AN EVALUATION OF SIDE EXHAUST AND PROTOTYPE AND PRODUCTION EMISSION CONTROL DEVICES TO PREVENT CARBON MONOXIDE POISONINGS FROM GENERATOR EXHAUST ON HOUSEBOATS

G. Scott Earnest, Ph.D., P.E., C.S.P.
Bryan Beamer, M.S., P.E.
Kevin Dunn, M.S., C.I.H.

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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

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Manuscript Prepared by:	Bernice L. Clark

DISCLAIMER

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EXECUTIVE SUMMARY

Researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of carbon monoxide emissions and control 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. Emission and dispersion characteristics of side-exhausted generators and the performance of several emission control devices (ECDs) that were manufactured by Enviromarine LLC, were studied.

Recently developed prototype and production ECDs were retrofitted onto gasoline-powered generators used on houseboats to reduce the hazard of carbon monoxide (CO) poisonings from the exhaust. The prototype ECD had previously been evaluated by NIOSH when it was new and had been used on a houseboat generator for approximately 3,000 hours since the previous testing. The production ECD had several modifications from the prototype and had not been previously evaluated or used.

Study results presented in this report address CO emission and exposure performance of side-exhaust houseboats that had been rafted together and the performance of prototype and production ECDs that were rear exhausted. The majority of data gathered during ECD testing involved direct emissions monitoring rather than ambient air sampling. Tests were conducted to evaluate the performance of both ECDs during cold starts and under various loading conditions. Environmental monitoring was conducted for several air contaminants that had not been previously evaluated. This and future research reports will be shared with the U.S. Coast Guard office of Boating Safety and the American Boat and Yacht Council for potential future rulemaking and standard setting.

Based upon the results of this study, with side exhausted houseboats, it is clear that any uncontrolled exhaust from a gasoline-powered generator that is close to the water and boat could potentially be hazardous. Peak and average CO concentrations on the lower deck of three rafted, side-exhausted houseboats exceeded 1,000 ppm and 140 ppm respectively. CO concentrations near the waterline were even higher.

The current evaluation also showed that the ECD provided a safer environment to individuals on or near the houseboat, when compared to generators having no ECDs. Mean and peak CO concentrations were reduced at numerous locations on the houseboat when the ECD was operating. Average and peak CO concentrations were typically reduced by greater than 75% on the houseboat's lower deck; however, because measured CO concentrations were fairly low with the generator operating without the ECD, the magnitude of the CO reduction was fairly small. Emissions testing demonstrated that both the prototype and production ECDs were able to reduce generator CO emissions by over 50% during cold-starts and by several orders of magnitude during normal operating conditions when compared to the generator operating with no ECD. Comparison of the results from the prototype and production ECDs indicated that the design of

the production ECD is superior to the prototype version. Both versions were able to reduce CO concentrations, but the production model was more effective. It was also learned that brief (less than 1 minute) peak CO concentrations may occur during cold starts with the prototype or production ECD and that generator loading influences ECD performance.

Based upon the results of this and earlier studies, NIOSH investigators recommend that U.S. houseboats using gasoline-powered generators, should be evaluated for potential CO exposures and poisonings near the lower rear 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 performance of the evaluated ECDs was generally good and design modifications in the production model should enhance long term performance. NIOSH researchers continue to believe that the ECD is a promising emission control option. Because some performance complications were noted with the prototype ECD, additional testing and evaluation of production ECDs, having substantially more hours of operation, is warranted.

BACKGROUND

On October 29 through November 1, 2001, researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of side exhausted generators and several emission control devices (ECDs) retrofitted onto houseboat generators at Callville Bay Marina on Lake Mead, Nevada. A recently manufactured, prototype ECD was studied by NIOSH researchers during a field survey in June 2001 and further testing was recommended (Earnest, Dunn et al. 2001). This report provides background information and describes our evaluation methods, results, conclusions, and recommendations.

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. 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 a 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 2000 investigation 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). Engineering control studies began in February 2001 at Lake Powell and Somerset, Kentucky, (Dunn, Hall et al. 2001; Earnest, Dunn et al. 2001). Results from these studies 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 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 this problem. Following the meeting, NIOSH researchers were asked to evaluate the performance of an 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 interlock as a primary control option.

Beginning in September 2001, representatives of Fun Country Marine conducted periodic CO monitoring on the lower, rear deck of the houseboat utilizing the prototype ECD technology. A Genesis Electrochemical CO monitor (GasTech Inc., Newark, CA) was used. Results of this air sampling that was shared with NIOSH researchers indicated that CO concentrations were typically near zero ppm.

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 additional field evaluations and computational fluid dynamics (CFD) modeling to evaluate controls for carbon monoxide on houseboats and other marine vessels. The current study is part of this effort.

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 are provided for reference only and 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.

Ozone was sampled because there was some concern that the high voltages used on the ECDs had the potential to produce this gas. Ozone gas is an irritant of the mucous membranes (eyes, nose, throat) and lungs. Ozone is a chemical capable of inducing significant adverse health effects at low exposure concentrations, tenths of a ppm, with the susceptibility of exposed humans appearing to be at least equal to the most susceptible animal species. Ozone is also recognized as an agent which mimics the effects of ionizing radiation, capable of inducing premature aging changes (including thickening of alveolar septa) following exposures of 0.2 to 1 ppm. Air concentrations of ozone in excess of a few tenths of a ppm cause occasional discomfort to exposed individuals in the form of headache, eye irritation and dryness of the mucous membranes of the nose and throat. Based on the results of several studies, the threshold for effects in humans appears to be between 0.2 and 0.4 ppm (NIOSH 1977).

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 of 1,200 ppm (NIOSH 2000). The American Conference of Governmental Industrial Hygienists' (ACGIH®) recommends an 8-hour TWA threshold limit value (TLV®) for occupational exposure of 25 ppm (ACGIH 1996) and discourages exposures above 125 ppm for more than 30 minutes during a workday. The Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for CO is 50 ppm for an 8-hour TWA exposure (CFR 1997).

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

The 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).

METHODS

Measurements of CO and other air contaminants, ventilation, and wind-velocity were collected on four different houseboats built by Fun Country Marine Industries Inc (Muncie, IN). A photo of one of the evaluated houseboats is shown in Figure 1. The houseboats were approximately 2-3 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, during cold-starting, and under a variety of loading conditions. A description of the houseboats and engineering controls are provided below:

Description of the Evaluated Houseboats

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), 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: prototype and production Enviromarine LLC emissions control devices (ECDs) 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 (used for emissions testing); 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

2. **Houseboats #258, #240, #259**

   Engines: 2, 115 horsepower (hp) 4 cylinder, 2 cycle, Evinrude FICHT® outboard engines
   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: 59 ft. X 14 ft.
   Approximate dimensions of space below swim platform: 3 ft. X 14 ft. X 1.5 ft.
   Exhaust Configuration: 1) exhaust through original muffler and transom starboard side

Description of the Bench Test Configuration

1. **Kohler Generator**
   12.5 Kw Kohler, 4 cylinder, 4 stroke, 1,800 revolutions per minute (rpm), 79.0 cubic inches (in^3)
   Exhaust Configuration: Two options: 1) exhaust through production emissions control device (ECD); or 2) exhaust without ECD

Two inboard Volvo, 4-cylinder engines were used to provide propulsion for houseboat #22, and two Evinrude FICHT® outboard engines provided propulsion for the other three boats. The Evinrude FICHT® engines were fuel injected and designed to provide lower emissions than a typical carbureted engine. The 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. Houseboat #22 had a 15 Kw Westerbeke generator, and the other three boats had 12.5 Kw Kohler generators. A fourth 12.5 Kw Kohler generator was evaluated on a bench in a marine maintenance facility. Westerbeke generators are used on nearly 75% of houseboats in the U.S. (Westerbeke 2001).

When used on houseboats, the hot exhaust gases from the generators are injected with water near the end of the exhaust manifold in a process commonly called "water-jacketing." Water-jacketing is used for exhaust cooling and noise reduction. Because the generator 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. Houseboat #22 which was evaluated with and without the ECDs was rear exhausted, and houseboat #'s 258, 240, and 259 were side exhausted.

Description of the Evaluated Engineering Controls

The original exhaust system on houseboat #22 was modified to route the generator exhaust through an emissions control device (ECD) prior to the water jacketing 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. EnviroMarine L.L.C. (Whitehouse, TN) is currently developing and manufacturing the ECD for marine applications. 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, based on vendor literature (Envirolift 2001).

