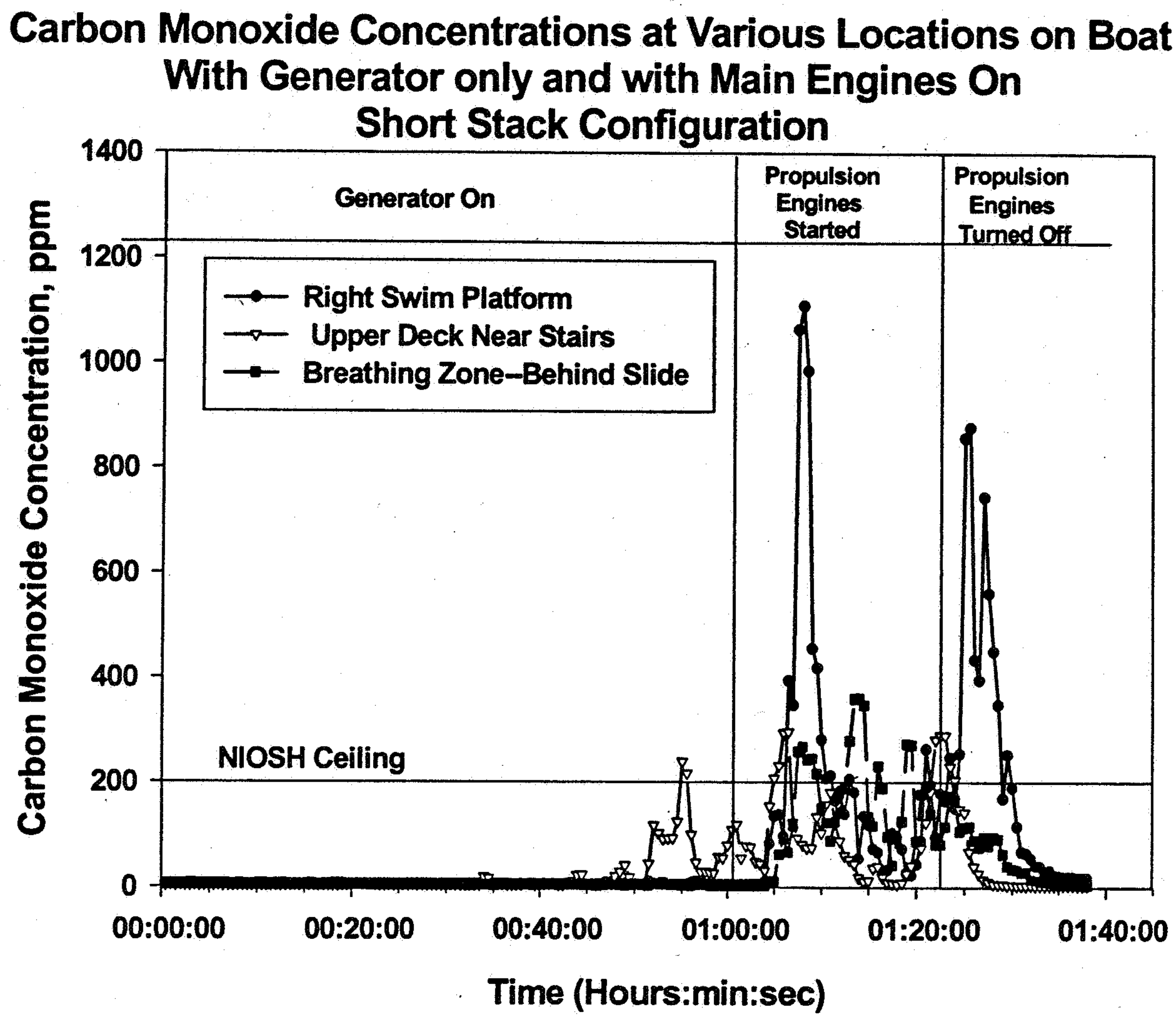


Figure 12. Comparison of CO concentrations at various locations with generator only and main engines on/off.

