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

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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 64 of these poisonings were attributable to generator exhaust alone. Seven of the 74 houseboat-related CO poisonings resulted in death. Many of the CO poisonings that have been reported occurred to the general public; however, some poisonings incidents and relatively high CO exposures have involved workers performing maintenance activities on houseboats. The National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of an engineering control retrofitted onto a gasoline-powered, generator on a houseboat to reduce the hazard of CO poisonings from the exhaust. The control consisted of a water separator and 17 foot long exhaust stack that extended 9 feet above the upper deck of the houseboat. When compared to no engineering control, results of the evaluation indicated that use of an exhaust stack provides a dramatically safer environment to individuals on or near the houseboat. CO concentrations were reduced by ten times or more at numerous locations on the houseboat. Average CO concentrations near the rear swim deck of the houseboat, an area where occupants frequently congregate, were reduced from an average of 606.6 ppm to 2.85 ppm, a reduction greater than 99%. CO concentrations were also reduced on the upper deck of the houseboat. Based upon the results of this study, NIOSH investigators recommend that all U.S. houseboats, using gasoline-powered generators, should be retrofitted with an exhaust stack that extends well above the upper deck, in order to reduce the hazard of CO poisoning and death to individuals on or near the houseboat.

Background

On February 6 through 8, 2001, the National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of an engineering control retrofitted onto a houseboat generator. The control, which consisted of a water separator and 17 foot exhaust stack, was retrofitted on to an existing generator that had been exhausting under the lower rear deck of the houseboat. The stack was designed to redirect the generator exhaust away from individuals on or near the houseboat in order to prevent carbon monoxide (CO) poisonings from the exhaust. The evaluation was conducted at Lake Powell, Arizona, which is in the U.S. National Park Service (USNPS) Glen Canyon National Recreational Area (GLCA). This report provides background information, and describes our evaluation methods, results, conclusions, and recommendations.

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 industrial hygiene air sampling. Extremely hazardous CO concentrations were measured on houseboats at Lake Powell during this visit (McCammon and Radtke 2000). Incident reports provided by the National Park Service revealed seven known houseboat-related CO poisoning deaths on Lake Powell since 1994. Some of these incidents involved numerous poisonings in addition to the deaths reported. Information regarding the fatalities were provided 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 64 of these poisonings were attributable to generator exhaust alone. Seven of the 74 houseboat- related CO poisonings resulted in death (McCammon, Radtke et al. 2001).

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.

A second investigation was conducted in October 2000 to gather additional CO concentration data on various types of houseboats at Lake Powell (Hall and McCammon 2000) and at Lake Cumberland (Hall 2000).

Carbon Monoxide 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).

The altitude of Lake Powell is 3,500 feet. Altitude effects the toxicity of CO. With 50 ppm CO in the air, the COHb level in the blood is approximately 1% higher at an altitude of 4,000 feet than at sea level. This occurs because the partial pressure of oxygen (the gas pressure causing the oxygen to pass into the blood) at higher altitudes is less than the partial pressure of CO. Furthermore, the effects of CO poisoning at higher altitudes are more pronounced. For example, at an altitude of 14,000 feet, a 3% COHb level in the blood has the same effect as a 20% COHb at sea level. However, the CO concentrations measured on houseboats at Lake Powell and at Lake Cumberland were clearly sufficient to cause severe health effects regardless of the altitude at which the boat was operated.

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). U.S. National Park Service and houseboat rental employees should be in a state of health typical of any industrial worker. Thus, occupational criteria for CO exposure are applicable to that group. However, 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. 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

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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[7]) Threshold Limit Values (TLVs[7]) recommends an 8-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 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 one-hour average (EPA 1991). The NAAQS for CO was established to protect Athe 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 Equipment (Anytown, Michigan) Model 5000 Four Gas Emissions Analyzer. This analyzer measures CO, carbon dioxide (CO_2), hydrocarbons, and oxygen. All measurements are expressed as percentages except hydrocarbons which is ppm. [One percent of contaminant is equivalent to 10,000 ppm.] Air contaminants in the space were determined first with only the generator operating and then with the generator and boat engines operating simultaneously.

