AN EVALUATION OF AN EMISSION CONTROL DEVICE, EXHAUST STACK, AND INTERLOCK TO PREVENT CARBON MONOXIDE POISONINGS OF INDIVIDUALS ON HOUSEBOATS

G. Scott Earnest, Ph.D., P.E., C.S.P.
Kevin H. Dunn, M.S.E.E.
Ronald M. Hall, M.S.
Jane B. McCammon, M.S., C.I.H.
Rob McCleery, M.S.
Aaron Jones

REPORT DATE:
August 2001

REPORT NO.:
EPHB 171-27a

FIGURES PREPARED BY:
Daniel S. Watkins

MANUSCRIPT PREPARED BY:
Bernice L. Clark

U.S. Department of Health and Human Services
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Division of Applied Research and Technology
4676 Columbia Parkway, MS - R5
Cincinnati, Ohio 45226

Plant Surveyed:	Callville Bay Marina Boulder City, Nevada
SIC Code:	N/A
Survey Dates:	June 18-21, 2001
Employer Representatives Contacted:	John Stenseth, General Manager Fun Country Marine Industries, Inc.
Employee Representatives Contacted:	None
Manuscript Prepared by:	Bernice L. Clark

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

Researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of several engineering control devices that were retrofitted onto gasoline-powered, generators on houseboats to reduce the hazard of CO poisonings from the exhaust. This evaluation was part of a series of studies conducted by NIOSH investigators during the past year to document hazardous CO concentrations on houseboats and evaluate and recommend appropriate engineering controls to reduce the CO hazard and eliminate CO poisonings. The evaluated engineering controls consisted of a recently developed emissions control device (ECD), an interlock, and an exhaust stack that extended 9 feet above the upper deck of the houseboat. Results provided in this report address the performance of the ECD, the interlock system, and the ECD with the exhaust stack used in series on a single houseboat. Additional data and details concerning the performance of the exhaust stack alone are provided in a separate report.

When compared to the generator having no engineering controls exhausting under the rear swim deck, results of the current evaluation indicated that use of these control systems provide a safer environment to individuals on or near the houseboat. Data gathered while the ECD was operating indicated that mean and peak CO concentrations were reduced by two to three orders of magnitude 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 395 ppm to less than 1 ppm, a reduction greater than 99%. CO concentrations were also greatly reduced on the upper deck of the houseboat. A five gas emissions analyzer indicated that mean CO concentrations in the generator exhaust were reduced by several orders of magnitude (from 4,534 ppm to approximately 13 ppm). The evaluated interlock was capable of shutting down the generator when the swim ladder was placed into the water, and the hazardous CO concentrations near the lower rear deck dissipated within two or three minutes.

Based upon the results of this study, NIOSH investigators recommend that all U.S. houseboats using gasoline-powered generators, should be retrofitted with engineering controls to reduce the hazard of CO poisoning and death to individuals on or near the houseboat. The performance of the evaluated ECD was excellent; however, some additional testing and evaluation of this device is warranted. The interlocking system performed as designed and could help to reduce some CO poisonings; but, this system has significant limitations that prevent it from being used as a primary control.

BACKGROUND

On June 18 through 21, 2001, the National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of several different engineering controls retrofitted onto houseboat generators. The evaluated controls included an emission control device (ECD), an exhaust stack, and an interlock that were designed to prevent carbon monoxide (CO) poisonings from the generator exhaust. Performance of the ECD, the interlock, and the ECD with an exhaust stack used in series are described in this report. Additional data and details concerning the performance of the exhaust stack alone and side exhaust are provided in a separate report (Dunn, Earnest et al. 2001). The evaluation was conducted at Callville Bay Marina on Lake Mead, Nevada. 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.

Further investigations were 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). An engineering control study began in February 2001 at Lake Powell and Somerset, Kentucky, (Dunn, Hall et al. 2001; Earnest, Dunn et al. 2001). Results from the data gathered during the engineering control evaluations at Lake Powell and Somerset, Kentucky, indicated that an exhaust stack extending 9 feet above the upper deck of the houseboat was capable of dramatically reducing the CO concentrations on and near the houseboat and provided a dramatically 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. The meeting was attended by houseboat manufacturers, marine product manufacturers, government representatives, and others interested in reducing this problem. Following the meeting, NIOSH researchers were asked to evaluate the performance of the ECD and interlock and to conduct further evaluations of the dry stack.

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).

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. 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 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 as 1,200 ppm (NIOSH 2000). The American Conference of Governmental Industrial Hygienists' (ACGIH®) recommends and 8-hour TWA threshold limit values (TLVs®) for occupational exposures 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).

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."

METHODS

Air sampling for CO, ventilation, and wind-velocity measurements were collected on two different houseboats built by Fun Country Marine Industries Inc. A photo of one of the evaluated houseboats is shown in Figure 1. The houseboats were approximately 2-3 years old. Data were collected in an effort to evaluate the performance of control systems that had been retrofitted onto the houseboats. A description of the houseboats and engineering controls are provided below:

Description of the Evaluated Houseboats and Engineering Controls

1. **Houseboat #22**

   Engines: 2, 135 horsepower (hp) 4 cylinder, 4 cycle, Volvo engines, with inboard/outboard drives

   Generator: 15 Kw Westerbeke, 4 cylinder, 4 stroke, 1,800 revolutions per minute (rpm), 79.1 cubic inches (in^3)

   Approximate dimensions of houseboat: 65 ft. X 14 ft.

   Approximate dimensions of space below swim platform: 3 ft. X 14 ft. X 1.5 ft.

   Exhaust Configuration: Enviromarine emissions control device (ECD) installed with two options for routing exhaust: 1) Combo-Sep® muffler/gas/water separator to vertical exhaust stack 9 feet above upper deck and port side water drain; or 2) exhaust through emissions control device (ECD), regular muffler and transom; or 3) generator exhaust without ECD through a lift muffler and out through the rear of the transom

2. **Houseboat #20**

   Engines: 2, 135 horsepower (hp) 4 cylinder, 4 cycle, Volvo engines, with inboard/outboard drives

   Generator: 12.5 Kw Kohler, 4 cylinder, 4 stroke, 1,800 revolutions per minute (rpm), 79.0 cubic inches (in^3)

Approximate dimensions of houseboat: 65 ft. X 14 ft.
Approximate dimensions of space below swim platform: 3 ft. X 14 ft. X 1.5 ft.
Exhaust Configuration: 1) Combo-Sep® muffler/gas/water separator to vertical gas exhaust 9 feet above upper deck and port side water drain; or 2) to exhaust through original muffler and transom starboard side

Two inboard Volvo, 4-cylinder engines were used to provide propulsion for the houseboats. These engines were housed in compartments beneath the rear deck of the houseboats. Access could be gained to the engines through a large door in the floor of the rear decks (Figure 2). The engines exhausted through their propellor shafts beneath the water. The evaluated houseboats had a full hull without enclosed spaces beneath the lower rear deck.

The generators on the houseboats provided electrical power for air conditioning, kitchen appliances, entertainment systems, navigation, and communications equipment. The generators were housed in the engine compartment beneath the rear deck near the drive engines. The generators are 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 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 sits 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 on houseboat #22 was modified to route the generator exhaust through an emissions control device (ECD) prior to the waterjacketing process. The ECD was originally manufactured by Unlimited Technologies International Inc (Charlotte, NC) and sold and distributed by Envirolift Inc. (Charlotte, NC). Envirolift Inc. currently sells ECDs for use on gas and propane-powered forklift trucks and other applications to reduce CO generated from engine exhaust. A company was formed from Marysville Marine Distributor's (Goodlettsville, TN) called EnviroMarine Incorporated (Whitehouse, TN) that will begin selling and distributing ECDs for marine applications later this year. Envirolift's product literature states that their ECD for forklift trucks is capable of reducing CO concentrations ten times less than a typical catalytic converter. This device has an estimated useful life of approximately 10,000 hours. Table I provides a comparison of several features of the Envirolift ECD sold for forklift truck applications and a typical catalytic converter (Envirolift 2001).

The ECD uses a ceramic substrate consisting of porous silica coated with two transition metals. The dimensions of the substrate are 4 inches in diameter by 4 inches in length having a volume of 50.27 cubic inches. The ECD uses a washcoat that consists of three different oxidizing agents. The substrate is contained in an outer 16 gauge stainless steel shell with Unifrax Corporation's NV type chemilucent material or intumescent mat to prevent vibration. The ECD is also mounted on rubber grommets to reduce vibration. The dimensions of the outer shell are approximately 11.25 inches long by 5 inches in diameter tapering to 4.5 inches in diameter (CARB 1998).

Exhaust gases exit the generator and pass by a series of baffles to ensure mixing as it enters the ECD. The gases then pass through a high voltage, electrically charged screen (30,000 volts) or "ignitor" made of 14 gauge stainless steel that begins breakdown of the exhaust gases. The gases then move through the base substrate that oxidizes the CO and hydrocarbons and converts them into carbon dioxide, oxygen, and water. Air is pumped into the ECD at a rate of approximately 24 cfm to aid in the post combustion process.

The houseboat was configured so that exhaust gases exiting the ECD could either be released under the lower, rear deck of the houseboat or could be carried through an exhaust stack approximately 9 feet above the upper deck of the houseboat. A photo of the ECD is shown in Figure 3 and a cross-sectional diagram is shown in Figure 4.

A 2-inch nominal, schedule 40 aluminum pipe, having an approximately 2.5-inch outside diameter and 2.0-inch inside diameter was used for the stack. The aluminum pipe was divided into two separate sections: a section between the lower rear deck and the upper deck and a section extending 9 feet above the upper deck. The portion of the stack located above the upper deck sat inside of a coupling that was held together by the weight of the stack. An o-ring was used to prevent leakage between the sections. The lower portion of the stack extended through the lower rear deck and was clamped to a high temperature exhaust hose. This design permitted relatively simple emissions sampling at various locations and more importantly could be used to easily remove the stack when the houseboat is being transported or shipped.

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 lower rear port-side engine compartment and the rear port-side of the upper deck which the pipe passed through. The original lift muffler was removed, and a Combo-Sep® muffler/gas/water 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 6 inches below the water line to reduce back pressure which could force some water up the stack. Finally, the exhaust hose between the Combo-Sep® and exhaust stack should not sag so that water deposited inside of the hose will flow back into the Combo-Sep® unit. Figure 5 is a photo of three houseboats that have an exhaust stack extending 9 feet above the upper deck.

