EVALUATION OF CARBON MONOXIDE CONCENTRATION WITH AND WITHOUT CATALYTIC EMISSION CONTROLS FROM GASOLINE PROPULSION ENGINES

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REPORT DATE:
April 2007

REPORT NO:
EPHB 289-12a

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Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
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SITES SURVEYED:	Punta Gorda, FL
SIC CODE:	N/A
SURVEY DATE:	December 11-13, 2006
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EXECUTIVE SUMMARY

National Institute for Occupational Safety and Health (NIOSH) researchers evaluated carbon monoxide (CO) emissions and exposures on a ski boat in Punta Gorda, Florida. This evaluation was conducted under an interagency agreement between the U.S. Coast Guard's Office of Boating Safety and NIOSH to evaluate the CO concentrations before and after installing a production catalytic control device to reduce CO concentrations. This catalytic control device was manufactured by Indmar Marine Engines. Similar NIOSH surveys regarding houseboats and other types of recreational boats have been conducted and are described in separate reports. The evaluated boat was propelled by a gasoline-powered engine and could be configured with and without the catalytic converter depending on the evaluation.

The boat was evaluated while stationary and at multiple speeds, ranging from 5 to 45 miles per hour (Open throttle). CO concentrations were measured by multiple real-time instruments, which were placed at different locations on the boats. A five gas emissions analyzer was also used to quantify CO emissions from cold crank start at the slip.

The Indmar system significantly reduced CO exposures to boat occupants during the current evaluation. For most conditions, a reduction above 90% was observed when compared to a standard exhaust system. This catalytic technology can greatly reduce the CO poisoning hazard to occupants of boats that have gasoline-powered engines. This study specifically evaluated the performance of the Indmar technology designed to reduce CO emissions and protect boat occupants. Engine performance did not seem to be affected by the incorporation of the catalytic converter in the exhaust manifold. The boat with and without the catalytic control device was able to reach the same top speed (45 mph) in about the same amount time. The performance of the Indmar technology was impressive and has the potential of preventing CO poisonings in a variety of settings. Due to the reduction achieved with this technology, the use of these engines with catalyst will reduce CO exposures for people engaging in water sports activities behind the boat as well as boat occupants.

The performance of the Indmar system was impressive with CO emissions directly into the exhaust opening of approximately 800 ppm and below for a fully warmed engine. CO concentrations are typically higher at the stern of the boat and become gradually lower toward the front of the boat. In order to ensure that the systems operate effectively, boat owners and operators should ensure that they follow all manufacturers' recommendations with regard to routine maintenance and replacement schedules.

BACKGROUND

On December 11 through 13, 2006, researchers from the National Institute for Occupational Safety and Health (NIOSH) working with the U.S. Coast Guard evaluated carbon monoxide (CO) emissions and exposures on a ski boat in Punta Gorda, Florida. This evaluation was conducted under an interagency agreement between the U.S. Coast Guard's Office of Boating Safety and NIOSH to evaluate the CO reduction achieved after installing a production catalytic control device manufactured by Indmar Marine Engines. Similar NIOSH surveys regarding houseboats and other types of recreational boats have been conducted and are described in separate reports. The evaluated boat was propelled by a gasoline-powered engine and could be configured with and without the catalytic converter depending on the evaluation. This report provides background information and describes the study methods, results, discussion, conclusions, and recommendations.

NIOSH Studies

In spring 2002, working with the United States Coast Guard, NIOSH researchers analyzed CO emissions and exposures on approximately twenty-five recreational boats in Nevada, Arizona, and North Carolina. The evaluated recreational boats (spanning from new to 27 years old) included ski boats, cabin cruisers, deck boats, fishing boats, and personal watercraft, all of which used gasoline powered propulsion engines. Many of the cabin cruisers also used gasoline-powered generators to provide electricity [Earnest, Echt, et al. 2003]

Air sampling for CO was performed for both stationary and underway boats with speeds ranging from 2.5 to 25 miles per hour. Electrochemical CO monitors were placed at various locations inside and on the stern of the boat. Additional monitors were located 8 to 12 feet behind the boat.

Under stationary conditions the CO concentrations were relatively high. ToxiUltra monitor measurements ranged from 500 to 1,000 ppm at the stern and less than 20 ppm in the interior of most boats. Cabin cruiser measurements ranged from 800 to 1,000 ppm on the lower deck and less than 15 ppm in the interior. The upper limit for the ToxiUltra CO monitors is approximately 1,000 ppm and may have been exceeded at times. CO concentrations were significantly lower when the boat was moving than when it was stationary. The highest concentrations were at the boats' stern and lowest were in the interior of the boat. CO concentrations were lower on boats with cleaner burning outboard engines and with increasing boat and wind velocities [Earnest, Echt, et al. 2003].

