COMPARISON OF A DRY STACK WITH EXISTING GENERATOR EXHAUST SYSTEMS FOR PREVENTION OF CARBON MONOXIDE POISONINGS ON HOUSEBOATS

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Executive Summary

During the period of 1990 to 2000, 111 carbon monoxide (CO) poisoning cases occurred on Lake Powell near the border of Arizona and Utah Seventy-four of the poisonings occurred on houseboats, and sixty-four of the poisonings were attributable to generator exhaust alone Seven of the 74 houseboat-related CO poisonings resulted in death

In February 2001, the National Institute for Occupational Safety and Health (NIOSH) conducted an initial evaluation of an engineering control installed on a houseboat generator to reduce the hazard of CO poisonings from the generator exhaust The control consisted of a water separator and an exhaust stack that extended 9 feet above the top deck of the houseboat outfitted onto a gasoline-powered generator This previous investigation, conducted at Lake Powell, showed substantial reductions (greater than 99%) in the concentration of CO on and around the swim platform of a Lakeview houseboat retrofitted with the "dry stack" generator exhaust system The Lake Powell evaluation was conducted on a single stationary boat docked under moderate ambient temperature and wind conditions

The current study investigated the effect of additional variables on the performance of the dry stack exhaust system These variables included elevated ambient temperature, boat in motion, and the effect of tying two or more boats together Alternative configurations including side and rear exhaust were also tested for comparison with the dry stack

While the boat was stationary, CO concentrations on the *lower rear deck* of the houseboat, averaged approximately 3 ppm with the dry stack configuration, 2 ppm with the side exhaust configuration (exhaust terminating at starboard side) and 285 ppm for the rear exhaust configuration (exhaust terminating at transom underneath swim platform) Exhausting the generator through the dry stack or side exhaust resulted in a reduction of approximately 99% when compared to the rear exhaust Peak concentrations on the upper deck of the houseboat exceeded the ACGIH excursion limit of 125 ppm for the side and rear exhaust configurations, but were dramatically lower for the stack exhaust The relatively low CO concentrations measured on the lower rear deck with side exhaust were surprising because previous NIOSH investigations have shown dangerously high CO concentrations (several hundred ppm) under similar conditions

When the boat was in motion (boat underway), CO concentrations were much higher due to the CO generated from the propulsion engines For the dry stack, average CO concentrations on the *lower rear deck* of the houseboat ranged between 18-87 ppm compared with 175 ppm and 129 ppm for the side and rear exhaust, respectively Finally, **when 3 boats were tied together**, only the dry stack performed well Average CO concentrations on the *lower rear decks* of the houseboats ranged from 6-14 ppm, compared with 104-777 ppm for side and rear exhaust configurations

Although average concentrations provide for a good comparison between generator exhaust configurations, the peak exposures provide information more relevant to the important health hazards In the current study, CO concentrations exceeded the NIOSH Immediately Dangerous to Life and Health (IDLH) concentration of 1,200 ppm on the swim platforms of several boats while tied together and exhausting the generators through a combination of rear and side exhaust ports Peak concentrations approaching the IDLH were also measured at the swim platform for the rear-exhausted boat while stationary and for the side-exhausted boat while in motion The concentration of CO inside the exhaust pipe of a generator during normal operation averaged 8 1% (81,000 ppm) This concentration is over 67 times greater than the IDLH Therefore, it is important to direct the generator exhaust away from the water level and any occupied region of the boat The results of this and prior NIOSH studies indicate that houseboats retrofitted with an exhaust stack that extends well above the upper deck will greatly reduce the risk of generator-related CO poisoning and possible death to individuals on or near the houseboat

Background

On June 18-20, the National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of an engineering control designed and retrofitted onto a houseboat generator The control, which consisted of a water separator and an exhaust stack, was designed to direct the generator exhaust away from individuals on or near the houseboat in order to prevent carbon monoxide (CO) poisonings from the exhaust Many houseboat generators exhaust through the transom under the swim deck on the rear of the boat while others exhaust to the side of the boat near the waterline The generator exhaust system design and modification was performed by Fun Country Marine Industries, Inc The evaluation was conducted at the request of Fun Country Marine, Inc whose boats are located at Callville Bay on Lake Mead, Nevada This study was performed in conjunction with another NIOSH survey which evaluated the use of an emissions control device and an interlock system for controlling CO concentrations (Earnest et al 2001) The dry stack exhaust system was tested under a variety of conditions that had not been previously evaluated by NIOSH including boat in motion and multiple boats tied together, as well as the boat stationary condition Alternate generator exhaust configurations, including side and rear transom vent, were also tested under the same conditions The previous dry stack exhaust studies were performed on a single boat docked in primarily quiescent atmospheric conditions This report provides background information, and describes the evaluation methods, results, conclusions, and recommendations from this survey

Initial investigations were conducted in September and October 2000 involving representatives from NIOSH, U S Coast Guard, U S National Park Service, Department of Interior, and Utah Parks and Recreation in response to CO related poisonings and deaths on houseboats at Lake Powell The September 2000 investigation characterized CO poisonings through epidemiologic data gathering and severely hazardous CO concentrations measured on houseboats at Lake Powell (McCammon and Radtke 2000) Incident reports provided by the National Park Service revealed seven known houseboat-related CO poisoning deaths on the lake since 1994 Some of these incidents involved numerous poisonings in addition to the deaths reported Information regarding the fatalities is described in the previous report (McCammon and Radtke 2000) Since that report, it has been discovered that from 1990 to 2000, 111 CO poisoning cases occurred on Lake Powell near the border of Arizona and Utah Seventy-four of the poisonings occurred on houseboats, and sixty-four of the poisonings were attributable to generator exhaust alone Seven of the 74 houseboat-related CO poisonings resulted in death (McCammon, Radtke et al 2001)

Some of the severely hazardous situations identified during the September evaluation included

- The open space under the swim platform could be lethal under certain circumstances (i e , generator/motor exhaust discharging into this area) on some houseboats
- Some CO concentrations above and around the swim platform were at or above the immediately dangerous to life and health (IDLH) level [greater than 1,200 parts of CO per million parts of air (ppm)]

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

Further investigations were conducted to gather additional CO concentration data on various types of houseboats at Lake Powell (Hall and McCammon 2000), Lake Cumberland, Kentucky (Hall 2000), and Lake Mead, NV (Hall 2001) Survey results showed that when the generator is exhausted under the rear deck or to the side of the boat near the waterline, hazardous concentrations of CO (greater than the IDLH) can occur in the space under the deck and around the swim platform

In February 2001, an engineering control evaluation was conducted on a Lakeview houseboat located at the Wahweap Marina on Lake Powell, Arizona (Earnest et al 2001) That study examined the effect of using an exhaust stack that extended 9 feet above the top deck of the houseboat for the generator compared to a more standard configuration of exhausting out of the rear transom in the space underneath the swim platform The results indicated average reductions in CO concentrations on the swim deck of greater than 99% (607 ppm vs 3 ppm) when the exhaust was vented through the stack versus to the airspace beneath the swim deck A second evaluation was conducted on a dry stack exhaust at Sumerset Custom Houseboats in March 2001 (Dunn, Hall et al 2001) This study confirmed the results of the previous study Average CO concentrations on the swim platform were approximately 1 ppm with the generator operating and exhausting through the stack

Carbon Monoxide Symptoms and Exposure Limits

Carbon monoxide (CO) is a lethal poison that is produced when fuels such as gasoline or propane are burned It is one of many chemicals found in engine exhaust resulting from incomplete combustion Because CO is a colorless, odorless, 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

The general boating public may range from infant to aged, be in various states of health and susceptibility, and be functioning at a higher rate of metabolism because of increased physical activity The occupational exposure limits noted below should not be used for interpreting general population exposures because they would not provide the same degree of protection they do for the healthy worker population

Exposure Criteria

The NIOSH Recommended Exposure Limit (REL) for CO is 35 ppm for full shift time weighted average (TWA) exposure, with 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 as 1,200 ppm (NIOSH 2000) The American Conference of Governmental Industrial Hygienists' (ACGIH®) Threshold Limit Values (TLVs®) recommends an eight-hour TWA TLV of 25 ppm (ACGIH 2001), and recommends that excursions above 125 ppm be prevented The Occupational Safety and Health Administration (OSHA) Permissible Exposure Limits (PELs) for CO is 50 ppm for an 8-hour TWA exposure (CFR 1997)

The US 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 one-hour average (EPA 1991) The NAAQS for CO was established to protect "the most sensitive members of the general population"

Methods

Description of the Evaluated Fun Country Marine Houseboat and Engineering Control

CO samples were collected on three Fun Country Marine houseboats having the specifications listed below

- **Houseboat # 20 (see Figure 1)**
  Engines: (2) 135 horsepower (hp) 4 cylinder, 4 cycle, Volvo engines, with inboard/outboard drives
  Generator: 12 5 kW Kohler, 4 cylinder, 4 stroke
  Approximate dimensions of houseboat: 65' X 14'
  Approximate dimensions of space below swim platform: 3' X 14' X 1 5'
  Exhaust Configuration: 1) Combo-Sep muffler/gas/water separator to vertical gas exhaust 9 feet above upper deck and port side water drain, and 2) Can modify to exhaust gas through muffler and starboard side

- **Houseboat # 173 (see Figure 1)**
  Engines: (2)135 horsepower (hp) 4 cylinder, 4 cycle, Volvo engines, with inboard/outboard drives
  Generator: 12 5 kW Kohler, 4 cylinder, 4 stroke
  Approximate dimensions of houseboat· 56' X 14'
  Approximate dimensions of space below swim platform: 3' X 14' X 1 5'
  Exhaust Configuration: 1) Combo-Sep muffler/gas/water separator to vertical gas exhaust 9 feet above upper deck and port side water drain, and 2) Can modify to exhaust gas through muffler and rear transom

- **Houseboat # 200 (see Figure 1)**
  Engines: (2) 135 horsepower (hp) 4 cylinder, 4 cycle, Volvo engines, with inboard/outboard drives
  Generator: 12 5 kW Kohler, 4 cylinder, 4 stroke
  Approximate dimensions of houseboat: 56' X 14'
  Approximate dimensions of space below swim platform: 3' X 14' X 1 5'
  Exhaust Configuration: 1) Combo-Sep muffler/gas/water separator to vertical gas exhaust 9 feet above upper deck and port side water drain, and 2) Can modify to exhaust gas through muffler and rear transom

The propulsion (drive) engines and generator were housed in compartments beneath the rear deck of the houseboat Access to the engines was through a large door in the floor of the rear deck These engines exhausted through their propellor shafts beneath the water The evaluated houseboats had a full hull without enclosed spaces beneath the lower rear deck The generator on these houseboats provided electrical power for air conditioning, electrical cooking, refrigeration, cabin appliances, and navigation and communications equipment The generator was housed in the engine compartment beneath the rear deck and was positioned near the two Volvo drive engines The generator is a 4-cylinder, 4-cycle, gasoline-powered engine that operates at approximately 1,800 revolutions per minute (rpm) and displaces 79 cubic inches (in^3)

The hot exhaust gases from this generator 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 The water-jacketed exhaust passes through a lift muffler that further reduces nose and forces the cooled exhaust gases out through a hole beneath the swim platform to either the dry stack, rear, or side exhaust configuration

A schedule 40, 2-inch nominal aluminum pipe was used for the stack (Figure 2) The aluminum pipe was divided into two separate sections a section between the lower rear deck and the upper deck, and a section extending 9 feet above the upper deck The portion of the stack located above the upper deck sat inside of a coupling that was held together by the weight of the stack An o-ring was used to prevent leakage between the sections The lower portion of the stack extended through the lower rear deck and was clamped to a high temperature exhaust hose This design permitted relatively simple emissions sampling at various locations and more importantly, could be used to easily remove the stack when the houseboat is being transported or shipped

To allow the pipe to pass from beneath the lower swim deck to 9 feet above the upper deck, a hole was made in the lower rear port-side of the engine compartment and the rear port-side of the upper deck which the pipe passed through The original lift muffler was removed, and a Combo-sep® muffler/gas/water separator (Centek Industries, Thomasville, GA) was installed to separate the exhaust gases from the water using gravity and centrifugal force In order to function properly, the exhaust stack must be properly sized based upon the exhaust gas, water flow rate, and the maximum back pressure permitted by the manufacturer It is also important that the separator releases the water less than 6 inches below the water line to reduce back pressure which could force some water up the stack Finally, the exhaust hose between the Combo-Sep® and exhaust stack should not sag so that any water deposited inside of the hose will flow back into the Combo-Sep® unit

Representatives from Fun Country Marine, Inc estimated that the evaluated dry stack exhaust system would cost between $500 and $1000 to retrofit to the houseboat while in the water and between $1000 and $1500 if it was necessary to remove the boat from the water to perform the installation The original purchase price for the evaluated houseboats was approximately $165,000 and these boats currently sell for approximately $180,000