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 500 ppm with the highest instantaneous reading of between approximately 1,000 and 1,200 ppm.

CO concentration data was also collected with detector tubes [Draeger A.G. (Lubeck, Germany) CO, CH 29901B range 0.3% (3,000 ppm) to 7% (7,000 ppm)] in the areas below and near the rear swim deck. The detector tubes are used by drawing air through the tube with a bellowsBtype 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) 50BmL 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 waxBimpregnated MSHA caps. The samples were then sent by overnight delivery 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 to the engine compartment was evaluated by visual inspection and 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 inlets to the engine compartment, and at the stack exhaust. The total flow rate was obtained by averaging the air velocity measurements and determining the cross-sectional area of the ventilation system where the air velocity measurements were made.

Description of the Evaluated Lakeview Houseboat and Engineering Control

CO samples were collected on a five bedroom, Lakeview houseboat built in 1999 (Figure 1) having the specifications listed below.

Engines: 2 Mercruiser 4.3 liter V-6, 190 horsepower (hp) carburated engines, propellor shaft exhaust
Generator: 12.5 Kw/ 27 hp Westerbeke, 4 cylinder, 4 stroke, 1,800 rpm, 79.1 in^3
Approximate dimensions of houseboat: 75' X 16'
Approximate dimensions of space below deck: 4' X 16' X 1.5'
Exhaust Configuration: 1) Engines exhausted below the rear swim deck; and 2) generator exhausted either below the rear swim deck (referred to in this report as Awithout the stack@) or through a stack exhausting 9 feet above the upper deck

Two inboard Mercruiser 4.3 liter, V-6, engines were used to provide propulsion for the houseboat. These engines were housed in compartments beneath the rear swim deck of the houseboat. Access could be gained to the engines through two large doors in the floor of the rear deck (Figure 2). These engines exhausted through their propellor shaft beneath the water. A picture of one of the engines is shown in Figure 3.

The generator on this houseboat (Figure 4) 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 79.1 cubic inches (in^3). This engine is similar in size to engines that are used on small cars. Westerbeke generators are used on nearly 75% of houseboats in the U.S. (Westerbeke 2001).

The hot exhaust gases from this generator are injected with water near the end of the exhaust manifold in a process commonly called Awater-jacketing.@ Water-jacketing is used for cooling and noise reduction prior to exiting the discharge of the engine. Because the inboard engines sit 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 beneath the swim platform.

The original exhaust system was modified to reroute the generator exhaust approximately 9 feet above the upper deck of the houseboat to prevent the buildup of hazardous concentrations of CO near the boat=s lower, rear deck. An 18 foot long, schedule 40 aluminum pipe, having a 2-inch outside diameter and 1.5-inch inside diameter was used for the stack (Figure 5). NIOSH researchers were informed that this relatively thick and heavy pipe, was the only thing available in Page, Arizona, at the time of construction. To allow the pipe to pass from beneath the lower swim deck to 9 feet above the upper deck, a hole was made in the rear corner of the transom which the 2 inch pipe passed through. A Gensep[7] water/exhaust separator (Centek Industries, Thomasville, GA) was installed between the muffler and the stack, to separate the exhaust gases from the water using the force of gravity. This separator is commonly used on some houseboats and other types of boats to further reduce noise related to water surges from the lift muffler. A diagram of this system is shown in Figure 6.

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. The current system was designed and installed by Lake-Time Houseboats, Page, Arizona, and Larry=s Marine, Page, Arizona.

Representatives from Lake-Time Houseboats estimated that the evaluated system would cost between $500 and $1,000 to retrofit to the houseboat while in the water and between $1,000 and $1,500 if it was necessary to remove the boat from the water and perform the installation. The evaluated houseboat=s original purchase price was between $200,000 and $250,000. It is common for Lake-Time Houseboats to sell their boats to as many as ten different owners who will pay $45,000 each and $1,000 per year maintenance fees.

