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AN EVALUATION OF CATALYTIC EMISSION CONTROLS TO PREVENT CARBON MONOXIDE POISONINGS FROM HOUSEBOAT GENERATOR EXHAUST

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DISCLAIMER

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

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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 was 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 prevent CO poisonings on houseboats and other recreational marine vessels.

The performance of two (20 KW and 14 KW) Westerbeke Safe-CO™ generators were tested after being used on rental houseboats for two full boating seasons. The evaluated generators had 2,835 and 4,656 hours of use respectively and were equipped with catalytic converters and electronic fuel injection systems. A 12.5 KW Westerbeke generator was also tested that had been retrofitted with a Zenith electronic fuel injection (EFI) retrofit kit. Each of the engineering control devices were designed to improve generator performance and reduce CO emissions. The houseboat containing the 14 KW generator had been modified so that testing could be accomplished using either a side exhaust or stack exhaust configuration.

The two Westerbeke Safe-CO™ generators used for two boating seasons performed well; average CO concentrations at various locations on the boat were generally below 5 parts per million (ppm). Peak CO concentrations were all well below 10 ppm. Both old and brand new catalysts were evaluated for the 14 KW generator. The new catalysts performed much better than the one used for two seasons. Degradation of the catalyst was observed on the 14 KW unit that had 4,656 hours of use. This generator was unable to keep CO concentrations below 4,000 ppm under load when measured directly in the exhaust plume. When the catalyst was replaced, the generator again performed according to its design criteria. CO concentrations were lower under the no-load conditions as compared to load conditions when measurements were collected directly in the exhaust plume. CO concentrations measured directly in the exhaust stack were below 1,000 ppm for the fully warmed generator. That compares to CO concentrations NIOSH researchers measured which usually exceeded 10,000 ppm on older Westerbeke generators without the Safe-CO™ control systems. When comparing side versus stack exhaust, the lower stern deck in the side exhaust configuration resulted in slightly higher concentrations. Use of the Safe-CO™ generator resulted in low ambient CO concentrations for both side and stack exhaust configurations.

It is important that the boater/owner/operator follow all of the maintenance recommendations provided by the manufacturer. Some of those recommendations include periodically changing the oxygen sensor in the generator and replacing the catalyst every 2,000 hours. Use of the vertical exhaust stack with the Safe-CO™ generator is recommended to ensure redundancy in the system in the event of catalyst degradation or oxygen sensor malfunction. Development and commercialization of these systems is a major step forward in control systems to ensure a safe environment around houseboats and other marine vessels.

The performance of the Westerbeke generator retrofitted with a Zenith EFI system was also an improvement when compared with old, non-EFI systems. CO concentrations measured on the boat were also typically below 5 ppm; however, the CO concentrations measured directly in the exhaust were higher than the Safe-CO™ generators. The Zenith EFI system did not perform as well when the generator was under load; CO concentrations measured directly in the exhaust were substantially higher. CO concentrations measured directly in the exhaust stack were constantly above 10,000 ppm when the generator was under load conditions.

BACKGROUND

On November 28 and 29, 2006, 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. The evaluation primarily involved the testing of Westerbeke Safe-CO™ generators installed on two houseboats. A 14 KW Safe-CO™ generator, equipped with an exhaust system that could be routed either to a side exhaust or to a vertical stack exhaust, was tested on a Fun Country Marine VIP XT (16 X 59') houseboat. The second generator, a 20 KW Safe-CO™ generator, was installed on a Fun Country Marine Millennium (16' X 70') houseboat. Additionally, a 12.5 KW Westerbeke generator, retrofitted with a Zenith electronic fuel injection (EFI) kit and installed on a Fun Country Marine Deluxe (14' X 59') houseboat was tested. All of the evaluations were conducted while the houseboats were docked at the marina.

Representatives from NIOSH, U.S. Coast Guard (USCG), U.S. National Park Service (USNPS), Department of Interior (DOI), and Utah Parks and Recreation (UPR) conducted initial investigations of CO-related poisonings and deaths on houseboats at Lake Powell in September and October 2000. These investigations measured hazardous CO concentrations on houseboats at Lake Powell (McCammon and Radtke 2000). Some of the very 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 2006, 176 CO poisoning cases occurred on Lake Powell near the border of Arizona and Utah. Eighty of the poisonings occurred inside the cabin of houseboats and all of these poisonings were attributable to generator exhaust. Thirty-six of the poisonings occurred outside the houseboats and twenty-nine of these poisonings were attributable to the generator exhaust. Ten houseboat- related CO poisonings on Lake Powell resulted in death (National Case Listing 2006). Further investigations have identified nearly 607 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. The USCG, Office of Boating Safety, Recreational Boating Product Assurance Division convened a meeting on May 3, 2001, in Lexington, Kentucky. Houseboat manufacturers, marine product manufacturers, government representatives, and others interested in addressing the CO hazard

attended this meeting. Following the meeting, NIOSH researchers were asked to evaluate the performance of a new prototype emissions control device (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). 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 that performed well. The prototype ECD consisted of a combination of stainless steel and cast iron while the production ECD consisted entirely of stainless steel to reduce corrosion with several engineering improvements. NIOSH researchers conducted a follow-up survey to evaluate the performance of the improved ECD after 2,000+ hours of use. The results showed that the improved ECDs were somewhat effective at reducing CO concentrations; however, their performance had substantially degraded from when they were new (Earnest, Dunn et al. 2003).

The following study was primarily conducted to evaluate the performance of Westerbeke Safe-CO™ generators that had been used for two boating seasons. These generators reduce CO emissions using EFI technology to efficiently combust the gasoline. To reduce the remaining CO emissions in the exhaust effluent, a catalytic converter was used. At the request of Fun Country Marine, a standard Westerbeke generator, retrofitted with a Zenith EFI system, was also tested.

Symptoms and Exposure Limits

CO is a lethal poison 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 performed 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 USNPS and concessionaire employees 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 consider these factors, and are listed following the occupational criteria.

The NIOSH Recommended Exposure Limit (REL) for occupational exposures to CO gas in air is 35 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 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).

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 the most sensitive members of the general population.