Houseboat #20 was retrofitted with three interlocking systems that were manufactured by MariTech Industries (Anderson, CA). The fail-safe, interlocking systems known as the "Marine Safety Systems" have been sold and used for preventing propellor strike injuries beginning in 1997. Since that time, approximately 1,800 systems have been sold for that purpose (MariTech 2001). The interlock integrates the ignition system of the houseboat's generator and/or drive engines with the usage of boarding ladders on the lower, rear deck of the houseboat. When the boarding ladder is placed into the water (Figure 6), a switch is activated, and the interlock automatically shuts down the generator, or both the generator and drive engines, depending upon the configuration. The switch that was used on the evaluated system was a CNK magnetic reed switch that is activated when a separation between 0.625 and 1.25 inches occurs between the contacts. This large gap was selected, in part, to prevent activation of the interlock resulting from ladder movement during rough waters. The switch has an estimated life expectancy of approximately 10 million operations.

Wiring for the interlock is connected to the positive side of the engine coil and when the switch is activated, the generator and/or drive engines are shut down by de-energizing the coil. After the engines have been shut down, they will remain inoperable until the ladder has been placed back into the original position. Keyed by-passes were located in the engine compartment and near the steering wheel inside of the lower deck of the houseboat. The by-passes should only be used during an emergency. All components were selected by the manufacturer for compatibility with auto and marine industry ignition and 12-volt DC systems. A partial wiring diagram for the interlocking system is shown in Figure 7.

As for costs, representatives from Fun Country Marine Inc. estimated that the evaluated dry stack system would cost between $500 and $1,000 to retrofit a houseboat 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 ECD will sell for approximately $4,000, and the evaluated interlock currently sells for approximately $209. The evaluated houseboats' original purchase price was approximately $165,000. These boats currently sell for approximately $180,000.

Description of the Evaluation Equipment

Emissions from the generator and drive engines were characterized using a Ferret Instruments (Cheboygan, MI) Gaslink LT Five Gas Emissions Analyzer and a KAL Equipment (Cleveland, Ohio) Model 5000 Four Gas Emissions Analyzer. Both analyzers measure CO, carbon dioxide (CO_2), hydrocarbons, and oxygen. The five gas analyzer also measures 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 concentration data was also collected with detector tubes [Draeger A.G. (Lubeck, Germany) CO, CH 29901– range 0.3% (3,000 ppm) to 7% (70,000 ppm)] in the areas below and near the rear swim deck. The detector tubes are used by drawing air through the tube with a 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 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 from the exhaust stack 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 exhaust stack. 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 Procedures

The evaluation occurred on two different houseboats. On houseboat #22 the performance of the ECD and ECD with exhaust stack were evaluated when connected to the 15 Kw Westerbeke generator. Data were collected for multiple runs. During some runs, the houseboat was stationary and during others the houseboat was in motion (Figure 8). During the evaluation, the generator alone operated for approximately 30 minutes followed by both motors and the generator operating for another 15 minutes. Baseline data was initially gathered to determine how the generator performed as originally configured. When operated, both drive engines exhausted beneath the rear swim deck of the houseboat. Additional data were collected on houseboat #20 to evaluate the performance of the interlocking system. Data were gathered to determine how quickly the hazardous CO concentrations dissipated after the interlock was activated.

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 Figure 9. The monitors were placed at various locations on both the upper and lower decks of the houseboats 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, several monitors were placed on this structure.

Real-time monitoring results for CO concentrations at various locations on the houseboat are presented in Figures 10 through 12 and summarized in Table II. Figure 10 provides CO concentrations on the houseboat when the generator operated without any emission control device and exhausted under the rear swim deck. Figure 11 provides CO concentrations on the houseboat when the generator was connected to the ECD and exhausted under the rear swim deck. Figure 12 provides CO concentrations on the houseboat when the generator was connected to the ECD and a stack that exhausted 9 feet above the upper deck. Figures 13 and 14 provide comparisons of mean CO concentrations between no control and exhausting under the rear swim deck, the ECD exhausting under the rear swim deck, and the ECD and stack at multiple locations on the houseboat.

The following summarizes the reduction in CO concentrations at multiple locations on the houseboat by exhausting the generator through the ECD under the rear swim deck as compared to operating the generator with no control device and exhausting under the rear swim deck (Figure 13):

- Center of the rear swim platform (Figure 9, Sample 2): On average, CO concentrations were reduced from 395.2 to 0.6 ppm. This is a reduction of approximately 99.9%.

- Rear swim deck near the back of the slide (Figure 9, Sample 1): On average, CO concentrations were reduced from 146.7 to 0.7 ppm. This is a reduction of approximately 99.5%.

- Upper deck near the stack (Figure 9, Sample 5): On average, CO concentrations were reduced from 35.7 to 1.9 ppm. This is a reduction of approximately 94.7%.

- Upper deck near the steering wheel (Figure 9, Sample 7): On average, CO concentrations were reduced from 11.9 to nondetectable.

As can be seen in Table II, when the exhaust stack was connected to the ECD, most of the CO concentrations dropped even further; however, the concentrations measured with the ECD alone were well below recognized exposure limits for CO.

Area Samples on the Lower Level, Rear Deck of Boat

The highest CO concentrations were found on the lower level, rear deck of the houseboat near the generator, and drive engines. Concentrations were particularly dangerous, (exceeding 1,000 ppm) when the generator operated without any control device as shown in Figure 10 and when the houseboat was underway as shown on the right side of Figures 11 and 12. Results gathered when the generator was connected to the ECD and to the ECD and stack simultaneously were excellent when the drive engines were not operating.

The CO monitor placed at the center of the rear swim platform (Figure 9, Sample 2) indicated an average CO concentration of 0.6 ppm and a peak of 1.0 ppm with the generator operating and the ECD connected. This same sample location indicated an average of 395.2 ppm and a peak greater than 534.0 ppm when the generator, operating without the ECD, exhausted under the rear swim deck. Similarly, the monitor located at breathing zone height, near the back of the slide on the lower level (Figure 7, Sample 1) indicated an average CO concentration of 0.7 ppm and a peak of 2.0 ppm with the generator operating and the ECD connected. This same sample location indicated an average of 146.7 ppm and a peak of 480.0 ppm when the generator, operating without the ECD, exhausted under the rear deck. Finally, the monitor located near the front, lower level of the boat near the cooler (Figure 7, Sample 6) indicated an average CO concentration of 0.6 ppm and a peak of 2.0 ppm with the generator operating and the ECD connected. This same sample location indicated an average of 27.7 ppm and a peak of 42.0 ppm when the generator, operating without the ECD, exhausted under the rear deck.

Data gathered with the ECD and stack connected to the generator are shown in Figure 12. A bar chart for comparison is also shown in Figure 14. As can be seen from the left side of Figure 12, CO concentrations continue to be quite low on the lower deck of the houseboat when the ECD and stack are used. Table II and Figure 14 show that for all locations on the lower deck, CO concentrations were reduced even further by connecting the stack to the ECD. In many cases, even though the percentage decrease was substantial, the CO concentrations were already so low due to the ECD that the magnitude of the decrease was relatively small (often less than 1 ppm).

Area Samples on Upper Deck of Boat
As originally configured, the upper deck of the houseboat generally had much lower CO concentrations than the lower deck because of its distance from the generator and drive engines. The CO monitor placed on the upper deck near the stack (Figure 9, Sample 5) indicated an average CO concentration of 1.9 ppm and a peak of 3.0 ppm with the generator operating and the ECD connected. This same sample indicated an average of 35.7 ppm and a peak of 72.0 ppm when the generator was operating with no control and exhausted under the lower rear deck. The monitor located on the upper deck near the steering wheel, at the opposite end of the boat from the generator (Figure 9, Sample 7), indicated nondetectable CO concentrations with the generator operating and the ECD connected. This same sample indicated an average of 11.9 ppm and a peak of 138.0 ppm when the generator was operating with no control device and exhausted under the lower rear deck. It is interesting to note that when the stack was connected to the ECD, the CO concentrations rose slightly near the stack but fell at other locations on the upper deck.

Air Samples Gathered When the Interlock was Evaluated
Air samples were gathered at various locations on houseboat #20 when the interlocking system was evaluated. Several tests were performed when the interlock was connected to the generator alone, and other tests were conducted to evaluate the interlock when it was connected to the

generator and drive engines. Results of the test are shown in Figures 15 (generator alone) and 16 (generator and drive engines). These figures indicate that CO concentrations rapidly exceeded the upper limit of the monitors (1,000 ppm) as shown by the horizontal lines. After the ladder on the swim platform of the houseboat was released into the water, the interlock quickly activated. The engines were shut down, and the hazardous CO concentrations dissipated within two to three minutes. CO concentrations exceeding 1,000 ppm were measured on the swim platform prior to interlock activation.

Wind Velocity Measurements

Wind velocity measurements were taken with an ultrasonic anemometer while CO sampling data was gathered. Data was gathered while the houseboats were stationary and underway. The boats were oriented in a variety of directions depending upon the day and time; however, an attempt was made to position the boats in a manner such that wind was moving from the rear of the houseboat (near the CO emission sources) toward the front of the houseboat to establish near worst case testing scenarios.

A sample of the wind velocity data collected on Tuesday morning is shown in Figure 17. On Monday afternoon, wind speeds were low to moderate, having an average speed of approximately 1.78 m/sec (3.98 miles per hour) and a standard deviation of 1.03 m/sec. On average, wind direction was at 209.88° SW. Tuesday morning, wind speeds were low to moderate, having an average speed of approximately 1.67 m/sec (3.74 miles per hour) and a standard deviation of 1.17 m/sec. On average, wind direction was at 206.14° SW. Tuesday afternoon, wind speeds were approximately 2.03 m/sec (4.54 miles per hour) and had a standard deviation of 1.04 m/sec. On average, wind direction was at 216.80° SW. Weather conditions on subsequent days were similar to Monday and Tuesday; however, wind velocity data is not available due to instrument problems.

