HHS Public Access
Author manuscript
J Occup Environ Hyg. Author manuscript; available in PMC 2015 August 12.

Published in final edited form as:
J Occup Environ Hyg. 2014 ; 11(7): D92–D103. doi:10.1080/15459624.2014.895374.

A Summary of Research and Progress on Carbon Monoxide Exposure Control Solutions on Houseboats

Ronald M. Hall, **G. Scott Earnest**, **Duane R. Hammond**, **Kevin H. Dunn**, and **Alberto Garcia**
Division of Applied Research and Technology, Engineering and Physical Hazards Branch, National Institute for Occupational Safety and Health, Cincinnati, Ohio

Abstract

Investigations of carbon monoxide (CO-related poisonings and deaths on houseboats were conducted by the Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health. These investigations measured hazardous CO concentrations on and around houseboats that utilize gasoline-powered generators. Engineering control devices were developed and tested to mitigate this deadly hazard. CO emissions were measured using various sampling techniques which included exhaust emission analyzers, detector tubes, evacuated containers (grab air samples analyzed by a gas chromatograph), and direct-reading CO monitors. CO results on houseboats equipped with gasoline-powered generators without emission controls indicated hazardous CO concentrations exceeding immediately dangerous to life and health (IDLH) levels in potentially occupied areas of the houseboat. Air sample results on houseboats that were equipped with engineering controls to remove the hazard were highly effective and reduced CO levels by over 98% in potentially occupied areas. The engineering control devices used to reduce the hazardous CO emissions from gasoline-powered generators on houseboats were extremely effective at reducing CO concentrations to safe levels in potentially occupied areas on the houseboats and are now beginning to be widely used.

Address correspondence to: Ronald M. Hall, National Institute for Occupational Safety and Health, 4676 Columbia Parkway, Cincinnati, OH, 45226; rmhall@cdc.gov.

DISCLAIMER
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. Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health (NIOSH). In addition, citations to Web sites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products. Furthermore, NIOSH is not responsible for the content of these Web sites. All Web addresses referenced in this document were accessible as of the publication date. This article is not subject to US copyright law.

INTRODUCTION

Investigations of carbon monoxide (CO)-related poisonings and deaths on houseboats were initially conducted at Lake Powell, Arizona, in September and October 2000, involving representatives from the National Institute for Occupational Safety and Health (NIOSH), the U.S. Coast Guard, the National Park Service (NPS), the U.S. Department of the Interior, and Utah State Parks and Recreation. These investigations measured hazardous CO concentrations on houseboats.(1) Some of the severely hazardous locations/situations identified included:

1. Areas above and around the swim platform (located at the rear of the boat) which could be lethal under certain circumstances (i.e., generator/motor exhaust discharging into this area) on some houseboats.

2. Areas above and around the swim platform (at the rear of the boat) which were at or above the immediately dangerous to life and health (IDLH) level of 1200 parts per million (ppm) for CO.(2)

3. Monitoring of CO concentrations during boat maintenance activities indicated potentially hazardous exposures.

Epidemiologic investigations revealed that from 1990 through April of 2008, 309 houseboat-related CO poisonings occurred in the United States. Nonfatal poisonings associated with houseboats numbered 283 with the majority of these poisonings being directly attributable to generator exhaust. Of the 309 houseboat-related CO poisonings, 26 resulted in death. More than 800 CO poisonings related to recreational boating in the United States have been identified, and that number continues to increase.(3)

This article will summarize the results of NIOSH studies on two potential emissions controls for houseboat generators including the dry stack exhaust and the catalytic converter.

BACKGROUND

NIOSH investigations on houseboats that exhaust uncontrolled generator combustion gases beneath or near the rear deck showed that extremely hazardous CO concentrations can accumulate in that area. These hazardous conditions are exacerbated when the drive engines are operating. CO concentrations in this area measured by three separate methods (i.e., real-time instruments, evacuated containers, and detector tubes) indicated concentrations well above the NIOSH IDLH value of 1200 ppm. Individuals swimming or working in the area under the swim deck, or around it (near the water level), could experience CO poisoning or death within a few minutes if the generator and/or drive engines were operating.(4)

Engineering control studies began in February 2001 at Lake Powell and Somerset, Kentucky.(5,6) 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. NIOSH's Division of Applied Research and Technology (DART) researchers signed an interagency agreement with the U.S. Coast Guard, Office of Boating Safety to investigate the problem and evaluate engineering control solutions to mitigate the CO hazard.

Health Effects Associated with Carbon Monoxide Exposure

CO is a colorless, odorless, tasteless gas produced by incomplete burning of carbon-containing materials such as gasoline or propane fuel. 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.(7–12) 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.