Two types of ECDs were evaluated during the current field survey: a prototype and a production model. The prototype ECD had previously been evaluated by NIOSH and at the time of the current study, it had approximately 3,000 hours of operating time. A photo of the two models are shown side by side in Figure 3, and a cross-sectional diagram of the prototype ECD is shown in Figure 4. There are several important differences between the prototype ECD and the production model. The outer shell of the prototype ECD was constructed from a combination of stainless steel and cast iron, and the shell of the production ECD was constructed exclusively from stainless steel. The prototype is 14 inches long and 5 inches in diameter. It weighs 8.5 lbs. The production model is 100% 316L stainless steel. It is 11 1/8 inches long and 5 inches in diameter. It weighs 6.9 lbs. The production ECD has been tested 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 Protection of Marine Products for unsealed devices,

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

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 is also mounted on rubber grommets to reduce vibration (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 several feet above the upper deck of the houseboat for sampling directly in the exhaust.

In the current survey, a stack was used to allow researchers to sample directly into the generator exhaust. In earlier surveys, the stack was evaluated as a carbon monoxide engineering control. 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. A 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. 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.

The evaluated ECD sells for approximately $4,000. The evaluated houseboats' original purchase price was approximately $165,000. New houseboats similar to the ones evaluated 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.

Area air samples were collected on thermal desorption media (Carbotrap 300 multi-bed thermal desorption tubes) to qualitatively identify volatile organic compounds. These samples were taken in order to more fully understand the various types of VOCs that are produced by the generator and ECD. Thermal desorption tubes are designed to trap a wide range of organic compounds for subsequent qualitative analysis via thermal desorption and GC-MS. Thermal desorption media for flow-level VOCs were prepared by the NIOSH laboratory using stainless steel tubes configured for thermal desorption in a Perkin-Elmer ATD 400 thermal desorption system. Each thermal desorption tube contained three beds of sorbent material: a front layer of Carbopack Y, a middle layer of Carbopack B, and a back section of Carboxen 1003.

The thermal desorption tubes were attached with Tygon tubing to personal sampling pumps, and the sampling trains were calibrated at a flow rate of 50 cubic centimeters per minute (cc/min). The air samples were collected using constant-volume SKC Model 223 low-flow sampling pumps. The pumps are equipped with a pump stroke counter and the number of strokes necessary to pull a known volume of air was determined during calibration. Flow rates and sample times were standardized (50 cc/min, 100 minute sample, 6 liter volume) to allow for comparison of results.

Ozone monitoring was conducted using a Metrosonics PM-7700 toxic gas monitor equipped with an ozone sensor. Each of these instruments was calibrated with a known concentration of chlorine prior to the site visit. Instrument sensor repeatability is two percent at an operating temperature of -5 to 400 °C.

CO and ozone concentrations were also measured with detector tubes [Draeger A.G. (Lubeck, Germany) CO, CH 29901– range 0.3% (3,000 ppm) to 7% (70,000 ppm)] and [O3, CH21001 – range 300 ppm and O3, 6733181 – range 0.7 ppm] in the areas below and near the rear swim deck and directly in the generator exhaust. The detector tubes are used by drawing air through the tube with a bellows–type pump. The resulting length of the stain in the tube (produced by a chemical reaction with the sorbent) is proportional to the concentration of the air contaminant.

Grab samples were collected using Mine Safety and Health Administration (MSHA) 50–mL glass evacuated containers. These samples were collected by snapping open the top of the glass container and allowing the air to enter. The containers were sealed with wax–impregnated MSHA caps. The samples were then sent to the MSHA laboratory in Pittsburgh, Pennsylvania, where they were analyzed for CO using a HP6890 gas chromatograph equipped with dual columns (molecular sieve and porapak) and thermal conductivity detectors.

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

Air flow from the exhaust 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 was performed over a 3-day period with four distinct operating conditions and two generator exhaust configurations that are listed below. The test conditions and operating configurations are summarized below:

1) **Boat Stationary** – Generator exhausting through the dry stack (for 5-gas emissions testing) or rear transom (for environmental CO sampling). The emissions of Boat 22 were tested with and without an ECD under various loading conditions. Cold starts were also evaluated.

2) **Boat Underway** – Generator exhausting through the side or rear transom. 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 (Figure 5). The trip to/from the marina lasted for approximately 30 minutes. This evaluation was also conducted over a two-day period with the side-exhaust tests run on October 29 (Boats 240, 258, 259) and the rear exhaust tests run on October 31 (Boat 22).

3) **Boats Tied Together** – Generator exhausting through the side transom. Evaluation of boats tied together included testing three boats (Boats 240, 258, 259) with the side generator exhaust configuration (Figure 6).

4) **Generator Bench Test** – The Kohler 12.5 kW generator was tested on October 31 in the maintenance bay with and without an ECD. Various loading conditions and cold-starts were evaluated (Figure 7).

Sampling locations for the ToxiUltra real-time CO monitors on the lower and upper decks of the houseboat, designated with pentagons, are shown in Figures 8 and 9 (3 boats tied together) and Figure 10 (single boat). The monitors were placed at various locations on both the upper and lower decks of the houseboat to provide representative samples of occupied areas when the generator was operating. Because people commonly enter and exit the water via the rear swim platform of the boat, two monitors were placed on either side of this structure.

RESULTS

Results of Air Sampling with ToxiUltra CO Monitors

Real-time monitoring results for CO concentrations at various locations on the houseboat are summarized in Tables II through IV.

Area Samples on Houseboats with Side Exhaust

The data on the CO concentrations in the three boats tied together, side exhaust configuration are presented in Tables II and III. The first row presents data when the generator is operating and the houseboats are stationary. The second row presents data when generator and drive engines are operating and the boats are underway.

The CO concentrations on the lower deck of the three houseboats were significantly higher than the CO concentrations on the upper decks of the boats. Average CO concentrations on the lower deck of the houseboats with the generator operating, ranged between 11 ppm on the rear deck of houseboat #258 to 142.7 ppm on the front deck of houseboat #240. Average CO concentrations on the upper deck of the houseboats with the generator operating ranged between 7.7 ppm on the rear deck of houseboat #258 to 23.5 ppm on the front deck of houseboat # 259. At certain locations, average CO concentrations exceeded 100 ppm (Sample #5) and peak concentrations exceeded 1,000 ppm (Sample #2).

The CO monitor placed on the lower rear deck, at the center of the swim platform on houseboat # 258 (Sample #1) indicated an average CO concentration of 11.0 ppm and a peak of 91.0 ppm with the generator operating. The same sample indicated an average of 31.1 ppm and a peak of 401.0 ppm when both the generator and drive engines were operating and the boat was underway. The monitor located at the lower, front deck of houseboat # 240 (Sample #5) had the highest average CO concentrations of 142.7 ppm and a peak of 425.0 ppm with the generator operating and an average CO concentration of 109.6 ppm and peak concentration of 510 ppm with both the generator and drive engines operating and the boat underway.

The CO monitor placed on the upper rear deck, at the center of the swim platform on houseboat # 258 (Sample #7) indicated an average CO concentration of 7.7 ppm and a peak of 40.0 ppm with the generator operating and an average of 6.7 ppm and a peak of 74 ppm when the generator and drive engines operating and the boat underway. The monitor located at the upper, front deck of houseboat # 259 (Sample #12) had the highest average CO concentrations on the upper decks of 23.5 ppm and a peak of 342.0 ppm with the generator operating. This same monitor had a lower average CO concentration and peak concentration of 12.6 ppm and 254 ppm, respectively, with both the generator and drive engines operating and the boat underway.

Area Samples on a Houseboat Operating with and without the Production ECD

Most of the CO concentrations measured on the single stationary houseboat with the generator operating were relatively low. All of the mean CO concentrations were below 5 ppm, and the peak CO concentrations were all below 35 ppm. CO concentrations were generally lower or in some cases the same on the houseboat when the generator operated with the production ECD compared to when it did not. In most cases, CO concentration fell by more than 50% when the generator operated with the production ECD. Peak CO concentrations were also reduced by the ECD.

The CO monitor placed on the lower rear deck, near the slide (Sample #1) indicated an average CO concentration of 1.5 ppm and a peak of 31.0 ppm with the generator operating and no ECD. This same sample location indicated an average of 0.3 ppm and a peak of 19.0 ppm when the generator was connected to the production ECD. The monitor located at the lower, front deck of the houseboat (Sample #5) had a mean CO concentration of 2.9 ppm and a peak of 13.0 ppm with the generator operating without the ECD. This same monitor had an average CO concentration of 0.6 ppm and a peak concentration of 3.0 ppm with both the generator connected to the ECD.

When the houseboat was underway, many of the average and peak CO concentrations were reduced when the production ECD was used; however, this observation was not universal. For example, mean CO concentrations increased from 169.6 ppm to 287.7 ppm on the lower deck near the slide (sample #1) and also increased slightly on the top deck near the slide (sample #6)

Gas Emissions Analyzer, Detector Tubes, and Evacuated Container Results

Gas emissions analyzers, detector tubes, and glass evacuated containers were used to characterize CO concentrations in and near the exhaust stack and 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 generator exhaust, the probe of the emissions analyzer was placed into the exhaust stack.