Statistical Analysis of Air Sampling Results

The retrofitted ECD significantly reduced CO concentrations at various locations on the houseboat when compared to samples gathered when the generator operated without the ECD. Air sampling data, collected when the generator operated without the ECD, with the ECD, and with the ECD and stack (with the drive engines off), were compared using a t-test. Statistical analysis of the data was performed using Statgraphics Plus 4.1 (Manugistics, Inc, Rockville, MD).

Details concerning the results for three different locations (center of the rear swim platform, back of the slide on the lower rear deck, and top deck near the stack) on the houseboat are shown in Table II. In all three locations, the CO concentrations when exhausting through the ECD were statistically significantly lower than the CO concentrations sampled when exhausting without the ECD. The p-values for the t-test were less than 0.0001 when comparing concentrations at all three locations.

Gas Emissions Analyzer, Detector Tubes, and Evacuated Container Results

Gas emissions analyzers, detector tubes, and glass evacuated containers were primarily used to characterize CO concentrations in and 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 have an upper limit of approximately 1,000 ppm. When measuring exhaust from the stack, the probe of the emissions analyzer was placed into the exhaust stack.

A summary of data collected with the Ferret Instruments 5-gas emissions analyzer is shown in Table III. This data was gathered in the exhaust stack of the generator with and without the ECD connected. When the ECD was not connected, a mean CO concentration of 4,534 ppm was measured in the stack with a standard deviation of 1,140 ppm. When the ECD was connected and operating, a mean CO concentration of 13.0 ppm was measured in the stack with a standard deviation of 34.8 ppm. Hydrocarbon and NO_x concentrations were also reduced by the ECD.

The KAL equipment 4-gas emissions analyzer showed CO concentrations in the exhaust ranging from 0.03% (300 ppm) to 0.04% (400 ppm) with the generator operating with the ECD. Evacuated container grab samples where also taken in the exhaust stack with the ECD operating, and CO concentrations ranged from 45 ppm to 338 ppm. The mean concentration was 222.8 ppm and the standard deviation was 131.3 ppm. Several detector tube measurements taken in the exhaust with the ECD operating gave CO readings of 10 and 20 ppm.

Measurements taken in the space below the lower rear deck with the KAL Instruments 4-gas emissions analyzer indicated CO concentrations in the range of 0.0% (0 ppm) to 0.01% (100 ppm) with the generator and ECD operating and exhausting under the deck. The mean CO concentration measured in this area with the KAL 4-gas emissions analyzer was 45 ppm. Detector tube samples taken in this space indicated CO concentrations of 5 and 10 ppm.

CO samples were also collected with evacuated containers 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.

Stack Velocity, Temperature and Humidity Results

Air velocity measurements were made at the face of the exhaust stack. The mean velocity was 1,315.4 feet per minute (fpm) with a standard deviation of 322.45 fpm. The mean air flow rate exhausting from the stack was 28.94 cubic feet per minute (cfm), and the mean temperature of the stack exhaust was 111.9°F with a standard deviation of 4.26°F. Relative humidity of the stack exhaust was approximately 77%. Temperature measurements were also made for the ambient air and water. The ambient temperature ranged from 87.5°F in the morning to 114.7°F in the afternoon. The mean ambient temperature measured during the survey was 101.4°F with a mean ambient air relative humidity of 20.65%. The mean water temperature was 83.23°F. Water temperature readings ranged from 82.0°F to 85.46°F.

DISCUSSION

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 approaching or exceeding 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 quickly experience CO poisoning or death.

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 may approach 1,200 ppm under certain conditions. The Fun Country Marine houseboats evaluated at Callville Marina were designed with a full hull and did not have enclosed spaces beneath the rear deck. This design is better than that of some other houseboats evaluated by NIOSH and should help to prevent some of the extremely high CO concentrations measured on other boats (Hall and McCammon 2000; McCammon and Radtke 2000; Earnest, Dunn et al. 2001).

This investigation confirms that the CO hazard to swimmers and occupants on houseboats can be greatly reduced by retrofitting control systems to the houseboat. Previous studies have shown that an exhaust stack (that releases the CO and other emission components high above the upper deck of the houseboat) allows the contaminants to diffuse and dissipate into the atmosphere away from boat occupants (Dunn, Hall et al. 2001; Earnest, Dunn et al. 2001). Additional work has been performed to evaluate how the dry stack performs while the houseboat is underway and when several houseboats are tied together. These results are presented in a separate report (Dunn, Earnest et al. 2001).

The present study evaluated the performance of an ECD, an interlock, and an ECD with a stack. Study results indicate that each of these control systems performed well. The ECD was shown to dramatically reduce CO concentrations in the generator exhaust and in the environment near the houseboat. The addition of a stack to the ECD further reduced most of the ambient CO concentrations but more importantly added redundancy to the system. Finally, the evaluated interlock worked as designed and quickly stopped the generation of CO when the swim ladder was released into the water. Although each of the evaluated controls performed well during the current study, there are other issues that should be considered.

Occupational exposures can be controlled by the application of a number of well-known principles including engineering measures, work practices, and personal protection. Engineering measures are the preferred and most effective means of control. These include material substitution, process and equipment modification, isolation and automation, and local and general ventilation. Control measures also may include good work practices, administrative controls, and use of personal protective equipment.

Each of these approaches must be considered when developing a comprehensive, effective control strategy; however, their optimum application varies from case to case. Built-in design modifications that eliminate contaminants at the source are the preferred method of control because they generally are not dependent on human behavior. Additionally, monitoring and maintenance of controls and boater education are important ingredients of a successful control system. Many of these issues should be considered when selecting the best approach to eliminating CO poisonings on houseboats.

Issues Related to the ECD

When large gasoline-powered generators operate 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. Generally speaking, an engine running rich, will tend to produce higher concentrations of CO than the same engine running lean. Simeone predicted CO concentrations exhausted from marine engines as a function of air inlet and several other parameters (Simeone 1990). There are many factors that influence the CO concentration exhausting from the engine.

Initial results from the evaluation of the ECD are extremely promising and demonstrate the ECD's capabilities. The ECD was shown to convert most of the CO produced by the generator, resulting in dramatic reductions in the CO concentration at the source. These data were collected with representatives of the manufacturer present throughout the evaluation to ensure that everything was working properly.

The present study was the first time that NIOSH investigators have evaluated the ECD and was somewhat limited in scope. It is indeed possible that the data collected during the current evaluation occurred during a best case scenario. The question must be asked, "What is a worst case scenario and what would the result be on the CO concentrations being produced?"

Data provided by the California Air Resources Board (CARB) based upon testing from an independent laboratory indicated that an earlier version of the ECD, produced for automobile applications, reduced CO concentrations by approximately 83.9% (CARB 1998). This value compares with the approximately 99.7% reduction seen in the current evaluation. It should also be noted that the ECD evaluated in the CARB report had some differences from the marine ECD which likely affected performance. Unpublished data provided to NIOSH researchers by Westerbeke Corporation following a standard 6-mode emission test (based upon 40 CFR 90 subpart E) under various loading conditions supported NIOSH results and showed that the marine ECD produced extremely low CO concentrations (ranging from 3 to 21 ppm) in the exhaust (Westerbeke 2001).

These generators and emission control devices are rather complex and do not always operate as designed. For a brief period during the evaluation, the hose that supplied cooling water to the generator exhaust was accidentally crushed causing the exhaust temperatures to rise. This resulted in a significant increase in CO concentrations emitted from the ECD. There are many other problems that periodically occur to gasoline-powered engines including spark plug fouling, air cleaners becoming dirty, etc. that may adversely effect the performance of the ECD. It would be useful to evaluate the effect of some of these other potential problems by conducting a long-term evaluation of the ECD.

Issues Related to the ECD and Stack

Data was collected to determine how the ECD performed when connected to a stack that extends well above the upper deck of the houseboat. The dry stack benefits from being a relatively simple and inexpensive control that has performed well during several previous NIOSH evaluations. Results from the current study indicate that both systems performed well together while providing system redundancy. In general, CO concentrations measured when both systems were operating were reduced further than when the ECD alone was used. The observed reductions were relatively minor in absolute terms; however, system redundancy provides an additional level of safety to individuals on the houseboat. The Envirolift ECD has an expected useful life of approximately 10,000 hours and has a warranty of 2 years or 4,000 hours. Electrical components have a 90 day warranty (Envirolift 2001). Because of the dire consequences that may occur if the ECD fails, redundancy provides a higher level of safety to the system.

Issues Related to the Interlock

The interlocking system manufactured and sold by MariTech Industries functioned as designed. This system was originally intended to reduce propellor strike injuries and could potentially play a role in reducing CO poisonings as well. Data gathered during the current evaluation demonstrated that the interlock shut down the source of CO, and the CO concentrations quickly dissipated. The rate at which the CO concentrations dissipate is largely a function of wind conditions. If wind velocities were dramatically lower than those observed during this study, the decay rate of CO concentrations could be substantially reduced.

Interlocking systems are lower on the hierarchy of controls than elimination of the contaminant at the source or removal by ventilation. Nevertheless, this relatively low cost device could be used by some houseboat manufacturers and owners as an interim device to help reduce the hazard of CO poisoning until more permanent solutions are implemented. Anytime an interlock is used, the likelihood of boat users trying to circumvent or disable the system must be considered.

For the evaluated system, it is possible and perhaps even likely that some individuals on the houseboat would be tempted to bypass the system to provide air conditioning or use other houseboat amenities while swimmers are in the water near the rear swim deck. A keyed bypass was readily available at several locations to aid users in circumventing the system. The evaluated interlocking system could also be easily bypassed simply by placing the swim ladder into its original position. Part of the reason that bypasses were in place relates to use of the interlock with the drive engines. If the interlock were connected to the drive engines and the interlock was activated while the boat was moving, the captain would temporarily lose control of the boat, creating a potential new hazard.

The evaluated interlock was connected to the swim ladder. In some situations, this setup could potentially help reduce CO poisonings from individuals who entered the water using the ladder. However, there are other means of access to the water in which this design would be completely ineffective. For example, it is possible that swimmers could access the water from the slide or the front of the boat and never use the swim ladder. It is also possible that CO concentrations found on the lower rear deck of the boat, could pose a hazard to individuals that never enter the water. Concentrations exceeding the ceiling level of 200 ppm have repeatedly been measured on the lower rear deck of many of these houseboats.