The World Health Organization (WHO) has 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

Carbon monoxide (CO) and other environmental measurements were collected on three houseboats built by Fun Country Marine Industries, Inc. (Muncie, IN). Testing involved the evaluation of Westerbeke Safe-CO™ generators installed on two houseboats. A 14 KW Safe-CO™ generator, equipped with an exhaust system that could be routed either to a side exhaust or to a vertical stack exhaust, was tested on a Fun Country Marine VIP XT (16' X 59') houseboat. The second generator, a 20 KW Safe-CO™ generator, was installed on a Fun Country Marine Millennium (16' X 70') houseboat. Additionally, a 12.5 KW Westerbeke generator, retrofitted with a Zenith EFI kit and installed on a Fun Country Marine Deluxe (14' X 59') houseboat was tested. All of the evaluations were conducted while the houseboats were docked at the marina.

The generators on the houseboats provided electrical power for air conditioning, kitchen appliances, entertainment systems, navigation, and communications equipment. The engine compartment beneath the stern deck near the drive engines housed the generators. The generators are similar in size to engines used on small automobiles. Nearly 75% of houseboats in the U.S. use Westerbeke generators (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.

Description of the Evaluated Engineering Controls

All evaluated houseboats had a continuous vertical exhaust stack fitted to the generator set. For the purposes of comparing the exhaust location on the results, a Fun Country Marine VIP XT (16' X 59') houseboat was configured to allow the exhaust emissions to be rapidly changed from a side to stack exhaust configuration. The Fun Country Marine Deluxe (14' X 59') and the Fun Country Marine Millennium (16' X 70') houseboats were only equipped with the stack configuration. The exhaust stacks on the three Fun Country houseboats 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.

The focus of this study was to evaluate the performance of Westerbeke Safe-CO™ generators specifically designed to produce low CO emissions. A 14 KW Safe-CO™ Westerbeke generator was tested on a Fun Country Marine VIP XT (16' X 59') houseboat. The generator logged 4,656 hours of use before the evaluation. Additionally, a 20 KW Safe-CO™ Westerbeke generator was tested on a Fun Country Marine Millennium (16' X 70') houseboat. This generator logged 2,835 hours of use prior to the evaluation. Given the proprietary nature of this technology, little information could be obtained regarding the specific control technologies used to reduce the CO emissions. However, an EFI system was employed to efficiently combust the gasoline to help reduce exhaust emissions, including CO.

Secondly, a catalytic pollution control device was designed to optimize the chemical oxidation of CO in the generator exhaust emissions. To prevent excessive heat buildup in the catalyst, the

device was water-jacketed. The manufacturer recommends replacing the catalyst after 2,000 hours of use and also that CO emissions be spot checked at 1,000 hours of use. The manufacturer also recommends inspecting the oxygen sensor every 1,000 hours and replacing it after 2,000 hours of use. Stainless steel was selected as the catalyst housing to inhibit corrosion from the harsh marine environment. The catalytic ingredients used in the catalyst were not revealed by the manufacturer, but normally catalyst are composed of metal or metal oxides (e.g., Pt, Pd, Rh, V_2O_5). These metals are normally dispersed onto a high surface area porous structure (e.g., Al_2O_3, SiO_2) located within the catalyst. Exhaust gases adsorbed onto the surface undergo catalytic reactions. A catalyst increases the rate of a chemical reaction without undergoing a permanent change itself (Heck, R.M., Farrauto, R.J., 1995).

As on previous evaluations, an older model 12.5 KW Westerbeke generator was also evaluated that had been retrofitted with an aftermarket electronic fuel injection kit. The aftermarket kit, a Zenith EFI Kit, contained a throttle body injection unit, an engine management module, and a fuel pump/vapor separator. The retrofit involved the removal of the manufacturer's carburetor, mechanical governor, and fuel pump. The generator was installed in a Fun Country Marine Deluxe (14' X 59') houseboat.

Description of the Evaluation Equipment

An ECOM (Gainesville, GA) and a Ferret Instruments (Cheboygan, MI) Gaslink LT five-gas emissions analyzer were used to characterize emissions from the generator. These analyzers measured CO, carbon dioxide (CO_2), hydrocarbons, oxygen, and nitrogen oxides (NO_x). All measurements are expressed as percentages except hydrocarbons and NO_x, which are expressed in ppm. One percent of contaminant is equivalent to 10,000 ppm. The sensors on the Ferret unit were replaced at the marina, and the instrument completed post-calibration procedures successfully.

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

CO concentrations were also measured with detector tubes [Dräger A.G. (Lubeck, Germany) CO, CH 29901 ranges 2-60 ppm, 10-3,000 ppm, and 3,000-70,000 ppm] in the areas adjacent to the side exhaust (i.e., ~5" above the exhaust) when testing a houseboat in this configuration mode and directly in the generator exhaust when testing a houseboat in a top exhaust configuration. 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 milliliter (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. Clayton Group Services (Novi, MI) analyzed the samples for CO using a GS-Gas Pro and a RT-Msieve gas chromatograph equipped with thermal conductivity and flame ionization detectors.

Wind velocity and direction, temperature, and relative humidity measurements were gathered during the air sampling using a HOBO Weather Station (Onset Computer Corporation, Bourne, MA). This instrument recorded information every second for the duration of the field investigation.

Description of Procedures

The evaluation was performed over a 2-day period using a variety of operating conditions and generator exhaust configurations. In each case, the houseboats were tested while moored at the marina. Details concerning the testing of each houseboat are summarized below:

- **Fun Country Marine VIP XT (16' X 59') with a 14 KW Safe-CO™ Westerbeke generator.** In this houseboat, the generator emissions could be configured to exhaust through either a side or vertical exhaust stack. Additionally, testing was accomplished under no-load and half-load conditions. Half-load conditions were created by running the air conditioning unit. In each case, the generator operated under half-load conditions when sufficiently warm (30+ minutes of operation under no-load generator operation).

- **Fun Country Marine Millenium (16' X 70') with a 20 KW Safe-CO™ Westerbeke generator.** In this houseboat, the generator emissions were configured to only exhaust from a vertical exhaust stack. Additionally, testing was conducted under no-load and half-load conditions. Half-load conditions were simulated by running the air conditioning unit. In each case, the generator operated under half-load conditions when sufficiently warm (30+ minutes of operation under no-load generator operation).