Exposure to CO limits the ability of the blood to carry oxygen to the tissues by binding with the hemoglobin to form carboxyhemoglobin (COHb). CO binds at the same site on the hemoglobin as oxygen, and with an affinity of 245 times higher.[(12)] Therefore, the presence of CO in the blood can interfere with oxygen uptake and delivery to the body. Once absorbed into the bloodstream and exposure has ceased, the half-life of bloodborne CO at sea level and standard pressure is approximately 5 hr. This means that an initial COHb level of 10% could be expected to drop to 5% in 5 hr, and then 2.5% in another hour. If oxygen is administered to the exposed person, as happens in emergency treatment, the COHb concentration drops more quickly. Once exposed, the body compensates for the reduced bloodborne oxygen by increasing cardiac output, thereby increasing blood flow to specific oxygen-demanding organs such as the brain and heart. This ability may be limited by preexisting heart or lung diseases that inhibit increased cardiac output.

Altitude affects the toxicity of CO. With 50 ppm CO in the air, the COHb level in the blood is approximately 1% higher at an altitude of 4,000 feet than at sea level. This occurs because the partial pressure of oxygen (the gas pressure causing the oxygen to pass into the blood) at higher altitudes is less than the partial pressure of CO. Furthermore, the effects of CO poisoning at higher altitudes are greater. For example, at an altitude of 14,000 feet, a 3% COHb level in the blood has the same effect as a 20% COHb at sea level.[(13)]

Occupational Exposure Limits for Carbon Monoxide

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

The NIOSH recommended exposure limit (REL) for occupational exposures to CO in air is 35 ppm for full shift time-weighted average (TWA) exposure, and there is also a ceiling limit of 200 ppm, which should never be exceeded.[14] NIOSH has established the IDLH value for CO of 1,200 ppm.[2] The American Conference of Governmental Industrial Hygienists (ACGIH®) recommends an 8-hour TWA threshold limit value (TLV®) for occupational exposure to CO of 25 ppm.[15] The OSHA permissible exposure limit (PEL) for CO is 50 ppm for an 8-hour TWA exposure.[16]

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.[17] 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 TWA exposures related to CO exposure in the general population.[18] 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 min
- 60 mg/m^3 (52 ppm) for 30 min
- 30 mg/m^3 (26 ppm) for 1 hour
- 10 mg/m^3 (9 ppm) for 8 hr

MATERIALS AND METHODS

Emissions from gasoline-powered generators were characterized using a Ferret Instruments (Cheboygan, Mich.) Gaslink LT Five Gas Emissions Analyzer. This analyzer measures CO, carbon dioxide (CO_2), hydrocarbons, oxygen, and nitrogen oxides (NO_x). All measurements were expressed as percentages except hydrocarbons and NO_x which was in ppm. (One percent of contaminant is equivalent to 10,000 ppm.)

CO concentrations were measured at various locations on the houseboats using ToxiUltra Atmospheric Monitors (Biometrics, Inc., Middletown, Conn.) with CO sensors. ToxiUltra (Biometrics, Inc., Middletown, Conn.) 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 30-sec sampling intervals. The instruments have a nominal range from 0 ppm to 999 ppm. Typical sampling locations for the ToxiUltra (Biometrics, Inc., Middletown, Conn.) real-time CO monitors on the lower and upper decks of the houseboats are shown in Figure 1. These monitors were placed at various locations on the upper and lower decks to provide representative samples of occupied areas. Several monitors were placed on the boats' stern swim platforms because it is common to enter and exit the water via this structure.

CO 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)] 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.

During the evaluations, grab samples were also 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 gas chromatograph equipped with dual columns (molecular sieve and porapak) and thermal conductivity detectors.

Exhaust Controls Evaluated

Exhaust stack controls on houseboats were evaluated. On houseboats equipped with exhaust stacks, the water-jacketed exhaust passed through a muffler/gas/water separator, designed to route the exhaust gases up through the stack while the water flows out just beneath the waterline on the starboard stern side of the houseboat. Exhaust gases are physically mixed with cooling water. Cooling water and exhaust gases must be separated during installation of the exhaust stack. Separation efficiency is important to avoid water entering the stack. Resistance to the water flow and exhaust exiting the generator should be minimized to prevent excessive back pressure. The exhaust stack and water outlet to the separator must be designed properly to ensure proper separation of exhaust gases and water.[(19)] See Figure 2 for a diagram showing the gas water separator configuration.

Performance evaluations of generators equipped with catalytic emission control devices were also conducted by NIOSH researchers. Given the proprietary nature of this technology, little information was obtained regarding the specific control technologies used to reduce the CO emissions. However, an electronic fuel injection system was employed to efficiently combust the gasoline fuel to reduce exhaust emissions, including CO. Secondly, a catalytic air pollution control device was designed to optimize the chemical oxidation of CO in the exhaust generator exhaust emissions.[(20)] According to the manufacturer, the catalyst should be replaced after 2000 hr of use. The manufacturer also recommends that CO emissions be spot checked at 1000 hr of use. Stainless steel was selected as the catalyst housing to inhibit corrosion from the harsh marine environment.[(20)] The catalytic ingredients used in the catalyst were not revealed by the manufacturer, but normally 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.[(21)]

RESULTS AND DISCUSSION

Over four initial field investigations were conducted by CDC, NIOSH industrial hygienists and engineers which indicated very high concentrations of CO on and around houseboats using gasoline-powered generators. Following these investigations, NIOSH researchers worked with major houseboat and generator manufacturers to evaluate novel engineering controls to reduce CO concentrations in occupied areas on houseboats. This work led to approximately 11 engineering control field evaluations and collaborations with external partners to evaluate new engineering technologies designed to reduce CO exposures and poisonings.