Approximately 90% of the boats evaluated in this study had potentially hazardous CO concentrations. The authors recommended the use of cleaner burning outboard engines, catalyst development for gasoline-powered, inboard or stern-drive engines, care when operating the boats below 5mph, and alternative ventilation systems for generator exhaust such as the vertical stack [Earnest, Echt, et al. 2003].

USCG/ABYC Carbon Monoxide Safe Distance Study

In the fall of 2003, the United States Coast Guard and American Boat and Yacht Council (USCG/ABYC) conducted a subsequent study of CO exposures from a single gasoline powered ski boat. The study was designed to determine the minimum safe distance to tow people behind an engine that generated a relatively large, representative quantity of CO. Tests were conducted using a 19-foot Correct Craft ski boat having a 350 cubic inch V-8 carbureted inboard engine. The ski boat towed a 10.5 ft Boss Boat Hardbody equipped with two ToxiUltra CO detectors at two and five feet above the water [USCG/ABYC 2003].

The main test variables were boat speed and distance from the stern. Data was not collected when wind speeds exceeded 5 mph. Concentration levels of CO were recorded at boat speeds of 7.5, 10, 20 and 25 mph and distances of 20, 40, 60, and 80 ft behind the transom of the tow boat [USCG/ABYC 2003].

The study showed that CO concentrations were the highest above the stern seat of the ski boat, near the water, and at slow boat speeds. The CO concentrations were greater at 2 feet compared to 5 ft above the water. CO concentrations were highest at 20 ft behind the tow boat. At distances beyond 20 ft the CO concentrations remained consistent at approximately 35 ppm. In general, the highest CO concentrations were at the ski boat's stern seat, at 2 ft above the water, and at distances of 20 ft or less. There was no need for concern at 5 feet above the water level at distances of 60 ft and beyond. CO concentrations at this level were low enough for the safe enjoyment of recreational water sport activities [USCG/ABYC 2003].

"Fresh Air Exhaust (FAE)™" CO Study

The manufacturer of "Fresh Air Exhaust (FAE)"™ collected data to better understand the potential risks for CO exposure on boat occupants and towed persons and to evaluate the performance of FAE in reducing CO exposures. Their experiments evaluated CO concentrations near two ski boats: a 1988 Correct Craft Ski Nautique with a 351 CID carbureted gasoline engine and a 2001 Tige' 20i with a 351 CID throttle body fuel injected engine [Mann 2004].

Measurements were collected on ToxiUltra CO monitors located 21 in. above the swim platform, on the transom, and on the back seat of each boat. Other monitors were mounted on a 16 ft Hobie Cat sailboat, at approximately 10 ft aft (off center to simulate the position of a wake surfer) and 100 ft aft at locations 2 ft and 5 ft above the water level. If the wind speed exceeded 5mph, measurements were not taken [Mann 2004].

Results from the Ski Nautique measurements indicated that at 5mph the CO concentration near the rear seat of the boat was 1 ppm average / 3 ppm peak. At 10 mph CO concentrations in the same location were 10 ppm / 50 ppm peak. CO measurements near the transom were significantly higher. At 10 mph, average CO measurements 100 feet behind the boat and in the "wake surf" zone were approximately 1 ppm. During wake surfing, boat occupants had a greater risk of CO exposure than the wake surfers.

CO measurements near the 2001 Tige' 20i at 10 and 20 mph at distances 60' and 80' feet behind the transom consistently reported CO concentrations of 0 ppm [Mann 2004].

The FAE manufacturer concluded that at 5mph, FAE greatly reduced the risk of CO exposure on the swim platform of the boat, with a reduction up to 98% at the transom and minimal CO concentrations within the boat. At the same speed, the FAE increased some of the CO concentrations behind the boat. At 10 mph and 20 mph CO concentrations were minimal at all measured locations inside and behind the boat. The FAE manufacturer theorized that wet scrubbing may reduce the overall levels of CO released into the air [Mann 2004].

The purpose of this study was to evaluate CO concentrations on and around two recreational boats when equipped with production catalytic converters on the exhaust manifold and without the previous mentioned control.

Carbon Monoxide Symptoms and Exposure Limits

CO is a lethal poison, produced when fuels such as gasoline or propane are burned. It is one of many chemicals found in engine exhaust, which results from incomplete combustion. Because CO is a colorless, odorless, and tasteless gas, it may 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 can occur without other symptoms. Coma or death can 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 blood to carry oxygen to tissues because it binds with the hemoglobin to form COHb. Blood has an estimated 210–250 times greater affinity for CO than oxygen; thus, the presence of CO in the blood interferes 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 between marine workers and boat passengers in this type of setting. NIOSH researchers have done a considerable amount of work related to controlling CO exposures in the past [Ehlers, McCammon, et al. 1996; Earnest, Mickelsen, et al. 1997; Kovein, Earnest, et al. 1998].

