AN EVALUATION OF VERTICAL EXHAUST STACKS AND AGED PRODUCTION EMISSION CONTROL DEVICES TO PREVENT CARBON MONOXIDE POISONINGS FROM HOUSEBOAT GENERATOR EXHAUST

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DISCLAIMER

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EXECUTIVE SUMMARY

Working under an interagency agreement with the United States Coast Guard, researchers from the National Institute for Occupational Safety and Health (NIOSH) evaluated carbon monoxide (CO) emissions, exposures, and controls from gasoline-powered generators on houseboats. This evaluation is part of a series of studies conducted by NIOSH investigators during the past several years to identify and recommend effective engineering controls to reduce the CO hazard and eliminate CO poisonings on houseboats and other recreational marine vessels. Performance of a 9-foot, vertical exhaust stack on three rafted houseboats and the performance of several production emission control devices (ECD) with several thousand operating hours manufactured by Enviromarine LLC, were studied.

The vertical exhaust stack has been retrofitted onto over 90% of the gasoline-powered generators used on the Forever Resort's houseboat rental fleet at Callville Bay Marina on Lake Mead near Henderson, Nevada. The vertical exhaust stacks used on Forever Resorts houseboats were constructed from continuous aluminum pipes that extended 9-feet above the houseboats' upper decks. The exhaust stacks were designed to comply with the recently revised American Boat and Yacht Council (ABYC) Standard P-1 for recreational boat exhaust. The remaining Forever Resorts houseboat generators were retrofitted with Enviromarine ECDs in order to address the carbon monoxide (CO) problem.

Production ECDs were retrofitted onto gasoline-powered houseboat generators to reduce the CO concentrations in the generator exhaust and prevent poisonings. In June 2001, NIOSH researchers evaluated a recently developed marine prototype ECD, and the performance was excellent (CO concentrations on the houseboat's lower stern deck were below 1 ppm and CO concentrations were reduced by approximately 99%). In October 2001, the same ECD was reevaluated after it had been used on the houseboat's generator and exposed to lake water and other natural elements for approximately 3,000 hours of operation. During this evaluation, the prototype ECDs performance was found to have substantially degraded due, in part, to internal corrosion from exposure to water and other elements. The current study evaluated several redesigned production ECDs with an outer shell casing made entirely of stainless steel. The production model ECD was designed to withstand the harsh marine environment. The ECDs evaluated during the current survey had over 2,000 operating hours.

During this study, the vertical exhaust stacks performed well, and the results were consistent with the results of previous NIOSH investigations. When the houseboats were rafted together and stationary, average CO concentrations measured at all locations on the houseboats were well below 5 ppm. Results from the aged production ECD evaluations showed that they were somewhat effective at reducing CO concentrations; however, their performance had substantially degraded from when they were new. CO concentrations exhausting from the 2 generators with ECDs were potentially hazardous (CO concentrations exceeding 500 ppm were measured on the lower rear deck of one boat). This degradation in ECD performance is believed to be related to lack of adequate maintenance on the generators.

Based upon the results of this and previous studies, NIOSH investigators recommend that houseboats using gasoline-powered generators, should be evaluated for potential CO exposures and poisonings near the lower stern deck. Houseboat owners should consider retrofitting the generators with engineering controls to reduce the potential hazard of CO poisoning and death to individuals on or near the houseboat. The vertical exhaust stack has performed well during all previous NIOSH evaluations and is successfully being used on many houseboats across the U.S. The ECD continues to be a promising emission control option; however, generator maintenance is critical to ensure that the ECD performs properly and does not present a potential CO or fire hazard. In many cases, installation of a high temperature shutoff switch should also help to prevent this problem. Because performance complications were noted during this and a previous NIOSH field evaluation, additional testing and evaluation of the ECD is warranted. Finally, other engineering control options such as fuel injected generators and other catalysts are being developed. These options could also play an important role in the future in reducing CO emissions and poisonings from marine generators and engines.

BACKGROUND

On September 30 through October 3, 2002, National Institute for Occupational Safety and Health (NIOSH) researchers evaluated control of carbon monoxide (CO) emissions and exposures at Callville Bay Marina on Lake Mead, Nevada. Evaluations involved 3 houseboats rafted together, each having 9-foot, vertical exhaust stacks that were connected to gasoline-powered generators. The vertical exhaust stacks were designed to comply with the recently revised American Boat and Yacht Council's (ABYC) Standard P-1 for generator exhaust titled, ***Installation of Exhaust Systems for Propulsion and Auxilliary Engines***. Several production emission control devices (ECDs) with substantial hours of use were also evaluated. These ECDs had been retrofitted onto two different houseboats' gasoline-powered generators.

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

! The open space under the swim platform could be lethal under certain circumstances (i.e., generator/motor exhaust discharging into this area) on some houseboats.

! Some CO concentrations above and around the swim platform were at or above the immediately dangerous to life and health (IDLH) level [greater than 1,200 parts of CO per million parts of air (ppm)].

! Measurements of personal CO exposure during boat maintenance activities indicated that employees may be exposed to hazardous concentrations of CO.

Epidemiological investigations have discovered that from 1990 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). Further investigations have identify nearly 400 CO poisonings related to recreational boats across the United States and that number continues to increase.

Engineering control studies began in February 2001 at Lake Powell and Somerset, Kentucky, (Dunn, Hall et al. 2001; Earnest, Dunn et al. 2001). Results of these studies demonstrated that an exhaust stack extending 9 feet above the houseboat's upper deck dramatically reduced the CO concentrations on and near the houseboat and provided a much safer environment. A meeting was convened by the U.S. Coast Guard, Office of Boating Safety, Recreational Boating Product Assurance Division on May 3, 2001, in Lexington, Kentucky. This meeting was attended by houseboat manufacturers, marine product manufacturers, government representatives, and others interested in addressing the CO hazard. Following the meeting, NIOSH researchers were asked to evaluate the performance of a new prototype ECD and an interlocking device and to conduct further evaluations of the dry stack. These evaluations were conducted in June 2001 at Callville Bay Marina, NV. The findings of these studies indicated that although the ECD, interlock, and dry stack each performed well, longer term testing of the ECD should be conducted (Dunn, Earnest et al. 2001; Earnest, Dunn et al. 2001). Concerns were also expressed regarding potential use of the safety interlock as a primary control option.