- **Fun Country Marine Deluxe (14' X 59') with a 12.5 KW Westerbeke generator retrofitted with a Zenith EFI Kit.** In this houseboat, the generator was also configured to only exhaust from a vertical exhaust stack. Additionally, testing was accomplished under no-load and half-load conditions. Half-load conditions were created by running the air conditioning unit. In each case, the generator operated under half-load conditions when sufficiently warm (30+ minutes of operation under no-load generator operation).

Figure 1 presents the typical sampling locations, designated with numbers, for the ToxiUltra real-time CO monitors on the lower and upper decks of the houseboats. The monitors were placed at nine sample locations on the upper and lower decks of the houseboat to provide representative samples of occupied areas. Grab samples using the Ferret Instrument Gas Analyzer, Dräger detector tubes, and evacuated containers were also taken near (side exhaust configuration) or within the generator exhausts (top exhaust configuration). Additionally, wind direction and velocity, temperature, and relative humidity measurements were collected during the evaluation.

RESULTS

Results of Air Sampling with ToxiUltra CO Monitors

Real-time CO monitoring was conducted at numerous locations on the evaluated houseboats (Figure 1). Tables I through V present the summary statistics for the data. Details concerning the sample results for each houseboat are summarized below:

- **Fun Country Marine VIP XT (16' X 59') with a 14 KW Safe-CO™ Westerbeke generator.** Tables I through III present the results for this generator. Tables I and II contain data for the old catalyst and Table III contains data for the new catalyst. The CO concentrations on both the lower and upper decks were low for all conditions tested (average CO concentrations were typically below 4 ppm even at the stern of the boat). Peak CO concentrations were typically below 7 ppm for all conditions. The real time results for the side exhaust showed minor differences when compared to the stack exhaust. For example, average CO concentration differences measured at the same location were generally less than 1 ppm. The lower deck showed slightly higher concentrations when using the side exhaust configuration compared to stack exhaust. There also did not appear to be major differences when the generator was under load compared to idling (again, typically less than 1 ppm difference).

- **Fun Country Marine Deluxe (14' X 59') with a 12.5 KW Westerbeke generator retrofitted with a Zenith EFI Kit.** Table IV shows the data for this generator. Average CO concentrations were comparable to the previous tests using vertical exhaust stacks. The highest peak concentration measured during this test was 4 ppm (sample location 4). A generator load increase to one-half of capacity did not appear to influence CO concentrations measured in the environment. Additional information about this generator performance is shown in Table IV.

- **Fun Country Marine Millennium (16' X 70') with a 20 KW Safe-CO™ Westerbeke generator.** The results for this larger Safe-CO™ generator were also extremely low as shown in Table V. The highest peak concentration measured during this test was 3 ppm (sample location 7 and 8). Most peak concentrations were less than 2 ppm and many average concentrations were less than 1 ppm. Unlike the Zenith EFI system, increasing the generator load to one-half of capacity did not increase CO emissions (with a warmed engine). CO concentrations measured when using the new catalyst appeared to be slightly lower than the old catalyst in this generator.

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. This additional equipment was used because it is capable of reading higher CO concentrations than the ToxiUltra CO monitors which have an upper limit of approximately 1,000 ppm. Tables VI (detector tubes) and VII (evacuated containers) summarize the grab sample data; these results are discussed for each houseboat in the following:

- **Fun Country Marine VIP XT (16' X 59') with a 14 KW Safe-CO™ Westerbeke generator.** CO concentrations for the side exhaust configuration for both the no-load and half-load conditions were often not detected or very low. Measurements taken within the vertical exhaust stack exhaust plume reached an instantaneous level of approximately 110,000 ppm during the cold start of the generator and decreased to very low values approximately 5 minutes later (400 ppm). When comparing the fully warmed half-load condition to the no load condition, there seemed to be a significant difference in CO measurements. CO measurements ranged from 1 to 3,000 ppm throughout the test. An instantaneous level of 4,000 ppm was observed when the generator was under half-load. This generator had 4,656 hours of use when the evaluation was conducted, and the catalytic converter element had never been replaced. NIOSH researchers observed a degradation of the performance of the catalyst with CO concentrations as high as 5000 ppm measured within the vertical stack for a fully warmed generator. The catalyst element was then replaced, and the generator was re-tested. CO concentrations measured with the exhaust plumes never exceeded 250 ppm for the new catalyst element under the evaluated conditions.

- **Fun Country Marine Deluxe (14' X 59') with a 12.5 KW Westerbeke generator retrofitted with a Zenith EFI Kit.** All CO concentrations reported were measured within the vertical exhaust stack. CO concentrations increased rapidly after the cold start, reaching eight percent (80,000 ppm) CO. Within several minutes, the CO measurements appeared to stabilize to below 3,000 ppm. CO concentrations were significantly higher when the generator was under half-load compared with no load, sometimes exceeding 10,000 ppm.

- **Fun Country Marine Millennium (16' X 70') with a 20 KW Safe-CO™ Westerbeke generator.** CO concentrations measured within the vertical exhaust plume increased rapidly after a cold start, at one time approaching seven percent (70,000 ppm) CO. Within several minutes, the CO measurements stabilized at approximately 100 ppm. After the generator had run for several minutes, CO concentrations measured in the stack were quite low (typically less than a few hundred ppm). When the generator was under half-load instantaneous CO readings taken directly in the exhaust plumes reached 1,900 ppm, but within seconds they returned to a few hundred ppm.

Weather Measurements

During the survey, a HOBO weather station gathered wind velocity and temperature measurements. All of the testing occurred at the marina where the houseboats were oriented at a constant bearing of approximately 300 (roughly northwest). Average ambient temperatures during the two days of data collection ranged from: 43ºF to 57ºF. Wind speeds were variable throughout the evaluation. On November 28, the average wind velocity was 6.5 miles per hour (mph) with a maximum-recorded speed of 17 mph. The predominant wind direction was roughly southeast (bearing of 167). On November 29, the average wind velocity was 17 mph with a maximum-recorded speed of 35 mph. The predominant wind direction for November 29 was roughly southwest (bearing of 303).

