Engineering Safety

Carbon Monoxide & Houseboats

An evaluation of a stack exhaust system to reduce poisonings associated with generator exhaust

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IN RESPONSE TO THE DROWNING of two young boys vacationing on Lake Powell, near the border of Arizona and Utah, the National Park Service (NPS), through the Dept. of the Interior, requested assistance from NIOSH and the U.S. Coast Guard to evaluate visitor and employee carbon monoxide (CO) exposures on houseboats. The initial investigation characterized CO poisonings through epidemiological data gathering and measurements of severely hazardous CO concentrations on houseboats at Lake Powell (McCammon and Radtke). NPS provided incident reports of known houseboat-related CO poisonings and deaths on the lake between 1994 and 2000. Since those initial reports, NIOSH has discovered that 111 CO poisoning cases occurred on Lake Powell from 1990 to 2000. Houseboats accounted for 74 of those poisonings, and 64 were attributable to generator exhaust alone. Of the 74 houseboat-related CO poisonings, seven resulted in death (McCammon, et al).

In 2001, NIOSH conducted three evaluations of an engineering control designed for houseboats, which was retrofitted onto a generator. This article discusses the results of these evaluations and compares the typical (rear-transom) generator exhaust configuration to the retrofitted (dry-stack) generator exhaust configuration.

Background

Houseboat generators are typically housed in a compartment under the boat's rear deck (Photo 1). Many houseboat generators exhaust through the transom and into an enclosed area under the swim deck, on the rear of the boat (rear-transom exhaust). A concern with these rear-exhausted boats is that the CO may be trapped in this area, which is accessible to swimmers (Figure 1; Photo 2). Measurements taken in this cavity beneath the rear deck of Lake Powell houseboats ranged from 1,700 to 30,000 parts per million (ppm) (McCammon and Radtke). Oxygen concentrations as low as 12 percent were also measured in this cavity. This combination of an oxygen-deficient, CO-rich atmosphere can be lethal within seconds to minutes. High levels of CO have also been measured on the back swim deck where swimmers commonly enter and exit the boat. CO concentrations on or around the back swim decks of many sampled houseboats reached levels greater than 1,000 ppm during NIOSH evaluations conducted on Lake Powell, AZ (Hall and McCammon), Lake Cumberland, KY [Hall(a)], and Lake Mead, NV [Hall(b)].

The engineering control that NIOSH evaluated consisted of a water separator and an aluminum exhaust stack that directed generator exhaust away from persons on or near the houseboat to prevent CO poisonings from the exhaust (Photo 3). The first engineering control evaluation was conducted on a Lakeview houseboat, located at Wahweap

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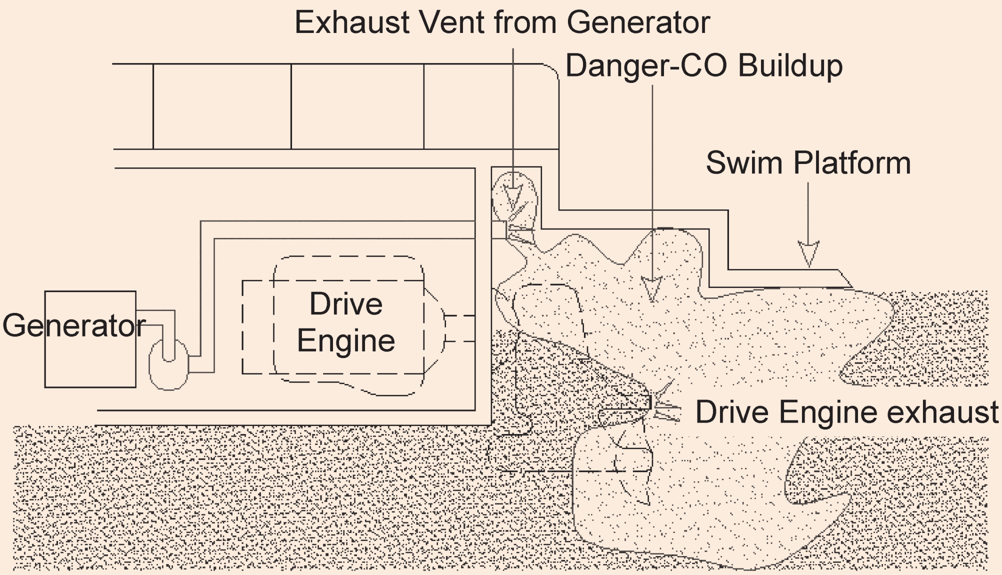
Figure 1

Generator Exhausting Through Rear Transom of a Houseboat



Marina, Lake Powell, AZ [Earnest, et al(a)]. That study examined the effect of having an exhaust stack for the generator, which extended nine feet above the top deck of the houseboat compared to the more standard configuration of exhausting from the rear transom into the space underneath the swim platform. A second evaluation was conducted on a dry-stack exhaust at Somerset Custom Houseboats, Somerset, KY, in March 2001 [Dunn, et al(a)]. In June 2001, NIOSH conducted a third evaluation at Callville Bay, Lake Mead, NV [Dunn, et al(b)]. The dry-stack exhaust system was tested under a variety of conditions: boat stationary, boat underway (in motion) and boats tied together. For comparison, the rear-transom vent design was also tested under the same conditions.

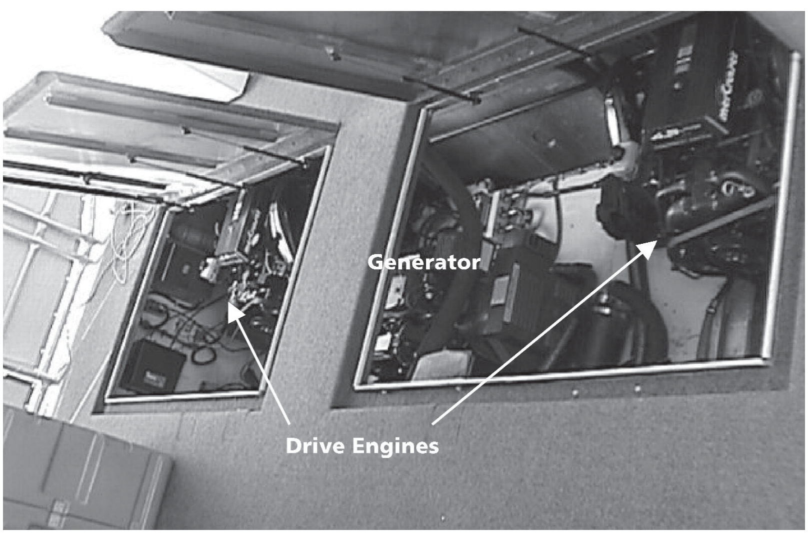


Photo 1 (above): Generator and drive engines in rear deck compartment.