A summary of data collected with the emissions analyzers is shown in Figures 13 through 16. This data was measured directly in the generator exhaust. Figure 13 provides a comparison of the Westerbeke generator exhaust on houseboat #22 when using and not using the prototype ECD. This data was taken during an engine "cold start." Cold starts occur when the engine is not warmed up and can be a significant cause of high concentrations of air pollution (Eastwood 2000). As can be seen in the figure, when the generator was started without the ECD, the exhaust was approximately 12% CO and fell to between 5 and 6% within a couple of minutes. When the prototype ECD was connected to the generator, the initial CO concentration was just under 6% and after approximately 7 minutes of operation, the CO concentration had leveled off to between 0.1 and 0.25%. These percentages are equivalent to between 1,000 and 2,500 ppm.

Figure 14 presents data for a brand new, production ECD on the same Westerbeke generator (installed on houseboat #22). As can be seen in the figure, the CO concentration begins near zero, rapidly peaks just below 6%, and then within approximately 2 minutes is very close to 0% or 0 ppm.

Figure 15 and 16 present bench test results for the Kohler generator evaluated in the marine maintenance facility. Figure 15 compares the Kohler generator being started with and without the new, production ECD. As can be seen by the solid circles, when the generator was connected to the ECD, there was a very minor peak CO concentration that occurred within 30 seconds of starting the generator, and the CO concentration rapidly moved close to 0 ppm. When the generator was started without the ECD, CO concentrations were initially near 1% and increased to between 2 and 3% after several minutes of operation. When the generator was placed under a load, CO concentrations increased near 6%. Figure 16 shows that when the same Kohler generator and production ECD was cold-started with no load, the concentration rapidly fell from approximately 1 to 0.2% and later began to increase near 1% CO.

Detector tube and evacuated container data are shown in Table V. The data in this table shows emission results for both the Westerbeke generator on houseboat #22 and the Kohler generator bench tests. In general, data collected when the generator operated with the ECD was significantly lower than when the generator operated without the ECD. The first row, provides data for the prototype ECD on the Westerbeke generator which was malfunctioning. The data for the prototype ECD was significantly higher than the data for the production ECD shown in the subsequent rows. There is significant variation in the numbers presented based upon the generator operating conditions.

Volatile Organic Compounds and Ozone Samples

Qualitative air sampling was performed using thermal desorption tubes to identify volatile organic compounds that might be present in the generator exhaust when used with the ECD. Based on the sampling results, the compounds that were identified included benzene, toluene, xylene, various C_9 - C_{11} alkyl substituted benzenes, styrene, naphthalenes, indans, and indenes, and aliphatic hydrocarbons in the C_4 to C_{16} range.

Sampling for ozone indicated that ozone concentrations emitted from the ECD were generally very low and did not appear to be a concern. Several detector tube samples were taken which indicated none detected and 0.15 ppm. Data collected with the Metrosonics toxic gas monitors indicated that ozone concentrations ranged from 0.2 to 0.0 ppm.

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 while doing environmental monitoring.

A summary of wind velocity data collected during the survey is shown in Table VI. This table provides data concerning the bearing of the houseboat, and the average wind direction and speeds. As can be seen in the table, the houseboat was oriented at direction of 275° NW while in the slip at the marina on Tuesday morning, Wednesday morning, and Wednesday afternoon. On Monday afternoon, and later on Wednesday afternoon, the boats were taken out on the lake and environmental sampling was conducted. Average wind speeds ranged from 0.51 m/sec to 1.97 m/sec. Average wind direction ranged from 81.7° NE to 186.4° SW.

DISCUSSION AND CONCLUSIONS

This and previous investigations confirm that the CO hazard to swimmers and occupants on many houseboats that have gasoline-powered generators can be greatly reduced by retrofitting 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 use of side-exhaust on three houseboats that had been tied together and the performance of prototype and production ECDs.

Side Exhaust

Data gathered when the houseboats were rafted together showed that this design could potentially result in hazardous CO concentrations on the houseboat, particularly on the lower deck. CO concentrations peaked above the NIOSH ceiling limit of 200 ppm in five of the six sampling locations on the lower decks of boats 258, 240 and 259. The peak concentration of 1015 ppm on the lower rear deck of houseboat 240 approached the NIOSH IDLH of 1200 ppm. CO concentrations on the upper decks of houseboats 258 and 259 exceeded the NIOSH ceiling limit.

Although the side exhaust was at the rear of the boat, wind conditions were such that the highest CO concentrations occurred near the front of the houseboat and high CO concentrations were able to channel to the front of the boats via the gap on either side of the center boat. The mean concentration on the lower front deck of houseboat # 240 was 142.7 ppm while the mean concentration on the lower rear deck of the same houseboat was only 35.4 ppm. Both of these concentrations exceed the NIOSH REL for CO of 35 ppm. It is clear from the data in this study that any uncontrolled exhaust from a gasoline-powered generator that is close to the water and boat could potentially be hazardous.

The Prototype and Production ECDs

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.

The prototype ECD had over 3,000 hours of use when evaluated during the current study. It was discovered on the second day of the study that significant internal corrosion had occurred inside of the prototype ECD. This corrosion and several other factors that are discussed below caused the performance of the prototype ECD to degrade from when it was new. Study results indicate that the new production ECD performed better than the prototype system.

The prototype ECD was the first water-cooled Enviromarine ECD. It was rapidly constructed to demonstrate that the concept could work in the lab and field. It was intended to be used for EPA certification testing and the initial NIOSH testing rather than for long periods of time. The prototype was constructed with fittings made of cast iron because it is relatively easy to weld and modify compared to stainless-steel. Due to the urgency of the health hazard associated with CO emissions from generator exhaust , and the success of the initial tests, Enviromarine Inc. was asked to put as much time on the system as quickly as possible.

The expansion rates of cast iron and 316L stainless-steel are dramatically different. These differences caused the welds on the prototype ECD to crack and eventually allowed water to leak into the catalyst. This occurrence contaminated the prototype ECD causing a dramatic reduction in performance. The production ECD is 100% 316L stainless steel and is shorter and lighter than the prototype version. The operating temperatures are much lower. The inlet temperature is approximately 165 °F compared to close to 400 °F on the prototype. The outlet temperature is only 265 °F vs 700 °F on the prototype. The higher operating temperatures combined with water entering the catalyst resulted in premature failure. Installation of the production ECD was shown to immediately improve performance.

Cold-starts and Loading

The tests conducted to evaluate CO emissions during cold starts and under a variety of loading conditions demonstrated that CO emission rates can change significantly based upon many factors. For example, it was typical to see fairly dramatic peaks occur during a cold start (Figures 13 and 14). When the ECD was working and adjusted properly, the height and length of the peak could be minimized (Figure 15), thereby preventing a significant hazard.

Loading conditions also influenced the CO concentration in the exhaust. It was common for the ECD to be adjusted for a typical loading scenario. It was acknowledged during our bench testing on the Kohler generator that if a generator was operated under no load conditions, this could potentially increase CO concentrations. These issues require further consideration.

Results from the prototype and production ECD evaluation demonstrate the ECD's capabilities. The ECD was shown to convert a substantial percentage of 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 the unit was functioning properly.

RECOMMENDATIONS

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

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

2) In general, the emission control device (ECD) performed well during the current evaluation. Because there were complications related to long-term performance of the prototype ECD, it is important to conduct additional testing of production ECDs to determine their reliability and performance over longer periods. It would also be useful to conduct additional cold-start and loading tests. 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) 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.