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

A second evaluation of the prototype ECD in October 2001 showed that performance of the prototype ECD had substantially degraded after thousands of hours of use; however, a new production ECD was developed and performed well. The prototype ECD was constructed from a combination of stainless steel and cast iron while the production ECD was constructed entirely of stainless steel to reduce corrosion. Other differences relate to the physical size and shape of the ECD housing and substrate to improve performance. Finally, a thermocouple and shut-off switch was added to new production ECDs to prevent excessive temperatures which can potentially destroy the catalyst as well as present a potential fire hazard. The current study evaluated the performance of two production ECDs that had been installed and used on gasoline-powered generators for several thousand hours and the vertical exhaust stack. This report provides background information and describes our evaluation methods, results, conclusions, and recommendations.

Symptoms and Exposure Limits

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

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

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

Exposure Criteria

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

The NIOSH Recommended Exposure Limit (REL) for occupational exposures to CO gas in air is 35 parts per million (ppm) for full shift time-weighted average (TWA) exposure, and a ceiling limit of 200 ppm, which should never be exceeded (CDC 1988; CFR 1997). The NIOSH REL of 35 ppm is designed to protect workers from health effects associated with COHb levels in excess of 5% (Kales 1993). NIOSH has established the immediately dangerous to life and health (IDLH) value for CO of 1,200 ppm (NIOSH 2000). The American Conference of Governmental Industrial Hygienists: (ACGIH[7]) recommends an 8-hour TWA threshold limit value (TLV[7]) for occupational exposure of 25 ppm (ACGIH 1996) and discourages exposures above 125 ppm for more than 30 minutes during a workday. The Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for CO is 50 ppm for an 8-hour TWA exposure (CFR 1997).

The NIOSH REL for ozone is 0.1 ppm as a ceiling exposure (NIOSH 2000). The OSHA PEL for, ozone is 0.1 ppm as an eight-hour TWA, with a Short Term Exposure Limit (STEL) of 0.3 ppm (CFR 1997). The STEL is a 15-minute TWA exposure limit which should not be exceeded at any time during the workday. The ACGIH TLV for ozone is 0.1 ppm as a ceiling (ACGIH 1996).

Health Criteria Relevant to the General Public

The U.S. Environmental Protection Agency (EPA) has promulgated a National Ambient Air Quality Standard (NAAQS) for CO. This standard requires that ambient air contain no more than 9 ppm CO for an 8-hour TWA, and 35 ppm for a 1-hour average (EPA 1991). The NAAQS for CO was established to protect Athe most sensitive members of the general population.@

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

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

METHODS

Measurements of CO and other air contaminants, ventilation, and wind-velocity were collected on five houseboats built by Fun Country Marine Industries, Inc. (Muncie, IN). Three of the houseboats had vertical exhaust stacks on their generators (Figure 1), and two houseboats had production ECDs. The houseboats were approximately 3-5 years old. Data was collected in an effort to evaluate the performance of the control systems that had been retrofitted onto the houseboats. CO concentrations on the houseboats were evaluated when the houseboat was stationary and underway, when the generator was connected to an ECD and when it was not, and during cold-starting. A description of the five houseboats and the evaluated engineering controls are provided below:

Description of the Evaluated Houseboats

1. Houseboat #240

Engines: 2, 1998, 115-horsepower (hp) 4-cylinder, 2-cycle, Evinrude FICHT**7** outboard engines
Generator: 12.5-Kw, 1998, Kohler, 4-cylinder, 4-stroke, 1,800 revolutions per minute (rpm), 79.0 cubic inches (in^3)
Approximate dimensions of houseboat: 59 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**7** muffler/gas/water separator to vertical exhaust stack 9 feet above upper deck (used for emissions testing) and port side water drain (at water level)

2. **Houseboats #185, #228**

Engines: 2, 135-horsepower (hp) 4-cylinder, carbureted, Volvo engines, with inboard/outboard drives
Generators: 12.5-Kw, 1997 and 1998, Kohler, 4-cylinder, 4-stroke, 1,800 revolutions per minute (rpm), 79.0 cubic inches (in^3)
Approximate dimensions of houseboat: 56 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[7] muffler/gas/water separator to vertical exhaust stack 9 feet above upper deck (used for emissions testing) and port side water drain (at water level)

3. **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), 90.0 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: production Enviromarine LLC emissions control devices (ECDs) installed with two options for routing exhaust: 1) Combo-Sep[7] muffler/gas/water separator to vertical exhaust stack 9 feet above upper deck (used for emissions testing) and port side water drain (at water level); or 2) exhaust through emissions control device (ECD), regular muffler and rear of the transom; or 3) generator exhaust without ECD through a lift muffler and out through the rear of the transom

4. **Houseboat #340**

Engines: 2, 1998, 115-horsepower (hp) 4-cylinder, 2-cycle, Evinrude FICHT[7] outboard engines
Generator: 12.5-Kw 2002 Westerbeke, 4-cylinder, 4-stroke, 1,800 revolutions per minute (rpm), 79.0 cubic inches (in^3)
Approximate dimensions of houseboat: 59 ft. X 14 ft.
Approximate dimensions of space below swim platform: 3 ft. X 14 ft. X 1.5 ft.
Exhaust Configuration: production Enviromarine LLC emissions control devices (ECDs) installed with two options for routing exhaust: 1) Combo-Sep[7] muffler/gas/water separator to vertical exhaust stack 9 feet above upper deck (used for emissions testing) and port side water drain (at water level); or 2) exhaust through emissions control device (ECD), regular muffler and port-side;

Two Evinrude Ficht**7**, 4-cylinder outboard engines provided propulsion for houseboats #240 and #340. Two inboard Volvo, 4-cylinder engines were used to provide propulsion for houseboats #185, #228, and #22 The Volvo engines were carbureted and the Evinrude Ficht**7** engines were fuel injected. The Evinrude Ficht**7** engines were designed to burn cleaner and provide lower emissions than a typical carbureted engine. The houseboats= drive engines were housed in compartments beneath the stern deck of the houseboats. Access could be gained to the engines through a large door in the floor of the stern decks. The engines exhausted through their propellor hubs beneath the water. Each evaluated Fun Country Marine houseboat had a full hull with no enclosed spaces beneath the lower stern 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 stern deck near the drive engines. The generators are similar in size to engines used on small automobiles. Houseboat #22 and #340 had 15-Kw and 12.5-Kw Westerbeke generators respectively. The three remaining houseboats each had 12.5-Kw Kohler generators. Westerbeke generators are used on nearly 75% of houseboats in the U.S. (Westerbeke 2001).