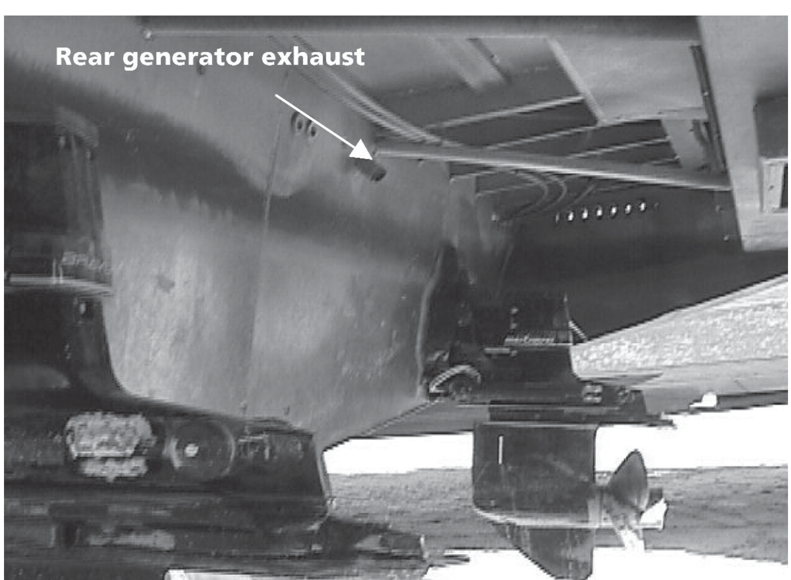


Photo 2 (right): Cavity under rear deck of a houseboat with rear generator exhaust.

Carbon Monoxide Symptoms & 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, 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. Exposure limits have been established for CO by NIOSH [NIOSH(a)(c)], American Conference of Governmental Industrial Hygienists, OSHA and World Health Organization. CO is also a criteria pollutant for which EPA has established limits that are set to protect "the most sensitive members of the general population" (EPA). These limits are shown in Table 1. While most of these limits were set to prevent adverse effects in health-compromised populations, the concentration established by NIOSH as immediately dangerous to life and health (IDLH) is the most relevant to acute CO poisoning. NIOSH currently defines an IDLH condition as one that "poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment" [NIOSH(b)].

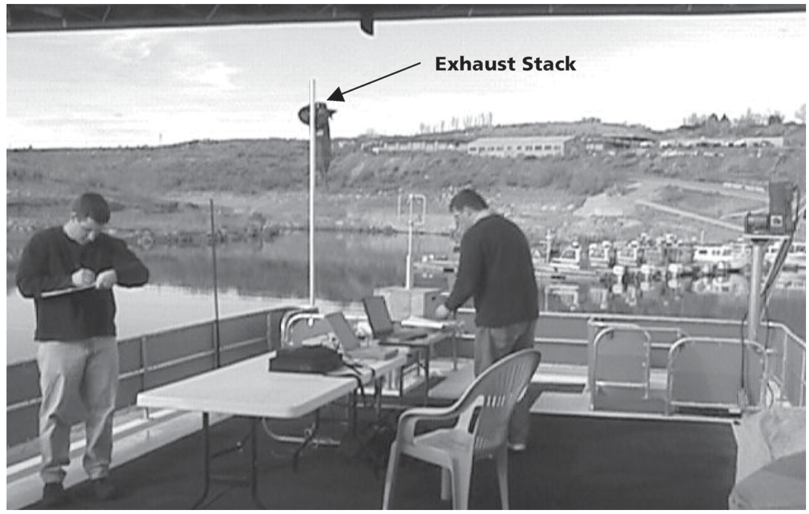


Photo 3: Dry exhaust stack extending well beyond upper deck.

Table 1

Exposure Limits for CO

Organization	TWA Exposure Limit	Short-Term Exposure Limit	Notes
ACGIH	25 ppm		8 hour TWA
NIOSH	35 ppm	 200 ppm ceiling 1,200 ppm IDLH	8 hour TWA
OSHA	50 ppm		
EPA	9 ppm	 35 ppm	8 hour TWA 1 hour average
WHO	9 ppm	 87 ppm 52 ppm 26 ppm	8 hours 15 minutes 30 minutes 60 minutes

Methodology

Description of Engineering Control

The generator on houseboats provides electrical power for air conditioning, refrigeration, cabin appliances, and navigation and communications equipment. It is housed in the engine compartment beneath the rear deck and is typically positioned near the two drive engines (Photo 1). Table 2 provides a description of the houseboat and generator evaluated during each of the NIOSH surveys.

The hot exhaust gases from the generator are injected with water near the end of the exhaust manifold in a process commonly called water-jacketing. Water-jacketing cools the discharge and reduces the noise prior to exhausting the gases from the engine.

The engineering control modifications separated the discharge gas from the water and exhausted the gases above the top deck of the houseboat. The original lift muffler was replaced by a muffler/gas/water separator (Figure 2). A schedule 40, two-inch nominal aluminum pipe was used for the stacks (Photo 3), which extended along the aft corner of the boat to a height above the lower deck. Table 3 indicates the stack location and terminus height for each boat evaluated. The lower portion of the stack penetrated the lower rear deck into the engine compartment and was clamped to a high-temperature exhaust hose. This process of dewatering the exhaust gases and discharging them above the boat has resulted in the configuration commonly referred to as the vertical dry-stack exhaust.

Stack height and location varied among the NIOSH evaluations. Table 3 also lists the configurations for each evaluation. In the Lake Mead and Lake Powell evaluations, the tall stack extended to a height of nine feet above the base of the upper deck.

In the Somerset evaluation, however, a shorter stack that terminated at the base of the upper deck was outfitted onto a houseboat for the investigation of the effect of stack height on performance (Photo 4). This short-stack configuration was devised to reduce any potential clearance problems both at the marina and during transport. Before houseboats are shipped to customers, the outfittings on the upper decks of boats (railings, flagpole, etc.) are removed to allow for adequate clearance under low roadway overpasses. In a tall-stack configuration, design provisions for removal of the stack during shipping would be needed.

Representatives from one manufacturer estimated that the evaluated dry-stack exhaust system would cost between $500 and $1,000 to retrofit onto a houseboat while in the water, and between $1,000 and $1,500 if the boat had to be removed from the water before performing the installation. The original purchase prices for the evaluated houseboats ranged from $165,000 to $250,000.

Description of Evaluation Procedures

Evaluations were performed on the three generator exhaust configurations described above—short stack, tall stack and rear transom. Some parameters of the stack designs changed between evaluations, including the stack's physical location and height. In summary, the exhaust configurations and operating conditions for each evaluation:

1) **Boat stationary.** Evaluation of boat stationary represents the most standard operating condition for houseboats. The boat is 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. Evaluations of boat stationary were conducted at Lake Powell, Lake Mead and Somerset.

Exhaust configurations tested: Generator exhausting through the short stack, tall stack or rear transom. During each stationary evaluation, the generator operated alone for approximately 30 minutes per run. When possible, generator exhaust was reconfigured after each run to alternate between the stack and rear-transom exhaust configuration. Between each run, a period of generator shutdown allowed ambient concentrations of CO to return to previous background levels.