DISCUSSION AND CONCLUSIONS

Retrofitting engineering emission control systems to the generators can greatly reduce the CO poisoning hazard to swimmers and occupants on houseboats that have gasoline-powered 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). This study specifically evaluated the performance of two Westerbeke Safe-CO™ generators designed to reduce CO emissions and protect boat occupants. This was the third evaluation of these generators by NIOSH and the second evaluation after their operation for significant hours (several thousand hours). Previously, NIOSH researchers evaluated these three houseboats in two tests to determine the performance of the generators with just a few hours of operation. Tests were conducted to determine the performance of the Safe-CO™ generators based upon the configuration (side exhaust versus top stack exhaust and to allow sampling directly in the exhaust) as well as the electrical load (no load versus half-load). Additional testing was performed on an older Westerbeke generator that had been retrofitted with an aftermarket Zenith EFI system.

Westerbeke Safe-CO™ *Generator Performance*

Results for both of the Safe-CO™ generators tested were outstanding and supported the results from the previous surveys conducted in March 2005 and November 2005. CO concentrations in the generator exhaust and in the ambient environment on the houseboats were low, usually single digit concentrations. The generator performed as designed and kept CO concentrations at low levels. On both of the Safe-CO™ generators, an increase in electrical load on the generators equipped with the catalyst (half-load) resulted in little difference in CO emissions compared to no-load conditions. The generators tested had approximately 2,900 to 4,700 hours of operation. As expected, the cold start condition resulted in very brief, high level CO concentrations. However, as the catalytic control device warmed to an optimal efficiency, the stack emissions dramatically reduced to less than a few hundred ppm (1,000 fold decrease) after approximately a few minutes.

The current study demonstrated that the Westerbeke Safe-CO™ generator performed well over time if the scheduled maintenance was performed as planned. Degradation was observed on the generator with 4,656 hours, and CO concentrations were observed to be close to 5,000 ppm when the generator was under load conditions. When the catalytic converter was replaced, the generator performed again as observed in previous evaluations. It is very important to keep in mind that manufacturers recommend changing the catalytic plug after 2,000 hours of operation. This evaluation has shown that 2,000 hours is a safe limit for scheduling maintenance, in conjunction with the manufacturer's recommendation to spot check concentrations after 1,000 hours of operation.

Exhaust Configuration

Data were gathered from a Fun Country Marine VIP XT (16' X 59') houseboat using a 14 KW Low CO Westerbeke generator that could be configured to exhaust from a side exhaust or top stack exhaust configuration. The results of air sampling with ToxiUltra CO monitors located on the lower and upper decks demonstrated low CO emissions for both configurations. When comparing the real-time results for the side exhaust versus vertical stack exhaust, there were slightly higher concentrations on the lower stern deck with the side exhaust configuration. Use of the Safe-CO™ generator resulted in low CO concentrations for both configurations. It is important that the boater/owner/operator follow all of the maintenance recommendations provided by the manufacturer. Some of those recommendations include periodically changing out the oxygen sensor and the replacement of the catalyst every 2,000 hours. Use of the vertical exhaust with these houseboats generators is a good redundant safety measure.

Westerbeke Generator Retrofitted with a Zenith EFI

CO results for the older 12.5 KW Westerbeke generator, retrofitted with an aftermarket EFI, were also good. The greatest difference in performance between this system and the Westerbeke system occurred while the generator was under half-load. CO concentrations in the exhaust increased significantly in this system while the generator was operating under half-load. The cold start condition also resulted in a transient increase in stack emissions that were greater than eight percent CO. The steady state CO concentrations for this generator set were generally low. Even though this system is not as efficient as the one installed in the low-emissions generators, the use of a dry stack to exhaust the gases into the atmosphere considerably reduced onboard CO concentrations and proved to be a good, viable, low-cost engineering control that will dramatically improve the safety of houseboat users.

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 evaluation of houseboats with gasoline-powered generators for potential CO exposures. It is recommended that these houseboats be retrofitted with effective control systems to reduce the potential hazard of CO poisoning.

2) The performance of the Westerbeke Safe-CO™ generators was impressive with exhaust stack CO emissions of approximately 200 ppm and below for a fully warmed generator. Due to diffusion, these emissions were significantly reduced. In fact, the highest average real-time CO readings, obtained from the monitors placed throughout the houseboat, were frequently single digit concentrations. All readings were below 10 ppm (side exhaust configuration). In order to ensure that the systems operate effectively, houseboat owners and operators should ensure that they follow all manufacturers' recommendations with regard to routine maintenance and replacement schedules.

3) The CO data obtained on the Westerbeke generator retrofitted with a Zenith EFI indicated that it was more effective than a regular generator without EFI and catalyst. With a stack exhaust, CO emissions were below 5,000 ppm for the fully warmed generator. Diffusion significantly reduced these emissions such that the highest average real-time CO reading obtained from the monitors placed throughout the houseboat, was 4 ppm. However, because of its design, this system was not as effective at lowering CO concentrations when the generator was operating under load.

4) 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 the vertical stack, when properly designed and installed, is a viable, low-cost, engineering control that will dramatically improve the safety of houseboat users. All houseboat manufacturers should be encouraged to retrofit a vertical exhaust stack to existing and older generators as well as onto those houseboats equipped with Safe-CO™ generators for system redundancy.

5) Houseboats manufacturers should continue to identify and correct any design or operational issues that may present problems related to the performance of the low-emissions generators and dry stack.

6) Public education efforts must be implemented immediately to inform and warn all individuals (including boat owners, renters, and workers) potentially exposed to CO hazards. Training about the specific boat-related CO hazards provided for houseboat renters, who may be completely

unaware of this deadly hazard, should be continued and enhanced to include specific information about the circumstances that most likely lead to excessive build up of CO concentrations.