System reliability and failure modes of the interlock should also be considered. Unfortunately, it was difficult to get a complete wiring diagram or failure rates for system components.

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. The data collected in this evaluation show that each of the evaluated control systems performed as designed. Based on these data, we recommend that houseboats with gasoline-powered generators be retrofitted with control systems to reduce the hazards of CO poisoning.

2) The emission control device (ECD) performed extremely well during the current evaluation, and it is likely that this device will continue to perform well in the future. Nevertheless, NIOSH investigators believe that it would be prudent to conduct additional testing of this device to determine its reliability and performance over longer periods under conditions that are less than

optimal. If houseboat manufacturers decide to install the ECD onto their generators before additional research has been conducted, it is recommended that the ECD be used in conjunction with either a stack, or side exhaust with a warning device, and that periodic air sampling and emissions testing be performed.

3) The evaluated interlocking system performed as designed. This system provides some protection; however, it may create additional hazards when used with the drive engines. It is also easily bypassed. Individuals desiring to wait for more permanent engineering controls approved by either the U.S. Coast Guard or the American Boat and Yacht Council may consider placing interlocking devices onto their houseboats as an interim measure. If this approach is followed, individuals who utilize these systems need to be fully cognizant of its short comings. NIOSH researchers see some benefit in using this system to reduce CO poisonings from the generator exhaust but do not recommend that it be used for drive engine exhaust.

4) Public education efforts should continue to 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 lakes 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 near the swim platform or exhaust terminus 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.

CARB (1998). Evaluation of Unlimited Technologies International, Inc.'s Series SA090 New Aftermarket Three-way Catalytic Converter for Exemption From the Prohibitions in Vehicle Code Section 27156, and Title 13 California Code of Regulations Section 2222(h). El Monte, CA, State of California Air Resources Board: 6.

CDC (1988). MMWR 37, supp (S-7) NIOSH Recommendations for Occupational Safety and Health Standards. Atlanta, GA, Department 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, DC: U.S. Federal Register.

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

Dunn, K. H., G. S. Earnest, et al. (2001). Comparison of a Dry Stack with Existing Generator Exhaust Systems for Prevention of Carbon Monoxide Poisonings on Houseboats. Cincinnati, Oh, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health: 30.

Dunn, K. H., R. M. Hall, et al. (2001). An Evaluation of an Engineering Control to Prevent Carbon Monoxide Poisonings of Individuals on Houseboats at Somerset Custom Houseboats. Cincinnati, Oh, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health: 35.

Earnest, G. S., K. H. Dunn, et al. (2001). An Evaluation of an Engineering Control to Prevent Carbon Monoxide Poisonings of Individuals on Houseboats. Cincinnati, Oh, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health: 35.

Earnest, G. S., R. L. Mickelsen, et al. (1997). "Carbon 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. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Envirolift (2001). Envirolift Product Literature. Charlotte, NC.

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

Forbes, W. H., F. Sargent, et al. (1945). "The 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: December 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: November 21, 2000.

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

Kales, S. N. (1993). "Carbon 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. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

MariTech (2001). Conversation between Dr. G. Scott Earnest of EPHB, DART, NIOSH, and Keith Jackson, President of MariTech Industries, July 24, 2001. Anderson, California..

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. Radtke, 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. Radtke, 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, Department 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 Carburetor 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 Carlton Bryant, Vice-President of Westerbeke Corporation, February 21, 2001. Avon, Massachusetts.

Westerbeke (2001). Unpublished Data: Engine exhaust emission test results. Taunton, MA: 2.

Table I
Comparison of Features of the Envirolift ECD and a typical Catalytic Converter

	Envirolift ECD	Typical Catalytic Converter
Time to Operational	Immediate upon ignition	Must reach operating temperature. to be effective
Range of Operation	No warm up period	Not efficient until operating temperature is reached
Operating Temperature	200°F - 300°F	650°F - 1,000°F
Heat Output at Exhaust	400°F	800°F
Effectiveness with LP fuel	As low as 10 ppm	Average of 150 ppm

Table II
Comparison of CO Samples (ppm) on the Houseboat for the Generator Alone, Generator with ECD and Generator with ECD and Stack

Sample Location (Sample #)	Generator Alone	Generator with ECD	Generator with ECD & Stack
Lower deck Back of slide (#1)	Mean= 146.7 Std. Dev. = 127.3 Peak = 480.0 Sample # = 114	Mean = 0.7 Std. Dev. = 0.7 Peak = 2.0 Sample # = 125.0	Mean = 0.2 Std. Dev. = 1.9 Peak = 18.0 Sample # = 199
Center of Rear Swim Platform (#2)	Mean= 395.2 Std. Dev. = 107.7 Peak = 534.0 Sample # = 113	Mean= .6 Std. Dev. = .5 Peak = 1.0 Sample # = 125	Mean = 0.3 Std. Dev. = 1.5 Peak = 13.0 Sample # = 198
Kitchen Table (#3)	Mean= 37.2 Std. Dev. = 3.4 Peak = 45.0 Sample # = 114	Mean= 1.0 Std. Dev. = 0.0 Peak = 1.0 Sample # = 125	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 Sample # = 199
Lower deck Right side (#4)	Mean= 257.6 Std. Dev. = 270.4 Peak = 1,103.0 Sample # = 115	Mean= 3.1 Std. Dev. = 7.2 Peak = 78.0 Sample # = 125.0	Mean = 2.0 Std. Dev. = 1.4 Peak = 16.0 Sample # = 199
Top deck Near stack (#5)	Mean= 35.7 Std. Dev. = 13.0 Peak = 72.0 Sample # = 116	Mean= 1.9 Std. Dev. = 0.4 Peak = 3.0 Sample # = 125.0	Mean = 3.6 Std. Dev. = 0.7 Peak = 5.0 Sample # = 199
Lower deck Front of boat near cooler (#6)	Mean= 27.7 Std. Dev. = 7.5 Peak = 42.0 Sample # = 113	Mean= 0.6 Std. Dev. = 0.5 Peak = 2.0 Sample # = 125.0	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 Sample # = 199
Top Deck near steering wheel (#7)	Mean= 11.9 Std. Dev. = 24.0 Peak = 138.0 Sample # = 117	Mean= 0.0 Std. Dev. = 0.0 Peak = 0.0 Sample # = 125.0	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 Sample # = 199

Table III
Comparison of 5-gas Emissions Analyzer Data for Generator Operating With and Without the ECD

	Without ECD	With ECD
Hydrocarbons (ppm)	Mean = 324.7 Std. Dev. =17.4 Sample # = 668	Mean = 29.4 Std. Dev. = 52.0 Sample # = 1,033
Carbon Monoxide (ppm)	Mean = 4,534 Std. Dev. = 1,140 Sample # = 668	Mean = 13.0 Std. Dev. = 34.8 Sample # = 1,033
Carbon Dioxide (%)	Mean = 0.6 Std. Dev. = 0.1 Sample # = 668	Mean = 0.6 Std. Dev. = 0.2 Sample # = 1,033
Oxygen (%)	Mean = 19.7 Std. Dev. = 0.2 Sample # = 668	Mean = 20.2 Std. Dev. = 0.3 Sample # = 1,033
Nitric Oxides (ppm)	Mean = 11.9 Std. Dev. = 6.9 Sample # = 668	Mean = 1.8 Std. Dev. = 1.5 Sample # = 1,033

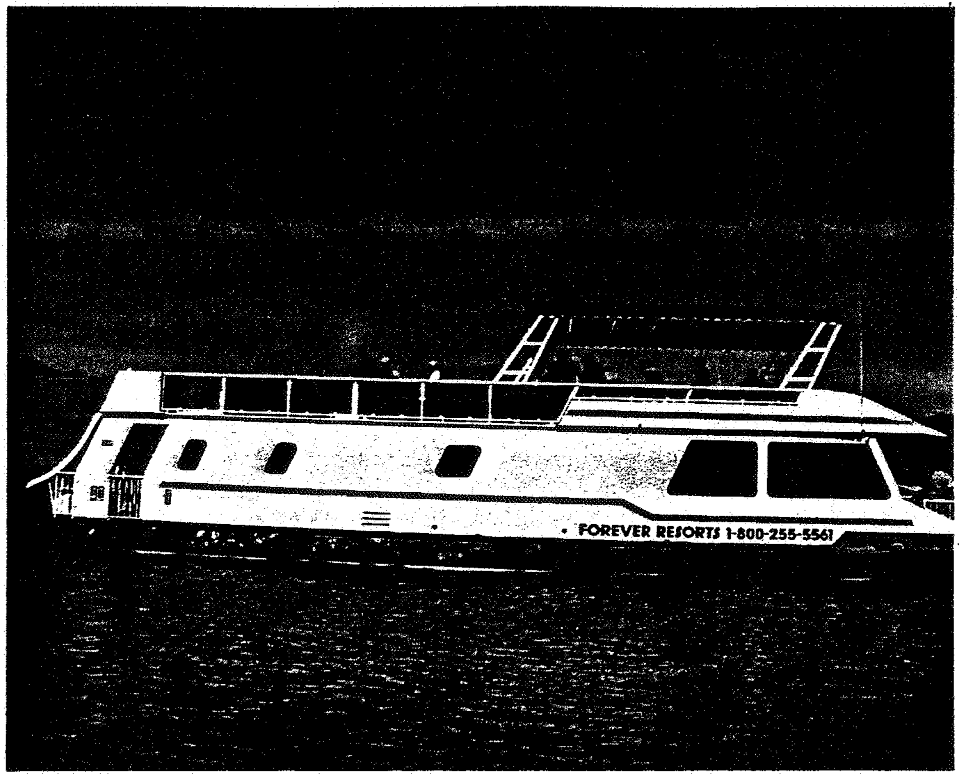

Figure 1. Photo of one of the evaluated 65 Foot Fun Country Marine houseboats.