Description of the Evaluation Equipment

Emissions from the exhaust stack were characterized using a KAL Equip Model 5000 Four Gas Emissions Analyzer (KAL Equipment, Cleveland, Ohio) This analyzer measures CO, carbon dioxide (CO_2), hydrocarbons, and oxygen CO and O_2 measurements are expressed as percentages [One percent of contaminant is equivalent to 10,000 ppm]

CO concentrations were measured at various locations on the houseboat using ToxiUltra Atmospheric Monitors (Bacou USA, Middletown, CT) with CO sensors ToxiUltra CO monitors were calibrated before and after use according to the manufacturer's recommendations These monitors are direct-reading instruments with data logging capabilities The instruments were operated in the passive diffusion mode, with a 30 second sampling interval The instruments have a nominal range from 0 ppm to 999 ppm

The ToxiUltra monitors are electrochemical type instruments which measure the electrical current generated by a reaction between the ambient CO and the electrolyte in the sensor The electrical current generated is proportional to the amount of reactant gas present and is used to indicate gas concentration Occasionally, negative gas concentration readings are logged generally due to two conditions 1) zeroing the instrument in an area which is not free of CO, or

2) performing measurements in the presence of interference contaminants which cause a negative potential across the electrode During this evaluation, a zero drift of -1 to -4 ppm occurred on a few of the sensors To account for this, a zero shift was added to the data for those monitors

CO concentration data was also collected with detector tubes [Draeger CO, CH 29901– range 0 3 % (3,000 ppm) to 7 % (70,000 ppm) and CH 25601– range 5-700 ppm)] at various locations on the boat The detector tubes are used by drawing air through the tube with a bellows–type pump The resulting length of the stain in the tube (produced by a chemical reaction with the sorbent) is proportional to the concentration of the air contaminant

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

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

Air velocity from the exhaust stack was measured through the use of a VelociCalc Plus Model 8360 air velocity meter (TSI Inc , St Paul, MN) Air velocity readings were collected, at the face of the stack exhaust outlet The exhaust velocity was measured on each boat evaluated and an average velocity was calculated from these measurements

Description of Procedures

The evaluation was performed over a 3-day period with three distinct operating conditions and 3 generator exhaust configurations The test conditions and operating configurations are summarized below

1) Boat Stationary – Generator exhausting through the dry stack, side or rear transom The generator exhaust was reconfigured after each run to alternate between the dry stack and the alternate configuration (side or rear exhaust) This evaluation was conducted over a two day period with the Stack/Side tests run on June 19 (Boat 20) and the Stack/Rear tests run on June 20 (Boat 200) During the stationary evaluation, the generator operated alone for approximately 30 minutes

2) **Boat Underway** (see Figure 3)–Generator exhausting through the dry stack, side or rear transom The boat underway evaluation consisted of measuring CO concentrations on the boat as the boat 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/from the marina lasted for approximately 30 minutes This evaluation was also conducted over a two-day period with the Stack/Side tests run on June 19 (Boat 20) and the Stack/Rear tests run on June 20 (Boat 200)

3) **Boats Tied Together** (rafting-see Figure 1)–Generator exhausting through the dry stack, side, or rear transom or combination of side and rear Evaluation of boats tied together included testing three boats with a combination of side (Boat 20) and rear (Boats 173 and 200) generator exhaust or dry stack exhaust configurations (all boats) A second evaluation of 2 boats with rear (Boats 173 and 200) or stack generator exhaust configurations (both boats) was also conducted During the evaluation, the generator operated alone for approximately 30 minutes per run

Sampling locations for the ToxiUltra real-time CO monitors on the lower and upper decks of the houseboat are shown in Figures 4 and 5 (single-boat), 6 and 7 (2 boats tied together), and 8 and 9 (3 boats tied together) The monitors were placed at various locations on both the upper and lower decks of the houseboat to provide representative samples of occupied areas when the generator was operating Because people commonly enter and exit the water via the rear swim platform of the boat, two monitors were placed on either side of this structure

Results

Results of Air Sampling with ToxiUltra CO monitors

Summary statistics of the ToxiUltra real-time CO concentration measurements at various locations on the houseboat are presented in Tables I through VIII Figures 10 through 12 provide a comparison of average CO concentrations on a single houseboat when the generator is exhausted through the dry stack, side, and rear transom while the boat is stationary and underway Figure 13 provides average CO concentrations at multiple locations on 2 houseboats (Boats 173 and 200) which were tied together and exhausting either through the stack or through the rear transom Figure 14 compares the average CO concentrations in a three house boat configuration with all boats exhausting through the stack or through a combination of side (Boat 20) and rear (Boats 173 and 200)

The following summarizes the CO concentrations at various locations on the houseboat(s) The stationary results reflect CO concentrations when only the generator is operational When the boat is underway, both the generator and drive engines were operating

Single boat, while stationary (only generator operating)

- Carbon monoxide concentrations on the lower deck were low for the dry stack on both days of testing with an average of 4 ppm and 3 ppm for June 19 and 20 The CO concentration when exhausting out of the side was also low with an average of 2 ppm In contrast, CO concentrations on the lower deck of the rear-exhausted boat were substantially worse with a mean of 285 ppm These values represent an average of all outside locations on the lower deck (swim platform, slide and stairs) Both the dry stack and side exhaust averages resulted in about a 99% reduction from the average concentration of the rear exhaust.

- Instantaneous CO concentrations on the swim deck were also low for the dry stack on both days of testing with a peak of 41 ppm and 20 ppm for June 19 and 20 The CO concentration when exhausting out of the side was also low with a peak of 12 ppm In contrast, the highest CO concentration on the swim platform of the rear-exhausted boat reached 983 ppm far exceeding the NIOSH Ceiling limit and approaching the IDLH

- Carbon monoxide concentrations on the upper deck were lower for the dry stack than the side or rear exhaust configurations CO concentrations across all upper deck locations averaged 2 ppm and 1 ppm for June 19 and 20 with the dry stack The average CO concentrations for the side and rear exhaust were 10 ppm, and 17 ppm, respectively The stack exhaust was approximately 80% lower than the side exhaust and 94% lower than the rear exhaust based on the average of all CO measurements on the upper deck

- Peak CO concentrations on the upper deck were low for all locations when exhausting through the dry stack with the highest reading of 19 ppm (aft corner, port) on either day of testing Peak CO concentrations were much higher for both the side and rear exhaust configurations with peaks reaching 155 ppm and 146 ppm, respectively Peak concentrations at two locations on the upper deck exceeded the ACGIH TLV excursion limit of 125 ppm when the generator was exhausting to the side of the boat

The results of all samples collected on the lower level rear deck are shown in Table I for each stationary houseboat generator exhaust configuration tested Figure 10 shows the average CO concentrations at the rear swim platform and behind the slide at breathing zone height (BZH) while the boat was stationary The scale on the plot is a log scale due to the wide range of CO concentrations The average CO concentration for the generator operating and exhausting through the stack was low with values of 4 ppm for the swim platform and 1 ppm at BZH behind the slide The values for the side exhaust were also low with averages of 1 ppm on the swim platform and 2 ppm behind the slide The generator rear exhaust resulted in substantially higher CO concentrations with an average of 688 ppm on the swim platform and 68 ppm behind the slide Although the average CO concentrations provide a good basis for comparing generator exhaust configurations, perhaps more important are the peak concentrations at these locations Table I also shows the peak concentrations measured at each location for various exhaust configuration—peak concentrations which exceed the NIOSH Ceiling Limit of 200 ppm are highlighted in bold typeface The highest concentration measured over two days of testing at any location on the lower rear deck of boats 20 and 200 was 41 ppm (swim platform) for the stack exhaust The analogous peak concentration for the side exhaust was 46 ppm (slide at BZH) and 983 ppm for the rear exhaust (swim platform)

The results of all samples collected on the upper deck are shown in Table II for each stationary houseboat generator exhaust configuration tested Figure 10 shows the average CO concentrations at the starboard aft location (across from the stack) and center of the top deck while the boat was stationary The average CO concentration for the generator operating and exhausting through the stack was low with values of 1 ppm for the starboard aft location and 1 ppm near the center of the top deck The values for the side exhaust were higher with averages of 17 ppm at the starboard aft location and 10 ppm near the center The generator rear exhaust resulted in slightly higher CO concentrations than the stack with average CO concentrations of 10 ppm on the starboard aft sampling location and 2 ppm near the center Table II also shows the peak concentrations measured at each upper deck sampling location for each exhaust configuration The highest concentration measured over two days of testing at any location on the upper deck of boats 20 and 200 was 19 ppm (port aft-near the stack) for the stack exhaust The analogous peak concentration for the side exhaust was 155 ppm (at the center of the top deck) and 146 ppm for the rear exhaust (at the port aft location)

Single boat, while in motion (with drive engines and generator operating)
Note: Increase in CO levels due to drive engines operation.

- The CO concentrations measured on the lower rear deck, on June 19, for all outside sampling locations (swim platform, slide and stairs) averaged 87 ppm and 175 ppm for the stack and side exhaust, respectively The average CO concentrations on the lower deck on June 20 were 18 ppm and 129 ppm for the stack and rear exhaust, respectively There was significant variation from June 19 to June 20 for measurements on the stack exhaust likely due to varying wind conditions

- Peak CO concentrations on the swim deck were high for all exhaust configurations with peaks of 681 ppm, 961 ppm and 422 ppm for the stack, side and rear exhaust, respectively These CO levels indicate extremely dangerous conditions on the swim platform with each exceeding the NIOSH Ceiling limit of 200 ppm and approaching the 1200 ppm IDLH limit

- Carbon monoxide concentrations on the upper deck were lower for the dry stack than the side or rear exhaust configurations The average CO concentration for all locations on the upper deck was 5 ppm on June 19 and 5 ppm on June 20 when exhausting through the stack The corresponding average CO concentrations for the side and rear exhaust were 7 ppm and 16 ppm, respectively

- Peak CO concentrations on the upper deck were lower for most locations when exhausting through the dry stack with the highest reading of 61 ppm (aft corner, near stack) on either day of testing Peak CO concentrations were generally higher for both the side and rear exhaust configurations with peaks reaching 97 ppm and 137 ppm, respectively

The results of all samples collected on the lower level rear deck are shown in Table III for each generator exhaust configuration tested while underway Some of these data are shown graphically in Figures 11 (stack vs side) and 12 (stack vs rear) Carbon monoxide concentrations were highly variable from day to day probably due to wind conditions Therefore, it is only appropriate to compare data from each day with the configurations tested on that day These figures show the average CO concentrations at the rear swim platform and behind the slide near the breathing zone height (BZH) while the boat was in motion The average CO concentration for the generator operating and exhausting through the dry stack was lower than the side or rear exhaust with values of about 141 ppm and 21 ppm for the swim platform on days 1 and 2 (June 19 and 20), respectively The average CO concentrations behind the slide near the BZH was 48 ppm on day 1 and 6 ppm on day 2 for the dry stack exhaust These values likely differed from day to day due to varying wind conditions The values for the side exhaust averaged 287 ppm on the swim platform and 71 ppm behind the slide The generator rear exhaust configuration resulted in average CO concentrations of 181 ppm on the swim platform and 65 ppm behind the slide The highest concentration measured over two days of testing at any location on the lower rear deck of boats 20 and 200 was 681 ppm (swim platform) for the stack exhaust The analogous peak concentration for the side exhaust was 1081 ppm (swim platform) and 422 ppm for the rear exhaust (swim platform)

The results of all samples collected on the upper deck are shown in Table IV for each underway houseboat generator exhaust configuration tested Figures 11 (stack vs side) and 12 (stack vs rear) show the average CO concentrations at the starboard aft location (across from the stack) and at the center of the top deck while the boat was in motion The average CO concentration for the generator operating and exhausting out of the dry stack was slightly lower than the side or rear exhaust with values of about 5 ppm and 11 ppm for the aft starboard location on days 1 and 2 (June 19 and 20), respectively These values likely differed from day to day due to varying wind conditions The average CO concentrations at the center of the top deck were 1 ppm on day 1 and 2 ppm on day 2 for the dry stack exhaust The values for the side exhaust averaged 10 ppm at the aft starboard location and 2 ppm at the center of the top deck The generator rear exhaust configuration resulted in average CO concentrations of 15 ppm at the aft starboard location and 6 ppm at the center of the top deck Table IV also shows the peak concentrations measured at each upper deck sampling location under each exhaust configuration The highest concentration measured over two days of testing at any location on the upper deck of boats 20 and 200 was 61 ppm (port aft-near the stack) for the stack exhaust The analogous peak concentration for the side exhaust was 97 ppm (at the starboard aft location) and 137 ppm for the rear exhaust (at the port aft location)

Houseboats Tied Together (only generator operating)

The houseboats tied together were tested in a 2 and 3 boat configuration The 2 boat configuration consisted of a comparison between both generators exhausting through the stack or out of the rear transom (underneath the swim platform) The 3 boats tied together evaluated all boats exhausting through the stack or a combination of rear and side exhaust (Figure 8) Note The generator exhaust for the side exhausted boat was pointed away from the adjacent houseboats