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Table I--CO Concentrations (ppm) on Fun Country Marine VIP XT (16' X59') Houseboat, 14 KW Safe-CO™ Westerbeke Generator, Old catalyst, Stack-Exhaust Configuration (11/28/2006)

Sample Location (Sample #)	Houseboat Generator – No load	Houseboat Generator – 1/2 load	Houseboat Generator – 3/4 load
Upper Deck Steering wheel (Sample #1)	Mean = 0.0 Std. Dev. = 0.2 Peak = 1.0 N = 92	Mean = 0.6 Std. Dev. = 1.5 Peak = 7.0 N = 41	Mean = 0.0 Std. Dev. = 0.2 Peak = 1.0 N = 50
Lower Deck Kitchen (Sample #2)	Mean = 0.0 Std. Dev. = 0.2 Peak = 1.0 N = 92	Mean = 0.2 Std. Dev. = 0.4 Peak = 1.0 N = 41	Mean = 0.0 Std. Dev. = 0.2 Peak = 1.0 N = 50
Upper Stern Deck Port Side (near stack) (Sample #3)	Mean = 0.5 Std. Dev. = 0.6 Peak = 3.0 N = 92	Mean = 0.9 Std. Dev. = 1.2 Peak = 6.0 N = 41	Mean = 0.6 Std. Dev. = 0.5 Peak = 1.0 N = 50
Upper Stern Deck Starboard Side (top of slide) (Sample #4)	Mean = 1.2 Std. Dev. = 0.4 Peak = 2.0 N = 92	Mean = 1.9 Std. Dev. = 1.2 Peak = 7.0 N = 41	Mean = 1.8 Std. Dev. = 0.5 Peak = 3.0 N = 50
Lower Stern Deck Near Slide (Sample #5)	Mean = 0.4 Std. Dev. = 0.5 Peak = 2.0 N = 92	Mean = 0.4 Std. Dev. = 0.7 Peak = 3.0 N = 41	Mean = 0.0 Std. Dev. = 0.2 Peak = 1.0 N = 50
Lower Stern Deck Port Side (Sample #6)	Mean = 1.4 Std. Dev. = 0.4 Peak = 2.0 N = 92	Mean = 1.5 Std. Dev. = 0.8 Peak = 5.0 N = 41	Mean = 1.5 Std. Dev. = 1.0 Peak = 6.0 N = 50
Lower Stern Deck Starboard Side (Sample #7)	Mean = 0.6 Std. Dev. = 0.4 Peak = 1.0 N = 92	Mean = 1.2 Std. Dev. = 0.7 Peak = 3.0 N = 41	Mean = 1.0 Std. Dev. = 0.3 Peak = 1.0 N = 50
Lower Stern Deck Port Side (Sample #8)	Mean = 0.3 Std. Dev. = 0.5 Peak = 1.0 N = 92	Mean = 0.7 Std. Dev. = 0.7 Peak = 3.0 N = 41	Mean = 0.3 Std. Dev. = 0.5 Peak = 1.0 N = 50
Lower Stern Deck Back of Slide (Sample #9)	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 92	Mean = 0.2 Std. Dev. = 0.7 Peak = 4.0 N = 41	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 50

N= number of data points

Table II--CO Concentrations (ppm) on Fun Country Marine VIP XT (16' X 59') Houseboat, 14 KW Safe-CO™ Westerbeke Generator, Old catalyst, Side-Exhaust Configuration (11/28/2006)

Sample Location (Sample #)	Houseboat Generator – No load	Houseboat Generator – 1/2 load	Houseboat Generator – 3/4 load
Upper Deck Steering wheel (Sample #1)	Mean = 0.0 Std. Dev. =0.2 Peak = 1.0 N = 55	Mean = 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 50	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 52
Lower Deck Kitchen (Sample #2)	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 55	Mean = 0.1 Std. Dev. = 0.2 Peak = 1.0 N = 50	Mean = 0.0 Std. Dev. = 0.2 Peak = 1.0 N = 52
Upper Stern Deck Port Side (near stack) (Sample #3)	Mean = 0.3 Std. Dev. = 0.4 Peak = 1.0 N = 55	Mean = 0.2 Std. Dev. = 0.4 Peak = 1.0 N = 50	Mean = 0.2 Std. Dev. = 0.4 Peak = 1.0 N = 50
Upper Stern Deck Starboard Side (top of slide) (Sample #4)	Mean = 1.7 Std. Dev. = 0.5 Peak = 3.0 N = 55	Mean = 1.8 Std. Dev. = 0.5 Peak = 3.0 N = 50	Mean = 2.2 Std. Dev. = 0.8 Peak = 7.0 N = 52
Lower Stern Deck Near Slide (Sample #5)	Mean = 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 55	Mean = 0.1 Std. Dev. = 0.2 Peak = 1.0 N = 50	Mean = 0.4 Std. Dev. = 0.5 Peak = 1.0 N = 52
Lower Stern Deck Port Side (Sample #6)	Mean = 1.4 Std. Dev. = 0.5 Peak = 3.0 N = 55	Mean = 1.5 Std. Dev. = 0.6 Peak = 3.0 N = 50	Mean = 2.4 Std. Dev. = 0.7 Peak = 4.0 N = 52
Lower Stern Deck Starboard Side (Sample #7)	Mean = 1.0 Std. Dev. = 0.2 Peak = 1 N = 55	Mean = 1.0 Std. Dev. = 0.1 Peak = 1.0 N = 50	Mean = 1.1 Std. Dev. = 0.3 Peak = 2.0 N = 52
Lower Stern Deck Port Side (Sample #8)	Mean = 0.5 Std. Dev. = 0.5 Peak = 1.0 N = 55	Mean = 0.5 Std. Dev. = 0.5 Peak = 1.0 N = 50	Mean = 0.9 Std. Dev. = 0.5 Peak = 2.0 N = 52
Lower Stern Deck Back of Slide (Sample #9)	Mean = 0.1 Std. Dev. = 0.4 Peak = 2.0 N = 55	Mean = 0.3 Std. Dev. = 0.6 Peak = 3.0 N = 50	Mean = 0.8 Std. Dev. = 1.0 Peak = 5.0 N = 52

N= number of data points

Table III--CO Concentrations (ppm) on Fun Country Marine VIP XT (16' X 59') Houseboat, 14 KW Safe-CO™ Westerbeke Generator, New catalyst, Stack-Exhaust (11/29/2006)