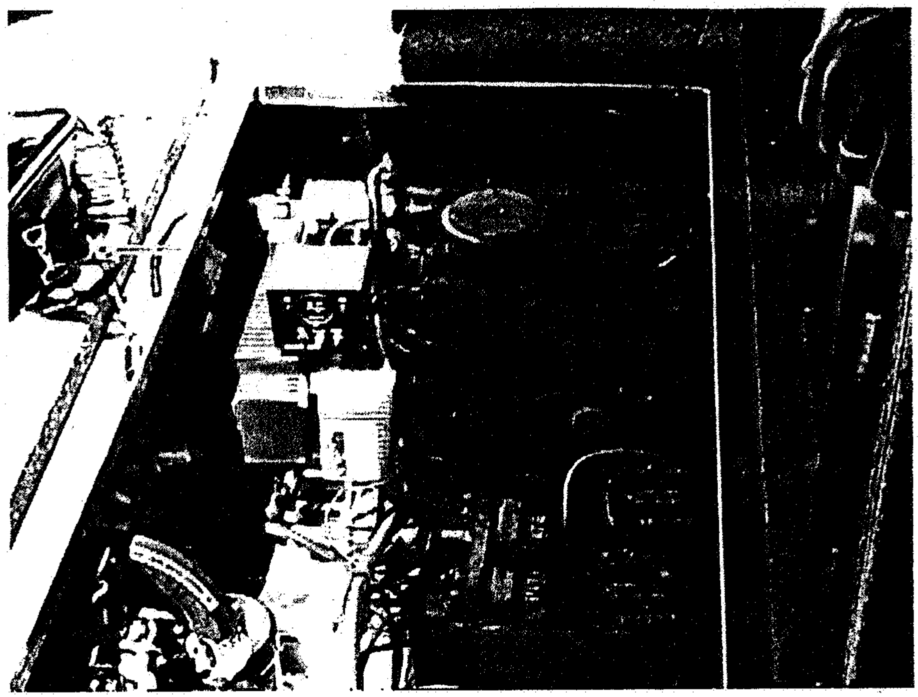

Figure 2. Engine and generator compartment on the rear deck of the houseboat.

Figure 3. The emissions control device sold and distributed by Envirolift/ Marysville Marine.

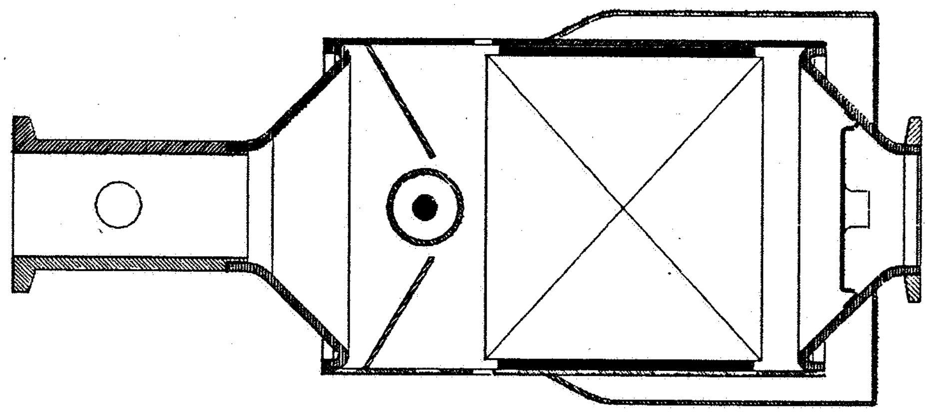

Figure 4. Cross-sectional diagram of the Envirolift emissions control device.

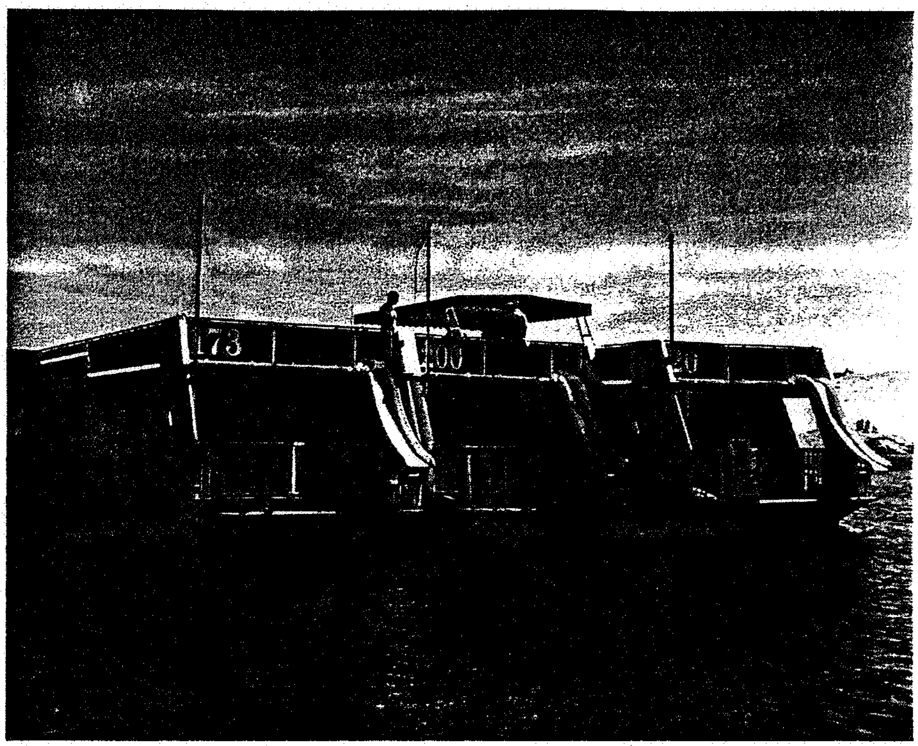

Figure 5. Photo of three houseboats having generator exhaust through a dry stack 9 feet above the upper deck.

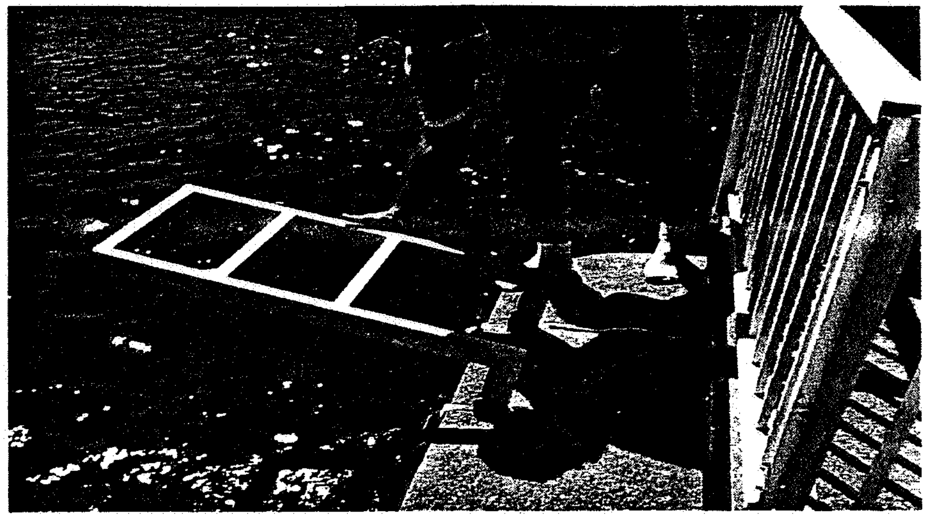

Figure 6. Photo of the interlock being activated by swim ladder on the houseboat.

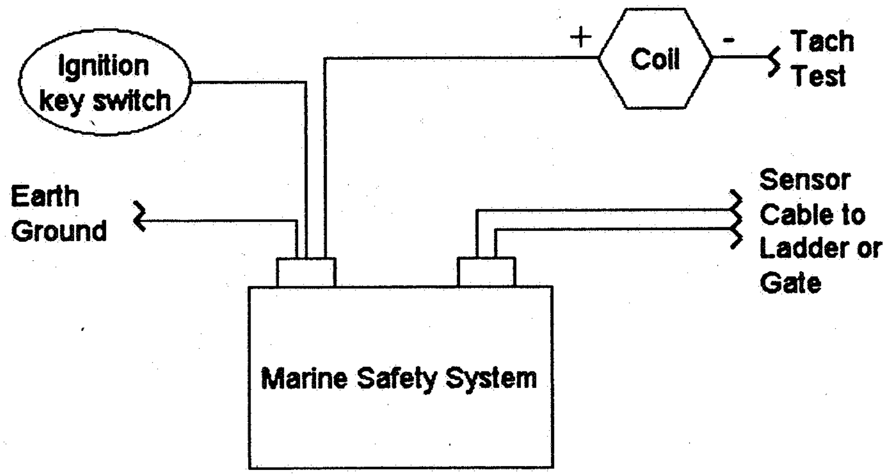

Figure 7. Wiring diagram for the interlock.