- For 2 boat configuration, the stack performed much better than the rear generator exhaust configuration With generators exhausting through the stack, the average CO concentrations measured on the swim platform of boats 200 and 173 were 1 ppm and 2 ppm, respectively With the generators exhausting out of the rear, the averages for boats 200 and 173 were 191 ppm and 53 ppm, respectively The reduction in average concentration was approximately 99% for boat 200 and 96% for boat 173

- For the 2 boat configuration, peak CO concentrations were also substantially reduced on the swim platform by the use of the generator exhaust stack With both boats exhausting through the stack, the peak concentration seen on the swim platform of either boat was 5 ppm while the corresponding peak for the rear exhausted boats was 979 ppm

- For the 3 boat configuration, the results were similar The average concentration on the swim deck for the three boats while using the stack exhaust was 14 ppm, 10 ppm and 11 ppm for boats 200, 173 and 20, respectively When the generators were switched to a combination of side and rear exhaust, the CO concentrations were dramatically higher with average concentrations of 777 ppm, 153 ppm, and 145 ppm for boats 200, 173 and 20, respectively

- Peak concentrations reached dangerously high levels on the swim platforms of all three boats when the generators were exhausted through the combination side and rear exhaust The peaks on boats 200 (1,243 ppm) and 173 (1,235 ppm) reached levels above the IDLH When the boats were exhausting through the stack, the highest CO concentration measured on the swim platform of any boat (84 ppm on boat 200) was well below the NIOSH Ceiling limit and the ACGIH excursion limit

- The average and peak concentrations on the upper deck were lower for every sampling location when the generators were exhausting through the stacks versus the alternate configurations (rear or side/rear) for both the 2 and 3 boat configurations

The results of all samples collected on the lower level rear deck with multiple houseboats tied together are shown in Table V (2 boats tied together) and Table VII (3 boats tied together) for each houseboat generator exhaust configuration tested Figures 13 (2 boats tied together) and 14

(3 boats tied together) show the average CO concentrations on the rear swim platform of all boats and at other rear platform locations For the 2 boat configuration, the average CO concentration for the generator operating alone and exhausting through the dry stack was lower than for the rear exhaust configuration with values of 1 ppm and 2 ppm compared with 191 ppm and 54 ppm on the swim platforms for boats 200 and 173, respectively The average CO concentrations at BZH on the stairs were 1 ppm for boats 200 and 173 when exhausting through the stack While the values for the rear exhaust configuration averaged 23 ppm and 10 ppm for boats 200 and 173 Although the average CO concentrations provide a good basis for comparing generator exhaust configurations, perhaps more important are the peak concentrations at these locations Table V shows the peak concentrations encountered on boats 173 and 200 for each location under both exhaust configurations–peak concentrations which exceed the NIOSH Ceiling Limit of 200 ppm are highlighted in bold typeface The highest concentration measured at any location on the lower rear deck of boats 173 and 200 was 5 ppm (swim platform on boat 173) for the stack exhaust The analogous peak concentration for the rear exhaust was 979 ppm (swim platform on boat 200)

For the 3 boats tied together configuration, the average CO concentration for the generator operating alone and exhausting out of the dry stack (on all boats) was lower than for the combination of rear (boats 200 and 173), and side exhaust (boat 20) configuration with values of 10 ppm, 14 ppm, and 11 ppm compared with 153 ppm, 777 ppm and 145 ppm on the swim platforms for boats 173 and 200 and 20, respectively The average CO concentration at BZH behind the slide on the center boat (boat 200) was 6 ppm when each boat exhausted through the dry stack compared with 104 ppm when exhausting through the combination of rear and side exhaust Table VII shows the peak concentrations encountered on boats 173, 200 and 20 for each location under both exhaust configurations–peak concentrations which exceed the NIOSH Ceiling Limit of 200 ppm are highlighted in bold typeface The highest concentration measured at any location on the lower rear deck of boats 173, 200 and 20 was 84 ppm (swim platform on boat 200) for the stack exhaust The analogous peak concentration for the combination rear/side exhaust was 1,243 ppm (swim platform on boat 200)

The results of all samples collected on the upper deck are shown in Table VI (2 boats tied together) and Table VIII (3 boats tied together) for each houseboat generator exhaust configuration tested Figures 13 (2 boats tied together) and 14 (3 boats tied together) show the average CO concentrations at a few locations on the upper decks of boats 173, 200, and 20 while exhausting through the stack or through the rear or side For the 2 boat configuration, the average CO concentration for the generator operating alone and exhausting out of the dry stack (for both boats) was lower than the rear exhaust configuration with a value of 3 ppm compared with 5 ppm at the port, aft location for boat 173 The average CO concentrations at the starboard, aft location of boat 200 was 3 ppm for the stack exhaust compared with 54 ppm for both boats exhausting through the rear transom Table VI shows the peak concentrations measured on boats 173 and 200 for each location under both exhaust configurations The highest concentration measured at any location on the upper deck of boats 173 and 200 was 27 ppm (starboard, front on boat 173) for the stack exhaust The analogous peak concentration for the rear exhaust was 172 ppm (starboard, aft on boat 200)

For the 3 boats tied together configuration, the average CO concentration for the generator operating alone and exhausting out of the dry stack (on all boats) was lower than for the combination of rear (boats 200 and 173) and side exhaust (boat 20) configuration with a value of 4 ppm compared with 10 ppm at the port, aft location of boat 173 The average CO concentration at the front, starboard location of boat 20 was 3 ppm when each boat exhausted through the dry stack compared with 10 ppm when exhausting through the combination of rear and side exhaust Table VIII shows the peak concentrations measured on boats 173, 200 and 20 for each location under both exhaust configurations The highest concentration measured at any location on the upper deck of boats 173, 200 and 20 was 52 ppm (port, aft on boat 173) for the stack exhaust configuration The analogous peak concentration for the combination rear/side exhaust was 98 ppm at 2 sampling locations (port, aft on boat 200 and starboard, aft on boat 20)

Wind Velocity Measurements

Wind velocity measurements were taken with an ultrasonic anemometer while the CO sampling data was gathered During this study, evaluations occurred with the houseboats stationary and underway The boats were oriented in a variety of directions depending upon the day and time When possible, an attempt was made to position the boats in a manner such that wind was moving from the rear of the houseboat near the CO emission sources toward the front of the houseboat to establish a worst case testing scenario

A sample of the wind velocity data collected on the morning of June 19 is shown in Figure 15 On the afternoon of June 18, wind speeds were low to moderate, having an average speed of approximately 1 8 m/sec (4 miles per hour) and a standard deviation of 1 0 m/sec On average, wind direction was at 210° SW On the morning of June 19, wind speeds were low to moderate, having an average speed of approximately 1 7 m/sec (3 7 miles per hour) and a standard deviation of 1 2 m/sec On average, wind direction was at 206° SW On this morning, the boat heading was due North (0° N) On the afternoon of June 19, wind speeds were approximately 2 0 m/sec (4 5 miles per hour) and had a standard deviation of 1 0 m/sec On average, wind direction was at 217° SW The boat heading in the afternoon was 80° NE Data from June 20 was lost due to instrument problems The boat heading on the morning of June 20 was 210° SW

Gas Emissions Analyzer, Detector Tubes, and Evacuated Container Results

The gas emissions analyzer, detector tubes, and glass evacuated containers were used to characterize CO concentrations in the exhaust stack and at locations on and around the houseboat These instruments were utilized because they are capable of reading higher CO concentrations than the Toxiultra CO monitors which has an upper limit of around 1,000 ppm When measuring exhaust from the stack, the probe of the emissions analyzer was placed directly in the exhaust pipe Measurements taken with the gas emissions analyzer directly in the exhaust stack of the generator indicated CO concentrations in the range of 5 3 % (53,000 ppm) to 8 5 % (85,000 ppm) The average over the one-hour sample period was 8 1% (81,000 ppm) with a standard deviation of 0 65 % (n=22)

Instantaneous spot measurements taken with Draeger colorimetric detector tubes and evacuated containers were collected at several sampling points The colorimetric tubes results correlated well with the ToxiUltra measurements for all samples and are shown in Table IX The evacuated container samples were taken at many locations (where ToxiUltra monitors were not placed) and the results are shown in Table X Two samples indicated that there were high CO concentrations in the area around the side exhaust with one sample (2,130 ppm) above the IDLH level of 1,200 ppm Another evacuated container provided good agreement with the emissions analyzer with a reading of 75,836 ppm of CO in the generator exhaust stream

Exhaust Stack Velocity and Temperature Results

Air velocity measurements were made at the face of the exhaust stack on boats 20, 173 and 200 The velocity measured was similar for all boats primarily due to the fact that all boats shared the identical generator and exhaust design The average exhaust velocity for all readings was 1,025 feet per minute (fpm) The exhaust temperature closely followed the ambient temperature and ranged from 108-113°F The ambient temperature was measured throughout the day and ranged from 97°F in the morning to 108°F in the afternoon The ambient air was dry with measured relative humidity of 15-29% The water temperature was stable with temperature readings of about 84°F

Discussion

This and previous NIOSH investigations on houseboats indicate that exhausting generator combustion gases beneath or near the rear deck may result in extremely hazardous CO concentrations on or near the rear swim platform When the generator operates as designed (having no catalytic converter or other pollution control devices) dangerously high CO concentrations are emitted into the atmosphere Exhaust gases released from the generator outfitted on these houseboats averaged 8 1 % CO (81,000 ppm) during normal operation This concentration is 67 times greater than the NIOSH Immediately Dangerous to Life and Health (IDLH) level Because the CO exhaust concentrations are so high, it is particularly important to direct the generator exhaust gases away from areas where people may be located (i e the water or lower rear deck of the houseboat)

This evaluation found that the stack exhaust greatly reduced the CO hazard in occupied areas of the boat The dry stack, extending 9 feet above the upper deck, propelled exhaust gases with enough momentum to provide an adequate effective height for the dispersion and removal of CO Average and peak CO concentrations were found to be well below occupational exposure limits (OSHA, NIOSH and ACGIH), when only the generator operated When the boat was underway, uncontrolled exhaust from the drive engines is the major source of CO resulting in much higher CO concentrations

In general, the dry stack performed better than either the side or rear exhaust while the houseboat was stationary with only the generator operating Average CO concentrations for both the stack and side exhaust were relatively low, with averages below recognized exposure limits Rear exhaust resulted in substantially higher CO concentrations than stack or side exhaust at all sampling locations on the rear deck of the houseboat Peak CO concentrations exceeding the NIOSH Ceiling and approaching the IDLH were measured on the swim platform and on the lower deck (the stairs) while exhausting through the rear CO concentrations were much lower on the upper deck for all exhaust configurations The average CO concentrations on the upper deck were lower for the stack exhaust than the side or rear exhaust The stack reduced peak exposures on the upper deck, however, the side and rear exhaust produced peak CO concentrations greater than the ACGIH Excursion limit of 125 ppm

Although data collected while evaluating the side exhaust during the current survey is better than 3 previous surveys, CO concentrations on or near the swim platform has been shown to exceed the NIOSH Ceiling and IDLH concentrations with the generator operating and exhausting to the side of the boat (Hall 2000, Hall and McCammon 2000, Hall 2001) An evacuated container sample taken during the current study found a CO concentration of 2,130 ppm near the side exhaust Because the generator exhaust contained average CO concentrations of 81,000 ppm, it is extremely important to direct the exhaust away from water or other areas where people may be located At these levels, individuals swimming in the area around the exhaust, or around the area on or directly behind the swim platform (near the water), could quickly experience CO poisoning or death

During movement of the boat from the marina to the cove, peak CO concentrations exceeded the NIOSH Ceiling limit of 200 ppm on the swim platform while the drive engines were in operation and with the generator exhausting through the stack, side and rear Concentrations on the swim platform approached the IDLH value of 1,200 ppm when exhausting through the side (see Figure 16) At these concentrations, the swim platform can rapidly become dangerous Boaters should be made aware of the high CO concentrations measured on the swim platform and rear deck while the boat is in motion

When 2 or 3 houseboats were tied together, a practice that is common among many users, the stack performed well Peak and average CO levels on the swim platforms for the 3 boat configuration were low When the exhaust configuration was changed to a combination of side and rear exhaust, the average CO concentrations on the lower rear deck were dramatically worse with peak concentrations above the IDLH (1,200 ppm) on the swim platforms of several houseboats This occurred even though the generator exhaust of the side-exhausted boat was directed away from the other boats (see Figure 8) The CO concentrations on the upper deck of the 3 boats were lower for the stack than for the combination of the rear and side generator exhaust configuration

The measurement variability due to ambient wind conditions was evident during these tests with coefficients of variation (cv) for CO concentrations typically around 1 and ranging to greater than 2 Day to day variation was most evident with the boat underway data The CO concentrations recorded on June 19 while the boat was exhausting the generator through the dry stack averaged 48 ppm at BZH behind the slide while this same location averaged only 6 ppm on June 20 This indicates that a safe atmosphere on one day can become unsafe on another depending upon ambient wind conditions