Sample Location (Sample #)	Houseboat Generator – No load	Houseboat Generator – 1/2 load	Houseboat Generator – 3/4 load
Upper Deck Steering wheel (Sample #1)	Mean = 0.2 Std. Dev. = 0.5 Peak = 3.0 N = 84	Mean = 0.1 Std. Dev. = 0.2 Peak = 1.0 N = 43	Mean = 0.1 Std. Dev. = 0.2 Peak = 1.0 N = 34
Lower Deck Kitchen (Sample #2)	Mean = 0.6 Std. Dev. = 0.5 Peak = 1.0 N = 84	Mean = 0.5 Std. Dev. = 0.5 Peak = 1.0 N = 43	Mean = 0.2 Std. Dev. = 0.4 Peak = 1.0 N = 34
Upper Stern Deck Port Side (near stack) (Sample #3)	Mean = 0.1 Std. Dev. = 0.2 Peak = 1.0 N = 84	Mean = 0.1 Std. Dev. = 0.1 Peak = 1.0 N = 43	Mean = 0.1 Std. Dev. = 0.2 Peak = 1.0 N = 34
Upper Stern Deck Starboard Side (top of slide) (Sample #4)	Mean = 3.9 Std. Dev. = 0.4 Peak = 4.0 N = 84	Mean = 3.9 Std. Dev. = 0.4 Peak = 5.0 N = 43	Mean = 3.9 Std. Dev. = 0.4 Peak = 4.0 N = 34
Lower Stern Deck Near Slide (Sample #5)	Mean = 0.1 Std. Dev. = 0.1 Peak = 1.0 N = 84	Mean = 0.1 Std. Dev. = 0.1 Peak = 1.0 N = 43	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 34
Lower Stern Deck Port Side (Sample #6)	Mean = 2.7 Std. Dev. = 0.5 Peak = 4.0 N = 84	Mean = 2.8 Std. Dev. = 0.4 Peak = 4.0 N = 43	Mean = 2.9 Std. Dev. = 0.4 Peak = 4.0 N = 34
Lower Stern Deck Starboard Side (Sample #7)	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 84	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 43	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 34
Lower Stern Deck Port Side (Sample #8)	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 84	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 43	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 34
Lower Stern Deck Back of Slide (Sample #9)	Mean = 0.1 Std. Dev. = 0.1 Peak = 1.0 N = 84	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 43	Mean = 0.1 Std. Dev. = 0.4 Peak = 1.0 N = 34

N= number of data points

Table IV--CO Concentrations (ppm) on Fun Country Marine (14' X 59') Houseboat, 12.5 KW Westerbeke Generator Retrofitted with a Zenith Electronic Fuel Injection Kit and Stack-Exhaust (11/29/2006)

Sample Location (Sample #)	Houseboat Generator – No load	Houseboat Generator – 1/2 load	Houseboat Generator – 3/4 load
Upper Deck Steering wheel (Sample #1)	Mean = 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 27	Mean = 0.1 Std. Dev. = 0.2 Peak = 1.0 N = 29	Mean = 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 28
Lower Deck Kitchen (Sample #2)	Mean = 0.5 Std. Dev. = 0.5 Peak = 1.0 N = 27	Mean = 0.4 Std. Dev. = 0.5 Peak = 1.0 N = 29	Mean = 0.2 Std. Dev. = 0.4 Peak = 1.0 N = 28
Upper Stern Deck Port Side (near stack) (Sample #3)	Mean = 0.2 Std. Dev. = 0.4 Peak = 2.0 N = 27	Mean = 0.2 Std. Dev. = 0.4 Peak = 1.0 N = 29	Mean = 0.3 Std. Dev. = 0.7 Peak = 3.0 N = 28
Upper Stern Deck Starboard Side (top of slide) (Sample #4)	Mean = 3.3 Std. Dev. = 0.5 Peak = 4.0 N = 27	Mean = 3.3 Std. Dev. = 0.5 Peak = 4.0 N = 29	Mean = 3.3 Std. Dev. = 0.5 Peak = 4.0 N = 28
Lower Stern Deck Near Slide (Sample #5)	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 27	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 29	Mean = 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 28
Lower Stern Deck Port Side (Sample #6)	Mean = 2.4 Std. Dev. = 0.5 Peak = 3.0 N = 27	Mean = 2.4 Std. Dev. = 0.5 Peak = 3.0 N = 29	Mean = 2.9 Std. Dev. = 1.0 Peak = 6.0 N = 28
Lower Stern Deck Starboard Side (Sample #7)	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 27	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 29	Mean = 0.1 Std. Dev. = 1.0 Peak = 6.0 N = 28
Lower Stern Deck Port Side (Sample #8)	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 27	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 29	Mean = 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 28
Lower Stern Deck Back of Slide (Sample #9)	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 27	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 29	Mean = 0.5 Std. Dev. = 1.9 Peak = 9.0 N = 28

N= number of data points

Table V--CO Concentrations (ppm) on Fun Country Marine VIP XT (16' X 70') Houseboat, 20 KW Safe-CO™ Westerbeke Generator, Old catalyst, Stack-Exhaust Configuration (11/28/2006)