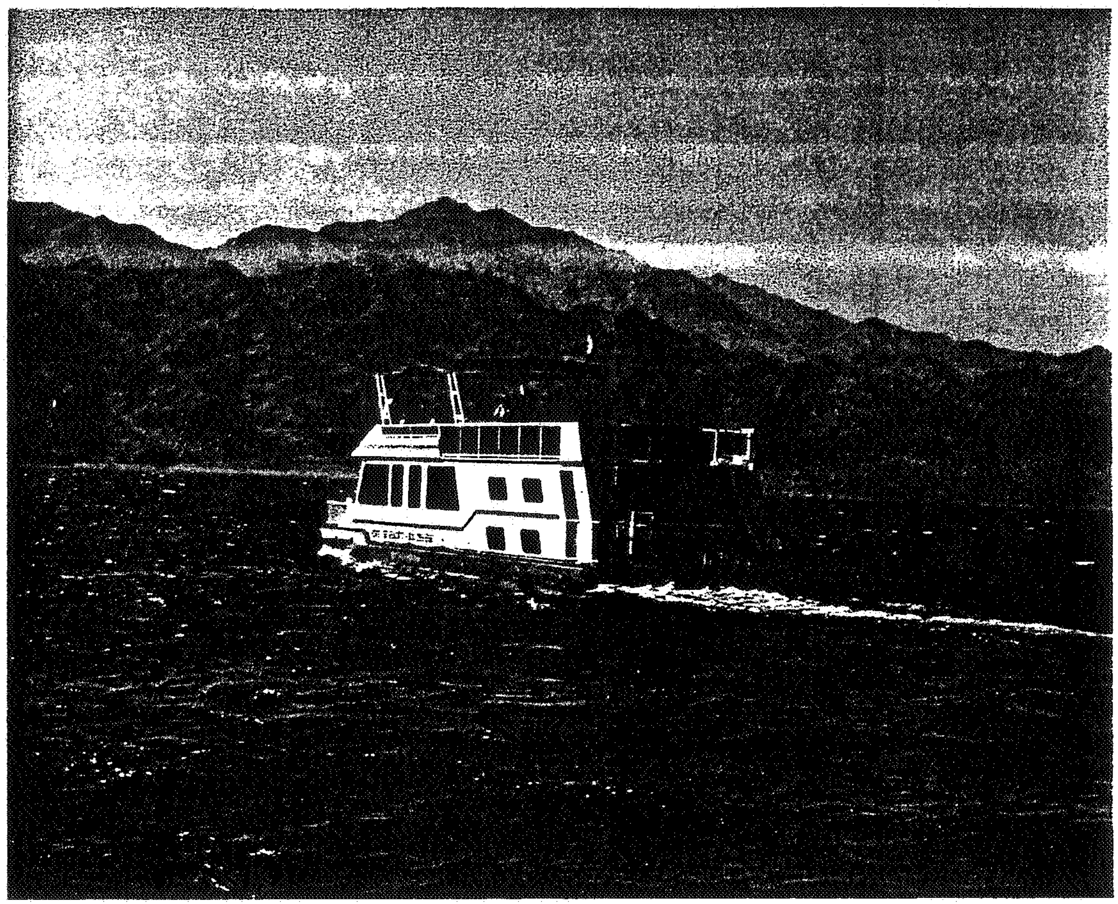

Figure 8. Houseboat being evaluated underway.

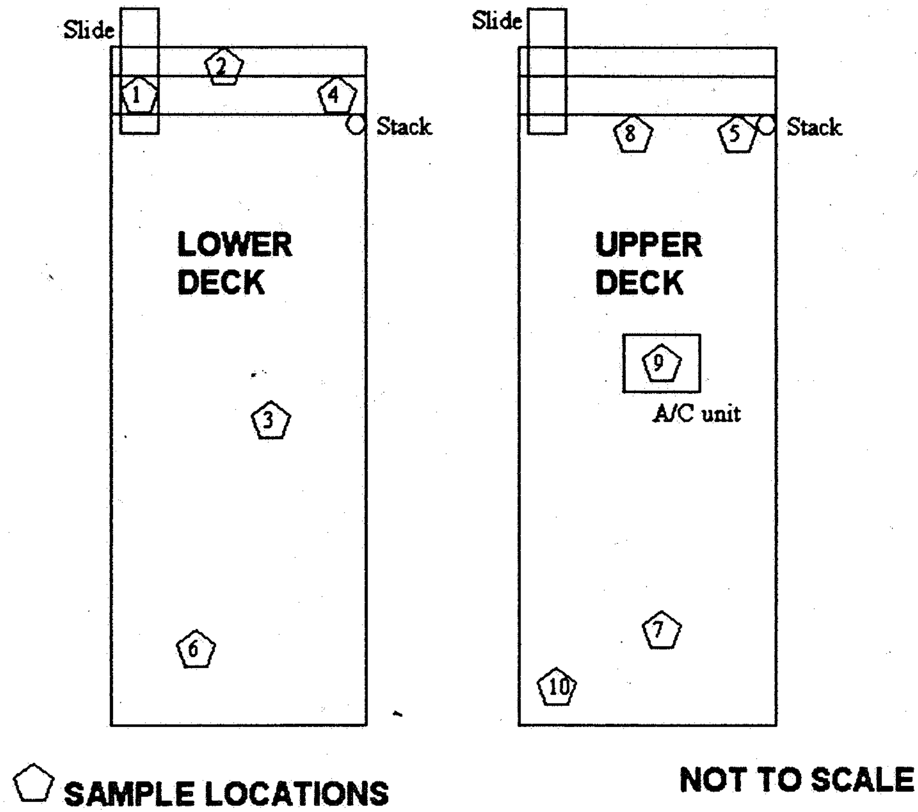

Figure 9. Sample locations on upper and lower decks of the houseboat.

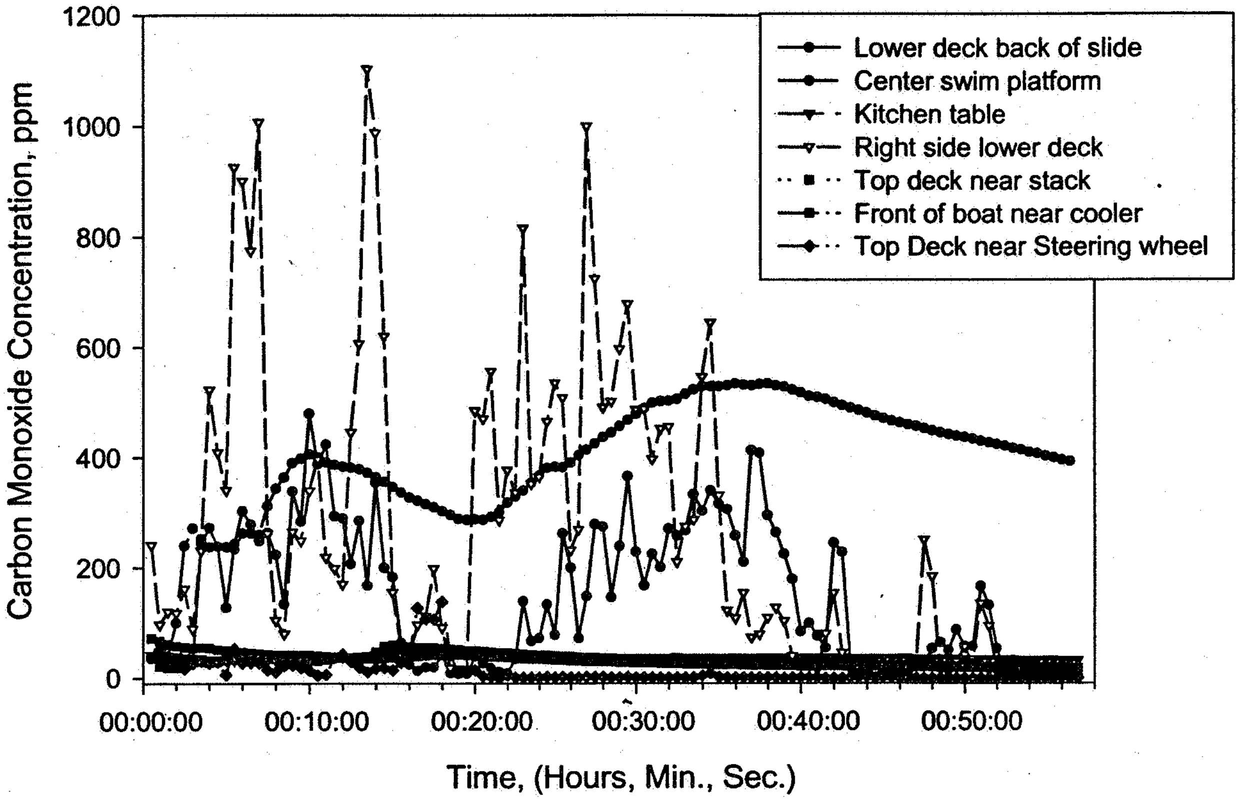

Figure 10. Carbon monoxide concentration at various locations on the houseboat (with ECD not connected).

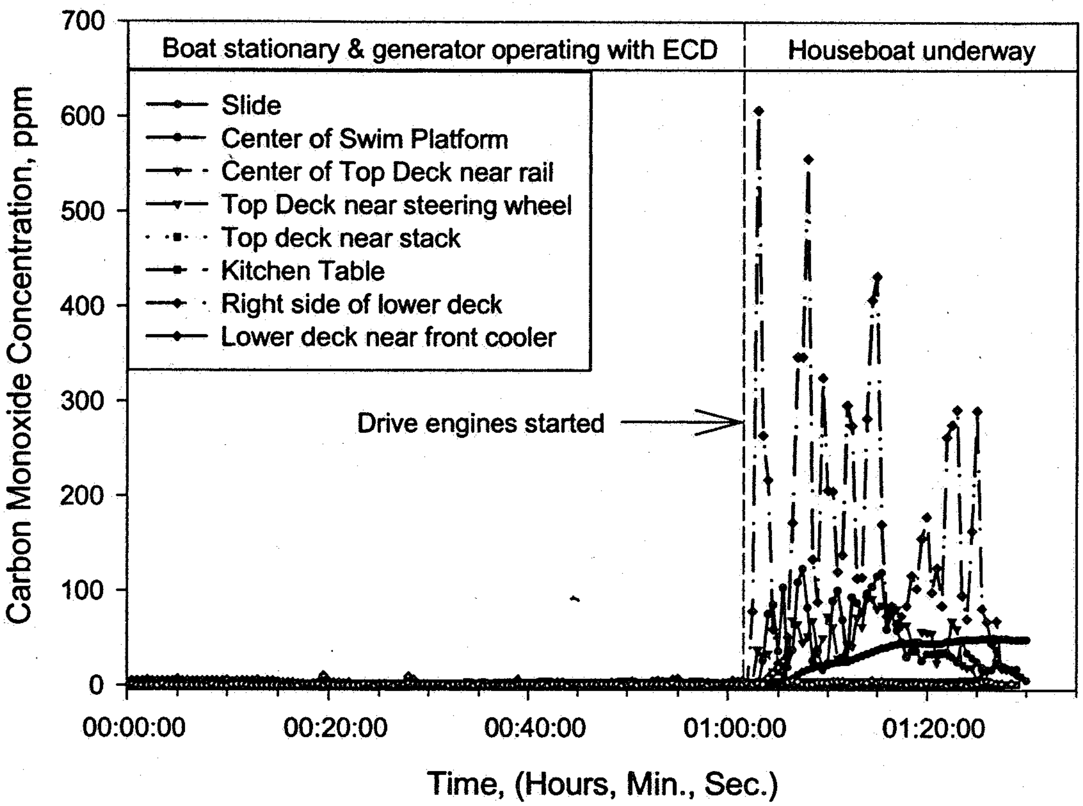

Figure 11. Carbon monoxide concentrations at various locations on the houseboat (with ECD connected and operating).