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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
Temperature at Exhaust	400°F	800°F
Effectiveness with LP fuel	As low as 10 ppm	Average of 150 ppm

Table II
CO Samples (ppm) on the Lower Deck of Three Houseboats Tied Together with Side-Exhaust Generator Configuration (No other engineering controls)– Stationary with Generator Only and Underway with Generator and Driven Engines On

Sample Location (Sample #)	Generator On (Stationary)	Generator and Drive Engines On (Boat Underway)
Lower Rear Deck Houseboat 258 (Sample #1)	Mean= 11.0 Std. Dev. = 17.2 Peak = 91.0 N = 639	Mean= 31.1 Std. Dev. = 44.8 Peak = 401.0 N = 754
Lower Rear Deck Houseboat 240 (Sample #2)	Mean= 35.4 Std. Dev. = 128.3 Peak = 1015 N = 639	Mean= 27.6 Std. Dev. = 48.0 Peak = 416.0 N = 560
Lower Rear Deck Houseboat 259 (Sample #3)	Mean= 44.7 Std. Dev. = 94.5 Peak = 594.0 N = 103	Mean= 33.4 Std. Dev. = 30.6 Peak = 221.0 N = 128
Lower Front Deck Houseboat 258 (Sample #4)	Mean= 75.4 Std. Dev. = 67.2 Peak = 274.0 N = 103	Mean= 50.4 Std. Dev. = 87.9 Peak = 317.0 N = 124
Lower Front Deck Houseboat 240 (Sample #5)	Mean= 142.7 Std. Dev. = 106.0 Peak = 425.0 N = 103	Mean= 109.6 Std. Dev. = 155.0 Peak = 510.0 N = 75
Lower Front Deck Houseboat 259 (Sample #6)	Mean= 43.3 Std. Dev. = 62.5 Peak = 377.0 N = 639	Mean= 12.1 Std. Dev. = 21.6 Peak = 105.0 N = 757

N= number of data points

Table III
CO Samples (ppm) on the Upper Deck of Three Houseboats Tied Together with Side-Exhaust Generator Configuration (No other engineering controls)–Stationary with Generator Only and Underway with Generator and Driven Engines On

Sample Location (Sample #)	Generator On (Stationary)	Generator and Drive Engines On (Boat Underway)
Upper Rear Deck Houseboat 258 (Sample #7)	Mean= 7.7 Std. Dev. = 8.9 Peak = 40.0 N = 61	Mean= 6.7 Std. Dev. = 16.8 Peak = 74.0 N = 53
Upper Rear Deck Houseboat 240 (Sample #8)	Mean= 10.5 Std. Dev. = 18.1 Peak = 107.0 N = 639	Mean= 0.1 Std. Dev. = 2.8 Peak = 25.0 N = 43
Upper Rear Deck Houseboat 259 (Sample #9)	Mean= 10.1 Std. Dev. = 37.3 Peak = 199.0 N = 103	Mean= 6.3 Std. Dev. = 10.6 Peak = 50.0 N = 128
Upper Front Deck Houseboat 258 (Sample #11)	Mean= 21.8 Std. Dev. = 33.3 Peak = 221.0 N = 103	Mean= 12.6 Std. Dev. = 23.5 Peak = 106.0 N = 127
Upper Front Deck Houseboat 259 (Sample #12)	Mean= 23.5 Std. Dev. = 44.2 Peak = 342.0 N = 103	Mean= 12.6 Std. Dev. = 40.7 Peak = 254.0 N = 130

N= number of data points

Table IV
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	Underway, without ECD	Underway, with ECD
Lower deck Back of slide (#1)	Mean= 1.5 Std. Dev. = 5.3 Peak = 31.0 N = 44	Mean= 0.3 Std. Dev. = 2.3 Peak = 19 N = 81	Mean= 169.6 Std. Dev. = 186.7 Peak = 1,002.0 N = 72	Mean= 287.7 Std. Dev. = 228.5 Peak = 806.0 N = 61
Swim Platform Port side (#2)	Mean= 0.2 Std. Dev. = 0.5 Peak = 5.0 N = 427	Mean= 0.0 Std. Dev. = 0.1 Peak = 1.0 N = 467	Mean= 38.7 Std. Dev. = 97.1 Peak = 1,013.0 N = 416	Mean= 33.8 Std. Dev. = 69.3 Peak = 547.0 N = 381
Kitchen Table (#4)	Mean= 0.2 Std. Dev. = 0.5 Peak = 2.0 N = 74	Mean= 0.0 Std. Dev. = 0.2 Peak = 1.0 N = 81	Mean= 7.4 Std. Dev. = 24.2 Peak = 167.0 N = 72	Mean= 2.6 Std. Dev. = 12.4 Peak = 82.0 N = 61
Lower deck Front of Boat (#5)	Mean= 2.9 Std. Dev. = 2.7 Peak = 13.0 N = 74	Mean= 0.6 Std. Dev. = 0.6 Peak = 3.0 N = 81	Mean= 5.6 Std. Dev. = 11.4 Peak = 54.0 N = 72	Mean= 2.8 Std. Dev. = 8.6 Peak = 45.0 N = 58
Top Rear Deck Near slide (#6)	Mean= 0.5 Std. Dev. = 1.4 Peak = 10.0 N = 458	Mean= 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 467	Mean= 20.1 Std. Dev. = 12.4 Peak = 55.0 N = 416	Mean= 21.0 Std. Dev. = 16.0 Peak = 78.0 N = 381
Top Rear Deck Port side (#7)	Mean= 0.0 Std. Dev. = 0.1 Peak = 1.0 N = 67	Mean= 0.0 Std. Dev. = 0.2 Peak = 1.0 N = 70	Mean= 16.4 Std. Dev. = 9.3 Peak = 41.0 N = 72	Mean= 12.1 Std. Dev. = 17.6 Peak = 84.0 N = 61
Top Deck Front of Boat (#8)	Mean= 1.3 Std. Dev. = 0.6 Peak = 6.0 N = 458	Mean= 0.9 Std. Dev. = 0.3 Peak = 2.0 N = 467	Mean= 2.3 Std. Dev. = 3.2 Peak = 27.0 N = 416	Mean= 1.5 Std. Dev. =1.8 Peak =13.0 N = 378
Top Deck Center of boat (#9)	Mean= 0.6 Std. Dev. = 1.7 Peak = 9.0 N = 34	Mean= 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 39	Mean= 2.4 Std. Dev. = 6.5 Peak = 38.0 N = 73	Mean= 0.9 Std. Dev. = 3.1 Peak = 12.0 N = 33

N= number of data points

Table V
Comparison of Detector tube and Evacuated Container CO Emission Results for Generators Operating under Various Conditions

Condition	Without ECD	With ECD
15 Kw, Westerbeke Generator on Houseboat #22 (Tuesday morning)	**Detector Tube:** 3.0%, 6.0%, 3.7%, 1.5% **Evacuated Container**: 3,067 ppm, 2,349 ppm, 2,651 ppm	**Detector Tube:*** 0.30%, 0.60%, 2.0% **Evacuated Container:*** 4,087 ppm, 3,537 ppm
15 Kw, Westerbeke Generator on Houseboat #22 (Wednesday morning)	**No Results (See above data for comparison)**	**Detector Tube:** 300 ppm, 250 ppm, ND, 3 ppm **Evacuated Container:** 3 ppm, 2 ppm
12.5 Kw, Kohler Generator Bench Test, No Load	**Detector Tube:** 3%, 6% **Evacuated Container**: 4,121 ppm, 5,416 ppm	**Detector Tube:** **Evacuated Container**: 6,681ppm, 36 ppm
12.5 Kw, Kohler Generator Bench Test, With Load	**No Results**	**Detector Tube:** 50 ppm, 10 ppm, **Evacuated Container**: 6 ppm, 12 ppm
15 Kw, Westerbeke Generator on Houseboat #22 (Wednesday afternoon--Measurements taken under swim deck)	**No Results**	**Detector Tube:** 100 ppm, 230 ppm, ND, ND **Evacuated Container**: 8 ppm, 2 ppm

* Note: These results were obtained using a prototype ECD that was found to be malfunctioning due to internal corrosion.
ND = Nondetected

Table VI
Boat Heading and Wind Velocity Data.

	Houseboat Bearing	Average Wind direction	Average Wind Speed	Std. Dev. Wind Speed
Monday afternoon (cove)	234°	159.3°	0.94 m/sec	0.71 m/sec
Tuesday, morning (marina)	275°	81.7°	0.51 m/sec	0.19 m/sec
Wednesday, morning (marina)	275°	181.4°	1.68 m/sec	0.75 m/sec
Wednesday, afternoon 1 (marina)	275°	124.4°	1.23 m/sec	0.49 m/sec
Wednesday, afternoon 2 (cove)	45°	186.4°	1.97 m/sec	0.46 m/sec