In addition to the Westerbeke generator, the evaluated houseboat had a Freedom marine inverter system (Heart Interface Corp., Kent, WA) that provided AC power and DC battery charging that allowed operation of many of the appliances on the houseboat (except the air conditioner) for up to 8 hours off batteries rather than the generator. There were numerous CO warning signs and CO detectors located at various locations on the houseboat. One CO detector manufactured by Xintex Corp. (Grand Rapids, MI), was hardwired into the houseboat=s electrical system. The other detectors, manufactured by Nighthawk Corp., were plugged into various electrical outlets.

Description of Procedures

During the evaluation, the generator alone operated for approximately 30 minutes followed by both motors and the generator operating for another 15 minutes. This 45-minute sequence constituted one complete run. Data was collected for six separate runs, in which half were evaluated with the generator exhausting through the exhaust stack 9 feet above the upper deck. The other half were evaluated with the generator exhausting under the rear swim deck. When they were operated, both Mercruiser[7] engines exhausted beneath the rear swim deck of the houseboat.

Previous reports have shown that gasoline-powered marine engines that have restricted air flow to the engines can have dramatically higher concentrations of CO in the exhaust (Ferguson 1986; Simeone 1990). A test was performed to evaluate whether the current design for providing fresh air flow to the engine compartment had any effect on generator exhaust. This was accomplished by comparing CO concentrations emitted from the generator when drawing air through the three small ports in the lower, rear deck with CO concentrations when drawing air through the two large door openings (over 2 feet wide by 3 feet long) providing access to the engine compartment.

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 7 and 8. 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, three monitors were evenly spaced across this structure (Figure 9).

Real-time monitoring results for CO concentrations at various locations on the houseboat are presented in Figures 10 through 16. Figures 10 through 14 provide a comparison of CO concentrations on the houseboat when the generator exhausted through the stack and when it exhausted under the rear swim deck. Figures 15 and 16 provide a comparison of CO concentrations at multiple locations on the houseboat simultaneously, with and without the stack. The following summarizes the reduction in CO concentrations at various locations on the houseboat by exhausting the generator through the stack as compared to when the generator exhausted under the rear swim deck:

- CO concentration on the center of the rear swim platform (Figure 7, Sample 2): On average, CO concentrations were reduced from 606.6 to 2.85 ppm. This is a reduction of approximately 99.5%.

- CO concentration on rear swim deck near wall separating rear deck and cabin (Figure 7, Sample 7): On average, CO concentrations were reduced from 62.5 to 5.45 ppm. This is a reduction of approximately 91.4%.

- CO concentration on the upper deck near the slide (Figure 8, Sample 10): On average, CO concentrations were reduced from 13.8 to 2.22 ppm. This is a reduction of approximately 83.9%.

- CO concentration on the upper deck near the stairs (Figure 8, Sample 11): On average, CO concentrations were reduced from 14.36 to 1.79 ppm. This is a reduction of approximately 87.5%.

Area Samples on the Lower Level, Rear Deck of Boat

The CO monitor placed at the center of the rear swim platform (Figure 7, Sample 2) indicated an average CO concentration of 2.85 ppm and a peak of 13.0 ppm with the generator operating and the stack connected. This same sample indicated an average of 606.61 ppm and a peak greater than 1,200 ppm when the generator exhausted under the rear swim deck. These results are shown in Figure 10.

Similarly, the monitor located near the wall separating the rear deck from the cabin (Figure 7, Sample 7) indicated an average CO concentration of 5.44 ppm and a peak of 15.0 ppm with the generator operating and the stack connected. This same sample indicated an average of 62.55 ppm and a peak of over 281 ppm when the generator exhausted under the rear deck. Figures 11 and 12 show results of the monitor located beneath the slide (Figure 7, Sample 4) and on the rear swim platform opposite the stack (Figure 7, Sample 3). In both cases, the CO concentrations were dramatically different with peak concentrations near baseline when exhausting the generator through the stack versus the highest peak concentrations between 400 and 1,200 ppm when exhausting under the rear deck. In virtually all samples evaluated on the rear lower deck, concentrations were dramatically worse when the main engines were started, and the houseboat remained stationary. This is shown by looking at what occurs on the right side of the graphs. On the rear lower deck, concentrations rapidly exceeded the NIOSH IDLH concentration of 1,200 ppm. The results of other samples collected on the lower level rear deck are shown in Table 1.