Exposure Criteria

Occupational criteria for CO exposure are applicable to U.S. National Park Service (USNPS) and concessionaire employees who have been shown to be at risk of boat-related CO poisoning. The occupational exposure limits noted below should not be used for interpreting general population exposures (such as visitors engaged in boating activities). Occupational standards do not provide the same degree of protection for the general population as they do for healthy workers; the effects of CO are more pronounced in a shorter time if the person is physically active, very young, very old, or has preexisting health conditions such as lung or heart disease. Persons at extremes of age and persons with underlying health conditions may have marked symptoms and may suffer serious complications at lower levels of carboxyhemoglobin. Standards relevant to the general population take these factors into consideration and are listed following the occupational criteria. The NIOSH Recommended Exposure Limit (REL) for occupational exposures to CO gas in air is 35 ppm for a full shift time-weighted average (TWA) exposure, and a ceiling limit of 200 ppm, which should never be exceeded [CDC 1988; CFR 1997]. The NIOSH REL of 35 ppm is designed to protect workers from health effects associated with COHb levels in excess of 5% [Kales 1993]. NIOSH has established the immediately dangerous to life and health (IDLH) value for CO as 1,200 ppm [NIOSH 2000]. The American Conference of Governmental Industrial Hygienists (ACGIH®) recommends an 8-hour TWA threshold limit value (TLV®) for occupational exposures of 25 ppm [ACGIH 1996] and discourages exposures above 125 ppm for more than 30 minutes during a workday. The Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for CO is 50 ppm for an 8 hour TWA exposure [CFR 1997].

Health Criteria Relevant to the General Public

The U.S. Environmental Protection Agency (EPA) has promulgated a National Ambient Air Quality Standard (NAAQS) for CO. This standard requires that ambient air contain no more than 9 ppm CO for an 8-hour TWA and 35 ppm for a 1-hour average [EPA 1991]. The NAAQS for CO was established to protect "the most sensitive members of the general population" by maintaining increases in carboxyhemoglobin to less than 2.1%.

The World Health Organization (WHO) has recommended guideline values and periods of time-weighted average exposures related to CO exposure in the general population [WHO 1999]. WHO guidelines are intended to ensure that COHb levels not exceed 2.5% when a normal subject engages in light or moderate exercise. Those guidelines are:

100 mg/m^3 (87 ppm) for 15 minutes
60 mg/m^3 (52 ppm) for 30 minutes
30 mg/m^3 (26 ppm) for 1 hour
10 mg/m^3 (9 ppm) for 8 hours

METHODS

CO and wind-velocity measurements were conducted on a ski boat equipped with a small block 5.7L (350 in^3) automotive engine modified for inboard marine use. This engine could be configured with and without a catalytic converter on the exhaust manifold. The switching of exhaust manifolds was performed to compare emissions from an uncontrolled engine to an engine with the new Indmar catalytic exhaust system. The engine was tuned to manufacturer's specifications. Data were collected to evaluate the CO emissions of gasoline-powered engines equipped with catalytic control devices and CO exposures on and near the boats, operating under various conditions. The ski boat had a V-drive inboard engine in which the engine and drive train were permanently mounted near the rear of the boat's hull, and the propeller shaft penetrated beneath the hull. To facilitate analysis, the results were separated and evaluated as two separate boats. Boat 1 represents the evaluation of the Indmar Marine Engine Catalytic Converter System, and Boat 2 represents the evaluation of the standard exhaust system.

Description of the Evaluated Ski Boats

Boat 1 (21')

- **Engine:** Small block 5.7L with Indmar catalytic converter system
- **Generator:** N/A
- **Approximate dimensions of boat:**
    - Length: 21'6"
    - Beam: 8' 2"
    - Draft: 24"
- **Exhaust Configuration:** Exhaust through transom at water level

Boat 2 (21')

- **Engine:** Small block 5.7L without catalytic converter
- **Generator:** N/A
- **Approximate dimensions of boat:**
    - Length: 21'6"
    - Beam: 8' 2"
    - Draft: 24"
- **Exhaust Configuration:** Exhaust through transom at water level

It is important to mention that all tests were conducted on the same boat, with the same engine and same exhaust configuration. The only change was replacing the exhaust manifold to include or remove the catalytic converter system.

Exhaust Configurations Evaluated

The evaluated boat was configured to exhaust through the transom. In the transom exhaust configuration, the exhaust is directed through openings located on the transom (stern) of the vessel, usually above or at water line.