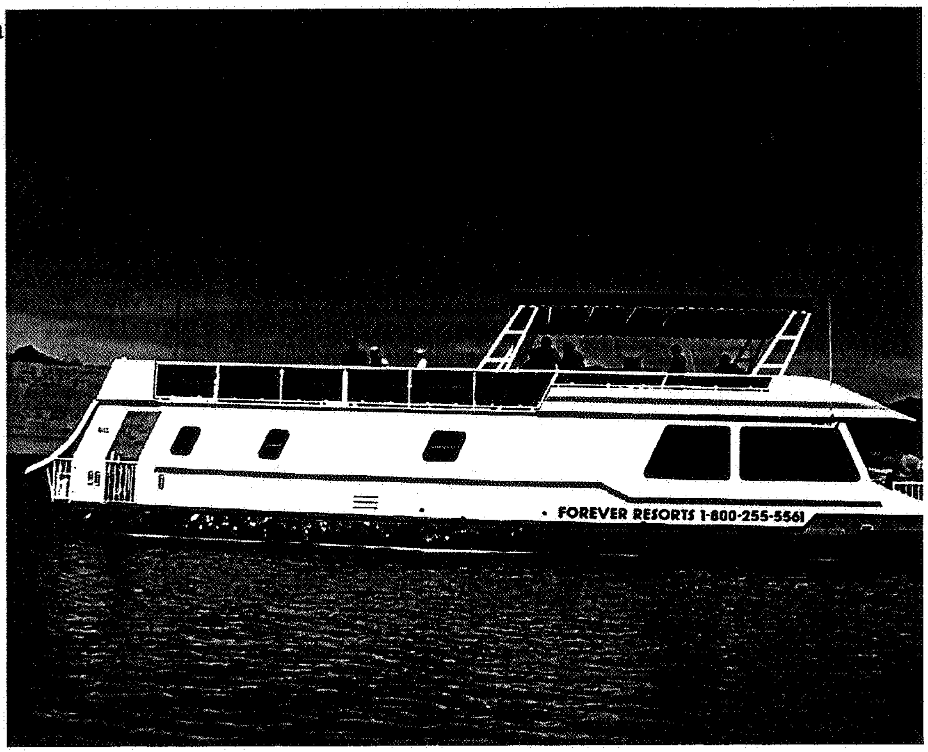

Figure 1. Photo of one of the evaluated 65-Foot Fun Country Marine houseboats.

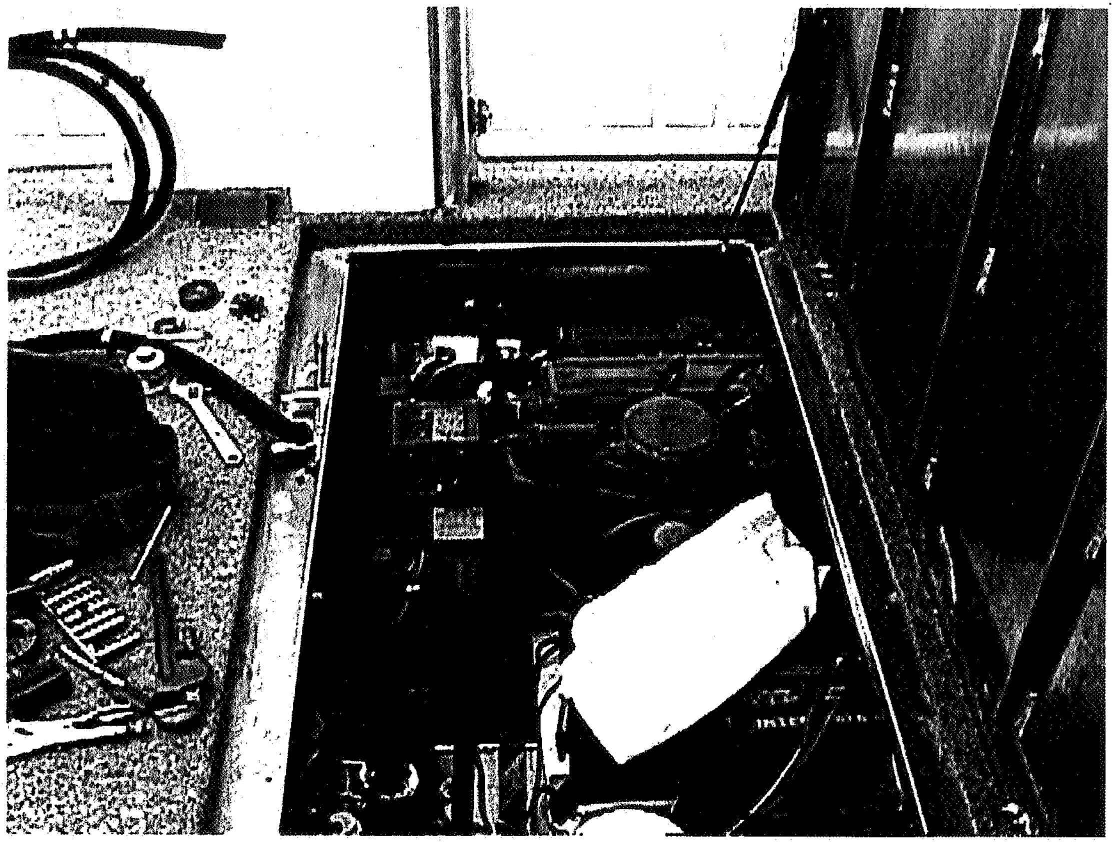

Figure 2. Engine and generator compartment on the rear deck of the houseboat.

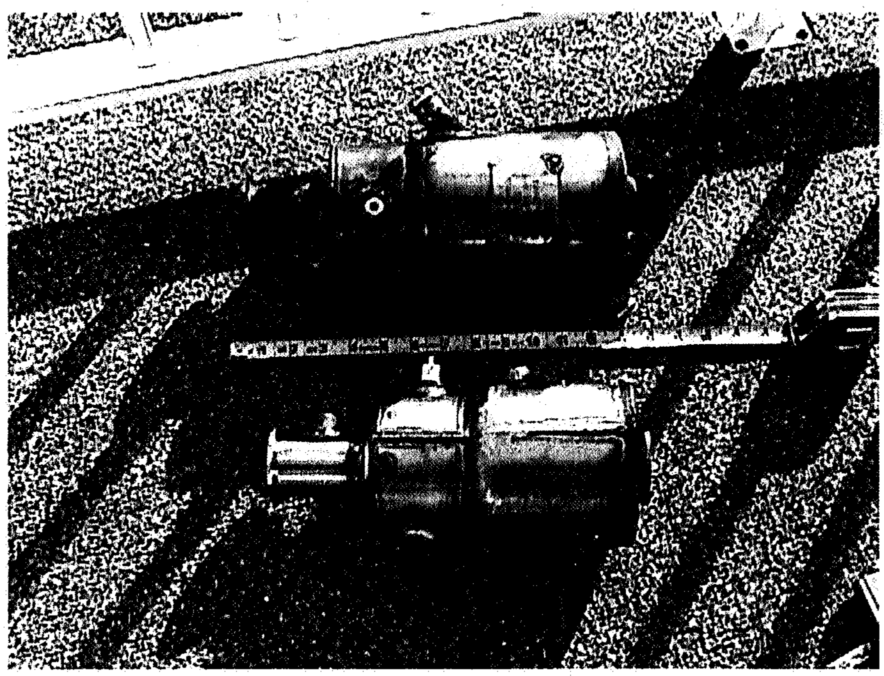

Figure 3. Photo of the prototype (above) and production ECD (below).

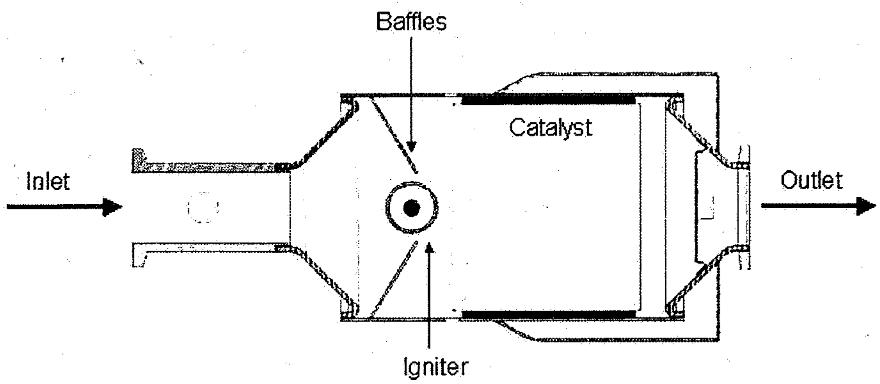

Figure 4. Cross-sectional diagram of the EnviroMarine emissions control device.