This investigation confirms that the CO hazard to swimmers and occupants on houseboats can be greatly reduced by running the generator exhaust through a stack that releases the CO and other emission components well above the upper deck of the houseboat Exhausting the generator high above the upper deck, allows the contaminants to diffuse and dissipate into the atmosphere away from boat occupants This survey also showed that while CO concentrations increased when the boat was in motion, compared to stationary, the stack still provides a good alternative to the rear or side exhaust configuration The majority of CO emitted while the boat was underway likely came from the drive engines Results from testing multiple boats tied together showed that the stack performed extremely well when compared to a combination of side and rear exhaust The effect of tying multiple side-exhausted boats together, a worst case side exhaust condition, was not evaluated in the current study

Issues related to the Ambient Temperature and the Density of CO

Some concerns have been raised about the effect of a temperature difference between the effluent from the stack and the surrounding environment The question posed was whether a large temperature difference between the ambient and the stack exhaust would cause the CO to descend onto the upper deck of the boat The stack has been evaluated under mild ambient conditions (45°F at Lake Powell and 50°F at Somerset) and at elevated ambient temperatures in this study (99-108°F) The CO concentration on the upper deck of the single stationary boat (while exhausting the generator through the stack) in this study averaged 1-2 ppm with the highest peak of 19 ppm at any location on the top deck These concentrations were consistent with those measured on the top deck of houseboats evaluated at Lake Powell and Somerset–average CO concentrations were 2 ppm and 1 ppm with peaks of 25 ppm and 12 ppm, respectively

The reasons that this phenomenon has not been observed is likely due to the following

1) There have been only minor observed temperature differences between the stack exhaust temperature and the ambient temperature The stack is constructed of aluminum which is an

excellent conductor of heat and helps to minimize the temperature difference In each study, the measured exhaust temperature was within 10°F of the ambient temperature

2) At standard temperature and pressure, CO is slightly less dense than air (3% lower) There is only a minor difference between the molecular weight (and thus density) between CO and air and even less difference when the CO is a part of the exhaust mixture

3) Exhaust gases are ejected from the stack at a relatively high velocity In this study, the average velocity of the stack exhaust was greater than 1000 fpm This velocity provides the motive force for moving the exhaust away from the top deck so that it can be well dispersed in the atmosphere

High CO concentration on the upper deck of houseboats using the stack exhaust has not been observed in any of the previous field studies conducted to date (Earnest 2001, Dunn 2001) or the current study The factors listed above contribute to the movement of the exhaust away from the boat and seem to provide adequate dispersion under all conditions evaluated to date

Recommendations

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

1) All manufacturers/owners/users of U S houseboats that use gasoline-powered generators should be aware of and concerned about the location of the exhaust terminus The data collected in this and previous evaluations show that an exhaust stack, vented well above the upper deck of the houseboat, moves CO away from the airspace below the rear deck, and dramatically reduces CO concentrations on occupied areas of the boat (i e rear deck, swim platform, top deck) and near swimmers Based upon the data from this and other reports, it is recommend that houseboats with gasoline-powered generators be retrofitted with control systems that reduce the hazards of CO poisoning

2) Based upon the data that NIOSH has collected to date, an exhaust stack that extends well above the upper deck of the houseboat appears to be a reliable, cost-effective solution that is capable of dramatically reducing the CO hazard

3) Additional testing should be performed to evaluate the side exhaust under worst case ambient and operational conditions, including tying multiple houseboats together while exhausting towards each other

4) The use of analytical tools such as computational fluid dynamics (CFD) modeling should be employed to evaluate a range of variables which may effect CO dispersion for both the stack and side exhaust configurations CFD can provide data on the effect of many ambient conditions that are more difficult to evaluate during a field study

5) Houseboat manufacturers should continue to identify and correct any design or operational issues that may present problems related to the performance of the dry stack These issues may include selecting the appropriate water separator and verifying that the associated plumbing does not cause excessive backpressure on the generator

6) Additional research and development work should be performed by marine engine manufacturers to evaluate the efficacy of using catalytic converters, afterburners or other emission control devices on generators and propulsion engines that are used on houseboats

7) Public education efforts must be utilized to immediately inform and warn all individuals (including boat owners, renters, and workers) potentially exposed to CO hazards The U.S NPS has launched an awareness program to inform boaters on their lake about boat-related CO hazards This Alert included press releases, flyers distributed to boat and dock-space renters, and verbal information included in the boat check-out training provided for users of concessionaire rental boats These and other educational materials are available at the following web site http //safetynet smis doi gov/COhouseboats htm Training about the specific boat-related CO hazards provided for houseboat renters, who may be completely unaware of this deadly hazard, should be enhanced to include specific information about the circumstances and number of poisonings and deaths The training should specifically warn against entering air spaces under the boat (such as the cavity below the swim platform), or immediately behind the swim platform, that may contain a lethal atmosphere

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Table I CO Samples (ppm) taken on the Lower, Rear Deck of the Houseboat with Generator Operating **Boat Stationary.**

Sample Location (Sample #)	**Generator Operating with Stack**		**Generator Operating with Side and Rear Exhaust**	
	Day 1	**Day 2**	**Side Exh**	**Rear Exh**
Rear Swim Platform-Port (#1)	Mean= 8 78 S D = 12 49 Peak = 41 N = 54	Mean= 7 07 S D = 5 53 Peak = 20 N = 42	Mean= 1 54 S D = 1 73 Peak = 12 N = 92	No Data**
Rear Swim Platform-STBD (#2)	Mean= 4 29 S D = 2 11 Peak = 10 N = 97	Mean= 3 51 S D = 1 74 Peak = 9 N = 43	Mean= 1 37 S D = 2 49 Peak = 12 N = 41	Mean= 688 24 S D = 306 06 **Peak = 983*** N = 46
On Stairs (#3)	Mean= 3 47 S D = 2 17 Peak = 12 N = 98	Mean= 2 05 S D = 2 41 Peak = 14 N = 42	Mean= 1 58 S D = 1 34 Peak = 7 N = 91	Mean= 91 11 S D = 62 77 **Peak = 280*** N = 45
Behind Slide (#4)	Mean= 1 15 S D = 1 07 Peak = 5 N = 99	Mean= 1 16 S D = 0 95 Peak = 4 N = 43	Mean= 2 29 S D = 7 32 Peak = 46 N = 41	Mean= 67 76 S D = 43 40 Peak = 189 N = 45
Inside Cabin, lower level (#5)	Mean= 9 46 S D = 1 12 Peak = 12 N = 97	Mean= 0 51 S D = 0 59 Peak = 2 N = 43	Mean= 7 24 S D = 3 43 Peak = 13 N = 91	Mean= 2 11 S D = 4 62 Peak = 24 N = 45

* Peak CO concentrations exceeding NIOSH Ceiling Limit are highlighted in bold typeface
** CO monitor was not in operation during the evaluation

Table II CO Samples (ppm) taken on the Upper Deck of the Houseboat with Generator Operating **Boat Stationary.**

Sample Location (Sample #)	**Generator Operating with Stack**		**Generator Operating with Side and Rear Exhaust**	
	Day 1	**Day 2**	**Side Exh**	**Rear Exh**
Aft Corner-Port (near stack) (#6)	Mean= 2 87 S D = 2 50 Peak = 19 N = 98	Mean= 1 22 S D = 0 94 Peak = 5 N = 41	Mean= 2 13 S D = 1.77 Peak = 7 N = 92	Mean= 38 00 S D = 30 85 Peak = 146 N = 45
Aft Corner-STBD (#7)	Mean= 1 15 S D = 1 14 Peak = 5 N = 99	Mean= 1 12 S D = 0.39 Peak = 2 N = 43	Mean= 17 29 S D = 16 75 Peak = 75 N = 92	Mean= 10 49 S D = 12 33 Peak = 56 N = 45
Top Deck–Center (#8)	Mean= 1 19 S D = 1 28 Peak = 10 N = 98	Mean= 1 00 S D = 0 65 Peak = 3 N = 43	Mean= 9 50 S D = 22 01 Peak = 155 N = 92	Mean= 2 24 S D = 1 90 Peak = 7 N = 46
Front Corner-Port (#9)	Mean= 3 07 S D = 3 31 Peak = 15 N = 99	Mean= 1 12 S D = 0 50 Peak = 2 N = 42	Mean= 11 18 S D = 23 41 Peak = 145 N = 92	No Data**
Front Corner-STBD (#10)	Mean= 1 79 S D = 1 23 Peak = 7 N = 99	Mean= 2 07 S D = 0 46 Peak = 3 N = 42	Mean= 14 45 S D = 23 91 Peak = 90 N = 42	No Data**

** CO monitor was not in operation during the evaluation

Table III CO Samples (ppm) taken on the Lower, Rear Deck of the Houseboat with Generator Operating **Boat Underway**

Sample Location (Sample #)	**Generator Operating with Stack**		**Generator Operating with Side and Rear Exhaust**	
	Day 1	**Day 2**	**Side Exh**	**Rear Exh**
Rear Swim Platform-Port (#1)	Mean= 119 9 S D = 98 96 **Peak = 512*** N = 132	Mean=26 52 S D =18 36 Peak = 87 N = 67	Mean= 292 85 S D = 248 83 **Peak = 1081*** N = 115	Mean= 162 02 S D = 100 06 **Peak = 376*** N = 51
Rear Swim Platform-STBD (#2)	Mean= 141 1 S D = 111 9 **Peak = 681*** N = 132	Mean=20 66 S D = 14 18 Peak = 78 N = 67	Mean= 286 89 S D = 209 70 **Peak = 961*** N = 114	Mean= 180 90 S D = 123 36 **Peak = 422*** N = 51
On Stairs (#3)	Mean= 37 42 S D = 25 18 Peak = 156 N = 130	Mean=18 57 S D = 12 32 Peak = 55 N =-67	Mean= 47 59 S D = 33 71 Peak = 177 N = 114	Mean= 109 33 S D = 73 13 **Peak = 275*** N = 51
Behind Slide (#4)	Mean= 47 83 S D = 33 06 Peak = 189 N = 132	Mean=5 66 S D = 7 00 Peak = 32 N = 67	Mean= 71 31 S D = 38 41 Peak = 171 N = 113	Mean= 64 78 S D = 37 18 Peak = 173 N = 51
Inside Cabin, lower level (#5)	Mean= 14 40 S D = 8 88 Peak = 36 N = 132	Mean= 8 64 S D = 2 54 Peak = 13 N = 67	Mean= 19 10 S D = 4 85 Peak = 43 N = 114	Mean= 2 06 S D = 2 03 Peak = 11 N = 51

* Peak CO concentrations exceeding NIOSH Ceiling Limit are highlighted in bold typeface

Table IV CO Samples (ppm) taken on the Upper Deck of the Houseboat with Generator Operating **Boat Underway.**

Sample Location (Sample #)	**Generator Operating with Stack**		**Generator Operating with Side and Rear Exhaust**	
	Day 1	**Day 2**	**Side Exh**	**Rear Exh**
Aft Corner-Port (near stack) (#6)	Mean= 14 30 S D = 10 21 Peak = 61 N = 132	Mean= 6 66 S D = 5 66 Peak = 57 N = 67	Mean= 20 14 S.D = 16 11 Peak = 75 N = 114	Mean= 51 47 S D = 38 54 Peak = 137 N = 51
Aft Corner-STBD (#7)	Mean= 4 93 S D = 4 19 Peak = 21 N = 132	Mean= 11 66 S D = 12 07 Peak = 57 N = 67	Mean= 9 63 S D = 16 96 Peak = 97 N = 114	Mean= 15 37 S D = 12 30 Peak = 60 N = 51
Top Deck--Center (#8)	Mean= 1 11 S D = 1 33 Peak = 9 N = 132	Mean= 2 28 S D = 2 62 Peak = 13 N = 67	Mean= 1 92 S D = 3 12 Peak = 22 N = 114	Mean= 6 27 S D = 4 59 Peak = 19 N = 51
Front Corner-Port (#9)	Mean= 2 51 S D = 2 37 Peak = 14 N = 132	Mean= 2 45 S D = 4 09 Peak = 24 N = 67	Mean= 2 02 S D = 2 86 Peak = 23 N = 114	Mean= 3 02 S D = 1 68 Peak = 7 N = 51
Front Corner-STBD (#10)	Mean= 3 84 S D = 1 65 Peak = 14 N = 132	Mean= 3 87 S D = 3 07 Peak = 16 N = 67	Mean= 1 57 S D = 3 17 Peak = 27 N = 114	Mean= 4 96 S D = 2 84 Peak = 13 N = 51

Table V CO Samples (ppm) taken on the Lower, Rear Decks of Houseboats with Generators Operating **2 Boats Tied Together.**