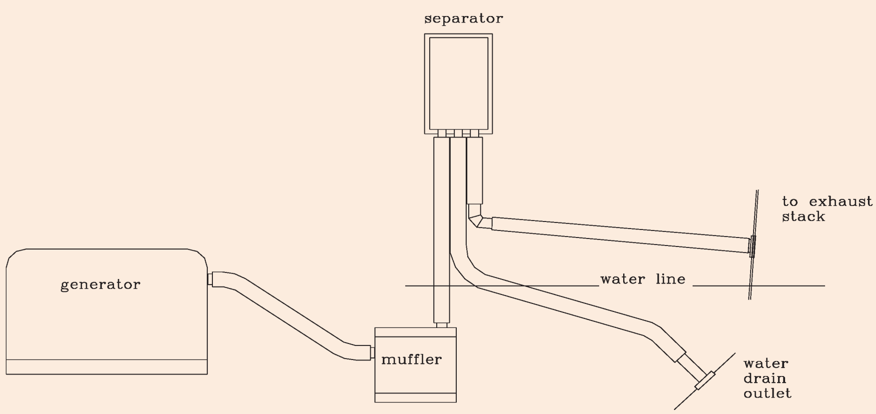
Table 2

Evaluated Boat/Generator Configurations

Location/Evaluation Date	Boat Size	Generator Type/Size
Lake Powell, AZ/Feb. 2001	75 ft. x 16 ft.	15.0 kW Westerbeke, 4 cylinder, 4 stroke, carburated, gasoline-powered engine
Somerset, KY/March 2001	80 ft. x 16 ft.	15.0 kW Westerbeke, 4 cylinder, 4 stroke, carburated, gasoline-powered engine
Lake Mead, NV/June 2001	56 ft. x 14 ft.	12.5 kW Kohler, 4 cylinder, 4 stroke, carburated, gasoline-powered engine

Figure 2

Dry-Stack Generator Exhaust Configuration



2) **Boat underway.** Evaluation of boat underway represents a boat moving forward to a destination or back to the marina. During evaluations of boat underway, CO contributions from both the generator and drive engines were measured. These evaluations were conducted only at Lake Mead.

Exhaust configuration tested: Generator exhausting through the tall stack or rear transom. The underway evaluation consisted of measurements for CO concentrations on the boat as it moved from the marina to a cove, or from the cove back to the marina. After exiting the no-wake zone, the boat captain maintained a constant speed en route to the cove. The trip to and from the marina took about 30 minutes.

3) **Boats tied together** (Photos 5 and 6). This condition, also called rafting, is popular with many boaters. By tying their boats together, they can move freely between boats for social visits. Evaluation of boats tied together was conducted at Lake Mead only.

Exhaust configurations tested: Generator exhausting through the tall stack or rear transom. Two-boat configurations, exhausting either through the rear or stack generator, were evaluated. The generator exhaust was reconfigured after each run on both boats to alternate between the vertical dry-stack and the rear-transom exhaust configurations. During the evaluation, the generator operated alone for approximately 30 minutes per run.

Evaluation of the Control Effectiveness

CO concentrations at various locations on the houseboats were measured simultaneously with ToxiUltra atmospheric monitors (Bacou USA, Middletown, CT). These direct-reading instruments have CO sensors and datalogging capabilities. The electrochemical instruments measure the electrical current generated by a reaction between the ambient CO and the electrolyte in the sensor. During the evaluations, the CO monitors were calibrated before and after use per the manufacturer's recommendations. The instruments were operated in the passive diffusion mode, having a 30-second sampling interval and a nominal range from 0 to 999 ppm. The electrical current generated is proportional to the amount of reactant gas present and indicated gas concentration present throughout this range. Above the nominal range, the response of the monitor becomes nonlinear. Therefore, when the monitor reports concentrations above 999 ppm, the actual CO concentration may be much higher.

Sampling locations for the real-time CO monitors on the lower and upper decks of the houseboat are shown in Figures 3 and 4 (single boat), and Figure 5 (two boats tied together). Monitors—placed at various locations, representing occupied areas on the upper and lower decks—recorded CO concentrations while the generator operated. A minimum of two monitors were placed on the swim deck because it is a high-traffic area commonly used to enter and exit the water via the boat's rear platform.

During each run, instantaneous CO concentrations were logged every 30 seconds. The length of each run varied slightly from one evaluation to another, but typically ranged from 20 to 30 minutes. The instantaneous CO concentrations from each monitor were averaged over the entire run period to give a single value of CO concentration for that sample location (Figures 3 to 5). When more than one monitor was in a given boat area (swim deck, lower rear deck, upper deck aft, upper deck fore), the data were averaged to give representative average area CO concentrations. The arithmetic means and standard deviations were calculated based on the averages from each run, for each boat area.

Stack exhaust velocity and temperature measurements were made at the face of the exhaust stack on each boat during every survey. Measurements of stack exit velocity and temperature were performed by using a VelociCalc Plus Model 8360 air velocity meter (TSI Inc., St. Paul, MN).

Statistical Analyses

The statistical analyses depend on the way the runs were conducted (whether the stack and rear runs were alternated or not) and the total number of runs. Short descriptions of the analyses are:

1) **Boats stationary.**

Tall stack versus rear transom: Runs were arranged

Table 3

Stack Design & Test Conditions

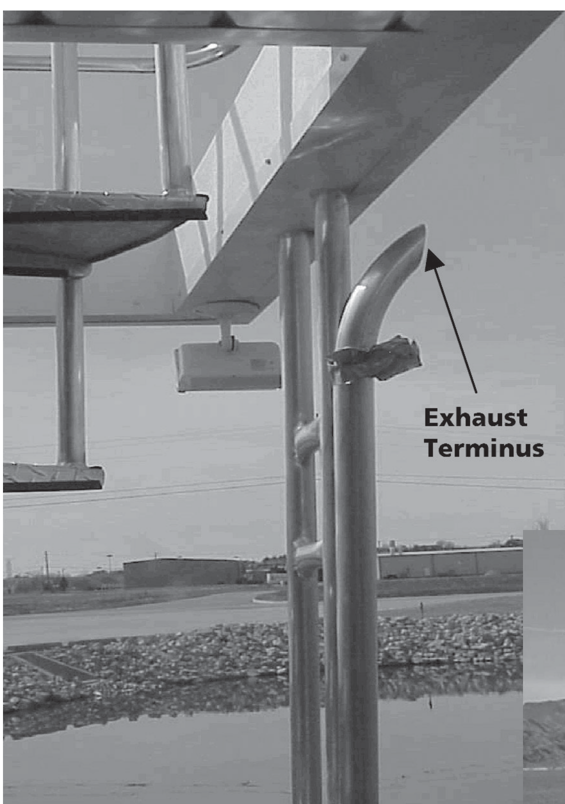
Location/Evaluation Date	Stack Design/Position	Exhaust Configuration & Operating Conditions
Lake Powell, AZ/Feb. 2001	Stack terminus @ 9 ft. above upper deck aft, starboard side of boat.	Tall stack versus rear transom; single boat stationary.
Somerset, KY/March 2001	1) Tall-stack terminus @ 7 ft. above upper deck aft, port side of boat. 2) Short-stack height @ base of upper deck aft, port side of boat.	Short stack versus tall stack; single boat stationary
Lake Mead, NV/June 2001	Stack terminus @ 9 ft. above upper deck aft, port side of boat.	Tall stack versus rear transom: 1) Single boat stationary 2) Boat in motion 3) Multiple boats tied together