Exhaust Stack Evaluations

Evaluation of a stationary houseboat represents the most standard generator operating condition. The boat is typically anchored or docked and the drive engines are not operating, but the generator is running to provide electrical power for air conditioning, lighting, and entertainment. Because CO exhaust concentrations can be very high, directing generator exhaust gases away from areas where people may be located (i.e., the water or lower rear deck of the houseboat) is particularly important.

Engineering control studies began in February 2001 at Lake Powell and Somerset, Kentucky.(5,6) Results of these studies demonstrated that a generator exhaust stack extending 9 feet above the houseboat's upper deck (Figure 3) dramatically reduced the CO concentrations on and near the houseboat and provided a much safer environment. NIOSH conducted considerable research to evaluate the exhaust stack to reduce the high CO concentrations on houseboats.

NIOSH evaluations found that the stack exhaust greatly reduced the CO hazard in occupied areas of the boat (Table I). The extended stack on the upper deck propelled exhaust gases with enough momentum to disperse CO concentrations. Average and peak CO concentrations at all locations on the houseboats with exhaust stacks were well below OELs (OSHA, NIOSH, and ACGIH®) when only the generator operated. A summary of the CO results obtained during the NIOSH research on stationary houseboats is presented in Table I.

NIOSH found that high temperature and high humidity levels, temperature inversions, generator loading, and houseboat trim angles had little effect on the exhaust stack performance. It also demonstrated the importance of proper design and installation of exhaust stacks to ensure that all exhaust gases are released through the stack.(19) Well-designed stacks have been shown to reduce CO concentrations on houseboats by as much as 99%.(22)

Catalytic Emission Control Evaluations

In one study, the performance of two (20 kilowatt (kW) and 14 kW) Westerbeke Safe-CO (Baton Rouge, La.) generators were tested after being used on rental houseboats for two boating seasons. The evaluated generators had 2835 and 4656 hr of use, respectively, and were equipped with catalytic converters and electronic fuel injection systems.(23) The two Westerbeke Safe-CO (Baton Rouge, La.) generators used for two boating seasons performed well; average CO concentrations at various locations on the boat were generally below 5 ppm. Peak CO concentrations were all well below 10 ppm.(23) However, results of this study indicated that degradation of the catalyst was observed on the 14 kW unit that had 4656 hr of use. This generator was unable to keep CO concentrations below 4000 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 measured directly in the exhaust stack were below 1000 ppm for the fully warmed generator with the new catalyst.

That compares to measured CO concentrations which usually exceeded 10,000 ppm on older Westerbeke generators without the Safe-CO control systems.[23]

A summary of CO results collected during the NIOSH research to evaluate the effectiveness of the catalyst control is presented in Table II.

It is important to follow the recommendations provided by the manufacturers and replace the catalytic emission control device as directed. Some of those recommendations include periodically changing the oxygen sensor in the generator and replacing the catalyst every 2000 hr.[23]

CONCLUSION

NIOSH has shown that CO concentrations from gasoline-powered generators on houseboats can reach dangerous concentrations.[1,4–6,22,24–27] CO measured in the exhaust and near the rear of boats has often exceeded the IDLH value of 1200 ppm. These uncontrolled generators routinely emitted CO at concentrations well above the IDLH and concentrations exceeding the NIOSH workplace ceiling limit of 200 ppm.

Approximately 11 in-depth technical evaluations of two types of engineering controls occurred over a ten-year period: 1) a generator exhaust stack that reroutes emissions from the water line to well above the upper deck of the houseboat; and 2) and engine emission controls (fuel injection and catalysts) that reduced CO at the source before being exhausted. Both engineering controls effectively reduced exposures by over 98%, to safe concentrations in potentially occupied areas of the houseboat.

In order to reduce CO concentrations on a houseboat, it is important that the generator exhaust stack, water separator, and associated piping and hoses be designed and installed properly. If the stack exhaust is not designed properly, the performance could be hindered. Rather than hazardous exhaust gases passing through the stack to a height well above the upper deck, high static pressure in the stack could force exhaust gases to pass out the side terminus near the water line.[19,28] While concentrations on the boat remain low with the stack exhaust as compared to the side exhaust, CO measurements taken directly at the stack outlet indicated a range of 5% to 8.6% CO (50,000 ppm to 86,000 ppm). Because this concentration is 42 to 72 times greater than the immediately dangerous to life and health value for breathing zone concentrations of CO, it is prudent for houseboat manufacturers to clearly label and identify the exhaust outlet to warn people.[28] A well- and properly designed water/gas exhaust separator and stack is a viable low-cost control that efficiently removes hazardous CO concentrations from any potentially occupied areas on or near the water level of a houseboat.