Area Samples on Upper Deck of Boat

The CO monitor placed on the upper deck near the slide (Figure 8, Sample 10) indicated an average CO concentration of 2.22 ppm and a peak of 7.0 ppm with the generator operating and the stack connected. This same sample indicated an average of 13.8 ppm and a peak of 93.0 ppm when the generator exhausted under the rear deck. These results are presented in Figure 13. The monitor located on the upper deck near the stairs (Figure 8, Sample 11) indicated an average CO concentration of 1.79 ppm and a peak of 16.0 ppm with the generator operating and the stack connected. This same sample indicated an average of 14.36 ppm and a peak of 72.0 ppm when the generator exhausted under the lower rear deck. These results are shown in Figure 14. It is interesting to note that although the upper deck is closer to the stack exhaust than the lower deck, the CO concentrations are still lower on the upper deck when the generator exhausts through the stack than when it does not. The results of other samples collected on the upper deck are shown in Table 2.

Figure 15 provides data showing how CO concentrations at various locations changed with time as the generator (exhausting through the stack) and later both the generator (exhausting through the stack) and main engines (exhausting through the propellor shaft) were operated. In contrast, Figure 16 provides data showing how CO concentrations at various locations changed with time as the generator (exhausting under the lower, rear deck) and later both the generator (exhausting under the lower, rear deck) and main engines (exhausting through the propellor shaft) were operated. These two graphs clearly show that the most hazardous location is the rear swim platform near the water; however, in Figure 15, 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. During this study, the rear of the boat was oriented to the West on an azimuth of approximately 260 degrees with respect to magnetic North, and the boat was stationary. Wind speeds were relatively low with an average wind speed of approximately 0.60 m/sec (118.1 ft/min) and a standard deviation of 0.26 m/sec (Figure 17). Although wind direction changed periodically, on average, it was in a Northeastern direction (338.05 degrees with respect to magnetic North: where magnetic North = 360 degrees). Based upon boat orientation, the wind direction was likely to move CO in the direction of the boat after it was exhausted.

Statistical Analysis of Air Sampling Results

The water separator and exhaust stack that was retrofitted onto the houseboat had a statistically significant effect on reducing CO concentrations at various locations on the boat when compared to exhausting under the lower rear deck. Air sampling data, collected when the generator operated with and without the stack, were compared using a t-test.

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

Gas Emissions Analyzer, Detector Tubes, and Evacuated Container Results

The gas emissions analyzer, detector tubes, and glass evacuated containers were used to characterize CO concentrations near the exhaust stack and under the lower, rear deck. These instruments were utilized because they are capable of reading higher CO concentrations than the Toxiultra CO monitors which has an upper limit of between 1,000 and 1,200 ppm. When measuring exhaust from the stack, the probe of the emissions analyzer was placed approximately 4 inches beyond the terminus of the exhaust stack.

Measurement taken with the gas emissions analyzer near the exhaust stack of the generator indicated CO concentrations in the range of 1.68% (16,800 ppm) to 5.53% (55,300 ppm). Measurements taken in the space below the lower, rear deck with the gas emissions analyzer indicated CO concentrations in the range of 0.27% (2,700 ppm) to 0.49% (4,900 ppm) with the generator running and exhausting under the deck. A detector tube sample taken in this space indicated a CO concentration of 0.3% (3,000 ppm)

When the generator and motors were in operation the gas emissions analyzer indicated CO concentrations in the range of 0.28% (2,800 ppm) to 3.85% (38,500 ppm) in the space below the swim platform. The gas emissions analyzer also indicated that the area under the swim platform was oxygen deficient (14.4% O_2) during the time period when the generator and motors were running.