so that the stack exhaust and rear-transom exhaust were evaluated in alternate runs. Eight runs total (on both Lake Powell and Lake Mead) were conducted in four pairs (stack exhaust, rear exhaust). An analysis of variance model on the natural log scale included terms for evaluation site (Lake Mead or Lake Powell), boat region area (e.g., lower rear deck, swim deck), monitor location (starboard, port, center), control (stack or rear exhaust) and interaction among these variables. The simultaneous collection of area and location data was accounted for by the inclusion of an extra error term in the model. Calculation of confidence limits were based on the Student's "t" distribution, which holds simultaneously at an overall error rate of five percent.

Short stack versus tall stack: Two consecutive runs of the short-stack exhaust system were followed by two consecutive runs of the tall-stack configuration. These runs were not alternated because of the time required to install or remove the stack extension. An analysis of variance model on the natural log scale included adjustments for control method (short or tall stack), monitor location (starboard, port, center), area (e.g., lower rear deck, swim deck) and interactions among these variables. The simultaneous collection of area and location data was accounted for by the inclusion of an extra error term in the model.

2) **Boats underway.**

Rear transom versus tall stack: Stack exhaust determinations were made in one run and rear exhaust



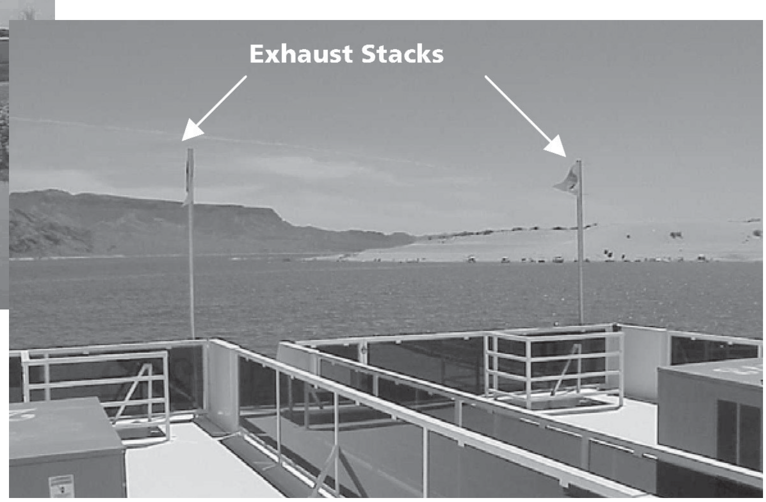


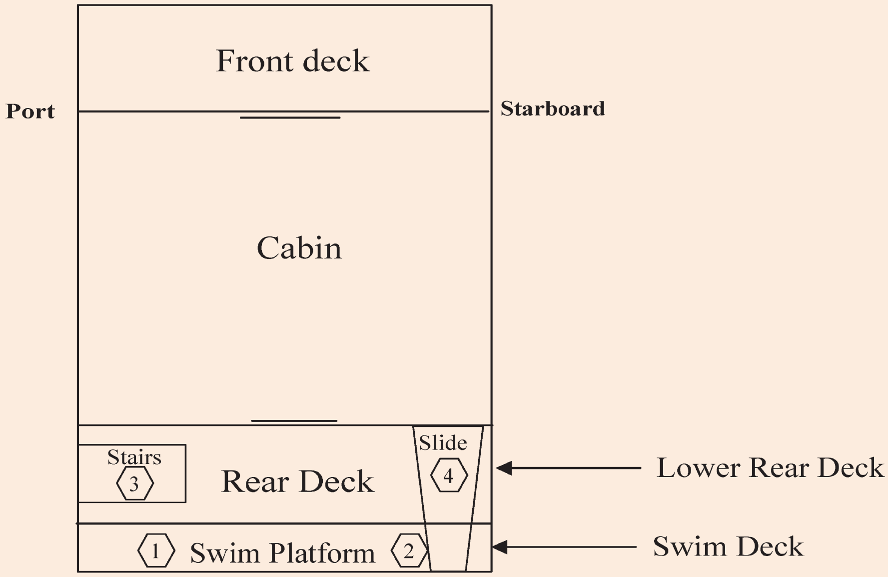
Photo 4 (above): Short stack terminus at the base of the top deck.

Photo 5 (top, right): Two boats tied together (rafting) during evaluation.

Photo 6 (bottom, right): Exhaust stack for two boats tied together.

Figure 3

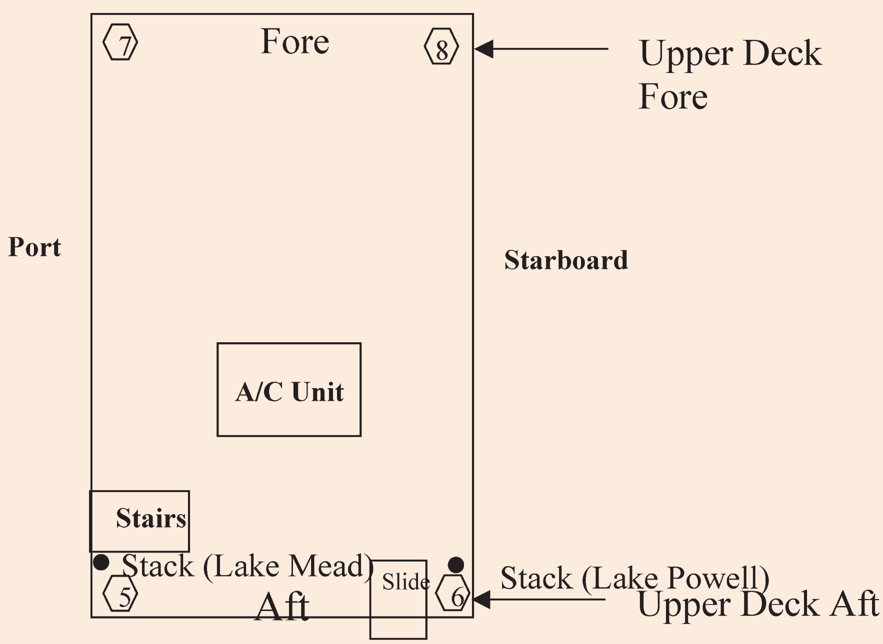
Lower Deck Sampling Locations*



**Single boat configuration.*
Note: Sample locations designated with hexagons.

Figure 4

Upper Deck Sampling Locations*



**Single boat configuration.*
Note: Sample locations designated with hexagons.

determinations in a subsequent run. Due to the low number of overall runs, no statistical modeling was performed; therefore, only means and peaks are presented for these data.