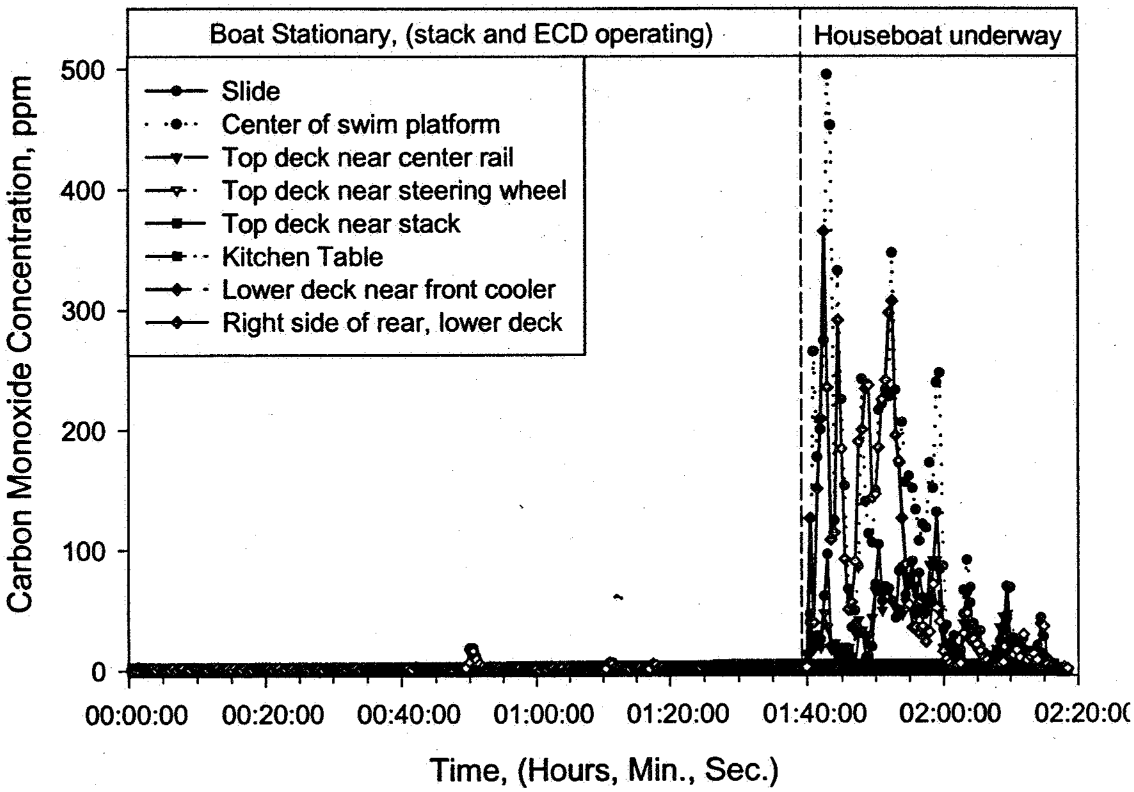

Figure 12. Carbon monoxide concentrations at various locations on the houseboat (with ECD and stack connected and operating).

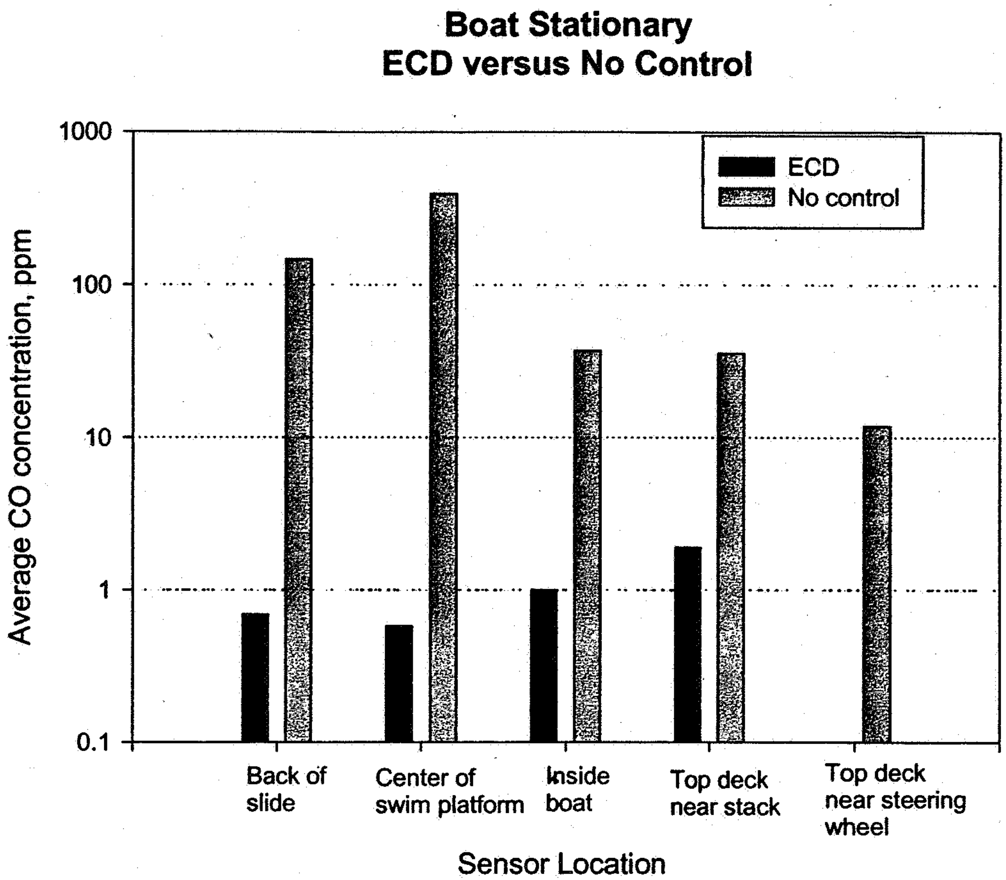

Figure 13. Comparison of the performance of the ECD versus no control by measuring CO concentrations at various locations on the houseboat (note the log scale).

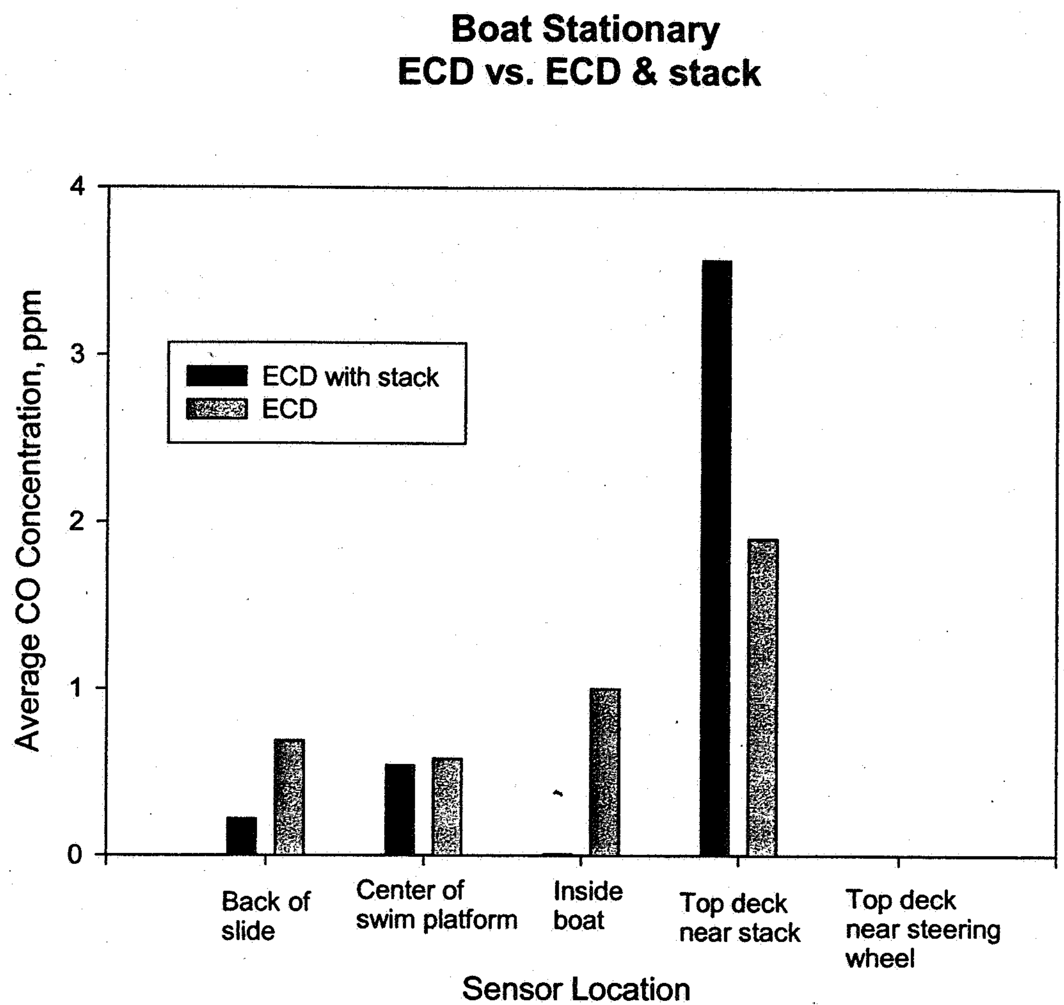

Figure 14. Comparison of the performance of the ECD versus ECD and stack by measuring CO concentrations at various locations on the houseboat.