Sample Location (Sample #)	**Generators Operating with Stack**	**Generators Operating with Rear Exhaust**
Rear Swim Platform-Boat 200 (#1)	Mean= 1 09 S D = 0 55 Peak = 3 N = 55	Mean= 191.18 S D = 229 50 **Peak = 979*** N = 51
Rear Swim Platform-Boat 173 (#2)	Mean= 1 93 S D = 0 82 Peak = 5 N = 57	Mean= 53 59 S D = 90 86 **Peak = 419*** N = 51
On Stairs-Boat 200 (#3)	Mean= 0 67 S D = 1 08 Peak = 5 N = 54	Mean= 22 84 S D = 38 18 Peak = 189 N = 51
On Stairs-Boat 173 (#4)	Mean= 0 85 S D = 0 87 Peak = 5 N = 55	Mean= 10 06 S D = 20 89 Peak = 88 N = 51
Inside Cabin, Boat 200 (#5)	Mean= 3 19 S D = 0 48 Peak = 4 N = 58	Mean= 7 39 S D = 2 36 Peak = 17 N = 51
Inside Cabin, Boat 173 (#6)	Mean= 7 05 S D = 1 18 Peak = 5 N = 58	Mean= 5 43 S D = 0 67 Peak = 7 N = 51

* Peak CO concentrations exceeding NIOSH Ceiling Limit are highlighted in bold typeface

Table VI CO Samples (ppm) taken on the Upper Decks of Houseboats with Generators Operating **2 Boats Tied Together.**

Sample Location (Sample #)	**Generators Operating with Stack**	**Generators Operating with Rear Exhaust**
Aft Corner-Port, Boat 173 (#7)	Mean= 2 49 S D = 0 88 Peak = 5 N = 55	Mean= 5 41 S D = 8 73 Peak = 53 N = 51
Front Corner-Port, Boat 173 (#8)	Mean= 1 30 S D = 0 81 Peak = 3 N = 56	Mean= 9 20 S D = 6 75 Peak = 28 N = 51
Front Corner-STBD, Boat 200 (#9)	Mean= 3 12 S D = 4 87 Peak = 27 N = 57	Mean= 18 10 S D = 20 49 Peak = 93 N = 29
Aft Corner-STBD, Boat 200 (#10)	Mean= 2 98 S D = 4 23 Peak = 22 N = 56	Mean= 54 10 S D = 50 06 Peak = 172 N = 29

Table VII CO Samples (ppm) taken on the Lower, Rear Decks of Houseboats with Generators Operating **3 Boats Tied Together.**

Sample Location (Sample #)	**Generators Operating with Stack Exhaust**	**Generators Operating with Combo Side/Rear Exhaust**
Rear Swim Platform-Boat 200 (#1)	Mean= 14 06 S D = 11 79 Peak = 84 N = 117	Mean= 777 35 S D = 445 15 **Peak = 1243*** N = 62
Rear Swim Platform-Boat 173 (#2)	Mean= 9 63 S D = 10 49 Peak = 82 N = 115	Mean= 153 34 S D = 274 96 **Peak = 1235*** N = 61
Rear Swim Platform-Boat 20 (#3)	Mean= 11 07 S D = 7 44 Peak = 65 N = 113	Mean= 144 59 S D = 105 27 **Peak = 607*** N = 61
Behind Slide-Boat 200 (#4)	Mean= 5.72 S D = 7 85 Peak = 37 N = 114	Mean= 104 08 S D = 84 89 **Peak = 382*** N = 61

* Peak CO concentrations exceeding NIOSH Ceiling Limit are highlighted in bold typeface

Table VIII CO Samples (ppm) taken on the Upper Decks of Houseboats with Generators Operating **3 Boats Tied Together.**

Sample Location (Sample #)	**Generators Operating with Stack Exhaust**	**Generators Operating with Combo Side/Rear Exhaust**
Aft Corner-Port, Boat 173 (#5)	Mean= 3 59 S D = 6 57 Peak = 52 N = 115	Mean= 9 84 S D = 18 33 Peak = 98 N = 61
Front Corner-Port, Boat 173 (#6)	Mean= 3 49 S D = 4 51 Peak = 32 N = 114	Mean= 7 54 S D = 8.85 Peak = 42 N = 61
Aft Corner-Stbd, Boat 20 (#7)	Mean= 9 38 S D = 6 21 Peak = 38 N = 116	Mean= 33 28 S D = 16 33 Peak = 98 N = 61
Front Corner-Stbd, Boat 20 (#8)	Mean= 2 72 S D = 3 25 Peak = 18 N = 114	Mean= 9 79 S.D = 7 47 Peak = 27 N = 61
Aft-Center, Boat 200 (#9)	Mean= 3 27 S D = 2 73 Peak = 15 N = 115	Mean= 27 13 S D = 18 75 Peak = 87 N = 62
Front-Center, Boat 200 (#10)	Mean= 3 23 S D = 3.36 Peak = 17 N = 115	Mean= 9 72 S D = 8 78 Peak = 33 N = 61

Table IX Colonmetnc detector tube sample results with ToxiUltra data from same region and time in parentheses for companson Note All samples were collected on June 19

Time of Sample (hh:mm)	CO concentration (ToxiUltra reading at same time/location)	Sample Location/Generator Exhaust Configuration
09 55	0 ppm (0ppm)	Center of top deck, stack exhaust/generator operating only
11 57	150 ppm (236 ppm)	Swim platform on railing, side exhaust/generator and dnve engines operating
14 02	100 ppm (122 ppm)	Lower deck near stairs, side exhaust/generator and dnve engines operating
14 05	15 ppm (10 ppm)	Top deck near stairs, side exhaust/generator and dnve engines operating

Table X Evacuated container sample results including sample time and location. Note All samples were collected on June 19

Time of Sample (hh:mm)	CO concentration	Sample Location, Generator Exhaust Configuration
09 53	75,836 ppm	Directly in generator exhaust stream, stack exhaust/generator operating only
10 38	2,130 ppm	Taken at side exhaust, side exhaust/generator operating only
10 40	206 ppm	Taken at side exhaust, side exhaust/generator operating only
12 00	619 ppm	Taken at swim platform, side exhaust/generator and dnve engines operating
14 00	114 ppm	Taken at swim platform, side exhaust/generator and dnve engines operating
15 04	3 ppm	Center of top deck, stack exhaust/generator operating only
15 55	Non Detectable (<3ppm)	Top deck near stairs, side exhaust/generator and dnve engines operating

Figure 1 Photo of the evaluated boats while tied together (Boats 20, 200 and 173)

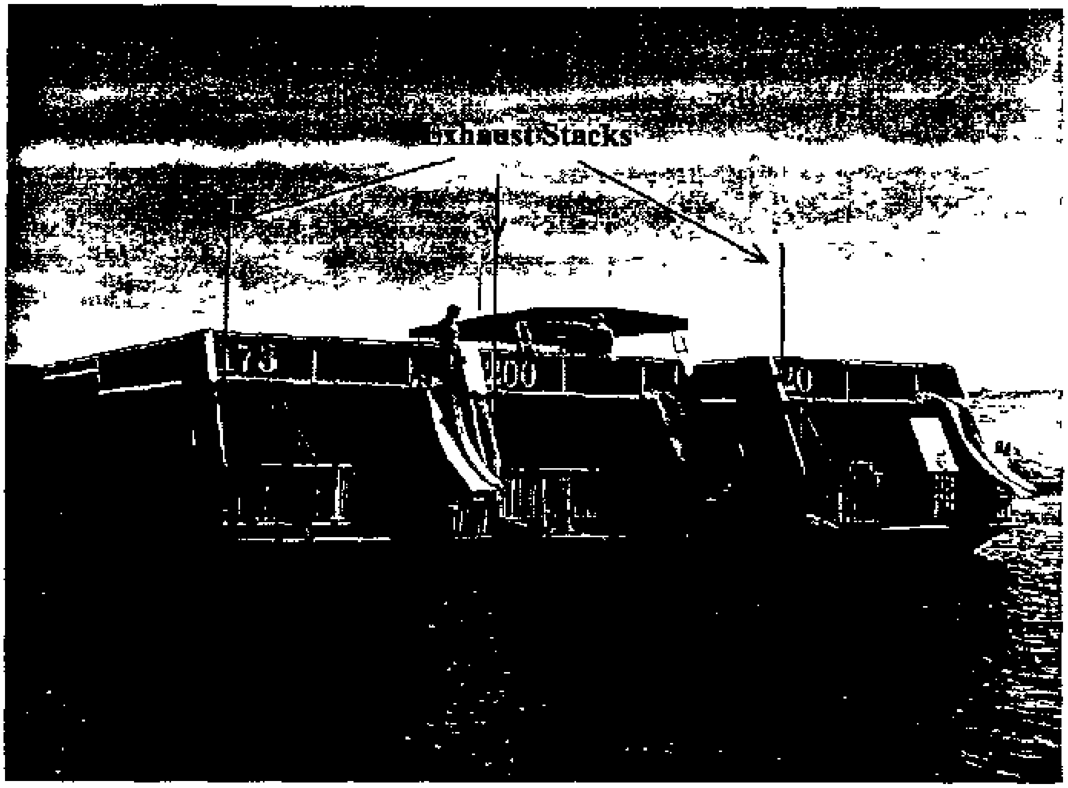


Figure 2 Dry stack with slip-fit coupling which allows removal/installation of upper pipe extending beyond upper deck

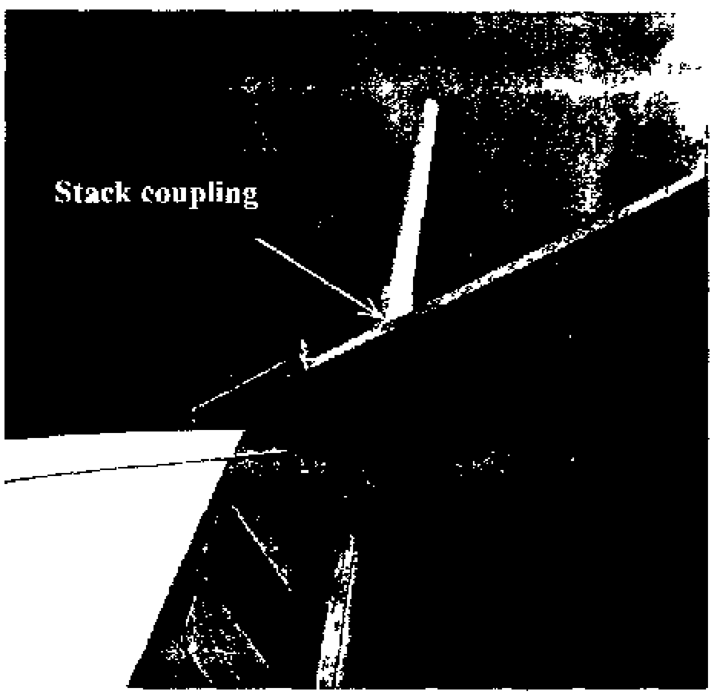


Figure 3 Photo of evaluated boat while underway on Lake Mead

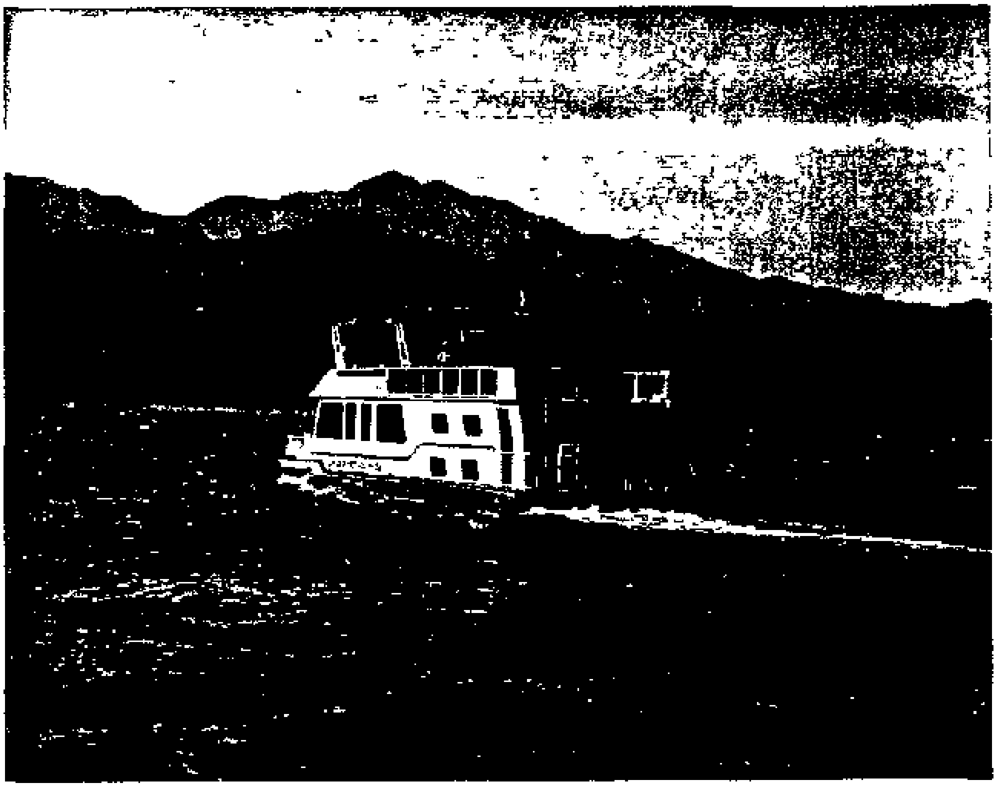


Figure 4 Sampling locations on the lower deck of each houseboat (in single boat configuration)
Note Sample locations designated with hexagons