3) **Boats tied together.**

Rear transom versus tall stack: Stack exhaust determinations were made in a single run and rear exhaust determinations in a subsequent run. Due to the low number of overall runs, no statistical modeling was performed; only means and peaks are presented for these data.

Results

Boat Stationary

Table 4 presents the results of the stationary, single boat tests. Arithmetic mean, standard deviations and peak for CO concentrations are shown for the Lake Powell and Lake Mead evaluations. Overall percent reductions and lower 95 percent confidence intervals were calculated based on the paired trials and are shown for each location in Figure 5. Only the paired trials from the Lake Powell and Lake Mead evaluations were included in this analysis as they included data for both rear exhaust and stack exhaust.

Differences in CO concentrations were more pronounced on the lower deck and swim deck regions of the boat. When the generator was exhausted from the rear transom of houseboats for the Lake Powell and Lake Mead evaluations, mean CO concentrations on the swim deck (403 ppm and 688 ppm, respectively) were greater than the NIOSH ceiling. Exhausting the generator out of the stack resulted in a reduction of 99 percent (p value <0.0001; lower 95 percent confidence limit = 98 percent) in average CO concentrations on the swim deck, compared to the rear-transom exhaust. Concentrations on the lower deck of the houseboat were also significantly reduced, by an average of 95 percent when the generator exhausted out of the stack versus the rear transom (p value <0.001; lower 95 percent confidence limit = 80 percent). When the stack is compared to the rear-transom exhaust, average CO concentrations on the upper deck at the rear of the boat were lower, but the relative CO concentrations were generally low in this area for both exhaust configurations. Average CO concentrations measured on the top deck at the front of the boat were slightly lower for the rear-transom exhaust than for the stack exhaust configuration.

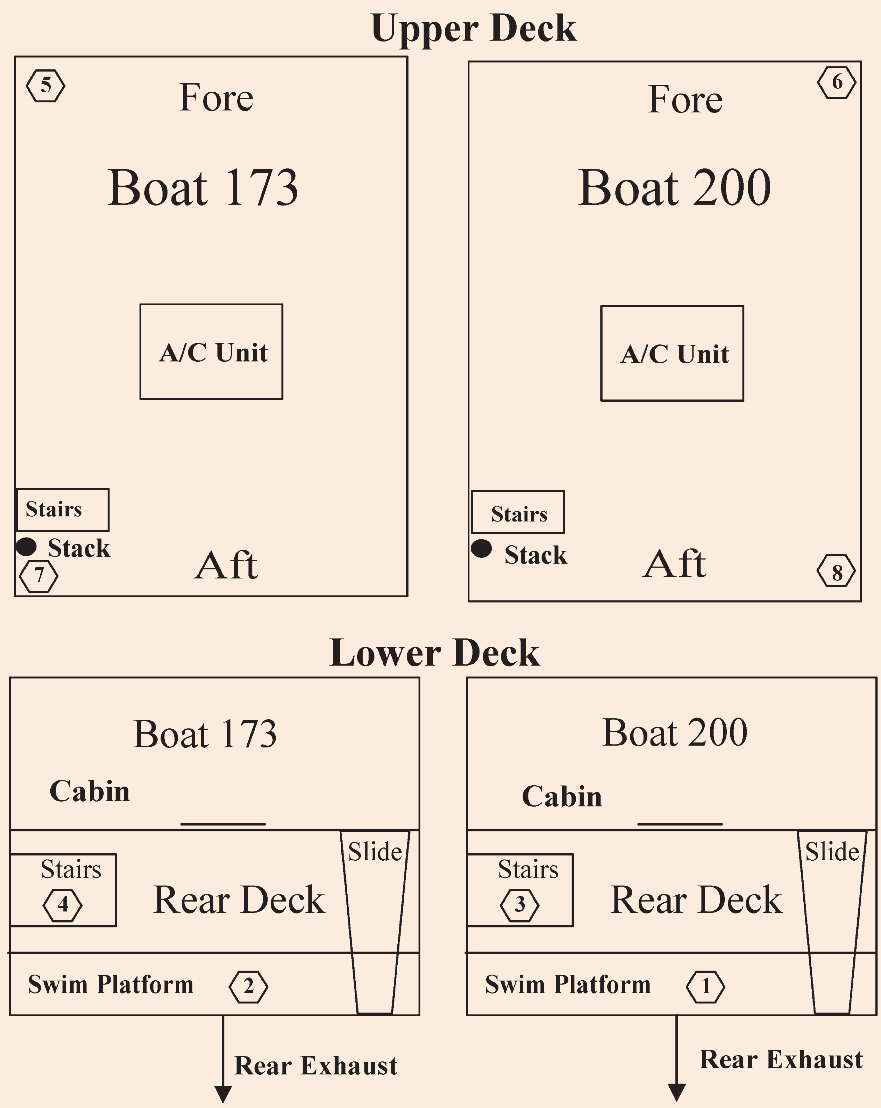
Peak concentrations on the swim deck were consistently high throughout the trials when the generator exhausted from the rear transom. The instantaneous CO concentrations exceeded the NIOSH ceiling (of 200 ppm) 63 percent of the time and the peak concentration of 1,000 ppm was exceeded 10 percent of the time during the Lake Powell and Lake Mead evaluations, when the boat was stationary and only the generator was operating.

Boat Underway

Table 5 provides the results of the boat underway testing. The levels of CO were lower for the stack than for the rear exhaust at all measurement loca-

Figure 5

Upper & Lower Deck Sampling Locations*



*Two-boat configuration.
Note: Sample locations designated with hexagons.

tions. During boat movement, both the drive engines and generator emit exhaust, resulting in increased average CO concentrations for both the stack and rear-transom configurations. For both configurations, the drive engines emit exhaust gases through the propeller hub beneath the water. This source of uncontrolled emissions results in an increased CO release at the rear of the boat, particularly when drive engines are operated in the idle setting and the boat is stationary. During the NIOSH evaluation, when drive engines were started while the boat was not moving, CO levels on the swim deck approached the IDLH within minutes for both the stack- and rear-exhaust configuration (Figure 6). When the stack and rear-transom exhausted boats were in motion, CO concentrations were reduced due to the flow of air around the boat. During the stack evaluation, researchers were concerned that the exhaust might be entrained by the recirculation zones (eddies) created by the airflow around the back of the boat (the "station wagon effect"). However, the CO concentrations on both the lower and upper decks of the houseboat in motion were low when the exhaust of the generator was directed through the stack.