Initially, one of the major obstacles in the safe use of gasoline-powered generators was the absence of emission controls. NIOSH researchers have partnered with boat builders and marine engine manufacturers since 2001 to address this hazard. Work in this area has resulted in new low-emission generators and other engine technology which has greatly reduced the risk of CO poisoning in the marine environment. Two major manufacturers of marine power generation systems, Westerbeke and Kohler, have developed low-CO emission generators. Our evaluations have shown that the addition of technologies such as catalytic converters and electronic fuel injection to marine generators has helped to dramatically reduce CO emissions by 99%.[23,29] To ensure that the systems operate effectively, houseboat owners and operators should follow all manufacturers' recommendations regarding maintenance and replacement schedules.

Controlling exposures to occupational hazards is the fundamental method to protect workers. Traditionally, a hierarchy of controls has been applied. Following the hierarchy normally leads to the implementation of inherently safer systems, where the risk of illness or injury is reduced. Clean burning fuel-injected generators fitted with properly functioning and maintained catalytic emission controls connected to a properly designed water/gas separator and exhaust stack have the potential to provide added protection against possible CO poisoning than the stack or the catalyst emission control device alone.

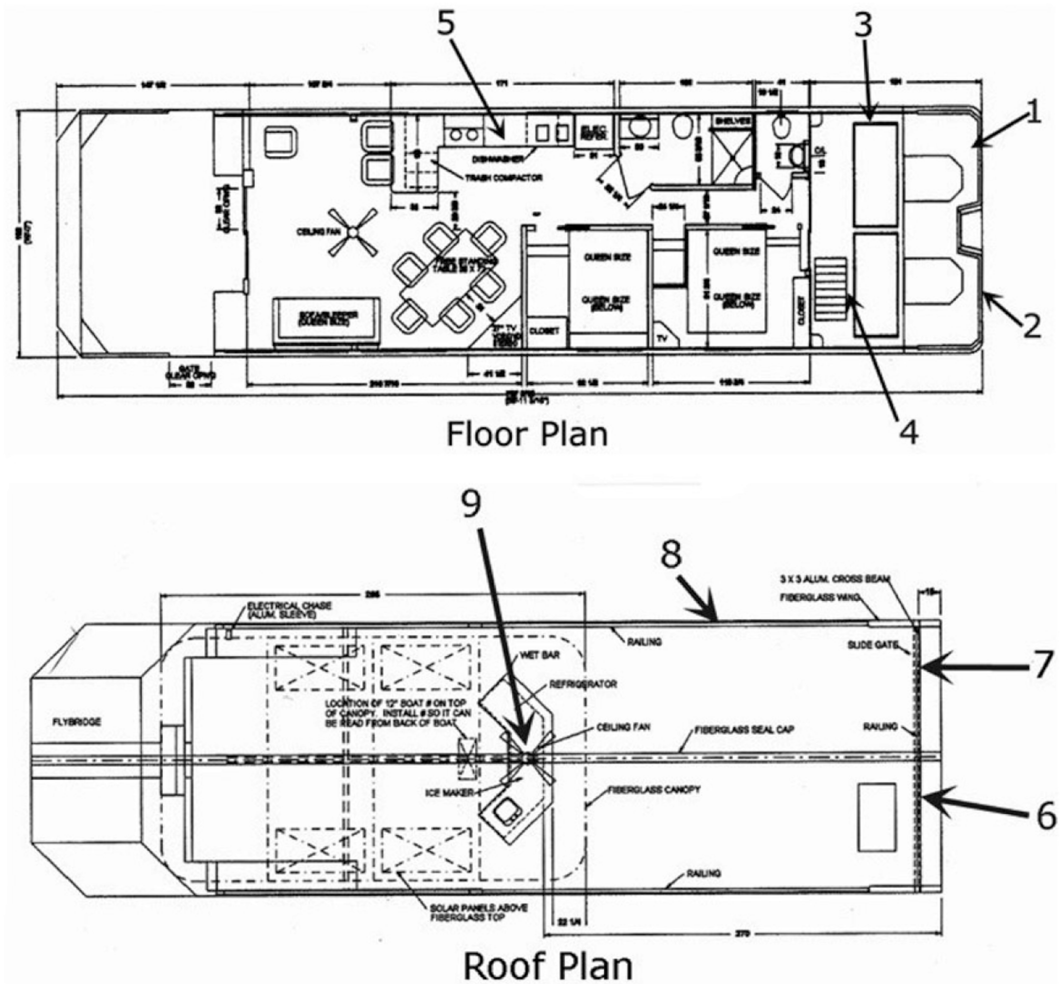
Recommendations from this effort have enabled the marine industry to widely embrace these innovative solutions to the problem of this hazard. In addition, regulations have been enacted based upon the technological advances documented by this research. The American Boat and Yacht Council (ABYC) modified their standards for generator exhaust to include exhaust stacks.[30,31] As of 2009, U.S. generator and marine engine manufacturers have been manufacturing commercially available cleaner burning engines that dramatically reduce CO emissions. This has been codified through Environmental Protection Agency (EPA) regulations.[32] The California Air Resources Board (CARB) also acted to implement CO requirements.[33] In addition, the U.S. NPS has issued new requirements for concession boat rental and marina operations to prevent CO poisoning.[34] Several major houseboat rental companies have retrofitted their entire fleet with control systems.