Sample Location (Sample #)	Houseboat Generator – No load	Houseboat Generator – 1/2 load	Houseboat Generator – 3/4 load
Upper Deck Steering wheel (Sample #1)	Mean = 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 142	Mean = 0.1 Std. Dev. = 0.1 Peak = 1.0 N = 73	Mean = 0.1 Std. Dev. = 0.2 Peak = 1.0 N = 35
Lower Deck Kitchen (Sample #2)	Mean = 0.7 Std. Dev. = 0.5 Peak = 1.0 N = 142	Mean = 0.5 Std. Dev. = 0.5 Peak = 1.0 N = 73	Mean = 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 35
Upper Stern Deck Port Side (near stack) (Sample #3)	Mean = 0.3 Std. Dev. = 0.5 Peak = 1.0 N = 142	Mean = 0.2 Std. Dev. = 0.4 Peak = 1.0 N = 73	Mean = 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 35
Upper Stern Deck Starboard Side (top of slide) (Sample #4)	Mean = 1.7 Std. Dev. = 0.5 Peak = 2.0 N = 142	Mean = 1.2 Std. Dev. = 0.4 Peak = 2.0 N = 73	Mean = 1.3 Std. Dev. = 0.5 Peak = 2.0 N = 35
Lower Stern Deck Near Slide (Sample #5)	Mean = 0.1 Std. Dev. = 0.1 Peak = 1.0 N = 142	Mean = 0.0 Std. Dev. = 0.0 Peak = 0.0 N = 73	Mean = 0.1 Std. Dev. = 0.2 Peak = 1.0 N = 35
Lower Stern Deck Port Side (Sample #6)	Mean = 1.7 Std. Dev. = 0.5 Peak = 3.0 N = 142	Mean = 1.5 Std. Dev. = 0.5 Peak = 2.0 N = 73	Mean = 1.6 Std. Dev. = 0.5 Peak = 2.0 N = 35
Lower Stern Deck Starboard Side (Sample #7)	Mean = 0.8 Std. Dev. = 0.4 Peak = 2.0 N = 142	Mean = 1.2 Std. Dev. = 0.4 Peak = 3.0 N = 73	Mean = 1.4 Std. Dev. = 0.6 Peak = 3.0 N = 35
Lower Stern Deck Port Side (Sample #8)	Mean = 0.1 Std. Dev. = 0.3 Peak = 1.0 N = 142	Mean = 0.3 Std. Dev. = 0.6 Peak = 3.0 N = 73	Mean = 0.1 Std. Dev. = 0.2 Peak = 1.0 N = 35
Lower Stern Deck Back of Slide (Sample #9)	Mean = 0.6 Std. Dev. = 0.5 Peak = 2.0 N = 142	Mean = 0.7 Std. Dev. = 0.5 Peak = 2.0 N = 73	Mean = 0.8 Std. Dev. = 0.4 Peak = 1.0 N = 35

N= number of data points

Table VI -- CO Detector Tube Results (ppm) taken adjacent (Side Exhaust Configuration, ~5" above the exhaust) or within the Exhaust Plumes (Top Exhaust Configuration)

Boat, Condition (Test Date)	Sample	Condition	Sample Result
CO Concentrations (ppm) on Fun Country Marine VIP XT (16' X 59') Houseboat, 14 KW **Safe-CO™** Westerbeke Generator	1	3 (Old)	120
	2	3 (Old)	500
	3	4 (Old)	1600
	4	4 (Old)	>3000
	5	4 (Old)	5000
	6	4 (Old)	5000
	7	4 (Old)	3000
	8	3 (Old)	250
	9	1 (Old)	150
	10	2 (Old)	100
	11	2 (Old)	300
	12	3 (New)	70,000 CS
	13	3 (New)	30,000 CS
	14	3 (New)	250
	15	3 (New)	10
CO Concentrations (ppm) on Fun Country Marine (14' X 59') Houseboat, 12.5 KW Westerbeke Generator Retrofitted with a Zenith Electronic Fuel Injection Kit	16	3	70,000 CS
	17	3	5,900
	18	3	3,000
	19	4	4,000
	20	4	10,000
Fun Country Marine VIP XT (16' X 70') Houseboat, 20 KW Safe-CO™ Westerbeke Generator	21	3 (Old)	70,000 CS
	22	3 (Old)	3,000 CS
	23	3 (Old)	60
	24	3 (Old)	30
	25	4 (Old)	100

ND = none detected; CS = cold start

Condition 1: side exhaust, no generator load
Condition 2: side exhaust, generator load
Condition 3: stack, no generator load
Condition 4: stack, generator load

Old: Old Catalyst
New: New Catalyst

Table VII -- CO Evacuated Container Results (ppm) taken adjacent (Side Exhaust Configuration, ~5" above the exhaust) or within the Exhaust Plumes (Top Exhaust Configuration)

Boat, Condition (Test Date)	Sample	Condition/ Comment	Sample Result
CO Concentrations (ppm) on Fun Country Marine VIP XT (16' X 59') Houseboat, 14 KW Safe-CO™ Westerbeke Generator	1	3, Cold start (Old)	49,000
	2	3 (Old)	ND
	3	4 (Old)	ND
	4	4 (Old)	ND
	5	4 (Old)	ND
	6	1 (Old)	ND
	7	1, Cold start (New)	ND
	8	1 (New)	ND
	9	2 (New)	4,500
	10	2 (New)	7,800
CO Concentrations (ppm) on Fun Country Marine (14' X 59') Houseboat, 12.5 KW Westerbeke Generator Retrofitted with a Zenith Electronic Fuel Injection Kit	11	3, Cold start	38,000
	12	3	22,000
	13	4	11,000
Fun Country Marine VIP XT (16' X 70') Houseboat, 20 KW Safe-CO™ Westerbeke Generator	14	3, Cold start (Old)	ND
	15	3 (Old)	ND
	16	4 (Old)	ND
	17	4 (Old)	ND
	18	4 (Old)	ND
	19	4 (Old)	ND

ND = none detected;
Condition 1: side exhaust, no generator load
Condition 2: side exhaust, generator load
Condition 3: stack, no generator load
Condition 4: stack, generator load