Boats Tied Together

Table 6 shows the results of the two boats tied together during testing. When two houseboats were tied together, the stack performed well. Peak and average CO levels on the swim platforms for the two-boat configuration were low when the generator was exhausted through the stack. The stack averaged reductions in CO concentration of 99 percent and 96 percent on the swim decks of each respective boat. While the rear-transom-exhausted boats exhibited instantaneous peak CO concentrations of up to 979 ppm on the swim deck, the corresponding peak concentration for each of the stack-exhausted boats was 5 ppm. Even on the upper deck, the highest concentration measured during the Lake Mead evaluation was 22 ppm for the stack-exhaust configuration.

Stack Height Effect: Tall vs. Short Stack

Table 7 presents the results of the exhaust stack height testing. Although average concentrations in the occupied areas were low for both the short stack and the tall stack, peak concentrations above the NIOSH ceiling were measured on the top deck while the boat exhausted through the short stack. On the top deck of the boat, near the short-stack exhaust terminus, an instantaneous CO concentration of 459 ppm was measured. The corresponding peak for the extended stack reached only 12 ppm in that area. Generally, instantaneous peak concentrations were decreased by an order of magnitude at most measurement locations when the short stack was extended to a height of seven feet above the top deck. Additionally, average CO concentrations were reduced between 78 percent and 91 percent on both the lower and upper decks, depending on measurement location.

Exhaust Stack Velocity & Temperature Results

The stack velocity measurements were similar for all boats evaluated, regardless of stack height, because all boats shared the identical generator and exhaust design. The average exhaust velocity for all surveys ranged from 700 to 1,080 feet per minute (fpm). The stack exhaust temperature closely followed the ambient temperature with a difference in temperature of only 3° to 7°F. The ambient temperature was measured during each survey and ranged from 45°F at Lake Powell (in February) to 108°F at Lake Mead (in July).

Table 4

Results for Stationary, Single Boat by Survey & Sample Location

Sample Location		Lake Powell, AZ February 2001 Stack Exhaust (ppm)	Rear Exhaust (ppm)	% Reduction	Lake Mead, NV June 2001 Stack Exhaust (ppm)	Rear Exhaust (ppm)	% Reduction	Overall Reduction % Reduction (Lower 95% CL)§
Swim deck	Mean=	6.5	403	98	5.3	688	99	99 (98)
	SDev=	4.3	103		20	**983***		
	Peak=	41	**1208***¶		1	1		
	N=	3	3		†	†		
Lower rear deck	Mean=	3.7	56	93	1.6	79.4	98	96 (80)
	SDev=	1.9	18.5		14	**280***		
	Peak=	28	**357***		1	1		
	N=	3	3		†	†		
Upper deck aft	Mean=	1.9	14.2	87	1.2	24.2	95	91 (54)
	SDev=	0.94	3.8		5	146		
	Peak=	16	93		1	1		
	N=	3	3					
Upper deck fore	Mean=	2.8	1.1	0	1.6	‡	0	0 (0)
	SDev=	0.83	0.93		3			
	Peak=	34	6		1			
	N=	2	6					

**Instantaneous measurements above the NIOSH ceiling of 200 ppm are shown in bold type.*
†Standard deviation are not available since only one run was conducted.
‡No CO data is available at these locations. Monitors were relocated to swim deck following sensor overload/poisoning.
§Reductions based on the arithmetic means; lower confidence limits based on statistical analysis on natural log scale.
¶Concentrations above 999 ppm are above the range of the instrument; actual CO concentrations may be higher than the value indicated.

Table 5

Results for Boat Underway, Lake Mead, NV

Sample Location		Stack Exhaust	Rear Exhaust	% Reduction
Swim deck	Mean=	23.8	172	86
	Peak=	87	**422***	
	N=	1	1	
Lower rear deck	Mean=	12.1	87.1	86
	Peak=	55	**275***	
	N=	1	1	
Upper deck aft	Mean=	9.40	33.6	72
	Peak=	57	137	
	N=	1	1	
Upper deck fore	Mean=	3.3	4.0	18
	Peak=	24	13	
	N=	1	1	

**Instantaneous measurements above the NIOSH ceiling of 200 ppm are shown in bold type.*

Discussion

Sampling of the exhaust gases released from the houseboat generators ranged from an average CO concentration of 3.7 to 9.4 percent (37,000 to 94,000 ppm) during normal operation. These concentrations are 31 to 78 times greater than the NIOSH IDLH level. 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 extremely important. NIOSH evaluations found that the stack exhaust greatly reduced the CO hazard in occupied areas of the boat. The extended stack on the upper deck propelled exhaust gases with enough momentum to disperse CO. Average and peak CO concentrations at all locations on the retrofitted houseboats were well below occupational exposure limits (OSHA; NIOSH; ACGIH) during normal operation.

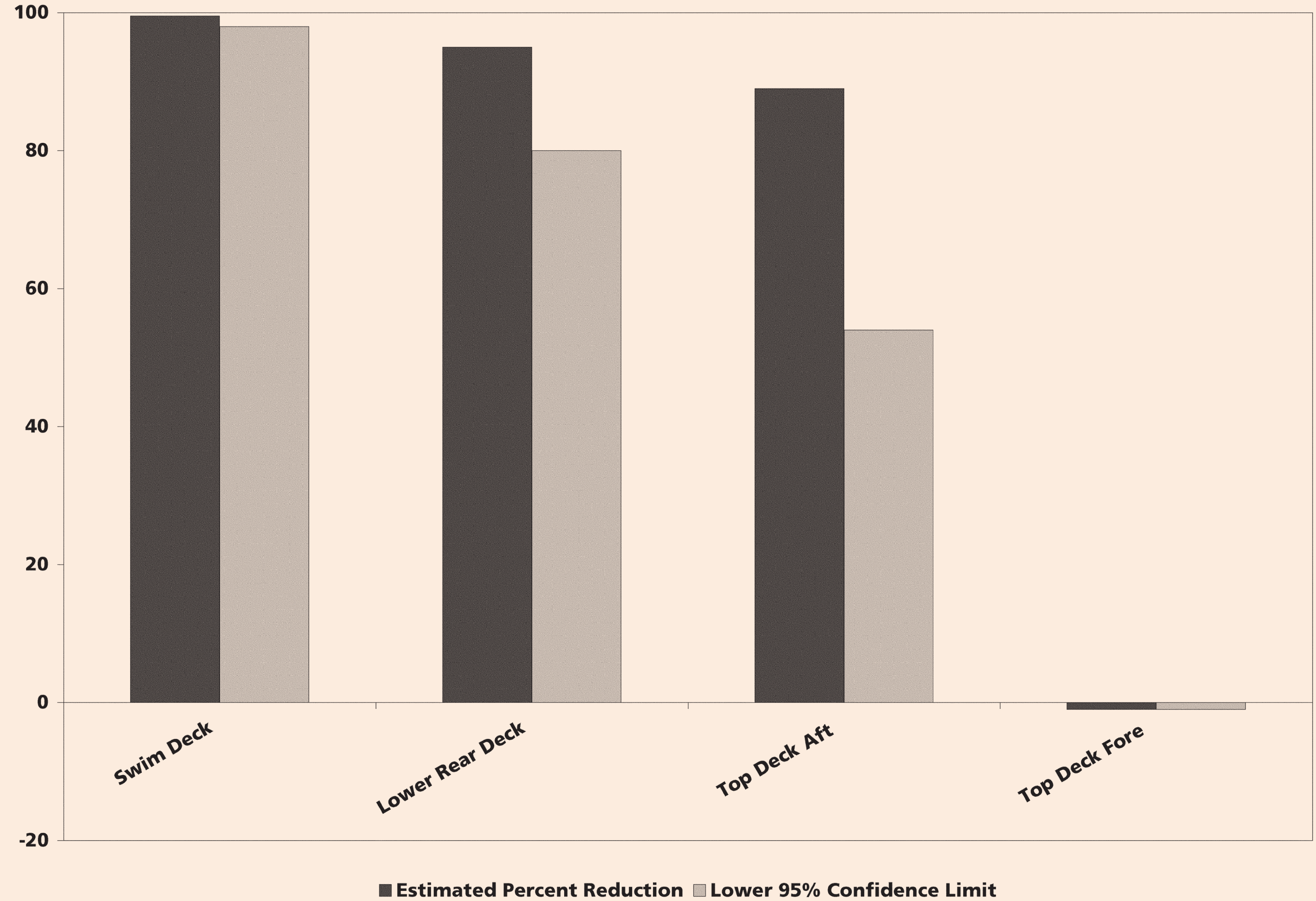
When a boat was underway, uncontrolled exhaust from the drive engines was a major source of CO. Although the airflow induced by the boat's motion transported some of the exhaust away, high concentrations could still be encountered. In comparison to the uncontrolled, rear-transom exhaust, the stack-exhaust system showed reductions in CO concentrations for all locations. During the evaluations of two houseboats tied together, the stack-exhaust configurations performed well, and peak and average CO concentrations on the swim platforms and top decks were low.