There are several differences between automobile engines and marine engines used on recreational boats related to the cooling and exhaust systems. The cooling system in an automobile engine is closed-loop having air-to-water radiators. In contrast, marine engines are open-loop drawing sea or lake water into the engine's water pump. The second big difference between auto and marine engines is that marine engines use water-cooled exhaust manifolds and mix water with exhaust gases after the manifold for cooling. The objective is to keep all surface temperatures within the boat below 200°F. In contrast, automobile engines do not add water into the engine exhaust. A third difference relates to the treatment of the exhaust gases before releasing them to the atmosphere. In automobile engines, the exhaust passes through a catalytic converter which removes many of the air pollutants, including CO. In contrast, exhausts from many marine engines are directly released into the environment without passing through a catalyst. The new engine from Indmar includes the addition of a catalytic converter on the exhaust manifold to reduce pollutants (including CO) from exhaust gases.

Description of the Evaluation Equipment

- Ferret Gaslink LT Five Gas Emissions Analyzer
- Biometrics Inc., ToxiUltra Atmospheric Monitors with CO sensors (0 – 1,000 ppm)
- Dräger PAC III detectors with CO sensors (0 – 10,000 ppm)
- TSI Inc., Q-trak equipped with CO sensor
- HOBO weather station
- Dräger Accuro handheld colorimetric detector tubes
- Mine Safety and Health Administration (MSHA) Glass evacuated containers
- Garmin 276C global positioning system (GPS)

A Ferret Instruments (Cheboygan, MI) Gaslink LT five-gas emissions analyzer was used to characterize emissions from the propulsion engine. These analyzers measured CO, carbon dioxide (CO_2), hydrocarbons, oxygen, and nitrogen oxides (NO_x). All measurements are expressed as percentages except hydrocarbons and NO_x, which are expressed in ppm. One percent of contaminant is equivalent to 10,000 ppm.

CO concentrations were measured at various locations on the boat by ToxiUltra atmospheric monitors (Biometrics, Inc.) and Dräger PAC III monitors, equipped with CO sensors. ToxiUltra and PAC III 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 using a 30-second sampling interval. The ToxiUltra instruments have a nominal range from 0 ppm to approximately 1,000 ppm and the PAC III from 0 ppm to approximately 10,000 ppm.

CO concentration data was also collected with colorimetric detector tubes (Dräger A.G. [Lubeck, Germany] CO, CH 29901– range 0.3% [3,000 ppm] to 7% [70,000 ppm]) in the areas near the rear swim deck. Using a bellows–type pump, air is drawn through the tube. 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 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. Then, containers were sealed with wax–impregnated MSHA caps. The samples were then sent to Clayton Group Services in Novi, MI, where a GS-Gas Pro and a RT-Msieve gas chromatography equipment with thermal conductivity and flame ionization detectors analyzed the samples for CO.

Wind velocity and direction, temperature, and relative humidity measurements were gathered during the air sampling using a HOBO Weather Station (Onset Computer Corporation, Bourne, MA). This instrument recorded information every second for the duration of the field investigation. Boat speed and direction were estimated using a Garmin 276C global positioning system.

Description of Procedures

Evaluations were conducted on one boat and involved teams of several people. Each team consisted of: 1) a person to steer the boat, start the engine, and provide mechanical assistance when necessary; this person was usually from the collaborating organization; 2) two NIOSH researchers to collect data and organize experimentation; 3) a representative from the USCG to act in an advisory capacity. Following each day of data collection, NIOSH researchers downloaded data and recalibrated instruments. One system was evaluated per day. Testing took approximately three to four hours for each system and included both stationary and underway conditions.

Testing was made with the boats operating under various conditions. At a minimum, each boat was tested under the following conditions: 1) stationary; 2) 5 mph heading North and South; 3) 10 mph heading North and South; 4) 15 mph heading North and South; 5) 25 mph heading North and South, and 6) Wide Open Throttle heading North and South.

Researchers measured CO concentrations at various locations on the boat using ToxiUltra and PAC III monitors (see Figure 1). Monitors near the swim platform were partially wrapped in plastic (leaving the sensor portion exposed) to protect them from water spray. All CO monitors, the weather station, and stop watches were synchronized with the computer's clock to accurately correlate each test with downloaded data. Monitors were placed at various locations on the boat, in part, to approximate passenger position during operation. Because CO emissions originate from engine exhaust near the stern of the boat, multiple CO monitors were placed in this area.

RESULTS

Results of Air Sampling with ToxiUltra and PAC III CO Monitors

Summary statistics for the data collected with the ToxiUltra and PAC III CO monitors are shown in Tables 2 through 9. These tables are organized to show the experiment number along the left-hand column and the ToxiUltra or PAC III number across the top row. For each sample location and condition, a CO mean (Tables 2, 4, 6, and 8) and peak concentration (Tables 3, 5, 7, and 9) are reported. For the ToxiUltra instruments, CO concentrations exceeding 1,000 ppm in Tables 2 through 5 indicate that the upper limit of the instrument was reached; the exact CO concentration and duration are uncertain. Graphs depicting the average CO concentrations in Tables 2 through 9 for the two boats and conditions are shown in Figures 2 through 7. Comparisons were made between the mean CO concentrations for the boat with the Indmar catalytic converter and the one equipped with a standard exhaust system.