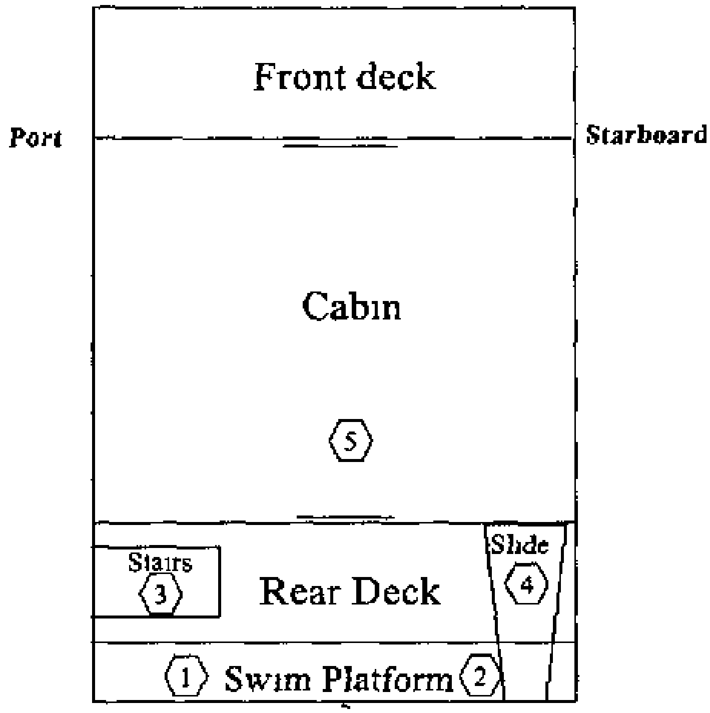
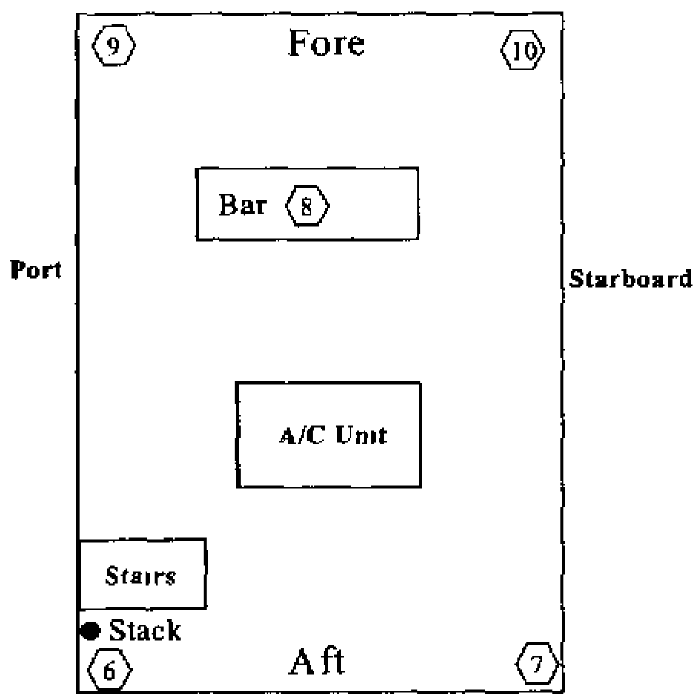


Figure 5 Sampling locations on the upper deck of each houseboat (in single boat configuration)



Note Sample locations designated with hexagons

Figure 6 Sampling locations on the rear, lower deck of houseboats (for two boats tied together configuration)

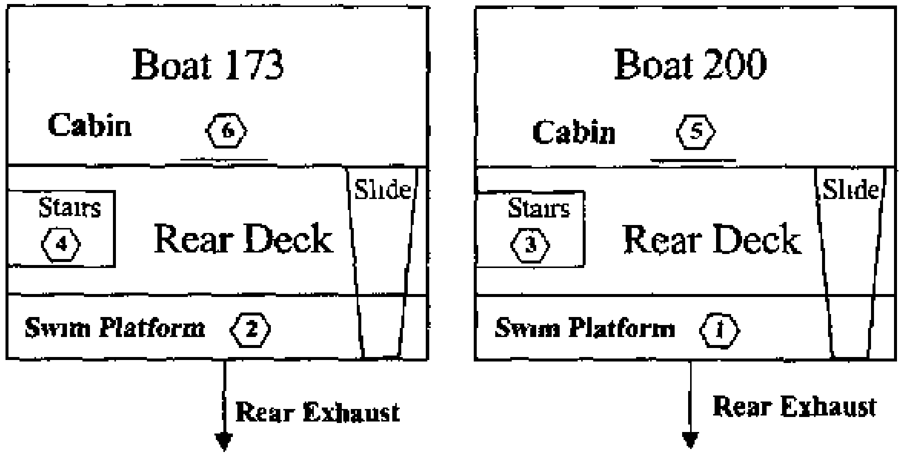
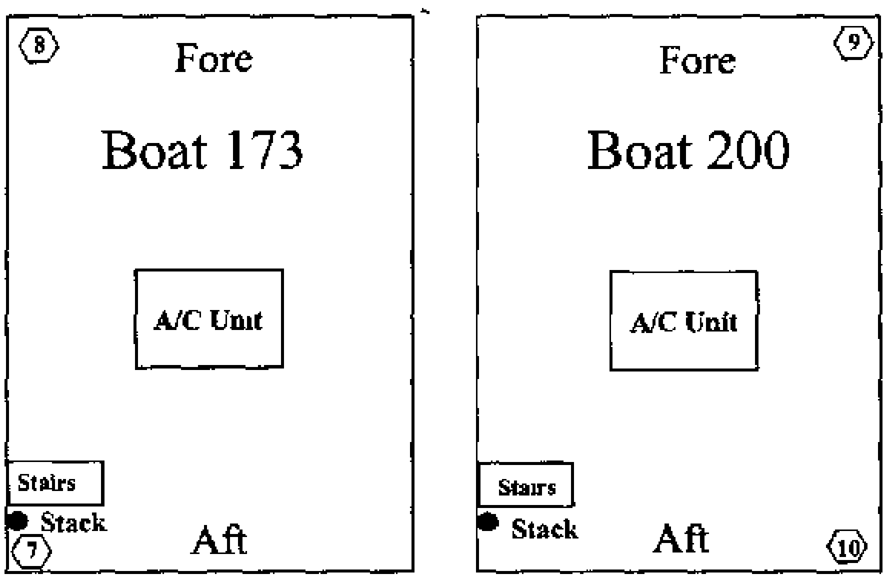


Figure 7 Sampling locations on the upper deck of houseboats (for two boats tied together configuration)



Note Sample locations designated with hexagons

Figure 8 Sampling locations on the rear, lower deck of houseboats (for three boats tied together configuration)

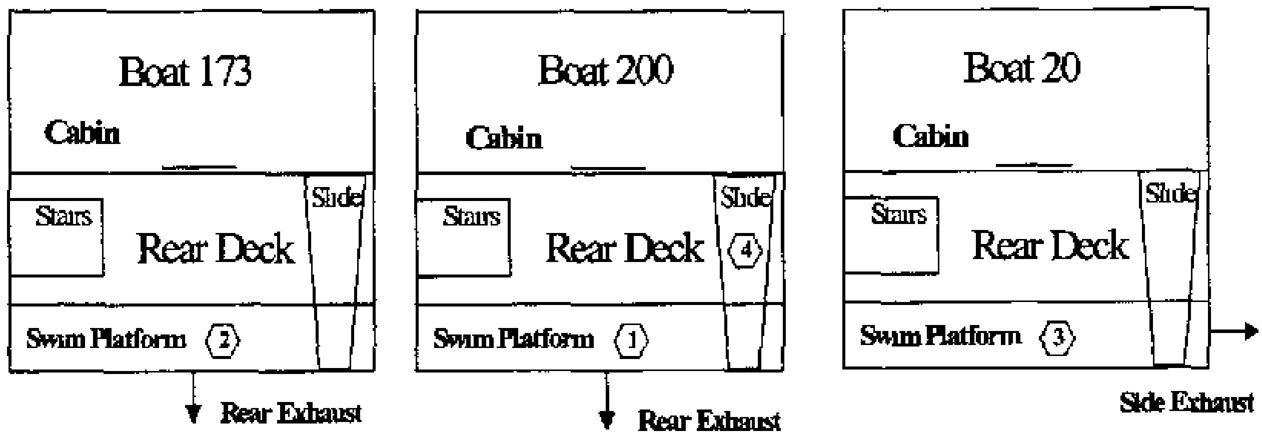
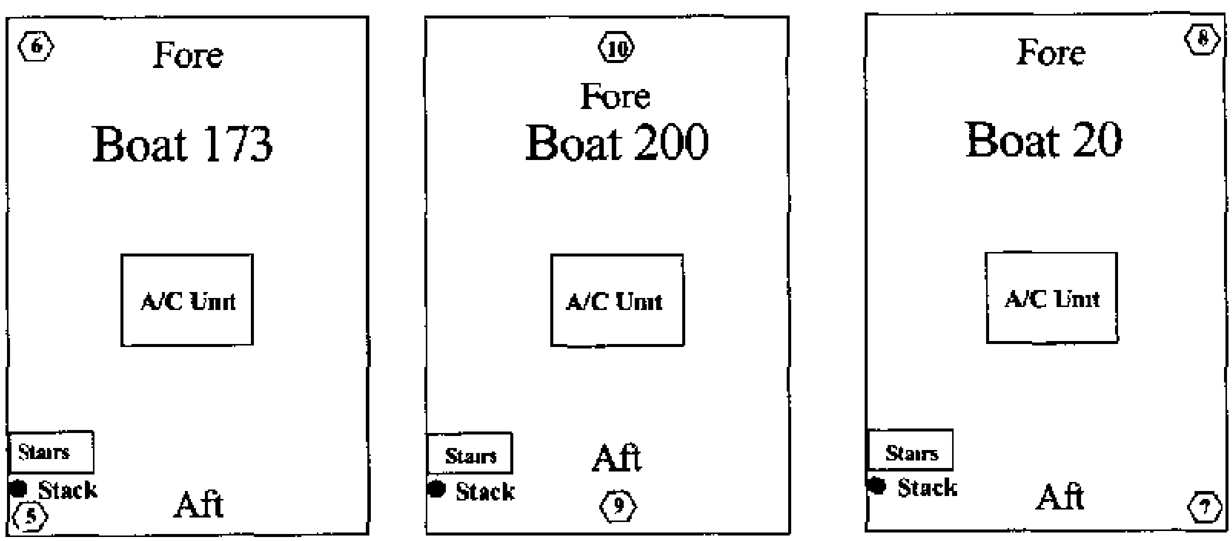


Figure 9 Sampling locations on the upper deck of houseboats (for three boats tied together configuration)