Stack-Exhaust Temperature & CO Density Effects

Concerns were raised about possible density differences between the CO and surrounding air and what effect a temperature difference would have between the effluent from the stack and the surrounding environment. Would a large temperature difference between the hot, ambient air and the

Figure 6

Estimated Reduction in Geometric Mean CO Concentration*



For a single, stationary boat across all sample locations. Stack compared to rear transom generator exhaust.

Table 6

Results for Multiple Boat Test: Lake Mead, NV

Sample Location		Boat 200 Stack Exhaust	Boat 200 Rear Exhaust	Boat 200 % Reduction	Boat 173 Stack Exhaust	Boat 173 Rear Exhaust	Boat 173 % Reduction
Swim deck	Mean=	1.09	191	99	1.93	53.6	96
	Peak=	3	**979***		5	**419***	
	N=	1	1		1	1	
Lower rear deck	Mean=	0.67	22.8	97	0.86	10.3	92
	Peak=	5	189		5	88	
	N=	1	1		1	1	
Upper deck aft	Mean=	2.98	54.1	94	2.49	5.40	54
	Peak=	22	172		5	53	
	N=	1	1		1	1	
Upper deck fore	Mean=	3.12	18.1	83	1.30	9.20	86
	Peak=	22	93		3	28	
	N=	1	1		1	1	

Instantaneous measurements above the NIOSH ceiling of 200 ppm are shown in bold type.

water-cooled stack exhaust cause the CO to fall onto the upper deck of the houseboat?

High CO concentrations on the upper decks of the houseboats with retrofitted stack exhausts were not observed in any of the field studies conducted to date [Earnest, et al(a); Dunn, et al(a); (b)]. The fact that this effect was not observed is likely due to the following conditions:

1) Only minor temperature differences between the stack-exhaust temperature and the ambient temperature were observed. The stack was evaluated under mild ambient conditions (45°F at Lake Powell and 50°F at Somerset) and at elevated ambient temperatures (97° to 108°F at Lake Mead). The stack was constructed of aluminum, an excellent heat conductor, which helped to minimize the temperature difference. In each study, the measured stack-

Table 7

Results of Stack Height Testing: Somerset, KY

Sample Location		Short Stack Exhaust (ppm)	Tall Stack Exhaust (ppm)	% Reduction Tall Stack vs. Short Stack (Lower 95% CL)†
Swim deck	Mean=	6.02	0.86	86 (68)
	SDev=	0.99	0.06	
	Peak=	57	3	
	N=	2	2	
Lower rear deck	Mean=	4.07	0.85	79 (48)
	SDev=	1.2	0.10	
	Peak=	52	3	
	N=	2	2	
Upper deck aft	Mean=	14.4	0.70	95 (80)
	SDev=	2.9	0.18	
	Peak=	**459***	12	
	N=	2	2	
Upper deck fore	Mean=	4.45	0.86	81 (66)
	SDev=	2.5	0.26	
	Peak=	11	11	
	N=	2	2	

**Instantaneous measurements above the NIOSH ceiling of 200 ppm are shown in bold type.*
†Reductions based on the arithmetic means; lower confidence limits based on statistical analysis on natural log scale.

exhaust temperature was within 10°F of the ambient temperature.

2) At standard temperature and pressure, CO is slightly less dense (three percent) than air. Only minor differences in the molecular weight (and thus density) exist between CO and air, and even less when the CO is a part of the exhaust mixture.

3) Exhaust gases are ejected from a stack at a relatively high velocity. Velocity provides the motive force for moving the exhaust away from the top deck and dispersing it in the atmosphere. In this study, the average exhaust velocity from the stack ranged from 700 to 1,080 fpm.

Critical Stack Design Considerations

To function properly, the exhaust stack must be properly sized. Calculations should be based on the exhaust gas flow rate, water flow rate and the maximum backpressure permitted by the generator manufacturer. Exhaust velocity is another important consideration in correctly sizing the stack, because it ensures the exhaust stream has sufficient momentum for adequate dispersion. To minimize pressure drop in an exhaust system design, the pipe diameter is often increased. This increase in diameter has a dramatic effect on exhaust velocity. If the diameter of a pipe is increased by a factor of two, the exhaust velocity will decrease by a factor of four. Without sufficient velocity, the exhaust gases could potentially be propelled by the wind onto the occupied regions of the boat.

The height of the exhaust terminus is also critical during the design phase of these systems. The exhaust stack should extend well above the upper deck of the houseboat for adequate movement and dispersion of the exhaust, away from occupied regions of the boat. To investigate potential design concepts that address the requirement to transport boats under bridges and overpasses, the NIOSH researchers evaluated a short stack, which extended only to the base of the upper deck. Peak concentrations above the NIOSH ceiling of 200 ppm were then measured on the upper deck when exhausting the generator through the short stack. This evaluation showed that extending the stack well above the top of the upper deck significantly reduced peak CO concentrations at all measurement locations on the upper and lower decks of a houseboat by no less than approximately 50 percent, at the 95 percent confidence level.