When used on houseboats, the hot exhaust gases from the generators are injected with water near the end of the exhaust manifold in a process commonly called Awater-jacketing.@ Water-jacketing is used for exhaust cooling and noise reduction. Because the generator sets below the waterline, the water-jacketed exhaust passed through a lift muffler that further reduces noise and forces the exhaust gases and water up and out through a hole beneath the swim platform.

Description of the Evaluated Engineering Controls

Houseboat numbers 240, 185, and 228 each had a continuous, vertical exhaust stack retrofitted to their generator sets. The exhaust stacks were designed to comply with the revised American Boat and Yacht Council (ABYC) Standard P-1 for recreational boat exhaust. A 2-inch nominal, schedule 40 aluminum pipe, having an approximately 2.5-inch outside diameter and 2.0-inch inside diameter was used as the stack. On each houseboat, a portion of the stack extended through the boat=s lower stern deck and was clamped to a high temperature exhaust hose. 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 stern port-side engine compartment and the stern port-side of the upper deck which the pipe passed through. The original lift muffler was removed, and a Combo-Sep**7** muffler/gas/water separator (Centek Industries, Thomasville, GA) was installed to separate the exhaust gases from the water using gravity and centrifugal force.

The exhaust systems on houseboats #22 and #340 were modified to route the generator exhaust through production emissions control devices (ECD) prior to the water jacketing process. The generator exhaust was configured so that exhaust gases exiting the ECD could either be released near the water line or carried through an exhaust stack and expelled nine feet above the upper deck of the houseboat. Use of the vertical-exhaust stack allowed researchers to sample directly into the generator exhaust for emissions testing.

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. EnviroMarine L.L.C. (Whitehouse, TN) is developing and manufacturing the ECD for houseboat applications. This device has an estimated useful life of approximately 10,000 hours.

The two ECDs evaluated during the current field survey were production models. A prototype ECD had previously been evaluated by NIOSH researchers. (Earnest et al. 2002) During the current study, the two evaluated production ECDs had over 2,000 hours of operation. A photo of the production ECD is shown in Figure 2. There are several important differences between the prototype ECD and the production model. The outer shell of the prototype ECD was constructed from stainless steel and cast iron, and the shell of the production ECD was constructed exclusively from 316L stainless steel. The prototype is 14 inches long, 5 inches in diameter, and weighs 8.5 lbs. The production model is 11 1/8 inches long, 5 inches in diameter, and weighs 6.9 lbs.

The other primary difference between the two ECD versions was that the prototype ECD had a rectangular substrate, while the production version was cylindrical. The dimensions of the prototype substrate were 4 inches by 4 inches by 4 inches for a total volume of approximately 64 cubic inches. The production ECD substrate were 4 inches in diameter by 4 inches in length having a volume of 50.27 cubic inches.

The ECD uses a ceramic substrate consisting of porous silica coated with two transition metals. A washcoat consisting of three different oxidizing agents was applied to the substrate to provide a large specific surface area to disperse the metals. The substrate is contained in an outer 16 gauge stainless steel shell with a special mat to prevent vibration. The ECD was mounted on rubber grommets to reduce vibration (CARB 1998).

Exhaust gases exit the generator and pass by a series of baffles to ensure adequate mixing as it enters the ECD. The gases then pass through a high voltage, electrically charged screen (30,000 volts) or Aignitor@ 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.

Components of the evaluated vertical exhaust stacks cost between $500 and $1,000. Purchase of vertical exhaust stack components and installation was approximately $1500 or less. The evaluated ECD sells for approximately $2,800. The evaluated houseboats= original purchase price was approximately $165,000 to $200,000.

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. This analyzer measures CO, carbon dioxide (CO_2), hydrocarbons, oxygen, and nitrogen oxides (NO_x). All measurements are expressed as percentages except hydrocarbons and NO_x which is ppm. [One percent of contaminant is equivalent to 10,000 ppm.]

CO concentrations were measured at various locations on the houseboat using ToxiUltra Atmospheric Monitors (Biometrics, Inc.) with CO sensors. ToxiUltra CO monitors were calibrated before and after use according to the manufacturer=s recommendations. These monitors are direct-reading instruments with data logging capabilities. The instruments were operated in the passive diffusion mode, with a 15 - 30 second sampling interval. The instruments have a nominal range from 0 ppm to 999 ppm. Accuracy is +/- 1 ppm or 5 percent of the reading (whichever is greatest).

CO concentrations were also measured with detector tubes [Draeger A.G. (Lubeck, Germany) CO, CH 29901B range 0.3% (3,000 ppm) to 7% (70,000 ppm)] in the areas below and near the stern swim deck and directly in the generator exhaust. 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 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- and Y-axes. This instrument is capable of measuring wind velocities of up to 45 meters per second (m/sec) and take 100 measurements per second.

Air flow from the exhaust stacks was evaluated through the use of a VelociCalc Plus Model 8360 air velocity meter (TSI Inc., St. Paul, MN). Air velocity readings were collected at the face of the exhaust stack. 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 was performed over a 4-day period using a variety of operating conditions and generator exhaust configurations. Details concerning the test conditions are summarized below:

1) Boats Stationary B Generator exhausting through the vertical exhaust stack or through the ECD and rear or side-exhaust. Emissions from boat #22 and boat #340 were tested with and without an ECD under various loading conditions. Cold starts were also evaluated. Evaluation of boats rafted together involved three boats (Boats 240,185, 228) each having a vertical exhaust stack extending 9 feet above the upper deck (Figure 3). This test was performed at the marina and on the beach in a cove of the lake.

2) Boats Underway B Generator exhausting through the vertical exhaust stack or through the ECD and rear or side-exhaust. The underway evaluation consisted of measuring CO concentrations on the boat as the boat moved between the marina and a cove. After exiting the no-wake zone, the boat captain maintained a constant speed en route to the cove. The trip to/from the marina lasted for approximately 30 minutes.

Sampling locations for the ToxiUltra real-time CO monitors on the lower and upper decks of the houseboats, designated with pentagons, are shown in Figures 4 through 7 (3 boats rafted together) and Figure 8 (single boats with ECD). The monitors were placed at various locations on the upper and lower decks of the houseboat to provide representative samples of occupied areas. Because people commonly enter and exit the water via the boats=stern swim platforms, several monitors were placed on this structure.