ToxiUltra and PAC III CO Samples while the Boat was Underway

Air sampling data were collected while the boats were underway, resulting in generally lower concentrations than while the boats were stationary. Figure 1 lists specific locations where CO concentrations were measured, which include the following:

- On or near the swimming platform (Port, Center and Starboard)
- On the rear seat (Port, Center and Starboard)
- Inside the cabin (Captain and passenger seat)
- Front of the boat

Boat 1: 5.7L equipped with Indmar catalytic technology

Tables 2 – 3 and Tables 6 – 7 show the summary statistics analysis for the ToxiUltra and PAC III instruments. In general, mean onboard CO concentrations did not exceed 341 ppm for Boat 1. Peak concentrations for the same boat registered as high as 642 ppm (rear starboard) for a few seconds. Concentrations exceeding the NIOSH ceiling were usually at the swim platform (locations 1, 2 and 3) while concentrations in the cockpit (locations 7 and 8) of the boat never exceeded 15 ppm at any speed (even at 5 mph). Mean CO concentration in the cockpit of the boat fluctuated between 1 and 6 ppm for all evaluated conditions. North and South evaluations did not seem to have a big impact on onboard concentrations; the only effect noted was the shifting of high concentrations from port to starboard or vice versa.

Indmar representatives explained that this catalytic technology was designed to control pollutants from exhaust gases (including CO) by tightly controlling the amount of fuel and oxygen in the combustion process. Having a mixture rich in fuel will help reduce NOx molecules in the exhaust gases, and a lean mixture will reduce CO emissions from exhaust gases. It was mentioned to NIOSH researchers that cycling between rich and lean mixtures was required to control both pollutants from propulsion engine’s exhaust. This cycling is possible throughout the engine’s rpm range except at wide open throttle. The engine operates at a richer air/fuel ratio for engine protection at this setting. For this reason, it was expected to observe higher CO concentrations in the boat even when traveling at speeds close to 45 mph.

Peak CO concentrations on the swim platform of Boat 1 were 642 ppm when moving at 5mph heading south and gradually reduced to 12 ppm when the boat was traveling at 25 mph in the same direction. Peak CO concentrations at wide open throttle were 367 ppm when the boat was traveling at 45 mph (top speed) heading north (sample location # 3).

Mean CO concentrations at 5 mph were as high as 340 ppm and gradually reduced to 2 ppm when the boat was traveling at 25 mph. Mean CO concentrations for the wide open throttle condition were reported to be 291 ppm for sample location # 3. Figures 2 and 3 illustrate the average and peak CO concentrations for Boat 1.

Boat 2: 5.7L with standard exhaust system

Tables 4 – 5 and Tables 8 – 9 show the summary statistics analysis for the ToxiUltra and the PAC III instruments. At 5 mph, the ToxiUltra instruments were saturated for all sampling locations on the swim platform indicated by readings above 1,000 ppm. It is important to keep in mind that the nominal range for these instruments is 0 to 1,000 ppm. Readings above this range indicate CO concentrations exceeded 1,000 ppm but are not quantifiable with these instruments.

Mean CO concentrations using the PAC III instruments ranged from 194 to 2697 ppm reporting the higher reading when the boat was traveling at 25 mph heading north. Peak CO concentrations ranged from 280 to 5100 ppm. Air sampling for this boat reported high CO concentrations on the back of the boat (locations 1, 2 and 3) exceeding the NIOSH ceiling of 200 ppm for almost all evaluated conditions. At 5 mph, average CO concentrations on the swim platform ranged from 536 to 1,906 ppm. Mean CO concentrations in the cockpit of the boat for the same speed ranged from 4 to 154 ppm. Generally, when speed increased, CO concentrations tended to be reduced due to the amount of fresh air induced into the occupied areas of the boat. Wide open throttle conditions for this boat displayed high concentrations on the swim platform with a peak CO concentration of 1280 ppm and a mean CO concentration of 328 ppm (average for both directions).

Speeds of 5 and 10 mph for Boat 2 seemed to be problematic at the stern with mean CO concentrations exceeding the NIOSH IDLH of 1,200 ppm. Peak CO concentrations were above 2,500 ppm. For these speeds, the ToxiUltra instruments located on the swim platform were saturated and readings above 1,000 ppm were obtained with the PAC III instruments. Peak CO concentrations at 5 mph on the swim platform ranged from 2,220 to 3,940 ppm. Peak CO concentrations at 10 mph in the same location ranged from 1,300 to 4,000 ppm. At wide open throttle CO concentrations were displayed ranging from 280 to 1,280 ppm on the swim platform. Figures 4 and 5 illustrate average and peak CO concentrations for Boat 2.