Old: Old Catalyst
New: New Catalyst

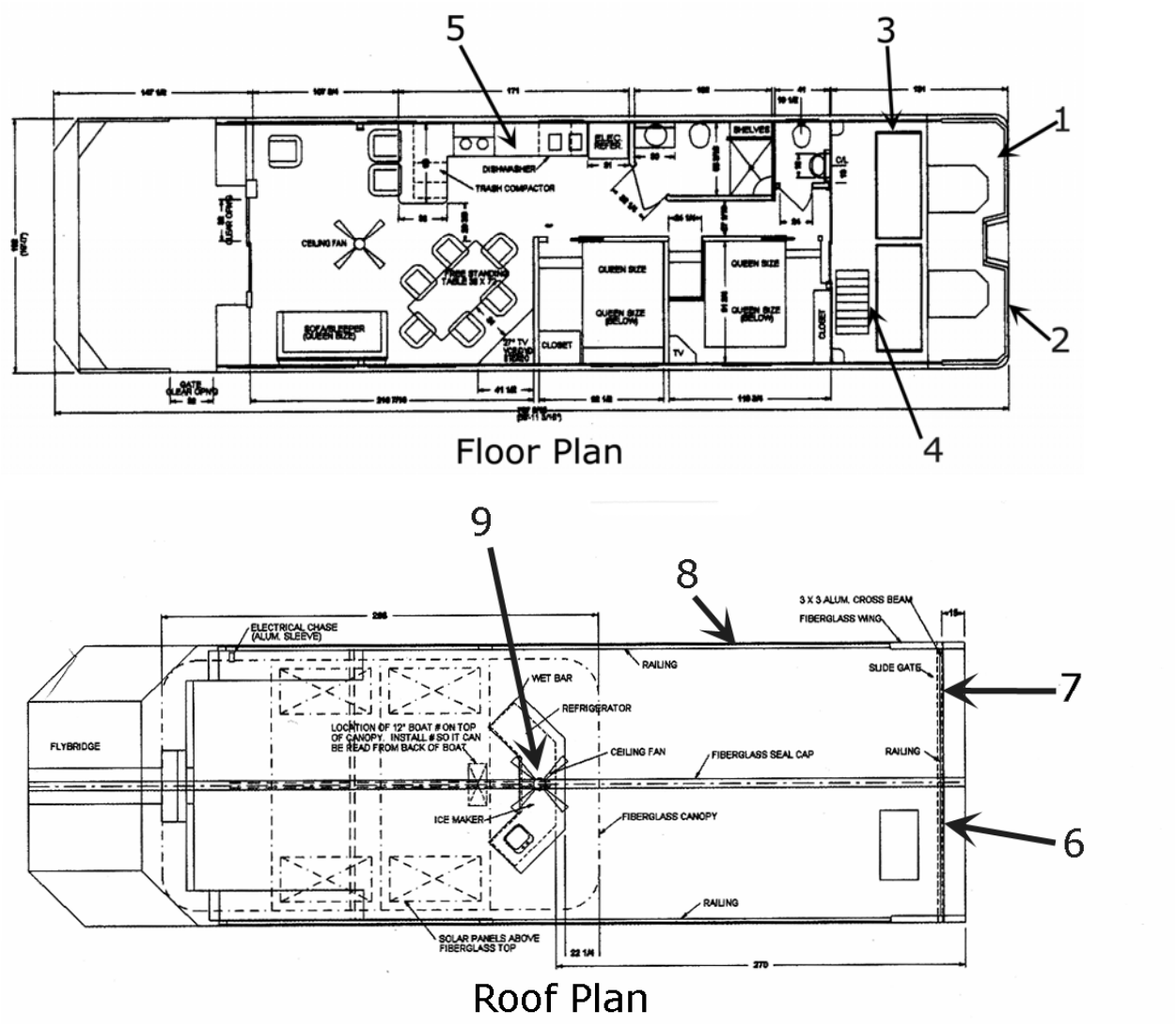

Figure 1. Diagram of evaluated houseboats and air sampling locations.

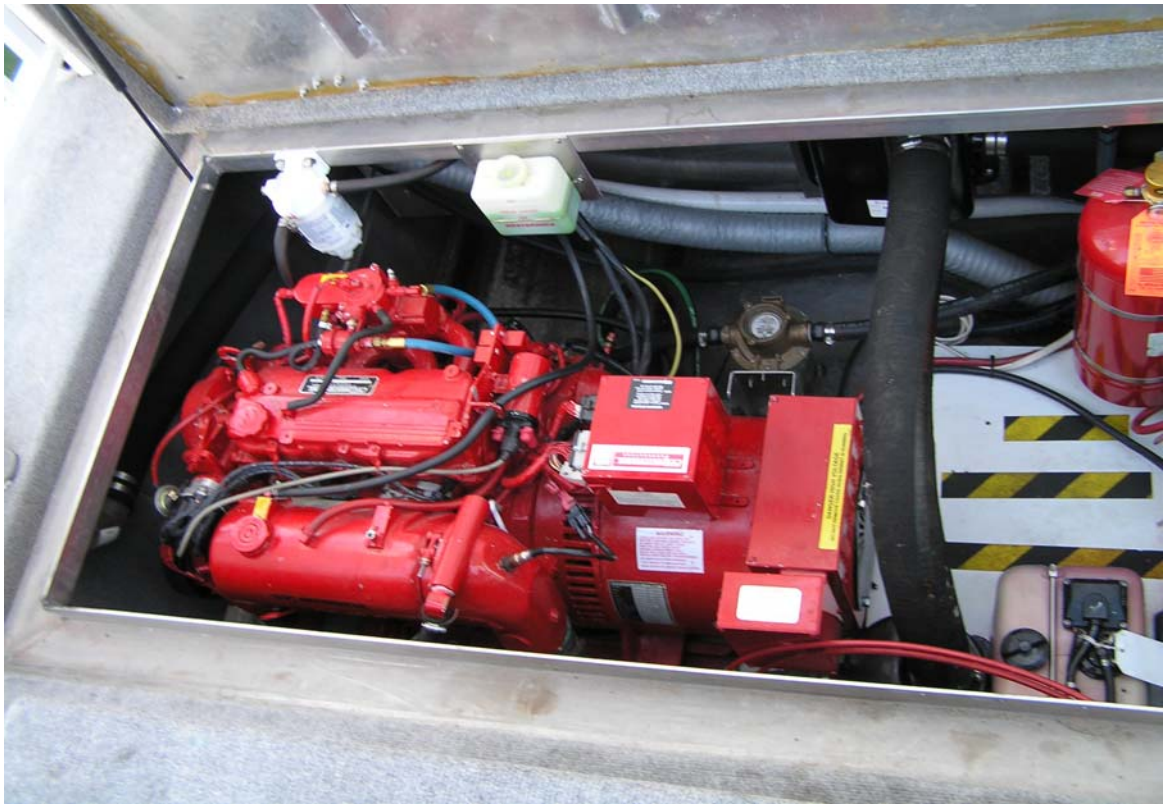

Figure 2. Photo of the Westerbeke Safe-CO generator.

Figure 3. Photo of Westerbeke Generator with Zenith Electronic Fuel Injection kit.