Note Sample locations designated with hexagons

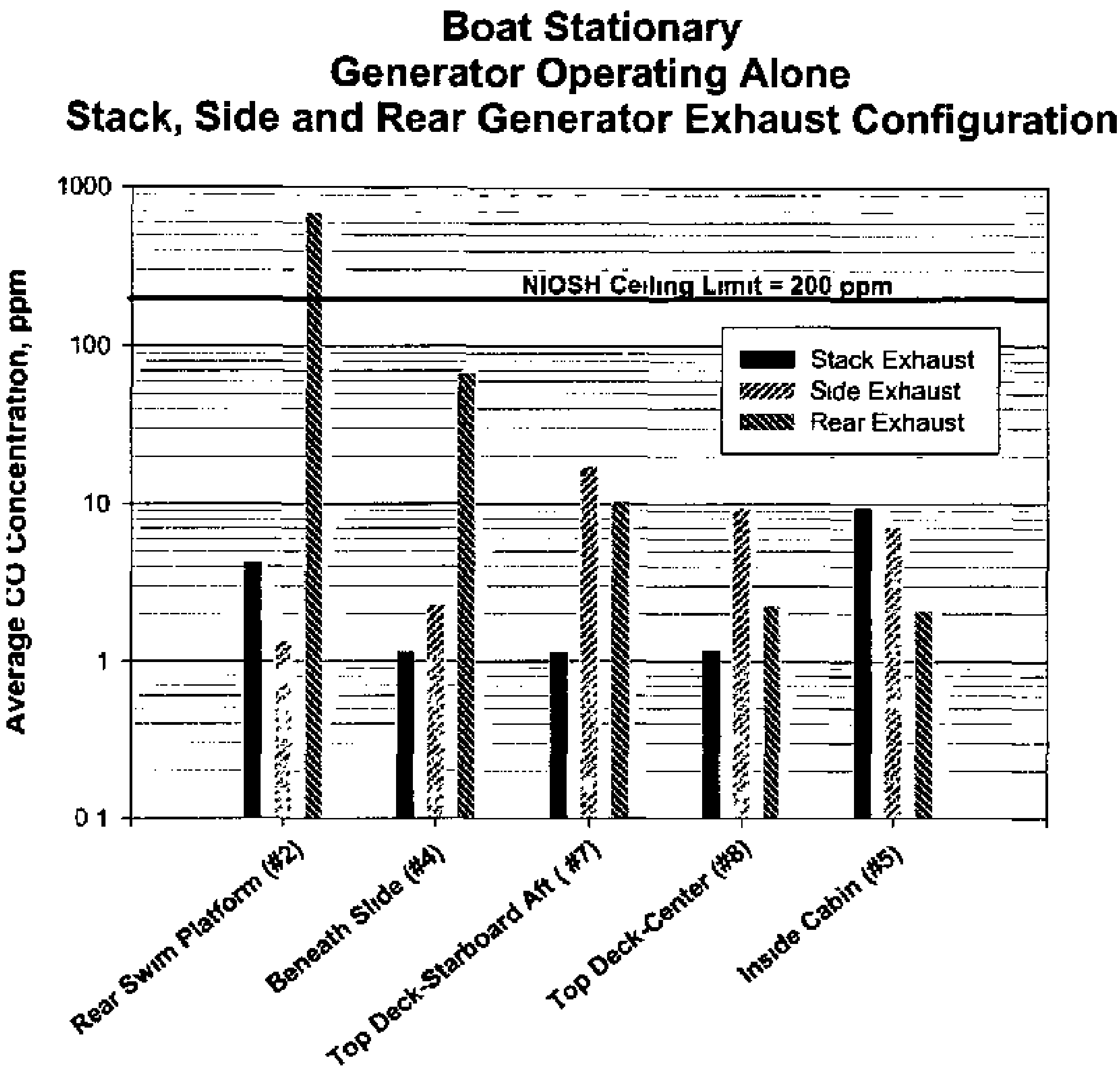


Figure 10 Comparison of average CO concentrations at various sampling locations for a single stationary boat with stack, side, or rear generator exhaust configuration Sample location numbers are in parentheses

Note Average CO concentrations are plotted on a common log scale due to the wide range of values

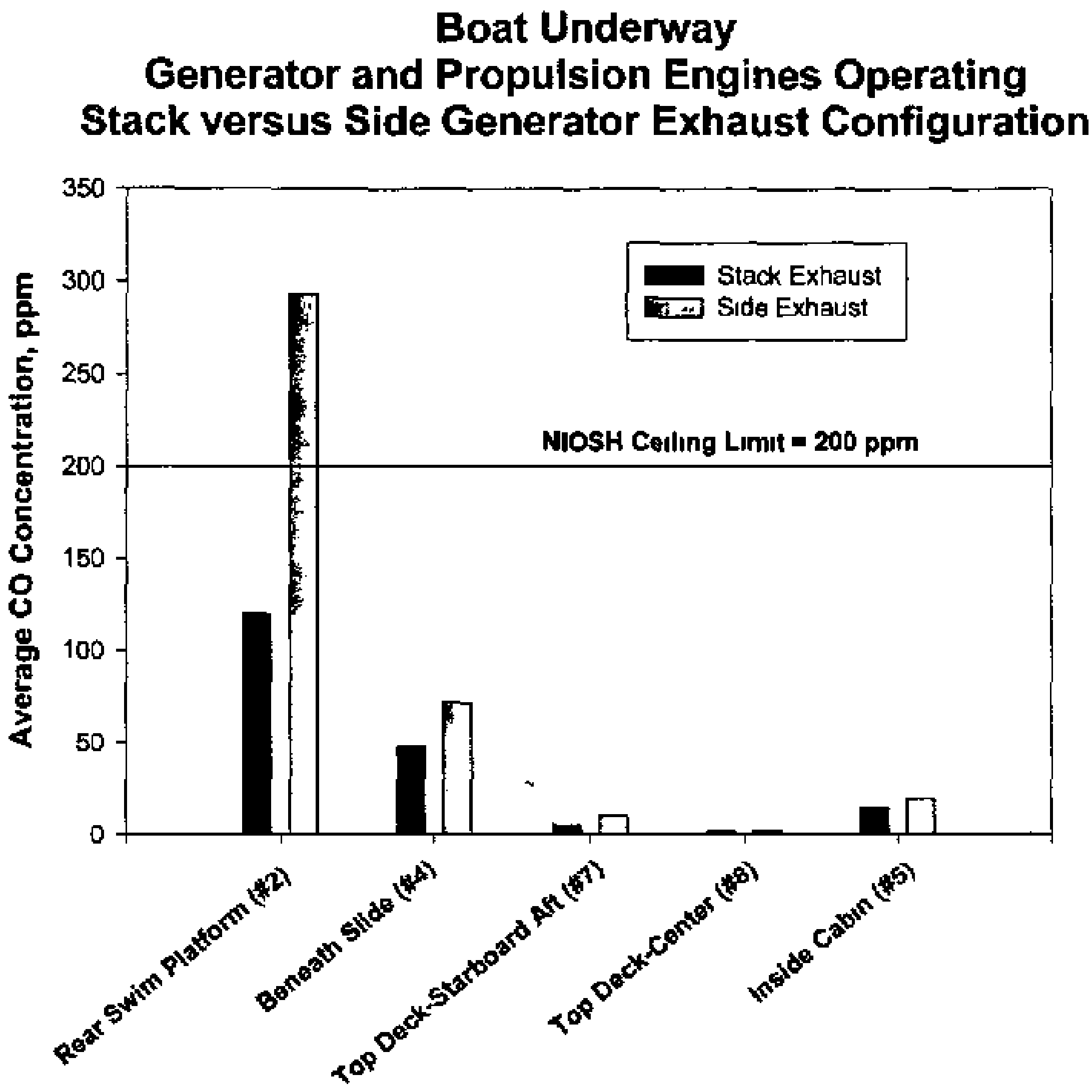


Figure 11 Comparison of average CO concentrations at various sampling locations for a single boat underway with stack or side generator exhaust configuration Sample location numbers are in parentheses

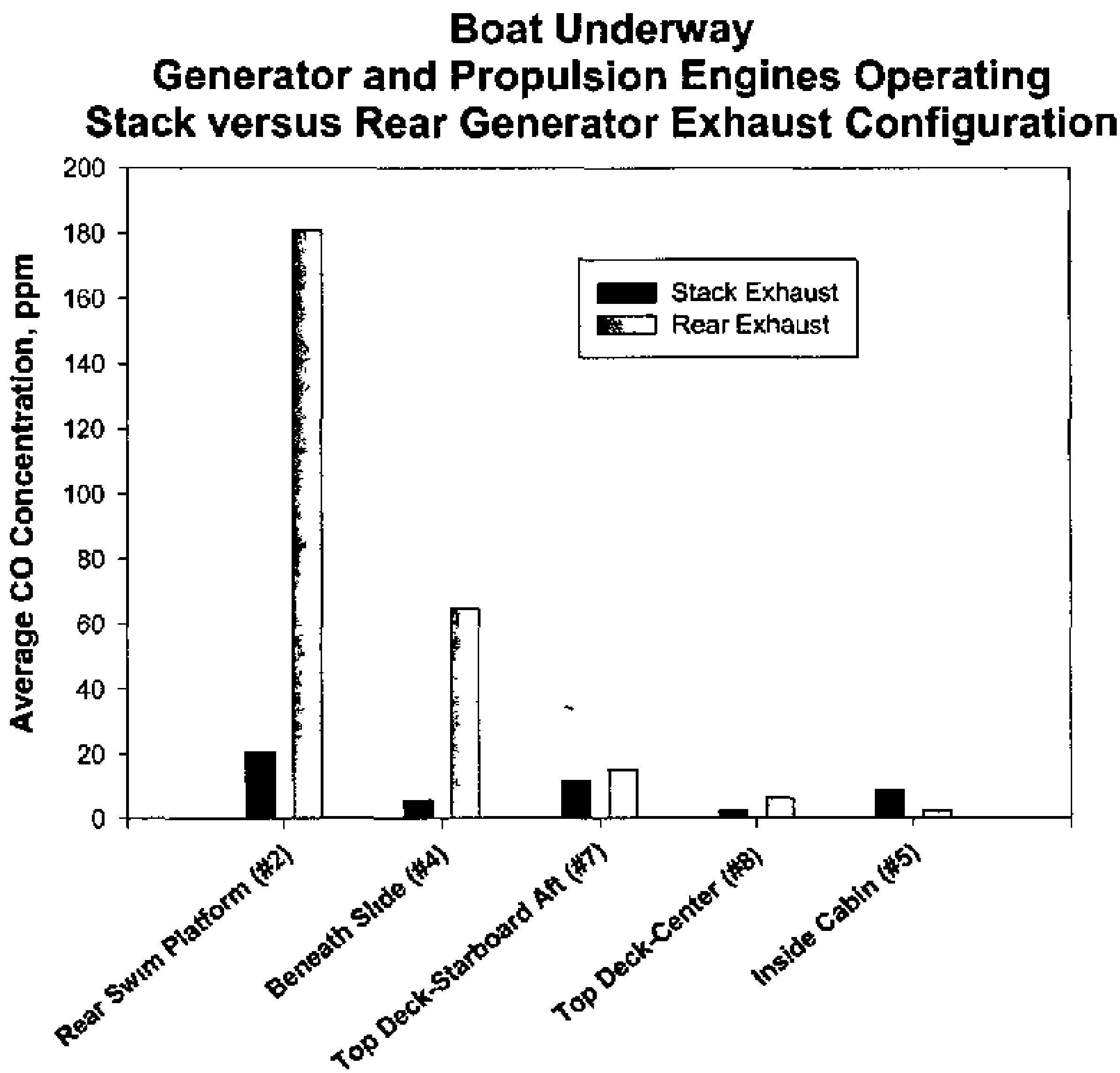


Figure 12 Comparison of average CO concentrations at various sampling locations for a single boat underway with stack or rear generator exhaust configuration Sample location numbers are in parentheses

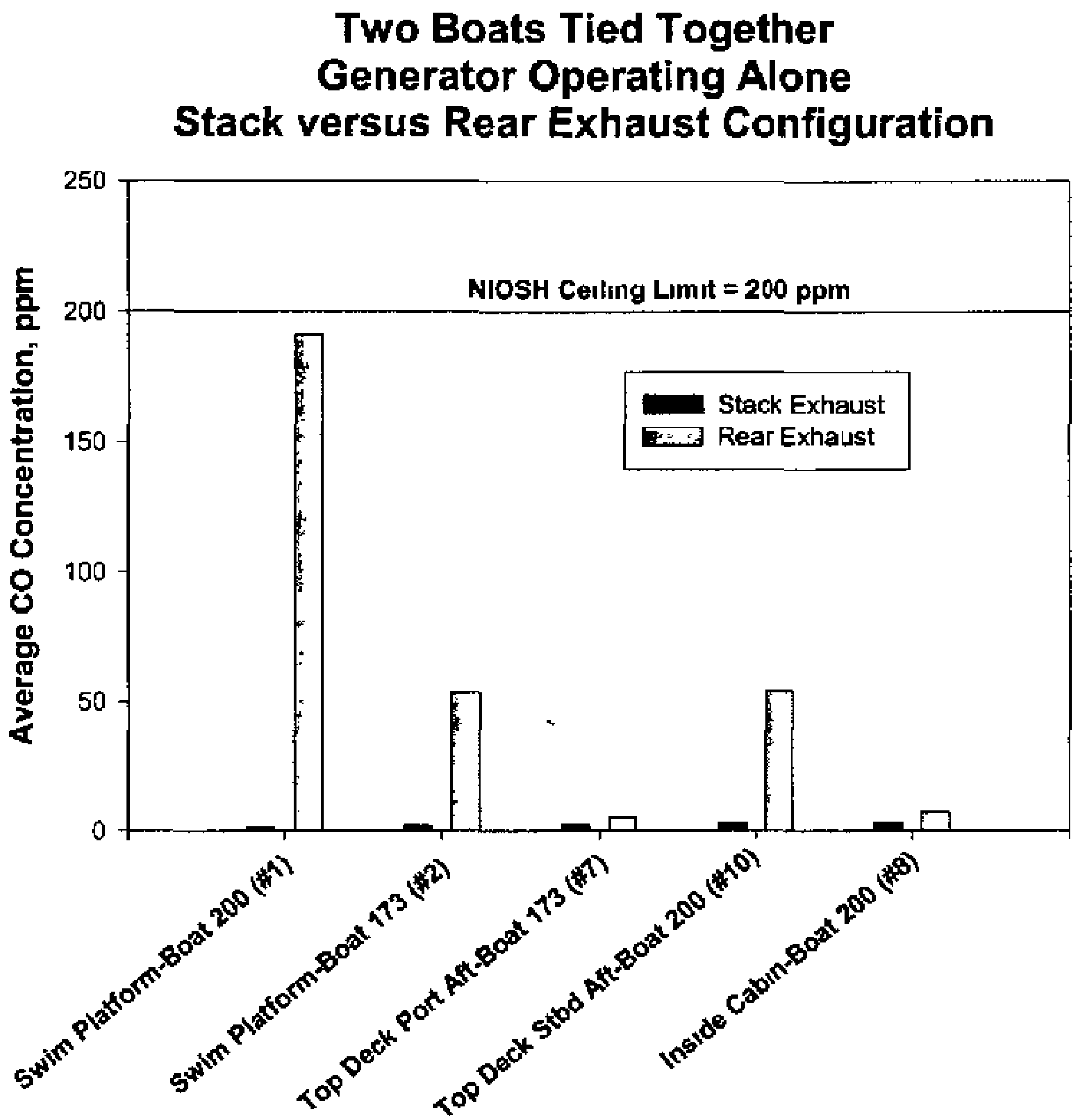


Figure 13 Comparison of average CO concentrations at various sampling locations for a 2 boats tied together with stack or rear generator exhaust configuration Sample location numbers are in parentheses