ToxiUltra and PAC III CO Samples While the Boats were Stationary

CO concentrations measured on stationary boats were generally medium to high. Peak CO concentrations ranged from single digit numbers to approximately 820 ppm for Boat 1 and from 20 to 3,980 for Boat 2. Stationary conditions usually resulted in higher CO concentrations than when the boat was moving for the evaluated engines. For most cases, when testing boats under stationary conditions, virtually no air circulation other than environmental wind was sweeping the CO away from the vessel.

Ferret Five Gas Emissions Analyzer Results

Emissions data were collected using a five gas analyzer when the boat was on the slip (outside the water). A water hose was attached to the engine's water pump to provide cooling during the evaluation. Both engines were tested at idle speed at cold crank start and during the following 5 – 10 minutes. The probe of the emissions analyzer was introduced into the exhaust opening. This probe was equipped with a water separator to remove water particles from the exhaust.

The two evaluated engines, with and without the catalytic converter, emitted similar concentrations when tested on the slip at cold crank conditions. Initial CO concentrations for the engine equipped with the catalytic converter reached 12,500 ppm compared to 14,000 for the engine equipped with standard exhaust. Within 10 seconds, CO concentrations for Boat 1 were reduced to 2,100 ppm and further reduced to 400 ppm 60 seconds after cold crank. The readings for Boat 1 were stable at 800 ppm approximately 8 min after cold crank start. CO concentrations for Boat 2 ranged between 10,300 and 13,000 two minutes after cold crank. Table 10 presents the data collected using the Ferret five gas emissions analyzer, and Table 11 presents the % reduction over time of the catalytic technology. Figure 8 shows these results graphically.

Detector Tubes and Evacuated Container Results

Colorimetric detector tubes and glass evacuated containers were primarily used to characterize CO concentrations at the rear of the vessel. Summaries of the detector tube air sampling results are shown in Table 12. In general, detector tube and evacuated container air sampling results support measurements made with the ToxiUltra and PAC III instruments. Any variations in readings among different CO detection instruments for a particular experiment can be explained by one of several, expected reasons: 1) readings for ToxiUltra CO and PAC III monitors have an upper limit of approximately 1,000 and 10,000 ppm respectively so that any readings above this level may be skewed; 2) although colorimetric detector tubes' accuracy is well established, this method makes a less precise measurement than other instruments used (typically within +/- 10%); and 3) measurements for any instrument will vary depending on the localized conditions at that instant.

Wind Velocity Measurements

On the whole, wind velocity measurements were taken to be used as a reference to further investigate unexpected trends in CO concentrations. Wind velocity and direction measurements were collected using a HOBO weather station. Table 13 provides relative wind velocities for the various test conditions. On day one (Boat 1) the wind was coming from the northeast (bearing 223°) with an average wind velocity of 7.75 mph and a maximum of 14.94 mph. On day two (Boat 2) the wind was also coming from the northeast (bearing 225°) with an average wind velocity of 2.52 mph and a maximum of 6.23 mph.

DISCUSSION

Description of Trends for Individual Boats

Boat 1: 21’ with Indmar catalytic converter system
CO readings collected with the Ferret directly into the exhaust opening were stable at approximately 800 ppm two minutes after cold crank start (warmed catalyst). Peak CO data collected with the ToxiUltra and PAC III monitors never exceeded 642 ppm in areas near the swim platform of the boat. In general, CO distributions were higher at the stern of the boat (near source) and tended to decline toward the front of the vessel. Mean CO concentration in the cockpit of the boat ranged from 0 to 6 ppm for all evaluated conditions, and peak concentrations were consistently below 12 ppm (location # 7 at 5 mph).

As explained by Indmar representatives, wide open throttle conditions produced higher CO concentrations because the ECU was controlling to a richer air/fuel ratio for engine protection. Mean CO concentrations for wide open throttle conditions were consistently below 300 ppm with a peak concentration of 367 ppm when traveling north. Refer to Tables 2 – 3, Tables 6 – 7, and Figures 2 – 3 for more details.

Boat 2: 21’ with standard exhaust system
CO readings collected with the Ferret directly into the exhaust opening were consistently above 10,000 ppm. Peak CO concentrations for this boat reached 5,100 ppm for the PAC III installed on the swim platform (port side) when traveling at 25 mph. As mentioned for the previous boat, CO distributions were higher at the stern of the boat and tended to decline toward the front of the vessel. Mean CO concentrations in the cockpit of the boat ranged from 0 to 154 ppm, and peak concentrations were reported to be as high as 336 ppm (location # 7 at 5 mph).

Peak CO concentrations near the stern of the boat were consistently above the NIOSH IDLH for almost all the test conditions with very few exceptions. At 15 mph Boat 2 displayed the lowest CO concentrations when compared to all testing speeds. Refer to Tables 4 – 5, Tables 8 – 9, and Figures 4 – 5 for more details.