RESULTS

Results of Air Sampling with ToxiUltra CO Monitors

Real-time CO monitoring results at various locations on the houseboats are shown in Figures 9 through 11. The summary statistics for this data are provided in Tables I through VI. CO concentrations of concern are shown in bold Tables I through VI.

CO Concentrations on three Houseboats with Vertical Exhaust Stack (Rafted together stationary and underway)

CO concentrations for the three rafted houseboats are shown in Tables I through IV and in Figure 9. Figure 9 shows three different conditions:

underway, moving between the marina and cove
stationary, with boats 228, 185, and 240 rafted together
underway, moving from the cove back to the marina

The data presented in Figure 9 shows that when the stationary houseboats were rafted together, the vertical exhaust stack effectively controlled the CO concentrations. There were two small increases in CO concentrations when the drive engines were briefly started to reposition the houseboats after they had begun to drift.

In Tables I through IV, the CO concentrations were extremely low on the upper and lower decks when the boats were stationary and rafted. The highest mean concentration was 2 ppm on the lower stern starboard side of houseboat #240. The highest peak CO concentration was 14 ppm on the lower, rear, deck of houseboat 228.

Measured CO concentrations were substantially higher when the boats were underway because the uncontrolled drive engines were operating. Table III shows that a mean CO concentration of 77.1 ppm was measured on the lower stern deck of houseboat 185. The peak concentration at the same location was 447 ppm. Because Houseboat 240 had the cleaner burning Evinrude Ficht drive engines rather than the Volvo drive engines on houseboats 228 and 185, the CO concentrations were substantially lower for houseboat 240 compared with the other 2 houseboats. Again, this can be seen in Table III where the highest mean CO concentration on the lower stern deck of boat 240 was only 18 ppm compared to 37 ppm and 77 ppm on the lower stern decks of boats 228 and 185, respectively.

CO Concentrations on Houseboats operating with and without the Production ECD

Real-time results of the ECD evaluations on boats 22 and 340 are shown in Figures 10 and 11. The summary statistics are provided in Tables V and VI. Figure 10 shows that the real-time CO concentrations ranged from approximately 50 ppm to near 600 ppm when the generator on houseboat 22 did not use the ECD. With the ECD connected, CO concentrations ranged from approximately 50 ppm to 300 ppm. Summary statistics for this experiment in Table V show that the ECD was able to reduce the mean CO concentrations for most locations on houseboat 22. The percent reduction ranged from approximately 60% to less than 10%. There was a minor increase in CO concentrations measured in the kitchen. In several locations, the peak CO concentrations increased slightly after the ECD was connected.

Data from the ECD tests on houseboat 340 are shown in Figure 11 and Table VI. Figure 11 shows that four generator exhaust conditions were evaluated:

- Vertical exhaust stack only

- Rear exhaust- No control
- ECD only
- ECD and vertical exhaust stack

Use of the vertical exhaust stack allowed the researchers to sample directly into the generator exhaust for comparison purposes. Figure 11 shows that the CO concentrations on the rear swim deck with the ECD operating approached 600 ppm. When the vertical exhaust stack was used either with or without the ECD, CO concentrations on the houseboat were much lower (50 ppm or less).

The data summarized in Table VI provide greater insight into the data in Figure 11. For example, the highest mean CO concentration for the stack only or for the stack and ECD together was 3 ppm (stern deck, back of slide), while the highest mean for no control was 154.8 ppm (swim platform). The highest mean for the ECD only was 70 ppm. Comparison of CO peak concentrations showed similar trends to the CO mean results. The highest peak concentration when only using the vertical exhaust stack was 27 ppm; however, the highest peak concentration for the ECD only was 563 ppm on the port-side of the swim platform. This value exceeded the highest peak CO concentration of 494 ppm measured on the starboard side of the swim platform when the generator operated with no control.

Gas Emissions Analyzer, Detector Tubes, and Evacuated Container Results

Gas emissions analyzers, detector tubes, and glass evacuated containers were used to characterize CO concentrations in and near the exhaust stack, on the swim platform, and under the lower stern deck. This equipment was utilized because it is capable of reading higher CO concentrations than the ToxiUltra CO monitors which have an upper limit of approximately 1,000 ppm.

Data collected with the emissions analyzer is shown in Figure 12. This data was measured directly in the generator exhaust of houseboat 22 after passing through the ECD and a vertical exhaust stack. As can been seen in the graph, CO concentrations initially increased rapidly exceeding eleven percent CO during the cold start and then stabilized between three and four percent.

Detector tube and evacuated container data are shown in Tables VII and VIII. The data in these tables show results for each of the conditions tested. In general, CO concentrations measured on the rafted houseboats were extremely low and in many cases no CO was detected. CO concentrations measured directly in the exhaust stack ranged from one to seven percent. A lot of variation was also observed when ECD performance was evaluated. For example, Table VII shows that CO concentrations of between one and four percent were measured in the vertical exhaust stack when the ECD was operating. CO concentrations of 60 and 100 ppm were measured under the lower stern deck. The evacuated container results in Table VIII were similar to the detector tube results. There was significant variation in the CO concentrations measured based upon the generator operating conditions.

Wind and Stack Velocity Measurements

Wind velocity measurements were gathered during the survey with an ultrasonic anemometer. Data was primarily gathered while the houseboats were stationary. Much of the testing occurred at the marina where the boats were oriented in the same direction. When sampling in the cove, an attempt was made to position the boats in a manner such that wind was moving from the stern of the houseboat (near the CO emission sources) toward the front of the houseboat to establish near worst case testing scenarios.

A summary of wind velocity data is shown in Table IX. This table provides data concerning the bearing of the houseboat, and the average wind direction, average wind speed, and standard deviations. As shown in the table, while at the marina, the houseboat was oriented at a direction of 300° NW. The exception to this orientation occurred during testing in the cove on Tuesday morning. Average wind speeds ranged from 1.7 m/sec to 4.7 m/sec. Average wind direction ranged from 147.1° SE to 172.9° SE.

Face velocities measured at the vertical exhaust stack of houseboat=s 185, 228, and 240 ranged from approximately 300 to 460 fpm. Stack temperatures ranged between 80 and 90 F while ambient temperatures were similar to the stack temperatures.