REFERENCES

1. McCammon JB, Radtke T. Letter of September 28, 2000, from J. McCammon, National Institute for Occupational Safety and Health, Denver, Colorado, and T. Radtke, U.S. Department of the Interior, to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, Arizona.
2. National Institute for Occupational Safety and Health (NIOSH). Pocket Guide to Chemical Hazards. Cincinnati, Ohio: NIOSH; NIOSH Publication No. 2005-149
3. Double Angle Foundation. Boat Related Carbon Monoxide (CO) Poisonings. Updated May 200 – April 2008. Available at http://www.doubleangel.org/documents/NatlCaseListingBoat-RelatedCOPoisoningsMay2007April2008_000.pdf.
4. Earnest GS, Dunn KH, Hall RM, McCleery R, McCammon JB. An evaluation of an engineering control to prevent carbon monoxide poisonings of individuals on and around houseboats. Am. Ind. Hyg. Assoc. J. 63:361–369.
5. Dunn, KH.; Hall, RM.; McCammon, JB.; Earnest, GS. An Evaluation of an Engineering Control to Prevent Carbon Monoxide Poisonings of Individuals on Houseboats at Somerset Custom Houseboats, Somerset, Kentucky. Cincinnati, Ohio: National Institute for Occupational Safety and Health; 2001. NIOSH Publication No. ECTB 171-26a
6. Earnest, GS.; Dunn, KH.; Hall, RM.; McCleery, R.; McCammon, JB. An Evaluation of an Engineering Control to Prevent Carbon Monoxide Poisonings of Individuals on and Around Houseboats. Cincinnati, Ohio: National Institute for Occupational Safety and Health; 2001. NIOSH Publication No. ECTB 171-25a
7. National Institute for Occupational Safety and Health (NIOSH). Criteria for a Recommended Standard: Occupational Exposure to Carbon Monoxide. Cincinnati, Ohio: National Institute for Occupational Safety and Health; 1972. NIOSH Publication No. 73-11000

8. National Institute for Occupational Safety and Health (NIOSH). Occupational Diseases: A Guide to Their Recognition. Cincinnati, Ohio: National Institute for Occupational Safety and Health; 1977. DHEW (NIOSH) Publication No. 77-181
9. National Institute for Occupational Safety and Health (NIOSH). A Guide to Work-relatedness of Disease. Cincinnati, Ohio: National Institute for Occupational Safety and Health; 1979. DHEW (NIOSH) Publication No. 79-116
10. Proctor, NH.; Hughes, JP.; Fischman, ML. Chemical Hazards of the Workplace. Philadelphia: J.B. Lippincott Company; 1988.
11. American Conference of Governmental Industrial Hygienists (ACGIH®). Cincinnati, Ohio: American Conference of Governmental Industrial Hygienists; 1996. Documentation of Threshold Limit Values and Biological Exposure Indices.
12. Stien, KE.; Brown, TM. Principles of Toxicology. Boca Raton, FL: Lewis Publishers. CRC Press Inc.; 1996. p. 114
13. American Gas Association. American Gas Association 1985 Operating Section Proceedings. Arlington, Virginia: American Gas Association; 1988. What You Should Know about Carbon Monoxide.
14. National Institute for Occupational Safety and Health (NIOSH). Recommendations for Occupational Safety and Health: Compendium of Policy Documents and Statements. Cincinnati, Ohio: National Institute for Occupational Safety and Health; 1992. NIOSH Publication No. 92–100
15. American Conference of Governmental Industrial Hygienists (ACGIH®). Threshold Limit Values for Chemical Substances and Physical Agents. Cincinnati, Ohio: American Conference of Governmental Industrial Hygienists; 2013. 2013 TLVs® and BEIs.
16. Occupational Safety and Health Standards, Subpart Z, Toxic and Hazardous Substances. Code of Federal Regulations Title. 1997; 29 1910.1000.
17. Environmental Protection Agency (EPA). Air Quality Criteria for Carbon Monoxide. Washington, D.C.: EPA;
18. World Health Organization (WHO). 2nd ed.. Geneva: WHO; 1999. Environmental Health Criteria 213 - Carbon Monoxide. NLM Classification: QV 662
19. Hammond DR, Earnest GS, Hall RM, Feng HA. An evaluation of conditions that may affect the performance of houseboat exhaust stacks in prevention of carbon monoxide poisonings from generators. J. Occup. Environ. Hyg. 2006; 3(6):308–316. [PubMed: 16627369]
20. Zimmer, AT.; Earnest, GS.; Kurimo, R. An Evaluation of Catalytic Emission Controls and Vertical Exhaust Stacks to Prevent Carbon Monoxide Poisonings from Houseboat Generator Exhaust, Callville Bay Marina, Boulder City, Nevada. Cincinnati, Ohio: National Institute for Occupational Safety and Health; 2005 Sep. NIOSH Publication EPHB 171-36a
21. Heck, RM.; Farrauto, RJ. Catalytic Air Pollution Control: Commercial Technology. New York: John Wiley & Sons, Inc;
22. Dunn KH, Shulman SA, Earnest GS, Hall RM, McCammon JB, McCleery RE. Carbon monoxide and houseboats: An evaluation of a stack exhaust system to reduce poisonings associated with generator exhaust. Prof. Safe. 48(11):47–57.
23. Garcia, A.; McCleery, R.; Dowell, C.; Dunn, KH.; Earnest, GS.; Hall, RM. An Evaluation of Catalytic Emission Controls to Prevent Carbon Monoxide Poisonings from Houseboat Generator Exhaust, Callville Bay Marina, Boulder City, Nevada. Cincinnati, Ohio: National Institute for Occupational Safety and Health; 2007 Mar. NIOSH Publication EPHB 171-05vv
24. Earnest, GS.; Dunn, KH.; McCleery, R.; McCammon, JB.; Hall, RM.; Jones, A. Comparison of Dry Stack With Existing Generator Exhaust Systems for Prevention of Carbon Monoxide Poisonings on Houseboats. Lake Mead, Nevada: Callville Bay Marina; 2001. U.S. DHHS, PHS, CDC, NIOSH, EPHB 171-28a
25. Hall RH. Letter of December 18, 2000, from R. Hall, National Institute for Occupational Safety and Health, to Rice Leach, Commissioner, Cabinet for Health Services, Commonwealth of Kentucky, Department for Public Health, Frankfort, Kentucky.
26. Hall RH. Letter of April 6, 2001, from R. Hall, National Institute for Occupational Safety and Health, to Bob Clark, Vice President, Seven Crown Resorts, Boulder City, Nevada.