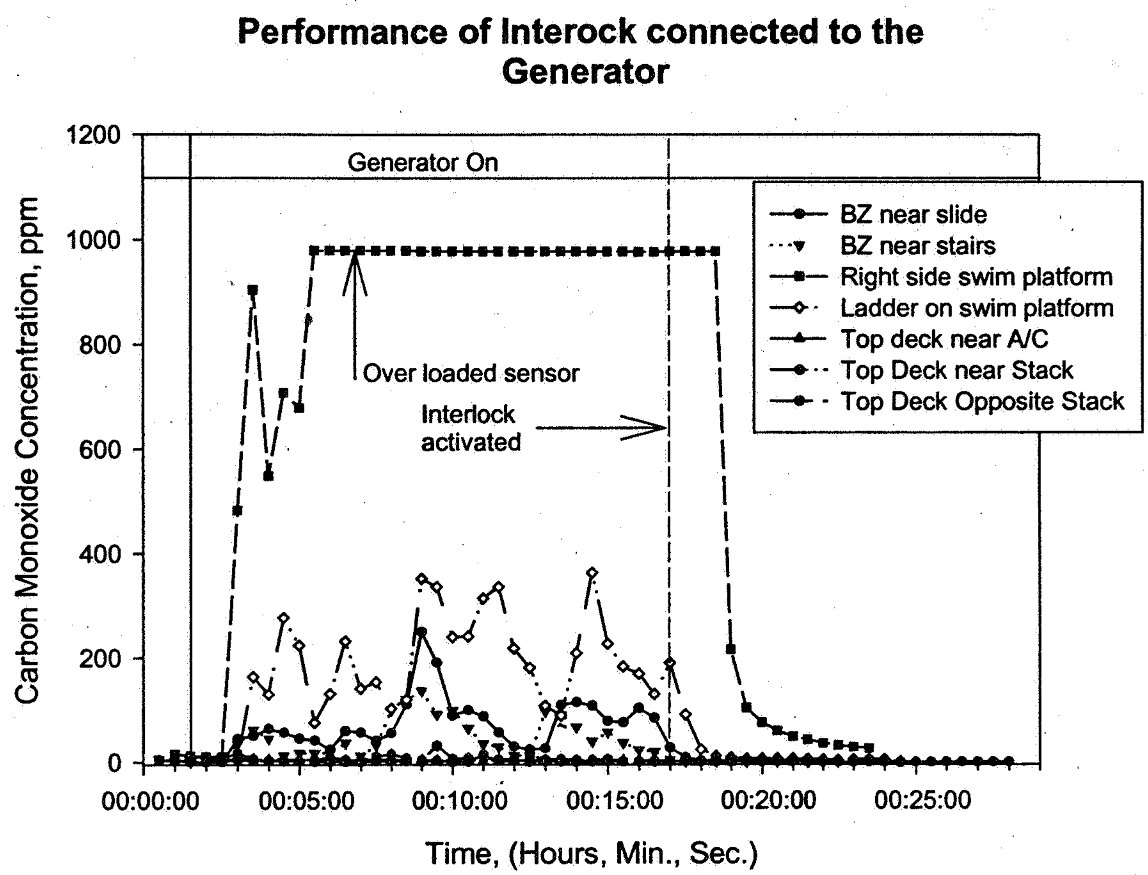

Figure 15. Performance of the interlock when connected to the generator.

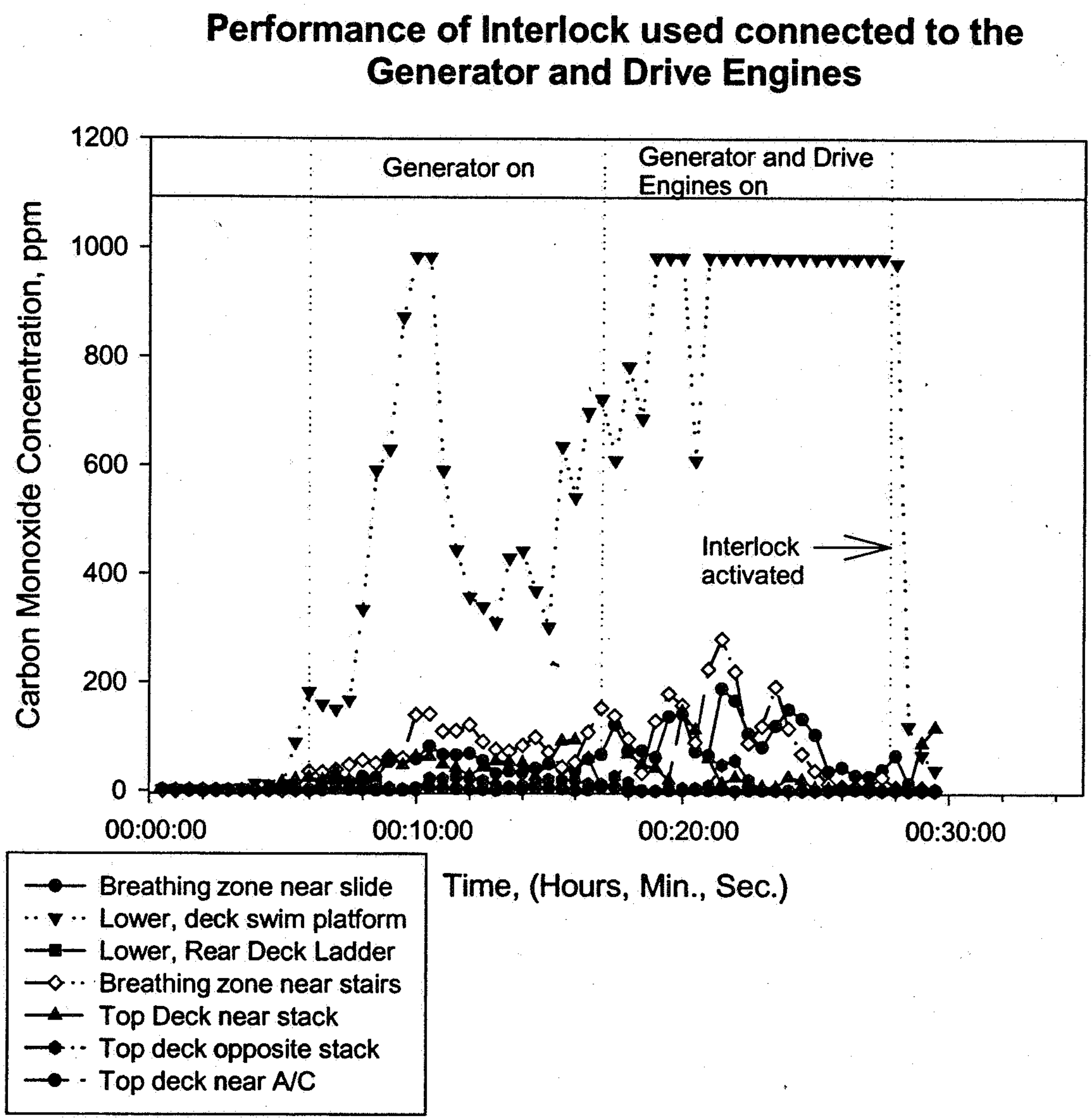

Figure 16. Performance of the interlock when connected to the generator and drive engines.

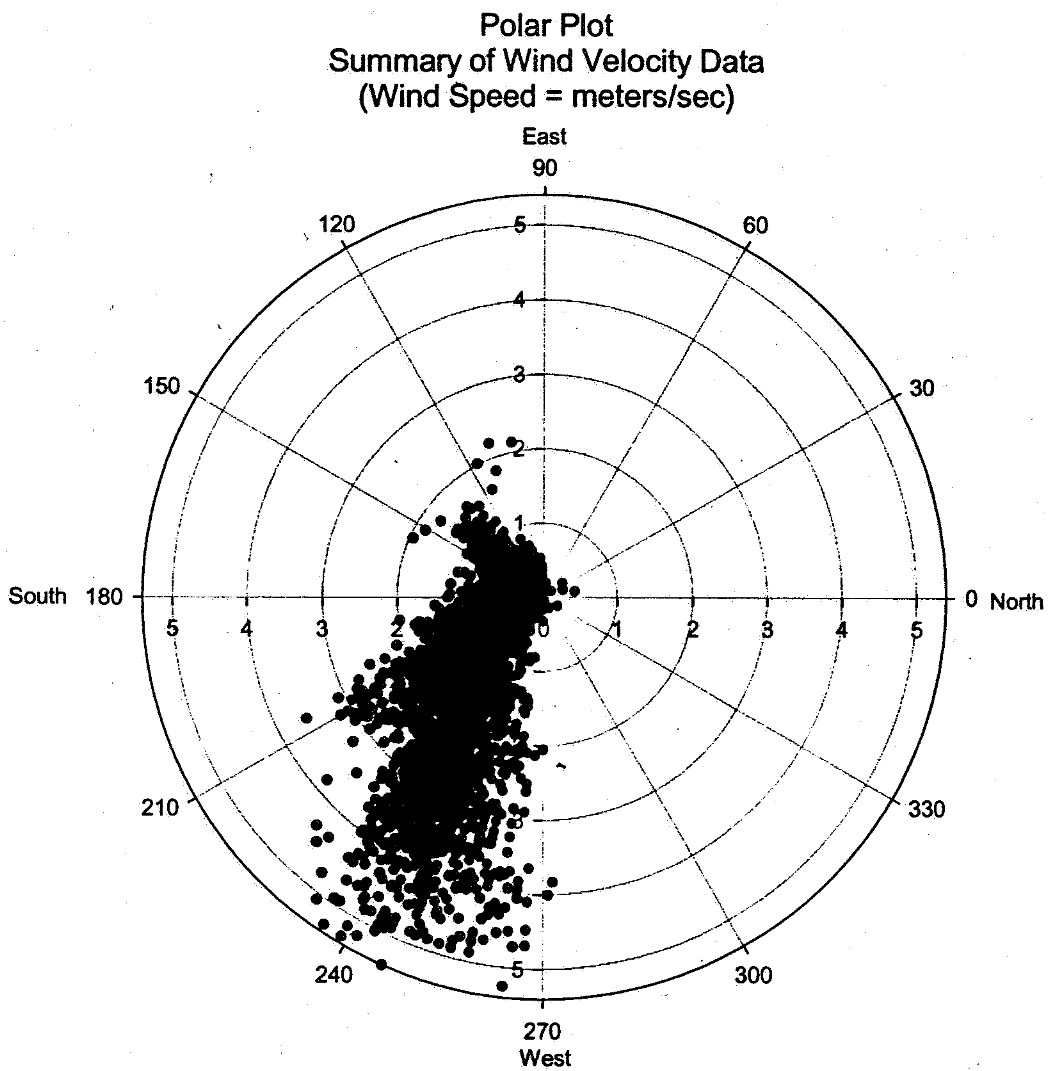

Figure 17. Wind velocity data gathered on Tuesday morning (mean = 1.67 m/s, 206.14°).