DISCUSSION AND CONCLUSIONS

The CO hazard to swimmers and occupants on houseboats that have gasoline-powered generators can be greatly reduced by retrofitting engineering control systems to the generators. Previous 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). The present study evaluated the vertical exhaust stack on three houseboats that had been rafted together and the performance of two production ECDs.

Stack Exhaust

Data gathered when the houseboats were rafted together showed that the vertical exhaust stack performed well and kept CO concentrations on both decks of the houseboat below hazardous levels. The highest mean CO concentration on the lower deck of a boat was 2 ppm. The highest mean concentration on the upper deck of a houseboat was 0.9 ppm. These values are indeed impressive and represent a dramatic improvement to the safety of houseboat users. In order to achieve these remarkably low levels of CO on a houseboat, it is important that the vertical exhaust stack, water separator, and associated piping and hoses be designed and installed properly. It is also clear that on any of these boats, uncontrolled exhaust from a gasoline-powered generator that is close to the water and boat could potentially be hazardous.

ECD Performance

Results from the ECD evaluation raised several concerns. Performance of the ECD dramatically degraded compared to previous evaluations when the ECD was new. Mean CO concentrations of approximately 44 ppm were measured on the lower, stern deck of houseboat 22, and a peak CO concentration of 260 ppm was measured exceeding the NIOSH ceiling level. On houseboat 340 a mean CO concentration of 70 ppm was measured on the lower stern deck and a peak of 563 ppm was measured. These high concentrations exceeded acceptable levels and present a potential health hazard.

ECD performance is related to generator operation and maintenance. Generators can run inefficiently, due to fouled spark plugs, bad ignition wires, defective carburetors, or malfunctioning chokes. Poor operation can cause the CO and hydrocarbon concentration to increase, and the electronic spark inside of the ECD can ignite unburned fuel in the catalyst. Over time (sometimes a few hours) this event can dramatically degrade performance or even destroy the ECD. An examination of the existing generator, spark plugs, and exhaust elbows showed that the spark plugs were badly fouled and there was significant blockage in an exhaust elbow that could have caused the poor ECD performance that was observed (Figures 13 and 14).

There are a number of similarities between the operation of an automobile engine and a marine generator. Westerbeke Corporation uses a 45 mile per hour conversion factor to compare generator operating hours to automotive miles driven. (5,000 generator operating hours is roughly equivalent to 225,000 miles driven in an auto and 8,000 generator operating hours relates to 360,000 miles driven in a car). The Forever Resort houseboats that were tested had over 5,000 hours on the spark plugs and over 8,000 hours on the distributor cap, rotor and ignition wires. Since this testing, Forever Resorts has made changes in the maintenance program to inspect and service their houseboat generators on more frequent intervals.

Other Reported ECD Concerns

Marinas International operates fifteen marinas across the U.S. and provides a full spectrum of services including boat rentals. The marinas are located in seven different states. In the Spring of 2002, Marinas International purchased and installed approximately 50 ECDs on their houseboat generators. Thirty-seven of the generators were made by Westerbeke and the remainder by Kohler. Forty generators were 12.5 Kw and the remainder were 15 Kw. Most, but not all, of the generators were older, some having 7,000 to 8,000 hours of operation. In general, if the generator ran well the ECD was fine, but if the generator needed to be tuned up, problems occurred. In some cases the ECD got so hot that it became Acherry red@ creating a potential fire hazard. Marinas International reported ECD failures on between 25-30 of their generators

Following development of the ECD, over 300 ECDs have been sold and installed on houseboats. During the past year, several problems have occurred with production ECDs. Four rental customers have had ECD failures. This problem is likely to be related to inadequate routine generator maintenance especially on rental boats having 2,000 to 3,000 operating hours during a season. Approximately 100 of the 300 ECDs have been installed on private rather than rental boats. No problems have been reported on private boats. Rental operations are frequently short staffed and have limited resources causing preventative maintenance to suffer. Enviromarine is working with the rental docks that have installed ECDs and experienced problems to get their generators running properly.

On all of the units that failed, none had a high temperature shut-off safety switch. They were early production units that the owners did not want the Generator shutting down while being rented. A thermal safety switch has been installed on approximately 80 newer ECDs. This switch shuts down the generator if the temperature exceeds 500 °F, but is not designed to indicate that high CO concentrations are present. According to Enviromarine, the surface temperature on the ECD casing should be between 180 °F and 280 °F.

Fire Safety

It is important to ensure that in the process of eliminating one hazard (CO), another hazard (fire and explosion) is not created. The problems noted above present a potential fire hazard and should be avoided. The production ECD was tested for ignition protection by Imanna Laboratories (Rockledge, FL), an independent third party test facility that specializes in marine testing (Imanna, 2001). The Enviromarine system passed all of the requirements for use in a gasoline engine room including:

1. Ignition test requirements of International Standards Organization (ISO) 8864, Air-conditioning and ventilation of wheel houses on board ships - Design conditions and basis of calculations,

2. United States Coast Guard (USCG) stated in Title 33 CFR 183.410, Ignition Protection,

3. Society of Automotive Engineers (SAE) J1171 Standard, Ignition Protectionof Marine Products for unsealed devices,

At no time during the high temperature operating test was a temperature in excess of the limit of the ignition protection standards (392 °F or 200 °C) detected on any exposed surfaces.

Despite ECD success during Imanna testing, ECD users must be diligent because of the potential fire hazard related to inadequate generator maintenance. Use of the high-temperature shut-off switch should help to address this concern.

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 with gasoline-powered generators should be aware of and concerned about the location of the exhaust terminus. Based on data from numerous NIOSH field surveys, we recommend that houseboats with gasoline-powered generators be evaluated for potential CO exposures and poisonings and retrofitted with control systems to reduce the potential hazard of CO poisoning.

2) The vertical exhaust stack on Fun Country Marine houseboats performed well during the current study. Based upon the results of this and previous NIOSH evaluations of the vertical exhaust stack, NIOSH research indicates that when properly designed and installed, the vertical stack is a viable, low-cost, engineering control that will dramatically improve the safety of houseboat users.

3) The performance of the emission control device (ECD) during the current evaluation has raised several important issues concerning long-term performance. Due to the complications observed, including degradation in CO removal efficiency and reported high-temperature failures, additional testing of this device is necessary.