27. Hall RH, McCammon JB. Letter of November 21, 2000, from R. Hall and J. McCammon, National Institute for Occupational Safety and Health, to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, Arizona.
28. Hall, RM.; Hammond, D.; Earnest, GS. Evaluation of Two Exhaust Stack Configurations on Two Houseboats at Table Rock Lake, Missouri. Cincinnati, Ohio: National Institute for Occupational Safety and Health; 2004 Jun. HETA 2003-0318-2936
29. Earnest, GS.; Hall, RM.; Garcia, A.; McCleery, R. An Evaluation of Catalytic Emission Controls to Prevent Carbon Monoxide Poisonings from Houseboat Generator Exhaust. Callville Bay Marina, Boulder City, Nevada. Cincinnati, Ohio: National Institute for Occupational Safety and Health; 2006 Sep. NIOSH Publication EPHB 171-38a
30. American Boat and Yacht Council (ABYC). Anapolis, MD: ABYC; Standards and Technical Information Reports for Small Craft. P-1 (ANS)—Installation of Exhaust Systems for Propulsion and Auxiliary Engines.
31. American Boat and Yacht Council (ABYC). Standards and Technical Information Reports for Small Craft. TH-23—Design, Construction, and Testing of Boats in Consideration of Carbon Monoxide. Anapolis, MD: ABYC;
32. Environmental Protection Agency (EPA). Office of Transportation and Air Quality: Emission Standards for New Nonroad Spark-Ignition Engines, Equipment, and Vessels. Washington, D.C.: EPA; 2008. EPA420-F-08-013
33. State of California Air Resources Board (CARB). Final Statement of Reasons for Rulemaking, Including Summary of Comments and Agency Response. Sacramento: CARB; 2008.
34. Memorandum of January 30, 2012, from R.M. Gordon Acting Associate Director, Business Services, National Park Service, U.S. Department of the Interior, Washington, D.C., to NPS Regional Directors. Requirements for Reducing the Potential for Carbon Monoxide Poisoning from Concessioner Boat Rental and Marina Operations.



Sample Location Descriptions on Lower Deck

#1 Lower Stern Deck Starboard Side
#2 Lower Stern Deck Port Side
#3 Lower Deck Starboard Side
#4 Lower Deck Port Side

Sample Location Descriptions on Upper Deck

#6 Upper Stern Deck Port Side
#7 Upper Stern Deck Starboard Side
#9 Upper Stern Deck Wet Bar

FIGURE 1.

Typical sampling locations on the lower and upper deck of the houseboats. Locations 5 and 8 were sample locations on previous houseboat studies and are not reported in this article.

Author Manuscript

Author Manuscript

Author Manuscript

FIGURE 2.
Houseboat with vertical exhaust stack.