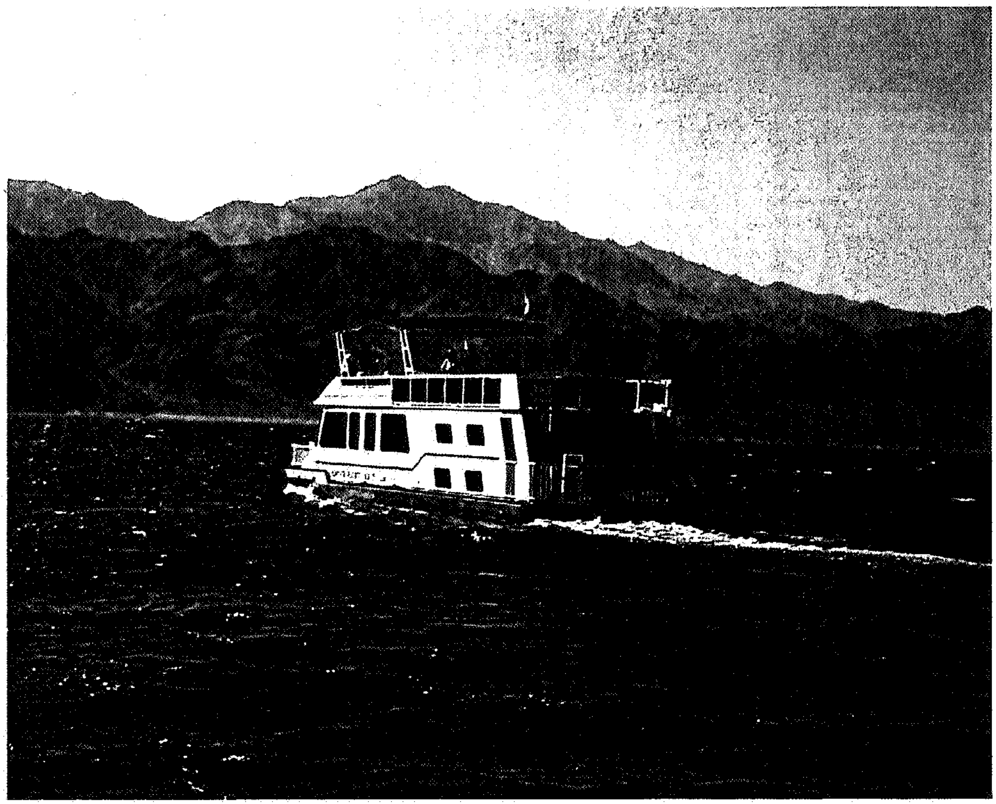

Figure 5. Houseboat being evaluated underway.

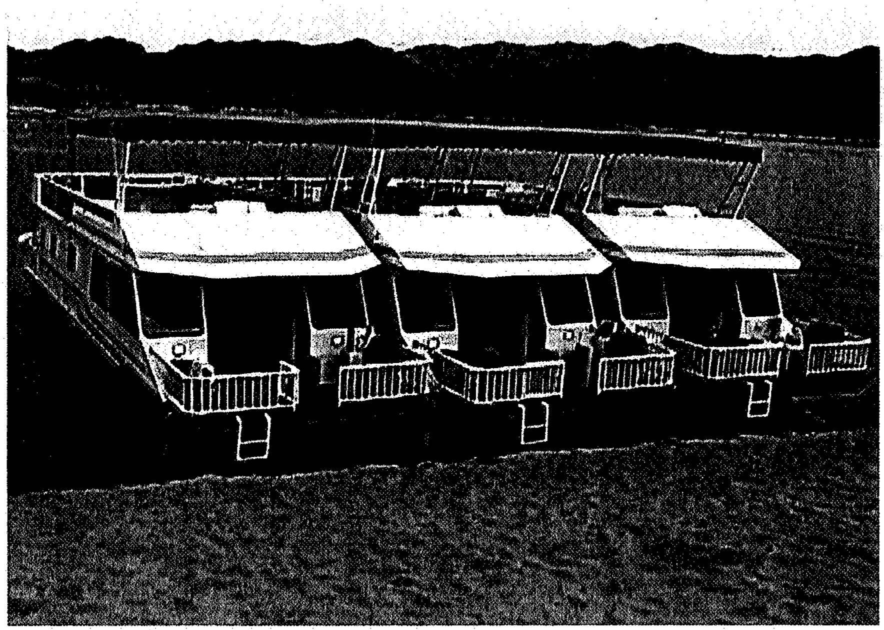

Figure 6. Photo of three side-exhaust houseboats tied together.

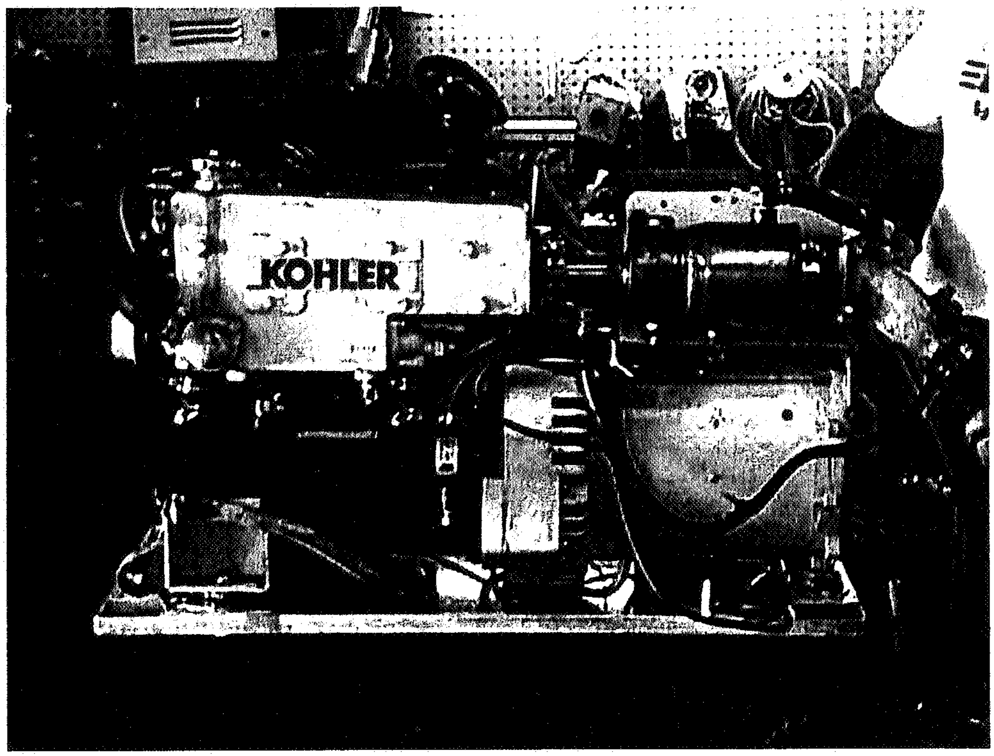

Figure 7. Photo of 12.5 Kw Kohler Generator emission tested with the Production ECD.

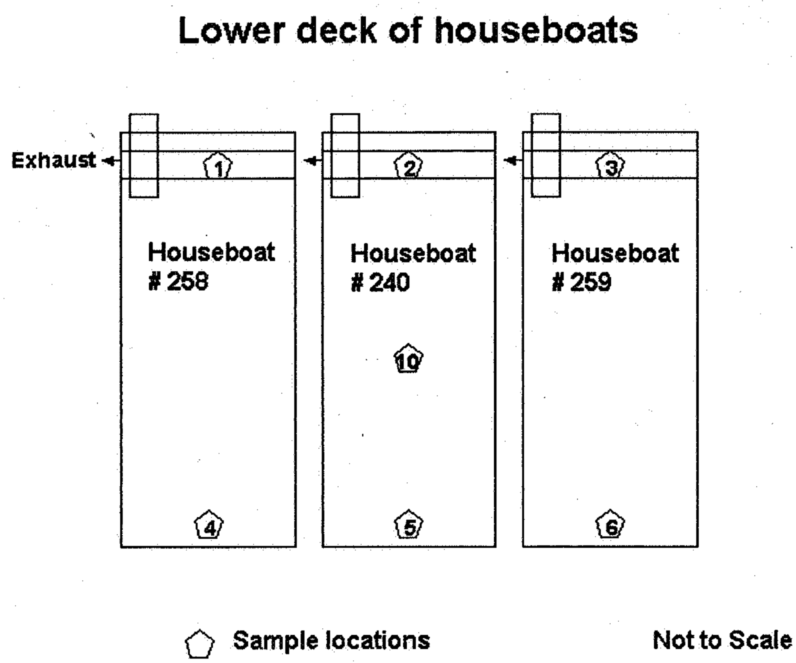

Figure 8. Sample locations on lower decks of the houseboats.