To date, most of the NIOSH evaluations of the ECD provided large quantities of data for a relatively small number of devices used on houseboats at Lake Mead. It would be helpful, to collect additional data regarding reliability and performance of a larger number of ECDs to see if performance characteristics are repeatable. Because of the performance issues identified during the current and previous ECD evaluations, it would be prudent for houseboat manufacturers who use the ECD on their generators to use the ECD with either a stack, or side exhaust with a warning device, and that periodic air sampling and emissions testing be performed. It would also be prudent to ensure that all new and existing ECDs be fitted with a thermocouple and shut-off switch to prevent overheating and potential fire hazards. Previous NIOSH evaluations of the ECD have focused on the devices ability to control CO emissions and exposures; however, the issue of ECD overheating has now become a concern and sufficient attention should be given to this issue to ensure that use of this device does not present an additional hazard.

4) As new engineering control devices for reducing CO emissions and exposures are developed, independent testing is needed to ensure that these systems perform adequately. These future devices could utilize a variety of methods to reduce the hazard. However, they all need independent testing and evaluation to ensure that they will meet the needs of the boating public.

5) 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.N.P.S. (United States National Park Service) 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. 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. Labeling should also be used for all exhaust terminus locations.

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Table I--CO Concentrations (ppm)
Lower Deck of Three Rafted Houseboats with vertical exhaust stacks
Stationary with Generator Only and Stationary with Generator and Drive Engines On
(Monday - 9/30/02)

Sample Location (Sample #)	Stationary Generator On	Stationary Generator and Drive Engines On
Kitchen Houseboat 228 (Sample #1)	Mean = 0 Std. Dev. = 0 Peak = 0 N = 626	Mean = 0 Std. Dev. = 0 Peak = 0 N = 72
Lower Stern Deck Houseboat 228 (Sample #2)	Mean = 1.0 Std. Dev. = 0.7 Peak = 6.0 N = 626	Mean = 10.2 Std. Dev. = 17.8 Peak = 82.0 N = 72
Kitchen Houseboat 185 (Sample #5)	Mean = 0.3 Std. Dev. = 0.5 Peak = 2.0 N = 626	Mean = 0.3 Std. Dev. = 0.4 Peak = 1.0 N = 72
Lower Stern Deck Houseboat 185 (Sample #6)	Mean = 0 Std. Dev. = 0 Peak = 0 N = 626	Mean = 7.0 Std. Dev. = 12.1 Peak = 72.0 N = 504
Lower Stern Deck (Starboard) Houseboat 240 (Sample #12)	Mean = 2.0 Std. Dev. = 1.0 Peak = 8.0 N = 626	Mean = 5.3 Std. Dev. = 3.4 Peak = 12.0 N = 70
Kitchen Houseboat 240 (Sample #13)	Mean = 0.8 Std. Dev. = 0.4 Peak = 2.0 N = 626	Mean = 0.7 Std. Dev. = 0.5 Peak = 1.0 N = 72
Lower Stern Deck (Port) Houseboat 240 (Sample #14)	Mean = 1.4 Std. Dev. = 0.6 Peak = 3.0 N = 626	Mean = 8.3 Std. Dev. = 23.6 Peak = 144.0 N = 70

N = number of data points
ND = non detected

Table II--CO Concentrations (ppm)
Upper Deck of Three Rafted Houseboats with vertical exhaust stacks
Stationary with Generator Only and Stationary with Generator and Drive Engines On
(Monday - 9/30/02)

Sample Location (Sample #)	Stationary Generator On	Stationary Generator and Drive Engines On
Upper Stern Deck Houseboat 228 (Sample #3)	Mean = 0.9 Std. Dev. = 0.5 Peak = 3.0 N = 626	Mean = 5.4 Std. Dev. = 6.9 Peak = 27.0 N = 72
Upper Center Houseboat 228 (Sample #4)	Mean = 0 Std. Dev. = 0 Peak = 0 N = 626	Mean = 0 Std. Dev. = 0 Peak = 0 N = 72
Upper Stern Deck Houseboat 185 (Sample #7)	Mean = 0.3 Std. Dev. = 0.6 Peak = 2.0 N = 626	Mean = 13.1 Std. Dev. = 13.5 Peak = 56.0 N = 72
Upper Center Houseboat 185 (Sample #8)	Mean = 0.2 Std. Dev. = 0.4 Peak = 2.0 N = 626	Mean = 0.2 Std. Dev. = 0.4 Peak = 1.0 N = 72
Upper Stern Deck (Port) Houseboat 240 (Sample #9)	Mean = 0.6 Std. Dev. = 0.5 Peak = 2.0 N = 626	Mean = 1.6 Std. Dev. = 1.0 Peak = 4.0 N = 72
Upper Stern Deck (Starboard) Houseboat 240 (Sample #10)	Mean = 0 Std. Dev. = 0 Peak = 0 N = 626	Mean = 0 Std. Dev. = 0 Peak = 0 N = 72
Upper Center Houseboat 240 (Sample #11)	Mean = 0.3 Std. Dev. = 0.5 Peak = 2.0 N = 626	Mean = 0.3 Std. Dev. = 0.4 Peak = 1.0 N = 72

N= number of data points
ND = non detected

Table III
CO Concentrations (ppm)
Lower Decks of Three Houseboats with vertical exhaust stacks
Stationary, Rafted on Beach in Cove and Separated Underway
(Tuesday - 10/1/02)

Sample Location (Sample #)	Stationary Generator On	Underway Generator and Drive Engines On
Kitchen **Houseboat 228** **(Sample #1)**	Mean = 1.2 Std. Dev. = 0.4 Peak = 2.0 N = 167	Mean = 2.3 Std. Dev. = 3.8 Peak = 42 N = 368
Lower Stern Deck **Houseboat 228** **(Sample #2)**	Mean = 0.8 Std. Dev. = 1.9 Peak = 14 N = 167	**Mean = 37.0** **Std. Dev. = 40.1** **Peak = 224** **N = 368**
Kitchen **Houseboat 185** **(Sample #5)**	Mean = 0 Std. Dev. = 0 Peak = 0 N = 167	Mean = 0.3 Std. Dev. = 0.5 Peak = 4.0 N = 368
Lower Stern Deck **Houseboat 185** **(Sample #6)**	Mean = 0 Std. Dev. = 0 Peak = 0 N = 167	**Mean = 77.1** **Std. Dev. = 74.4** **Peak = 447** **N = 368**
Lower Stern Deck **(Starboard)** **Houseboat 240** **(Sample #12)**	Mean = 0.8 Std. Dev. = 0.7 Peak = 4.0 N = 167	**Mean = 18.0** **Std. Dev. = 33.3** **Peak = 309** **N = 368**
Kitchen **Houseboat 240** **(Sample #13)**	Mean = 0 Std. Dev. = 0 Peak = 0 N = 167	Mean = 0 Std. Dev. = 0 Peak = 0 N = 368
Lower Stern Deck **(Port)** **Houseboat 240** **(Sample #14)**	Mean = 1.3 Std. Dev. = 1.3 Peak = 12.0 N = 167	Mean = 12.1 Std. Dev. = 18.5 Peak = 181 N = 368