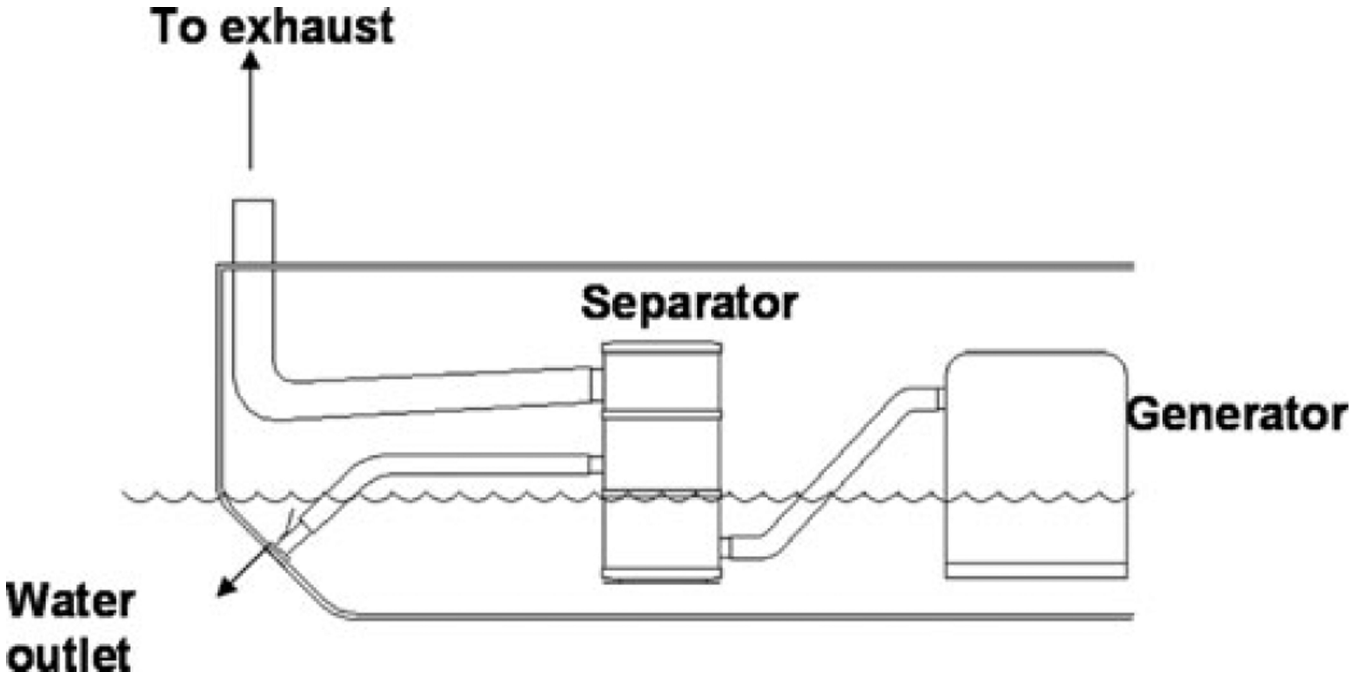


FIGURE 3.
Simplified gas water separator configuration

TABLE I

Mean and Peak CO Concentrations (ppm) Organized by Generator, Stack-exhaust Without Catalyst[A]

Sample Location [Sample #]	12.5kW-Westerbeke Generator Without Stack (No Controls)	12.5kW Westerbeke Generator with Stack	15kW-Westerbeke Generator with Extended Stack	12.5kW-Kohler Generator with Stack
Lower Stern Deck Starboard Side [#1]	Mean = 456.87	Mean = 9.39	Mean = 0.68	Mean = 4.29
	SD = 368.79	SD = 7.46	SD = 0.48	SD = 2.11
	Peak = 1200.0	Peak = 41	Peak = 2.0	Peak = 10.0
Lower Stern Deck Port Side [#2]	Mean = 242.91	Mean = 1.28	Mean = 1.11	Mean = 8.78
	SD = 153.73	SD = 0.54	SD = 0.59	SD = 12.49
	Peak = 653.0	Peak = 3.0	Peak = 3.0	Peak = 41
Lower Deck Starboard Side [#3]	NR	NR	Mean = 0.91	Mean = 1.15
			SD = 0.35	SD = 1.07
			Peak = 3.0	Peak = 5.0
Lower Deck Port Side [#4]	NR	NR	Mean = 0.82	Mean = 3.47
			SD = 0.48	SD = 2.17
			Peak = 2.0	Peak = 12.0
Upper Stern Deck Port Side [#6]	Mean = 14.36	Mean = 1.79	Mean = 0.2	Mean = 2.87
	SD = 15.49	SD = 1.92	SD = 0.48	SD = 2.5
	Peak = 72.0	Peak = 16.0	Peak = 4.0	Peak = 19.0
Upper Stern Deck Starboard Side [#7]	Mean = 13.80	Mean = 2.22	Mean = 1.15	Mean = 1.15
	SD = 17.76	SD = 2.09	SD = 1.33	SD = 1.14
	Peak = 93.0	Peak = 7.0	Peak = 12	Peak = 5.0
Upper Stern Deck Wet Bar [#9]	NR	NR	NR	Mean = 1.19
				SD = 1.2

[A]See Figure 1 for sampling locations.