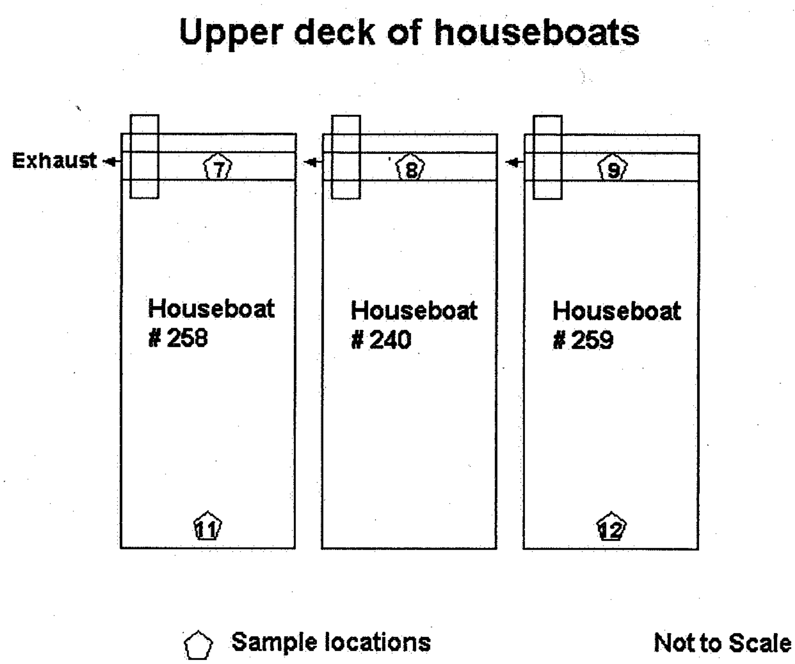

Figure 9. Sample locations on upper decks of the houseboats.

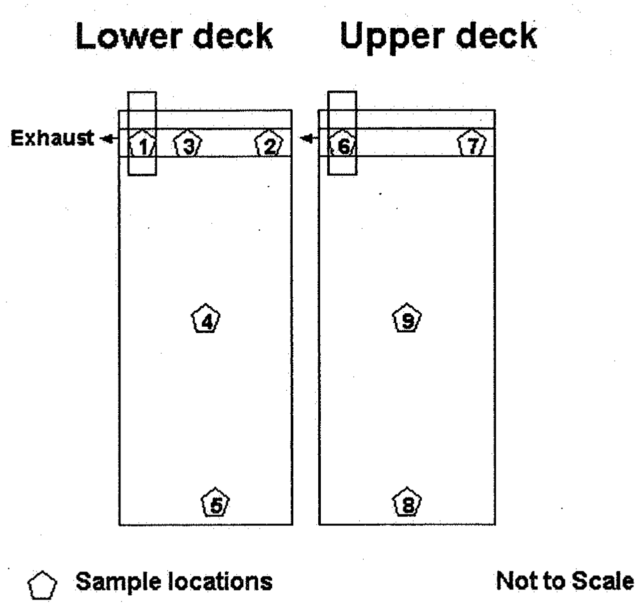

Figure 10. Sample locations on upper and lower decks of the houseboat.

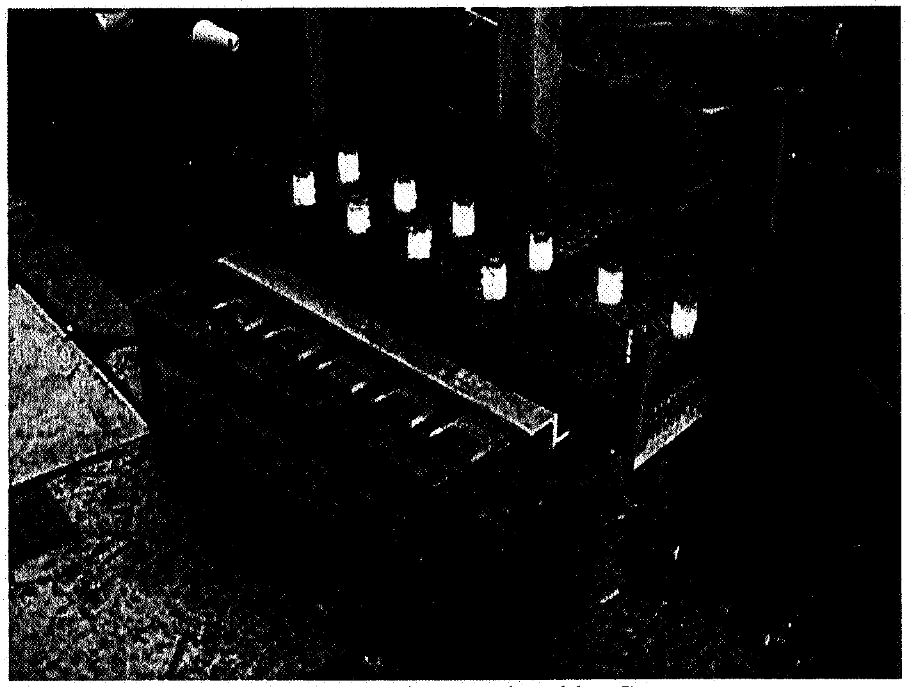

Figure 12. Photo of Device used to Load Kohler Generator set.

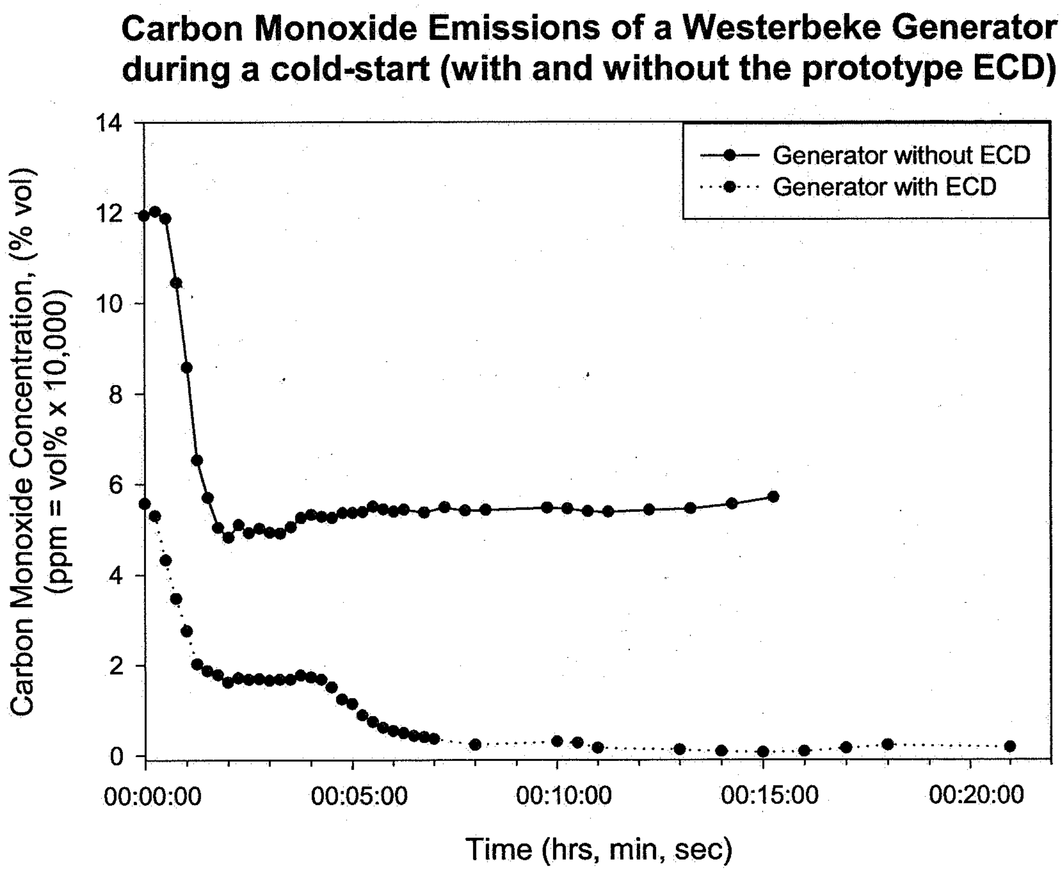

Figure 13. Carbon monoxide Emissions of a Westerbeke Generator during a Cold-Start (with and without the prototype ECD).