N = number of data points

Table IV
CO Concentrations (ppm)
Upper Decks of Three Houseboats with vertical exhaust stacks
Stationary, Rafted on Beach in Cove and Separated Underway
(Tuesday - 10/1/02)

Sample Location (Sample #)	Stationary Generator On	Underway Generator and Drive Engines On
Upper Stern Deck Houseboat 228 (Sample #3)	Mean = 0.9 Std. Dev. = 1.5 Peak = 9.0 N = 167	Mean = 14.1 Std. Dev. = 14.8 Peak = 78.0 N = 368
Upper Center Houseboat 228 (Sample #4)	Mean = 0.9 Std. Dev. = 0.4 Peak = 2.0 N = 167	Mean = 1.5 Std. Dev. = 1.4 Peak = 10.0 N = 368
Upper Stern Deck Houseboat 185 (Sample #7)	Mean = 0 Std. Dev. = 0 Peak = 0 N = 167	**Mean = 24.2** **Std. Dev. = 21.9** **Peak = 114.0** **N = 368**
Upper Center Houseboat 185 (Sample #8)	Mean = 0.1 Std. Dev. = 0.5 Peak = 1.0 N = 167	Mean = 1.6 Std. Dev. = 2.3 Peak = 19.0 N = 368
Upper Stern Deck (Port) Houseboat 240 (Sample #9)	Mean = 0.4 Std. Dev. = 0.7 Peak = 4.0 N = 167	Mean = 2.1 Std. Dev. = 3.9 Peak = 28.0 N = 368
Upper Stern Deck (Starboard) Houseboat 240 (Sample #10)	Mean = 0.7 Std. Dev. = 0.8 Peak = 5.0 N = 167	Mean = 1.4 Std. Dev. = 2.2 Peak = 20.0 N = 368
Upper Center Houseboat 240 (Sample #11)	Mean = 0 Std. Dev. = 0 Peak = 0 N = 368	Mean = 0 Std. Dev. = 0 Peak = 0 N = 368

N = number of data points

Table V
Comparison of CO Samples (ppm) on Houseboat #22 for the Generator Alone with and without the production ECD (Rear Exhaust)

Sample Location (Sample #)	Stationary, without ECD	Stationary, with ECD
Lower deck Kitchen (#1)	Mean = 0.8 Std. Dev. = 0.4 Peak = 2.0 N = 171	Mean = 1.2 Std. Dev. = 0.6 Peak = 3.0 N = 348
Swim deck Port side (#2)	**Mean = 48.2** **Std. Dev. = 35.6** **Peak = 158 N = 171**	**Mean = 22.6** **Std. Dev. = 23.6** **Peak = 196.0 N = 348**
Swim Platform Port side (#3)	Mean = 6.0 Std. Dev. = 4.0 Peak = 16.0 N = 171	Mean = 1.6 Std. Dev. = 2.6 Peak = 23.0 N = 348
Swim Platform Starboard side (#4)	**Mean = 104.6** **Std. Dev. = 105.8** **Peak = 560.0 N = 171**	**Mean = 43.9** **Std. Dev. = 44.8** **Peak = 260.0 N = 348**
Swim deck Starboard side (#5)	Mean = 5.2 Std. Dev. = 6.1 Peak = 31.0 N = 171	Mean = 4.3 Std. Dev. = 5.8 Peak = 35.0 N = 348
Swim deck Back of slide (#6)	Mean = 10.3 Std. Dev. = 13.2 Peak = 66 N = 171	Mean = 5.1 Std. Dev. = 7.6 Peak = 54 N = 348
Top Stern Deck Port side (#7)	Mean = 7.3 Std. Dev. = 4.4 Peak = 25.0 N = 171	Mean = 2.7 Std. Dev. = 1.8 Peak = 54.0 N = 348
Top Stern Deck near slide (#8)	Mean = 3.2 Std. Dev. = 2.2 Peak = 10.0 N = 171	Mean = 1.5 Std. Dev. = 1.3 Peak = 8.0 N = 348
Top Deck Center of boat (#9)	Mean = 0.8 Std. Dev. = 0.4 Peak = 1.0 N = 171	Mean = 0.4 Std. Dev. = 0.5 Peak = 1.0 N = 348
Top Deck Front Center of boat (#10)	Mean = 1.7 Std. Dev. = 0.5 Peak = 3.0 N = 171	Mean = 1.6 Std. Dev. = 0.5 Peak = 3.0 N = 348

N = number of data points

Table VI
Comparison of CO Samples (ppm) on Houseboat #340 while stationary
Generator Alone with and without the production ECD (Rear Exhaust)