Summary of Trends for All Boats
The Indmar system significantly reduced CO exposures to boat occupants during the current evaluation. For most conditions, a reduction above 90% was observed when compared to a standard exhaust system. This catalytic technology can greatly reduce the CO poisoning hazard to occupants of boats that have gasoline-powered engines. This study specifically evaluated the performance of the Indmar technology designed to reduce CO emissions and protect boat occupants. Engine performance did not seem to be affected by the incorporation of the catalytic converter in the exhaust manifold. The two boats were able to reach the same top speed (45 mph) in about the same amount of time. The performance of the Indmar technology was impressive and has the potential to prevent CO poisonings in a variety of settings. Since engine emissions are reduced by

90% or greater, the use of these engines with catalyst will reduce CO exposures of people engaging in water sports activities behind the boat as well as boat occupants.

Below are listed several general factors that influence CO exposures:

- Boat speed
- Wind conditions
- CO generation rate
- Boat design and shape
- Distance between exhaust outlets and individual's breathing zone
- Fresh air ventilation of the cockpit and occupied areas

The significance of these observations is that, depending on the various boat designs and ambient factors, operating the boat at higher speeds is no guarantee of adequately ventilating inhabited areas of the boat.

CONCLUSIONS AND RECOMMENDATIONS

Previous NIOSH studies indicate that approximately 90% of evaluated recreational boats produced potentially hazardous CO concentrations. When boats were tested during stationary conditions, the CO concentrations were high at the stern (500 to 1,000 ppm). In addition, cabin cruiser measurements ranged from 800 to 1,000 ppm on the lower deck.

Two ski boats were evaluated in the current study. One was equipped with a production catalytic converter and electronic fuel injection manufactured by Indmar Marine Engines. This engine was also equipped with an oxygen sensor in order to control the variables in the combustion process. The other engine was equipped with a standard exhaust system and electronic fuel injection. Both exhaust systems were water jacketed to keep temperatures of the exhaust manifolds below 200 °F.

The Indmar system significantly reduced CO exposures to boat occupants during the current evaluation. For most conditions, a reduction above 90% was observed when compared to a standard exhaust system. This catalytic technology can greatly reduce the CO poisoning hazard to occupants of boats that have gasoline-powered engines. This study specifically evaluated the performance of the Indmar technology designed to reduce CO emissions and protect boat occupants. This was the first evaluation of this system performed by NIOSH.

When comparing measurements collected directly in the exhaust opening, at idle, the Indmar technology showed reductions on the order of 93% vs. the standard technology. The Indmar engine produced relatively low ambient CO concentrations that were substantially less than the CO concentrations produced by the standard engine. Also, these concentrations were less than those from previous NIOSH studies. The data collected from Boat 1 indicated CO concentrations below occupational exposure limits, and most of the average CO data indicated concentrations below health criteria relevant to the general public.

The performance of the Indmar system was impressive with CO emissions read directly in the exhaust opening of approximately 800 ppm and below for a fully warmed engine. Due to diffusion in the environment, these emissions were significantly reduced. In fact, the highest average real-time CO readings, obtained from the monitors placed in occupied areas (other than the swim platform) of the ski boat, were frequently single digit concentrations. In order to ensure that the systems operate effectively, boat owners and operators should follow all manufacturers' recommendations with regard to routine maintenance and replacement schedules.

CO concentrations are typically higher at the stern of the boat and become gradually lower toward the front of the boat. Based on the preceding results and observations, the following recommendations are made regarding lowering CO concentrations on boats equipped with gasoline-powered propulsion engines to appropriate levels. Recommendations are also made for future research on this issue. Based on similar

NIOSH studies, underwater exhaust will potentially further reduce CO concentrations inside the cockpit and other occupied areas compared to surface exhaust. Additional research should be conducted to evaluate this catalytic control technology after extended hours of operation to verify proper functioning and potential degradation of the catalytic converter.

Public education efforts must be implemented immediately to inform and warn all individuals (including boat owners, renters, and workers) potentially exposed to CO hazards. Training about the specific boat-related CO hazards provided for boat buyers, owners, and those that rent boats, who may be completely unaware of this deadly hazard, should be continued and enhanced to include specific information about the circumstances that most likely lead to excessive build up of CO concentrations.

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**Evaluation of CO Concentration With and Without Catalytic Emission Controls from Gasoline Propulsion Engines.
Punta Gorda, FL.
December 12 & 13, 2006.**

Table 1: Experiment Conditions, Boats 1 & 2

Experiment #	Speed	Direction	Boat
1	5	South	1
2	5	North	1
3	10	South	1
4	10	North	1
5	15	South	1
6	15	North	1
7	25	South	1
8	25	North	1
9	Open	South	1
10	Open	North	1
11	5	South	2
12	5	North	2
13	10	South	2
14	10	North	2
15	15	South	2
16	15	North	2
17	25	South	2
18	25	North	2
19	Open	South	2
20	Open	North	2

Table 2: Mean ToxiUltra (TU) CO Values, Boat 1 (with catalyst).