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

Effect of Air Supply to Engine Compartment

Measurements were taken at inlets to the engine compartment while the generator was operating and while both the generator and main engines were operating. Air was supplied to the engine compartment through three separate ports in the lower deck of the houseboat (Figure 18). Each of these ports had a cross-sectional area of approximately 0.0447 square feet (ft^2) for a total cross-sectional area of 0.134 ft^2. Average air flow to the engine compartment when the generator was idling was 6.34 cubic feet per minute (cfm) with a standard deviation of 2.80 cfm. Average air flow to the engine compartment when both the generator and main engines idling was 21.47 cfm with a standard deviation of 3.65 cfm.

The average CO concentration of five samples emitted when the generator drew air through the three small ports was 5.56% with a standard deviation of 0.188%. The average CO concentration of five samples emitted when the generator drew air through the large doors was 5.17% with a standard deviation of 0.136%. This is a reduction of approximately 7%. A t-test was used to compare the data and indicated that the CO concentrations were statistically significantly lower ($p = 0.006$; alpha $=0.05$) when the generator drew air through the large doors than through the small ports.

Discussion and Recommendations

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 high above the upper deck of the houseboat. Exhausting the generator in this location, allows the contaminants to diffuse and dissipate into the atmosphere away from boat occupants.

The evaluated houseboat had a gasoline-powered, Westerbeke generator that provided electrical power for the on-board appliances. When this generator 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% CO (1,000 to 100,000 ppm). Engines operating at full-rated horsepower (hp) will produce exhaust gases having approximately 0.3% CO (3,000 ppm) (Heywood 1988).

The relative amounts of CO produced from gasoline-powered engines depend upon engine design, operating conditions, and most importantly the fuel/air equivalence ratio (Plog 1988). The fuel/air equivalence ratio is the actual fuel to air ratio divided by the stoichiometric fuel to air ratio. Simeone predicted CO concentrations exhausted from marine engines as a function of air inlet and several other parameters (Simeone 1990). Because there are so many factors that influence the CO concentration exhausting from the engine, the location of the exhaust is critical to prevent persons on or near the houseboat from being poisoned.

The EPA is currently phasing in emissions standards between 1998 and 2006 to reduce hazardous emissions from gasoline and diesel marine engines; however, these changes will only help to reduce but not eliminate this problem (EPA 1999). Incremental reductions in CO emissions by modifying engine design or operating parameters may slow the CO generation rate. However, these measures will not eliminate CO exposure and poisonings. Likewise, CO is also produced from engines operating on alternative fuels, such as diesel and liquified petroleum gas (LPG). If engines running on alternative fuels are not properly adjusted, hazardous CO concentrations can be produced.

This and previous NIOSH investigations on houseboats that exhaust generator combustion gases beneath or near the rear deck have shown that extremely hazardous CO concentrations accumulate in the space beneath the rear deck and near the rear swim platform when the generator is operated. These hazardous conditions are exacerbated when the main engines are operating. CO concentrations in this area measured with three separate methods (i.e., real-time instruments, evacuated containers, and detector tubes) indicated concentrations well above the NIOSH IDLH value of 1,200 ppm. 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 experience CO poisoning or death within a short period of time.

The area on the lower, rear deck of the houseboats is also a concern. 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 is substantiated by the CO poisonings and deaths that have been reported in this area of the boat. During this evaluation, CO measurements obtained in this area indicated that CO concentrations could reach or exceed 1,200 ppm. CO measurements obtained on the top deck of the houseboat, with peaks up to 183 ppm, were a concern, but were considerably less than those on the lower, rear deck.