Sample Location (Sample #)	Stack only	Rear Exhaust No Control	Rear Exhaust ECD only	ECD and stack
Lower deck Kitchen (#1)	Mean = 1.2 Std. Dev. = 0.7 Peak = 3.0 N = 78	Mean = .8 Std. Dev. = .6 Peak = 2 N = 66	Mean = 0.4 Std. Dev. = 0.5 Peak = 1 N = 73	Mean = 0.1 Std. Dev. = 0.4 Peak = 1.0 N = 200
Swim deck Port side (#2)	Mean = 2.0 Std. Dev. = 4.4 Peak = 21 N = 78	**Mean = 59.3** **Std. Dev. = 103.5** **Peak = 464 N = 66**	**Mean = 23.8** **Std. Dev. = 54.0** **Peak = 213 N = 73**	Mean = 0 Std. Dev. = 0 Peak = 0 N = 200
Swim Platform Port side (#3)	Mean = NA Std. Dev. = NA Peak = NA N = NA	Mean = NA Std. Dev. = NA Peak = NA N = NA	**Mean = 70.0** **Std. Dev. = 130.7** **Peak = 563 N = 73**	Mean = 0.1 Std. Dev. = 0.5 Peak = 2 N = 200
Swim Platform Starboard side (#4)	Mean = 2.8 Std. Dev. = 3.8 Peak = 15 N = 78	**Mean = 154.8** **Std. Dev. = 113.5** **Peak = 494 N = 66**	Mean = 0.7 Std. Dev. = 1.1 Peak = 5 N = 73	Mean = 0.1 Std. Dev. = 1.0 Peak =3 N = 200
Swim deck Starboard side (#5)	Mean = 2.4 Std. Dev. = 2.7 Peak = 12 N = 78	**Mean = 32.0** **Std. Dev. = 32.6** **Peak = 128 N = 66**	Mean =3.8 Std. Dev. = 7.5 Peak = 41 N = 73	Mean = 0.4 Std. Dev. = 0.5 Peak = 2 N = 200
Swim deck Back of slide (#6)	Mean = 3.0 Std. Dev. = 5.9 Peak = 27 N = 78	**Mean = 35.5** **Std. Dev. = 42.4** **Peak = 180 N = 66**	Mean = 15.3 Std. Dev. = 24.6 Peak = 105 N = 73	Mean = 0.1 Std. Dev. = 0.5 Peak = 1 N = 200
Top Stern Deck Port side (#7)	Mean = 2.0 Std. Dev. = 4.2 Peak = 20 N = 78	Mean = 15.1 Std. Dev. = 17.3 Peak = 91 N = 66	Mean = 0 Std. Dev. = 0 Peak = 0 N = 73	Mean = 0.1 Std. Dev. = 1.2 Peak = 5 N = 200
Top Stern Deck near slide (#8)	Mean = 2.0 Std. Dev. = 4.5 Peak = 19 N = 78	Mean = 6.7 Std. Dev. = 8.4 Peak = 36 N = 66	Mean = 1.0 Std. Dev. = 3.9 Peak = 17 N = 73	Mean = 0.1 Std. Dev. = 0.5 Peak = 1 N = 200
Top Deck Center of boat (#9)	Mean = 2.0 Std. Dev. = 3.4 Peak = 18 N = 78	Mean = 0.2 Std. Dev. = 1.3 Peak = 3 N = 66	Mean = 0.3 Std. Dev. = 0.9 Peak = 3.0 N = 73	Mean = 0.1 Std. Dev. = 0.5 Peak = 1 N = 200
Top Deck Front Center of boat (#10)	Mean = 1.6 Std. Dev. = 3.9 Peak = 22 N = 78	Mean = 0.2 Std. Dev. = 0.9 Peak = 5 N = 66	Mean = 0 Std. Dev. = 0 Peak = 0 N = 73	Mean = 0.1 Std. Dev. = 0.5 Peak = 1 N = 200

N= number of data points
NA = not applicable

Table VII
Detector Tube Results.

Boat and Condition	**Detector Tube Location and Results**
3 boats with 9" stack, rafted together at dock	Boat 240, lower stern deck = ND Boat 240, lower stern deck = ND Boat 240, lower stern deck = ND Boat 240, sample in exhaust stack = 6.5% Boat 185, sample in exhaust stack = 3.1% Boat 228, sample in exhaust stack = 1.5%
Boat 228 underway	on lower stern deck = 100 ppm
3 boats with 9" stack, rafted together beached	Boat 228, lower stern deck = ND Boat 185, lower stern deck = ND
Boat 22 at dock	generator operating without ECD, under stern deck = 0.3% generator operating with ECD, under stern deck = 100 ppm generator operating with ECD, under stern deck = 60 ppm
Boat 340 at dock	generator operating with ECD, 6" above side exhaust = 100 ppm beneath lower stern deck with 2 Ficht outboards on = 10 ppm
Boat 22	generator on without ECD (cold start sample in stack = 7.0%) generator on without ECD (sample in stack = 1.5%) generator on without ECD (stern exh, near deck = 2,000 ppm) generator on with ECD (lower rear deck = 50 ppm) generator on with ECD and stack, (sample in stack = 3.8%) generator on with ECD and stack, (sample in stack = 1.0%) generator on with ECD and stack, (sample in stack = 1.5%)

ND = non detected

Table VIII
Evacuated Container Results.

Boat and Condition	**Detector Tube Location and Results**
	Boat 228, lower stern deck, drive eng on, stationary = 157 ppm Boat 228, top stern deck, drive eng on, stationary = ND
3 boats with 9" stack, rafted together at beach	Boat 228, generator on, lower stern deck = ND Boat 185, generator on, lower stern deck = ND Boat 228, in exhaust stack = 10,200 ppm
Boat 22 at dock	Gen on without ECD, under stern deck = 52 ppm Gen on without ECD, on stern deck = 38 and 152 ppm Gen on without ECD, top stern deck = ND
Boat 340 at dock	Gen on with ECD, 6 inches from side exhaust = 20 ppm Gen on without ECD, sample in stack = 113,400 ppm Gen on without ECD, sample in stack = 25,800 ppm Gen on without ECD, top deck = ND Gen on without ECD, bottom deck = ND Gen on without ECD, lower stern deck, near water = 2,300 ppm Gen on without ECD, lower stern deck, breathing zone = 9 ppm Gen on without ECD, top deck, breathing zone = 3 ppm Gen on with ECD, lower stern deck, near water = 172 ppm Gen on with ECD, lower stern deck, near water = 7 ppm Gen on with ECD, lower stern deck, breathing zone = 8 ppm Gen on with ECD, top stern deck, = 1 ppm Gen on with ECD, sample in stack = 52,200 ppm Gen on with ECD, sample in stack = 21,300 ppm

ND = non detected

Table IX
Boat Heading and Wind Velocity Data.

Day	Houseboat Bearing	Average Wind direction	Average Wind Speed	Standard Deviation Wind Speed
Monday afternoon (marina)	300°	151.3°	3.8 m/sec	1.1 m/sec
Tuesday, morning (cove)	20°	147.1°	4.7 m/sec	1.3 m/sec
Wednesday, morning (marina)	300°	172.9°	3.2 m/sec	1.0 m/sec
Thursday, afternoon (marina)	300°	154.1°	1.7 m/sec	0.6 m/sec