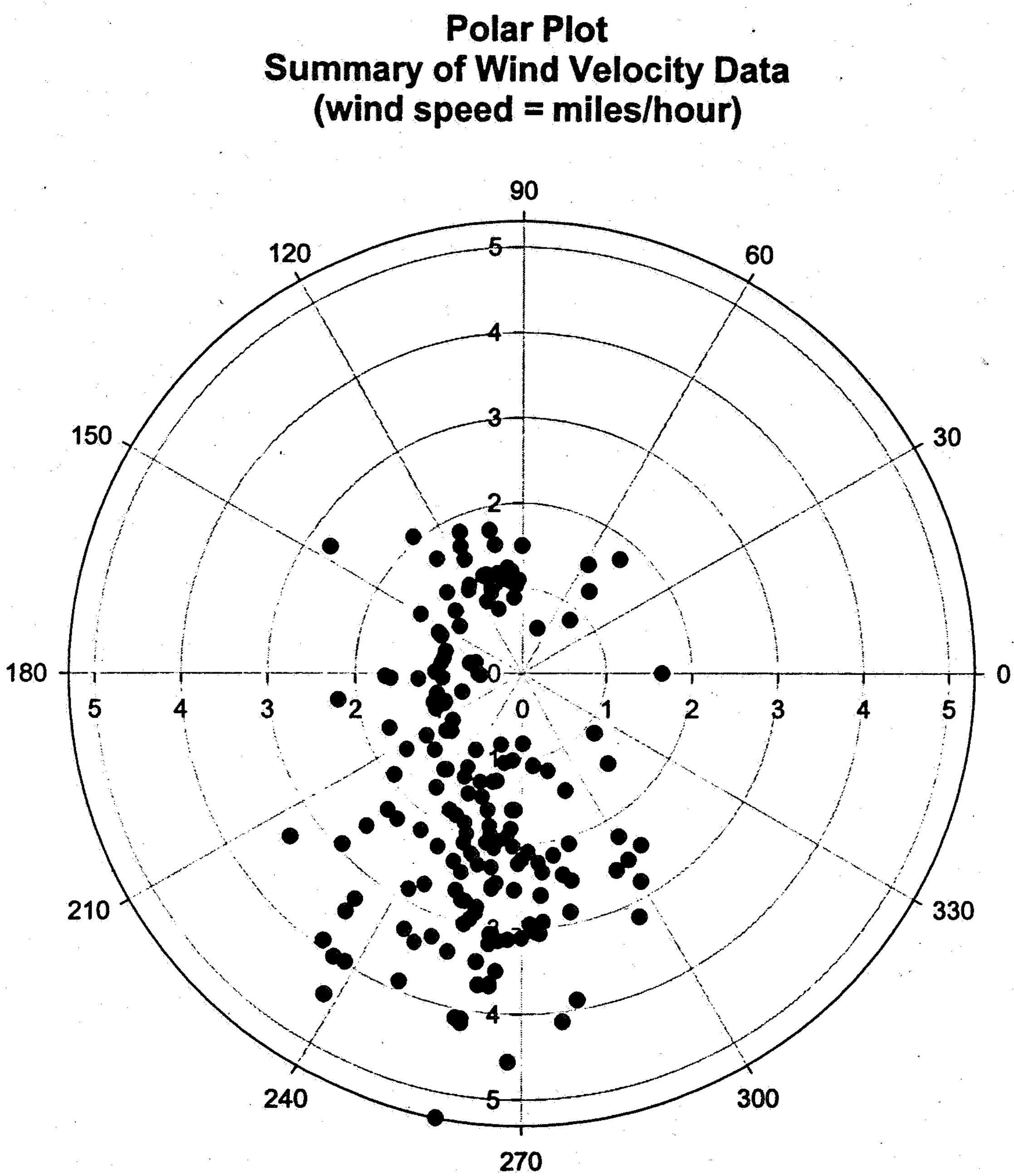


Figure 13. Summary of wind velocity data (in miles per hour).