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

1) All manufacturers/owners/users of U.S. houseboats that use gasoline-powered generators should be aware of and concerned about the location of the exhaust terminus. The data collected in this evaluation show that an exhaust stack, vented 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 previous 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. The current system was very effective at reducing CO concentrations on the boat; however, houseboat manufacturers will need to do some development work to determine the optimum stack height and size as well as selecting the appropriate water separator. The evaluated system consisted of schedule 40 pipe which is unnecessarily thick, but was the only material available in Page, Arizona, at the time of construction. Size of the pipes may change slightly based upon the size of the generator and configuration of the houseboat.

3) The cavity beneath the swim platform should be modified by keeping the area under positive pressure to prevent the buildup of hazardous CO concentrations from the main engines.

4) 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.

5) Further work should be performed to evaluate the adequacy of air supply to the engine compartment. Although this problem will not eliminate the CO hazard, it will help to incrementally reduce the CO concentrations emitted from the engine.

6) Additional research and development work should be performed by marine engine manufacturers to evaluate the efficacy of using catalytic converters or other pollution control devices on generators that are used on houseboats.

7) 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 campaign 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 checkout training provided for users of concessionaire rental boats. These and other educational materials are available at the following web site: **http://safetynet.smis.doi.gov/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 target warnings 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.

References

ACGIH (1996). Documentation of Threshold Limit Values and Biological Exposure Indices. Cincinnati, OH, American Conference of Governmental Industrial Hygienists.

CDC (1988). MMWR 37, supp (S-7) NIOSH Recommendations for Occupational Safety and Health Standards. Atlanta, GA, Dept. of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

CFR (1997). 29 CFR 1910.1000, Chapter XVII - Occupational Safety and Health Administration. Code of Federal Regulations, Table Z-1, Limits for Air Contaminants. Washington, D.C: U.S., Federal Register.

CFR (1997). 29 CFR 1910.1000, Code of Federal Regulations. Washington, D.C: U.S., Government Printing Office, Federal Register.

Earnest, G. S., R. L. Mickelsen, et al. (1997). ACarbon Monoxide Poisonings from Small, Gasoline-Powered, Internal Combustion Engines: Just What Is a "Well-Ventilated Area"?@ Am. Ind. Hyg. Assoc. J. **58**(11): 787-791.

Ehlers, J. J., J. B. McCammon, et al. (1996). NIOSH/CDPHE/CPSC/OSHA/EPA Alert: Preventing Carbon Monoxide Poisoning from Small Gasoline-Powered Engines and Tools, U.S. DHHS, PHS, CDC, NIOSH.

EPA (1991). Air Quality Criteria for Carbon Monoxide. Washington, D.C., U.S. Environmental Protection Agency.

EPA (1999). Technical Highlights: Organization of Gasoline and Diesel Marine Engine Emission Standards. Washington, D.C., U.S. Environmental Protection Agency.

Ferguson, C. R. (1986). Internal Combustion Engines. New York, New York, John Wiley and Sons.

Forbes, W. H., F. Sargent, et al. (1945). AThe Rate of CO uptake by Normal Man.@ Am Journal of Physiology **143**: 594-608.

Hall, R. M. (2000). Letter of December 18, 2000 from Ronald M. Hall, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services and to Rice C. Leach, Commissioner, Cabinet for Health Services, Department of Public Health, Commonwealth of Kentucky. Cincinnati, OH, NIOSH**:** Dec. 18, 2000.

Hall, R. M. and J. B. McCammon (2000). Letter of November 21, 2000 from Ronald M. Hall and Jane B. McCammon, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services and to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, Arizona. Cincinnati, OH, NIOSH**:** Nov. 21, 2000.

Heywood, J. B. (1988). Internal Combustion Engine Fundamentals. New York, New York, McGraw-Hill Inc.

Kales, S. N. (1993). ACarbon Monoxide Intoxication.@ American Family Physician **48**(6): 1100-1104.

Kovein, R. J., G. S. Earnest, et al. (1998). CO Poisoning from Small Gasoline-Powered Engines: A Control Technology Solution, U.S. DHHS, PHS, CDC, NIOSH.