SD = Standard Deviation
NR = Not reported

TABLE II

CO Mean and Peak Concentrations (ppm) Organized by Generator, Stack-Exhaust with Catalyst[A]

Sample Location [Sample #]	12.5kW-Westerbeke Generator Without Stack or Catalyst (No controls)	14kW Westerbeke Generator New Catalyst	14kW-Westerbeke Generator New Catalyst	14kW-Westerbeke Generator Old Catalyst	14kW-Westerbeke Generator New Catalyst	14kW-Westerbeke Generator Old Catalyst	15kW-Kohler Generator New Catalyst	15kW-Kohler Generator Old Catalyst
Lower Stern Deck Starboard Side [#1]	Mean = 456.87	Mean = 2.8	Mean = 1.3	Mean = 1.4	Mean = ND	Mean = 0.2	Mean = 0.9	Mean = 4.8
	SD = 368.79	SD = 1.4	SD. = 0.4	SD = 0.5	SD = ND	SD = 0.7	SD = 0.4	SD = 0.9
	Peak = 449.31	Peak = 8.0	Peak = 2.0	Peak = 2.0	Peak = ND	Peak = 4.0	Peak = 2.0	Peak = 10.0
Lower Stern Deck Port Side [#2]	Mean = 242.91	Mean = 6.3	Mean = 5.0	Mean = 1.2	Mean = 2.8	Mean = 1.5	Mean = 4.6	Mean = 11.3
	SD = 153.73	SD = 2.6	SD = 0.3	SD = 0.5	SD = 0.4	SD = 0.8	SD = 1.5	SD = 0.7
	Peak = 653.00	Peak = 11.0	Peak = 6.0	Peak = 2.0	Peak = 4.0	Peak = 5.0	Peak = 14	Peak = 15.0
Lower Deck Starboard Side [#3]	NR	Mean = 3.4	Mean = 0.4	Mean = 1.2	Mean = ND	Mean = 1.2	Mean = 0.9	Mean = 6.0
		SD = 0.7	SD = 0.5	SD = 0.4	SD = ND	SD = 0.7	SD = 0.4	SD = 0.8
		Peak = 5.0	Peak = 1.0	Peak = 2.0	Peak = ND	Peak = 3.0	Peak = 3.0	Peak = 8.0
Lower Deck Port Side [#4]	NR	Mean = 1.5	Mean = 1.0	Mean = 1.8	Mean = ND	Mean = 0.7	Mean = 0.6	Mean = 2.1
		SD = 0.7	SD = 0.4	SD = 0.4	SD = ND	SD. = 0.7	SD = 0.5	SD = 0.7
		Peak = 4.0	Peak = 2.0	Peak = 2.0	Peak = ND	Peak = 3.0	Peak = 1.0	Peak = 6.0
Upper Stern Deck Port Side [#6]	Mean = 14.36	Mean = 1.9	Mean = 1.3	Mean = 1.0	Mean = 0.1	Mean = 0.9	Mean = 2.4	Mean = 1.0
	SD = 15.49	SD = 1.5	SD = 0.6	SD = 0.4	SD = 0.1	SD = 1.2	SD = 1.1	SD = 0.6
	Peak = 72.00	Peak = 8.0	Peak = 4.0	Peak = 2.0	Peak = 1.0	Peak = 6.0	Peak = 4.0	Peak = 2.0
Upper Stern Deck Starboard Side [#7]	Mean = 13.80	Mean = 7.8	Mean = 1.1	Mean = 0.8	Mean = 3.9	Mean = 1.9	Mean = 4.7	Mean = 8.4
	SD = 17.76	SD = 1.8	SD = 0.4	SD = 0.4	SD = 0.4	SD = 1.2	SD = 1.5	SD. = 0.9
	Peak = 93.00	Peak = 14.0	Peak = 2.0	Peak = 1.0	Peak = 5.0	Peak = 7.0	Peak = 7.0	Peak = 12.0
Upper Stern Deck Wet Bar [#9]	NR	Mean = 2.2	Mean = 1.1	Mean = 1.9	NR	NR	Mean = 1.7	Mean = 5.8
		SD = 0.6	SD = 1.3	SD = 0.4			SD = 0.5	SD = 0.6
		Peak = 5.0	Peak = 6.0	Peak = 3.0			Peak = 3.0	Peak = 9.0
Gas Emissions Analyzer	16,800–55,300	ND–1500	1–39	1–39	250	1–3000	100–200	500–8000

[A] See Figure 1 for sampling locations.

* The CO Emissions are significantly lower after a short warm up period when compared to the cold start of the engine.

** Catalytic converters were old and replaced after reporting these numbers. All generators listed on this table were under a 50% load.

SD = Standard Deviation

NR = Not reported

ND = non detected