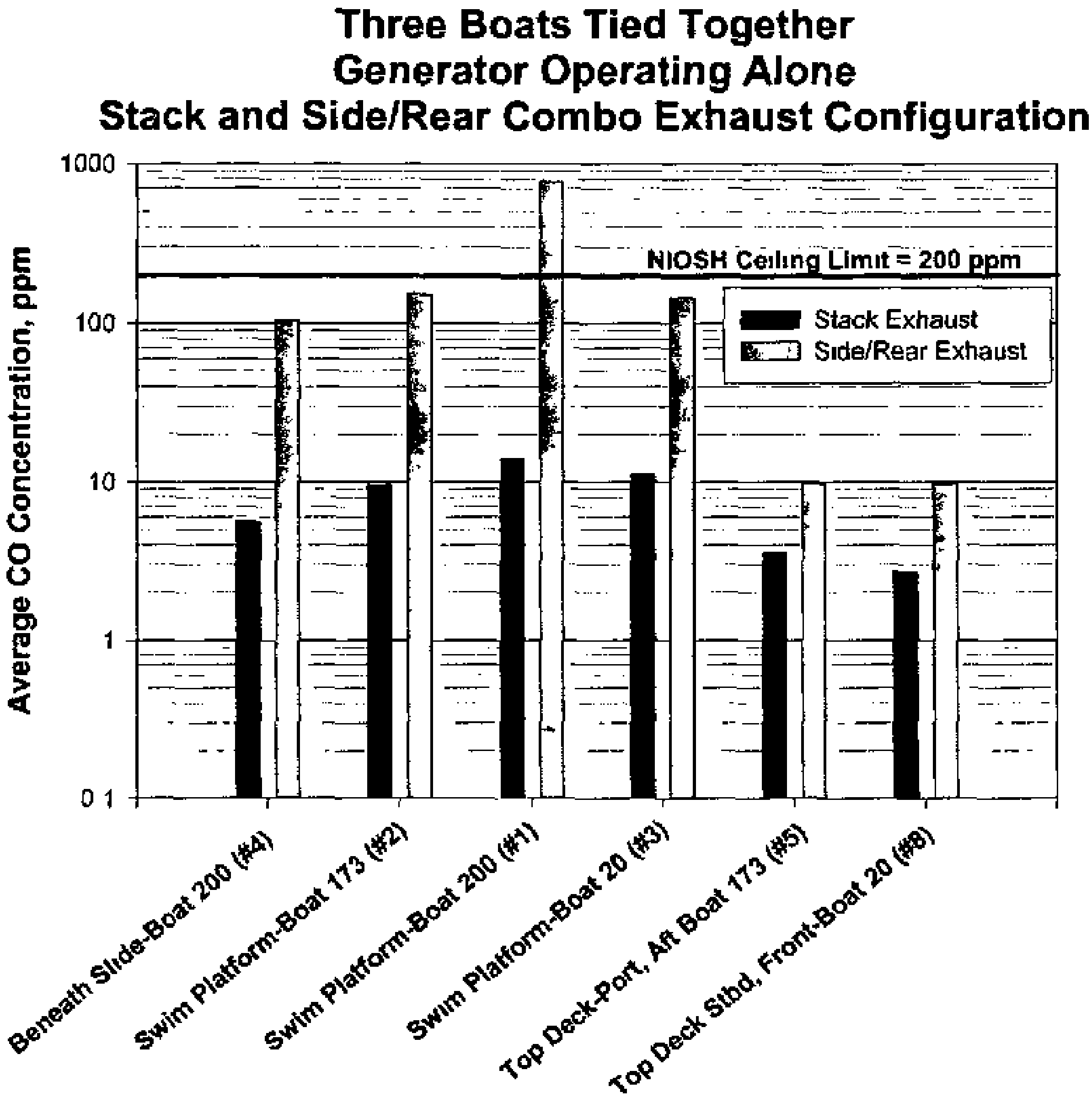


Figure 14 Comparison of average CO concentrations at various sampling locations for 3 boats tied together with stack or side/rear combination generator exhaust configuration Sample location numbers are in parentheses

Note Average CO concentrations are plotted on a common log scale due to the wide range of values

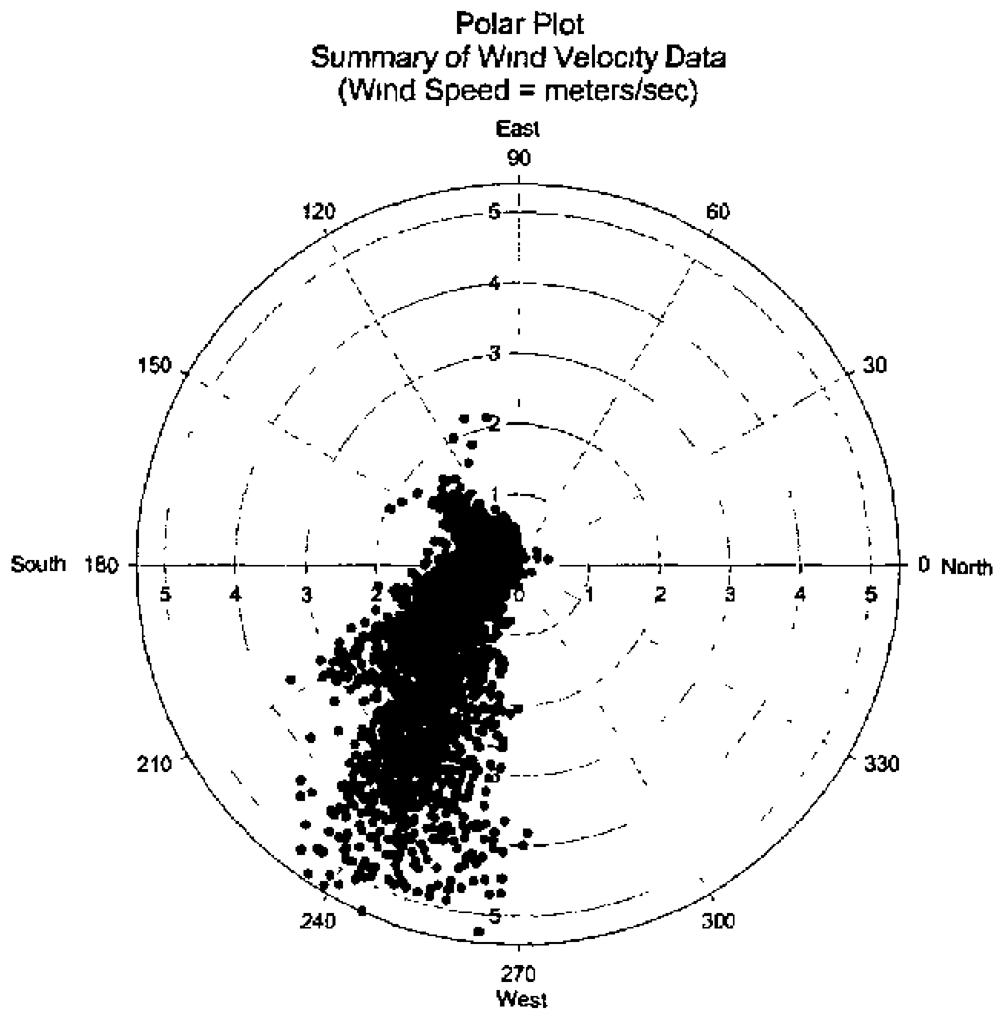


Figure 15 Wind velocity data gathered on the morning of June 19, 2001 (mean wind speed 1 7 m/s, direction 206°

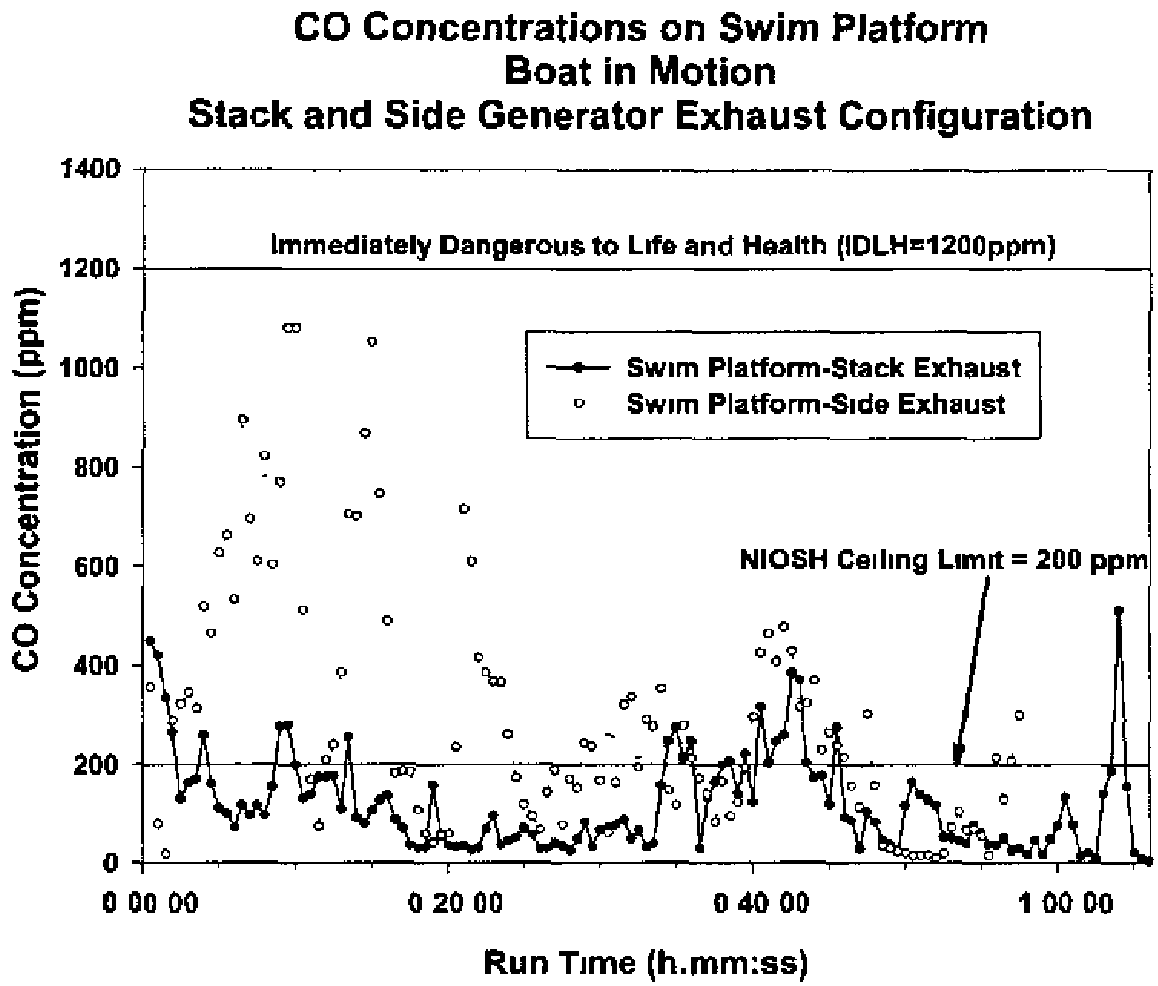


Figure 16 Comparison of stack and side exhaust configuration CO concentrations on the swim platform while the boat is in motion