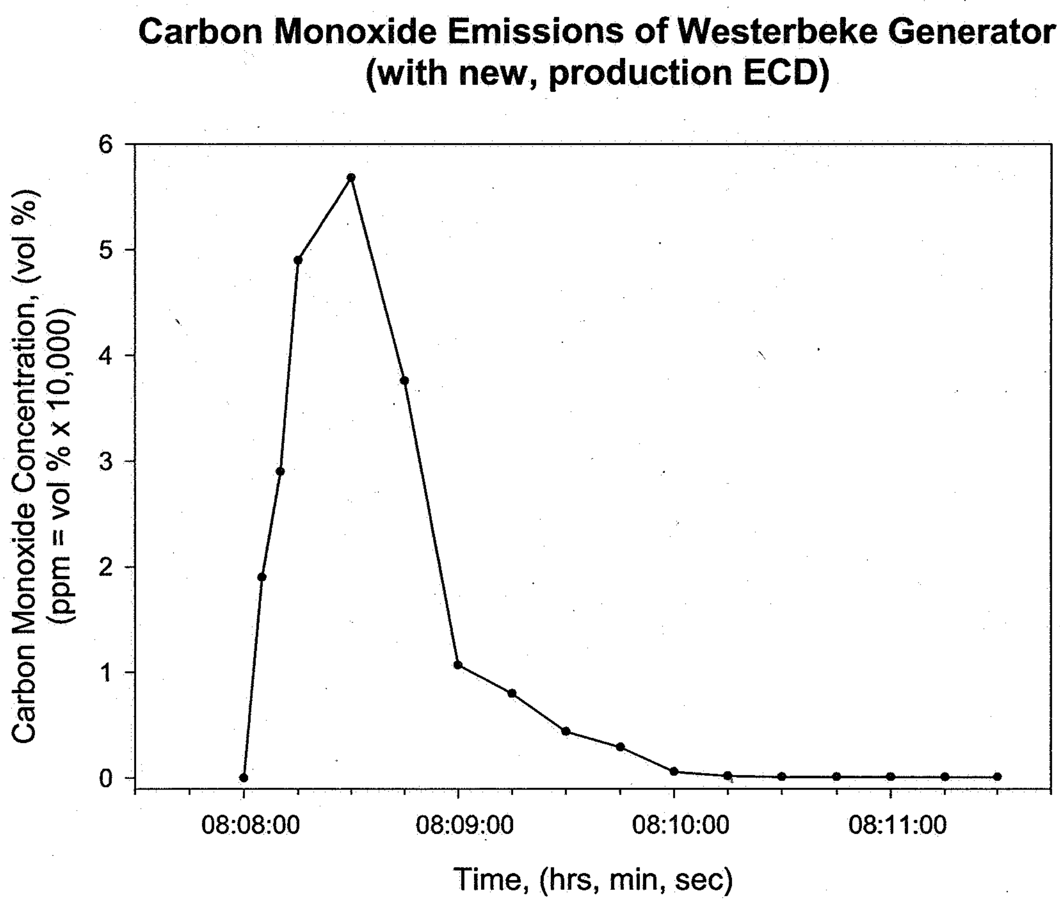

Figure 14. Carbon Monoxide Emissions of a Westerbeke Generator (with the new, prodction ECD).

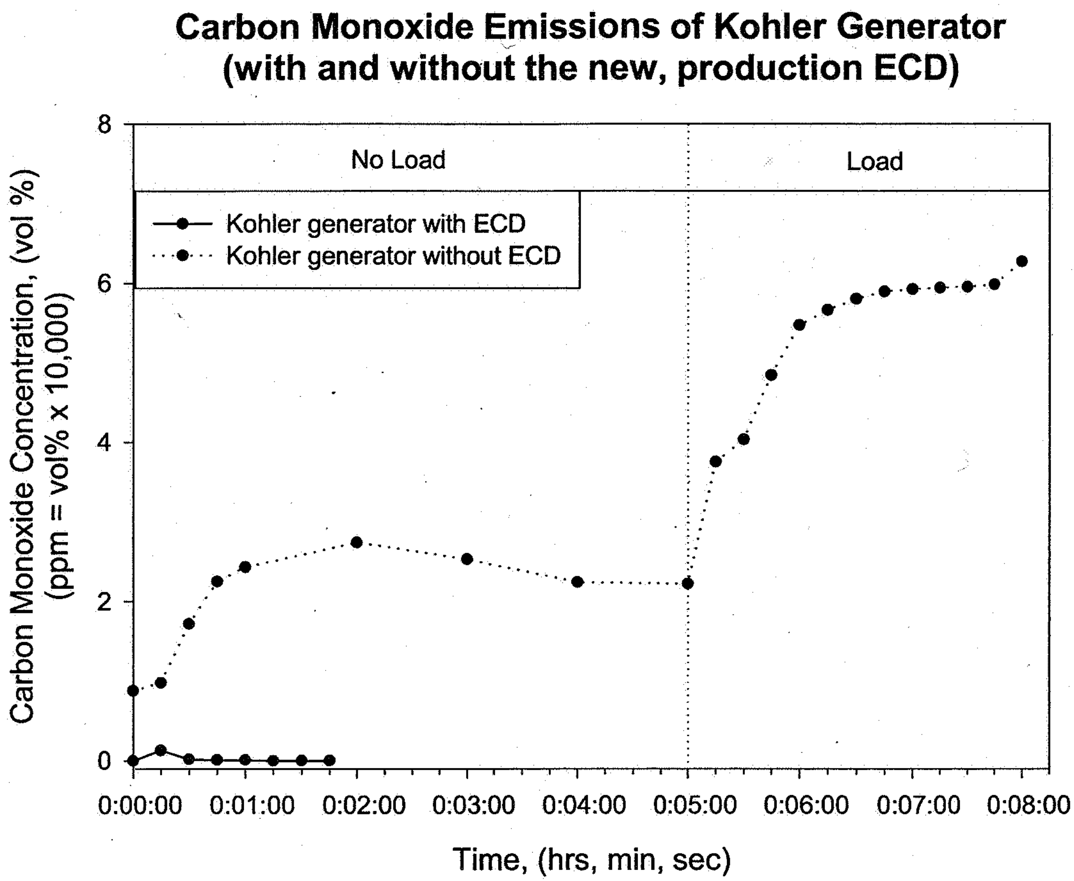

Figure 15. Carbon Monoxide Emissions of a Kohler Generator (with and without the New, Production ECD).

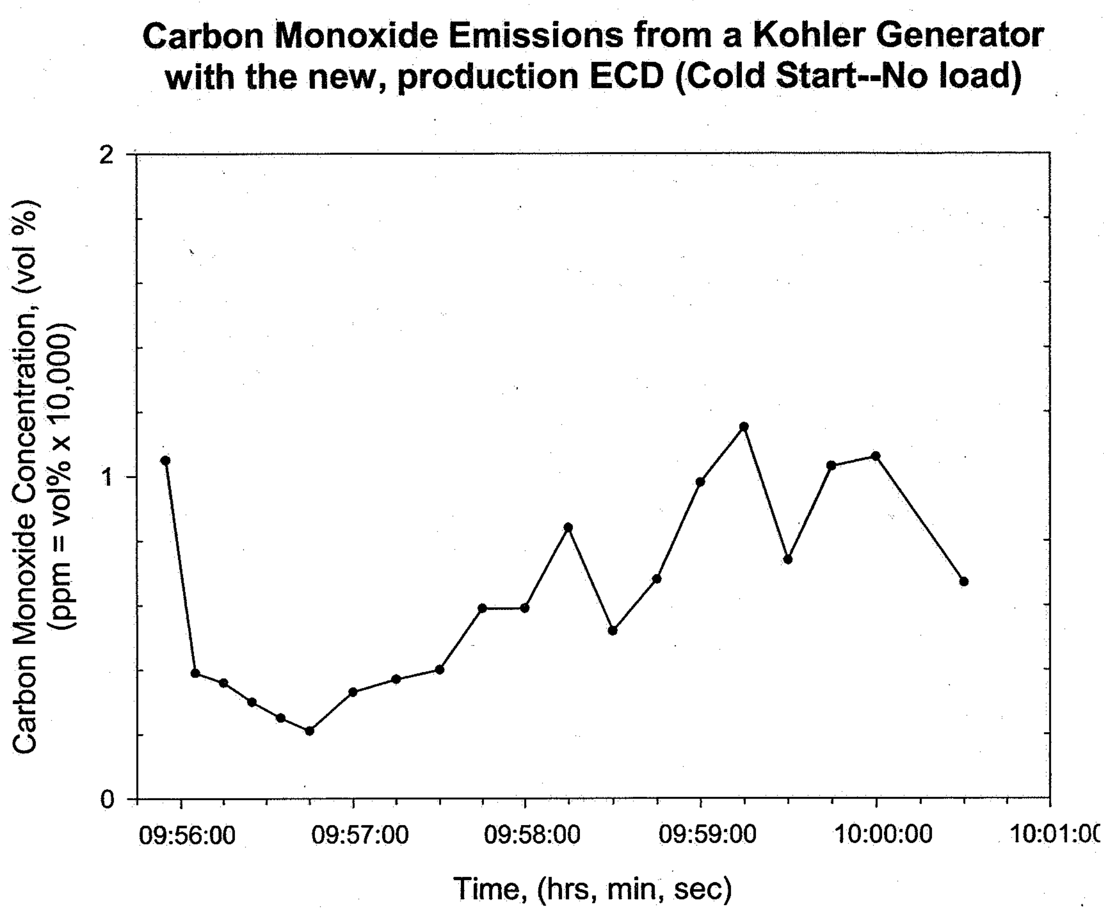

Figure 16. Carbon Monoxide Emissions from a Kohler Generator with the New, Production, ECD (Cold Start – No Load)