McCammon, J. B. and T. Radtke (2000). Letter of September 28, 2000 from J. McCammon, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services and T. Radke, U.S. Department of the Interior, to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, Arizona. Denver, CO, NIOSH.

McCammon, J. B., T. Radtke, et al. (2001). Letter of February 20, 2001 from J. McCammon, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services, T. Radke, U.S. Department of the Interior, and Dr. Robert Baron Prehospital Medical Care, Glen Canyon National Recreation Area, to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, Arizona. Denver, CO, NIOSH.

NIOSH (1972). Criteria for a Recommended Standard: Occupational Exposure to Carbon Monoxide. Cincinnati, OH, National Institute for Occupational Safety and Health.

NIOSH (1977). Occupational Diseases: A Guide to their Recognition. Cincinnati, OH, National Institute for Occupational Safety and Health.

NIOSH (1979). A Guide to Work Relatedness of Disease. Cincinnati, OH, Dept. of Health Education and Welfare, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.

NIOSH (2000). Pocket Guide to Chemical Hazards and Other Databases: Immediately Dangerous to Life and Health Concentrations, DHHS (NIOSH).

Plog, B. A. (1988). Fundamentals of Industrial Hygiene. Chicago, Illinois, National Safety Council.

Proctor, N. H., J. P. Hughes, et al. (1988). Chemical Hazards of the Workplace. Philadelphia, PA, J.P. Lippincott Co.

Simeone, L. F. (1990). A Simple Carbureter Model for Predicting Engine Air-Fuel Ratios and Carbon Monoxide Emissions as a Function of Inlet Conditions. Cambridge, Massachusetts, U.S. Department of Transportation, Research and Special Programs Administration**:** 11.

Westerbeke (2001). Conversation between Dr. G. Scott Earnest of EPHB, DART, NIOSH, and Bryant Carlton, Vice-President of Westerbeke Corporation, February 21, 2001. Avon, Massachusetts.

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

Sample Location (Sample #)	Generator Operating with Stack	Generator Operating without Stack
Rear Swim Platform (#1)	Mean= 9.39 S.D. = 7.46 Peak = 41.0 N = 186	Mean= 456.87 S.D. = 368.79 Peak = 1200.0 N = 111
Mid Rear Swim Platform (#2)	Mean= 2.85 S.D. = 1.88 Peak = 13.0 N = 216	Mean= 606.61 S.D. = 449.31 Peak = 1200.0 N = 116
Rear Swim Platform (#3)	Mean= 1.28 S.D. = 0.54 Peak = 3.0 N = 71	Mean= 242.91 S.D. = 153.73 Peak = 653.0 N = 54.0
Beneath Slide (#4)	Mean= 4.75 S.D. = 2.73 Peak = 21.0 N = 123	Mean= 41.61 S.D. = 44.95 Peak = 304.0 N = 181
Near exterior wall (#7)	Mean= 5.45 S.D. = 2.37 Peak = 15.0 N = 194	Mean= 62.55 S.D. = 59.11 Peak = 281.0 N = 178
Inside Cabin, lower level (#9)	Mean= 8.18 S.D. = 6.48 Peak = 35.0 N = 190	Mean= 44.50 S.D. = 28.80 Peak = 99.0 N = 178

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 without Stack
Near Slide (#10)	Mean= 2.22 S.D. = 2.09 Peak = 7.0 N = 192	Mean= 13.80 S.D. = 17.76 Peak = 93.0 N = 178
Near Stairs (#11)	Mean= 1.79 S.D. = 1.92 Peak = 16.0 N = 195	Mean= 14.36 S.D. = 15.49 Peak = 72.0 N = 178
13 feet from slide (#12)	Mean= 2.28 S.D. = 3.56 Peak = 20.0 N = 182	Mean= 8.62 S.D. = 24.58 Peak = 183.0 N = 167
Near canopy (#15)	Mean= 2.57 S.D. = 3.95 Peak = 25.0 N = 99	Mean= 8.38 S.D. = 10.92 Peak = 42.0 N = 97