Additional data are required to address the minimum stack height and exhaust velocity necessary to ensure that high CO concentrations do not occur in the occupied regions of a houseboat under nominal environmental conditions. However, the data collected in these surveys indicates that a stack height of nine feet above the base of the upper deck, along with an exhaust velocity of approximately 1,000 fpm, results in low CO concentrations under the test conditions encountered. When the generator was outfitted with a vertical exhaust stack, no peak CO concentration was greater than 50 ppm while the boat was stationary or greater than 90 ppm while the boat was in motion. NIOSH is developing computational fluid dynamics models to investigate these and other issues relating to boat exhaust designs. These models can simulate the effect of many variables, including stack design (height, velocity, temperature, etc.) and environmental conditions on exhaust gas dispersion.

Conclusion

CO poisoning on houseboats continues to be a serious problem. A combination of engineering controls, boater education and surveillance is needed to evaluate and mitigate the hazards. These investigations have shown that the installation of the vertical stack generator exhaust system greatly reduces the hazard associated with exposure to high concentrations of CO on houseboats. The inexpensive stack-exhaust system not only dramatically lowers average CO concentrations but also significantly lowers peak exposures that may be responsible for many houseboat fatalities. Several houseboat manufacturers and rental operators are beginning to install systems similar to that described in this report. The American Boat and Yacht Council has also updated its consensus safety standards to account for the development of the stack generator exhaust (ABYC). These systems should be used in conjunction with the existing CO monitoring devices that most houseboats have. However, more data and analyses are necessary to evaluate the effect of critical design parameters such as stack height, exhaust gas velocity and temperature on CO dispersion characteristics. These data will provide the basis for more definitive recommendations on stack diameter and height.

A workshop sponsored by NIOSH and the U.S. Coast Guard was conducted in March 2003 to discuss the state of the knowledge of new and existing technologies for controlling CO concentrations on recreational boats. This workshop brought together representatives from engine and generator manufacturers, recreation and houseboat manufacturers, boat rental companies, as well as government agencies. These stakeholders addressed the issues surrounding controlling CO concentrations on all types of recreational boats and from all sources (drive engines as well as generators). New technologies like cleaner-burning engines and exhaust treatment devices such as catalytic converters are being investigated to assess the impact that these developments may have on CO reduction for recreational boats. New and different solutions continue to be studied to address this important issue.

Public education efforts must continue to inform and warn persons (including boat owners, renters and workers) of the potential to be exposed to CO hazards around houseboats. These issues are currently being addressed by NPS, U.S. Coast Guard and other organizations. The NPS has launched an awareness program to inform boaters on its lakes about boat-related CO hazards. The U.S. Coast Guard is also developing warning labels and boater education materials to provide information about this hazard.

Training provided to houseboat renters, who may be completely unaware of this deadly CO hazard, should be enhanced to include specific information about the circumstances and number of poisonings and deaths. The training should specifically warn against entering, playing and swimming in air spaces under the boat (such as the cavity below the swim platform), or immediately behind or near the swim platform, which may contain a lethal atmosphere. ■

References

American Boat and Yacht Council Inc. (ABYC). Standard P-1, Installation of Exhaust Systems for Propulsion and Auxiliary Engines. Edgewater, MD: ABYC, 2002.

American Conference of Governmental Industrial Hygienists (ACGIH). *Documentation of Threshold Limit Values and Biological Exposure Indices.* Cincinnati: ACGIH, 2002.

Dunn, K.H., et al(a). "An Evaluation of an Engineering Control to Prevent Carbon Monoxide Poisonings of Persons on Houseboats at Somerset Custom Houseboats." DEPHB Report #171-26a. Cincinnati: CDC, NIOSH, 2001.

Dunn, K.H., et al(b). "Comparison of a Dry Stack with Existing Generator Exhaust Systems for Prevention of Carbon Monoxide Poisonings on Houseboats." DEPHB Report #EPHB Report #171-28a. Cincinnati: CDC, NIOSH, 2001.

Earnest, G.S., et al(a). "An Evaluation of an Engineering Control to Prevent Carbon Monoxide Poisonings of Persons on Houseboats." DEPHB Report #EPHB Report #171-25a. Cincinnati: CDC, NIOSH, 2001.

Earnest, G.S., et al(b). "An Evaluation of an Engineering Control to Prevent Carbon Monoxide Poisonings of Persons On and Around Houseboats." *AIHA Journal.* 63(2002): 361-369.

EPA. "Air Quality Criteria for Carbon Monoxide." Washington, DC: EPA, 1991.

Hall, R.M.(a). Letter of Dec. 18, 2000, from Ronald M. Hall, CDC, NIOSH, to Rice C. Leach, Commissioner, Cabinet for Health Services, Dept. of Public Health, Commonwealth of Kentucky. Cincinnati: NIOSH, HETA 2001-0026, 2000.

Hall, R.M.(b). Letter of April 5, 2001, from Ronald M. Hall, CDC, NIOSH, to John Stenseth, General Manager, Fun Country Marine Industries Inc. Cincinnati: NIOSH, HETA 2001-0090, 2001.

Hall, R.M. and J.B. McCammon. Letter of Nov. 21, 2000, from Ronald M. Hall and Jane B. McCammon, CDC, NIOSH, to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, AZ. Cincinnati: NIOSH, HETA 2000-0400, 2000.

McCammon, J.B., et al. Letter of Feb. 20, 2001, from J. McCammon, CDC, NIOSH; T. Radke, U.S. Dept. of the Interior; and Dr. Robert Baron Prehospital Medical Care, Glen Canyon National Recreation Area, to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, AZ. Denver: NIOSH, 2001.

McCammon, J.B. and T. Radtke. Letter of Sept. 28, 2000, from J. McCammon, CDC, NIOSH, and T. Radke, U.S. Dept. of the Interior, to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, AZ. Denver: NIOSH, 2000.

NIOSH(a). "NIOSH Criteria for a Recommended Standard: Occupational Exposure to Carbon Monoxide." DHEW (NIOSH) Publication No. HSM 73-11000. Cincinnati: CDC, NIOSH, 1972.

NIOSH(b). "NIOSH Respirator Decision Logic." DHHS (NIOSH) Publication No. 87-108 (NTIS Publication No. PB-88-149612). Cincinnati: CDC, NIOSH, 1987.

NIOSH(c). "Pocket Guide to Chemical Hazards and Other Databases: Immediately Dangerous to Life and Health Concentration." DHHS (NIOSH) Publication No. 97-140. Cincinnati: CDC, NIOSH, 1995.

OSHA. 29 CFR 1910.1000. Chapter 17, Table Z-1: Limits for Air Contaminants. Washington, DC: OSHA.

World Health Organization (WHO). International Programme on Chemical Safety Environmental Health Criteria 213: Carbon Monoxide. 2nd ed. Geneva, Switzerland: WHO, 1999.

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