All measurements are expressed in parts per million (ppm)

Experiment #	TU 1	TU 2	TU 3	TU 4	TU 5	TU 6	TU 7	TU 8	TU 9
1	340.81	61.99	96.3	3.065	1.12	1.38	1.95	1.03	0.49
2	39.04	84	337.57	2.88	1.08	2.08	5.42	0.78	0.75
3	15.37	3.82	6.92	2.59	0.84	0.41	0.37	0.54	0.64
4	7.83	12.76	25.55	3	1.46	1.21	1	0.56	0.3
5	9.29	7.27	2.86	2.22	0.29	0.11	0	0.65	0.65
6	5.23	8.8	6.25	2.46	0.82	1.17	0.98	0.38	0.69
7	5.83	3.06	1.63	2.66	0.4	0.53	0.53	0.6	0.53
8	2.71	2.06	5.75	2.28	0.43	0.87	0.43	0.34	0.43
9	212.5	30.81	14.56	2.87	0.56	0.87	0.56	0.81	0.56
10	43.41	52.35	291.52	1	0.05	0.76	0.11	0.58	0.41

Table 3: Maximum ToxiUltra (TU) CO Values, Boat 1 (with catalyst).

Above 50 ppm	
Above 200 ppm	
Above 1000 ppm	

All measurements are expressed in parts per million (ppm)

Experiment #	TU 1	TU 2	TU 3	TU 4	TU 5	TU 6	TU 7	TU 8	TU 9
1	555	167	642	4	5	7	7	2	2
2	105	230	601	4	2	3	12	2	2
3	30	9	282	4	4	2	2	2	3
4	37	61	124	3	8	2	3	2	2
5	17	15	9	3	1	1	0	2	1
6	11	13	18	3	2	2	2	1	2
7	26	9	12	4	2	2	2	1	1
8	9	6	13	3	1	2	1	1	1
9	294	52	71	4	1	2	1	1	1
10	126	82	367	2	1	1	1	1	1

Table 4: Mean ToxiUltra (TU) CO Values, Boat 2 (without catalyst).

All measurements are expressed in parts per million (ppm)

Experiment #	TU 1	TU 2	TU 3	TU 4	TU 5	TU 6	TU 7	TU 8	TU 9
11	1131.85	1146.16	1229.58	10.24	11.04	7.3	10.43	86.72	2.48
12	536.73	1146.11	1223.42	6.55	7.78	26.96	154.24	4.06	1.04
13	377.04	357.61	403.25	3.95	7.51	3.69	1.54	2.74	0.91
14	803.35	767.76	1229.1	5.12	38.5	27.43	49.23	2.28	1.06
15	373.46	701	1229.26	9.97	3.7	1.21	1	6.75	1.14
16	24.82	223.31	870.26	2.7	4.39	10.75	2.04	0.63	0.73
17	169.03	267.1	546.56	3.93	1.66	6.3	0.33	5.9	1.06
18	17.56	136.56	450.76	2.63	0.13	3.26	0.8	0.4	0.3
19	197	392.27	505.11	0.94	1.11	12	0.05	0.44	0.44
20	20.82	369.64	755	0.88	0.05	9.17	0	0.29	0.29

Table 5: Maximum ToxiUltra (TU) CO Values, Boat 2 (without catalyst).

Above 50 ppm	(light grey)
Above 200 ppm	(medium grey)
Above 1000 ppm	(dark grey)

All measurements are expressed in parts per million (ppm)

Experiment #	TU 1	TU 2	TU 3	TU 4	TU 5	TU 6	TU 7	TU 8	TU 9
11	1135	1151	1231	15	20	39	16	186	10
12	1135	1151	1233	13	15	51	336	14	2
13	658	1151	1233	27	112	89	18	22	2
14	1135	1151	1230	23	296	230	109	9	2
15	1135	1151	1233	98	31	5	5	58	5
16	287	452	1235	4	52	46	8	5	2
17	675	1151	1236	8	5	23	2	14	4
18	44	226	634	3	1	9	3	2	1
19	251	451	1235	4	4	17	1	2	1
20	112	565	1031	4	1	22	0	1	1

Table 6: Mean PAC III CO Values, Boat 1 (with catalyst).

All measurements are expressed in parts per million (ppm)

Experiment #	PAC III 355	PAC III 357
1	112.5	81.71
2	56.33	204.5
3	0.15	1.09
4	0.16	18.83
5	0	1.13
6	0	0.19
7	0	0.33
8	0	0
9	105.62	15
10	17.22	172.22

Table 7: Maximum PAC III CO Values, Boat 1 (with catalyst).

Above 50 ppm	
Above 200 ppm	
Above 1000 ppm	

All measurements are expressed in parts per million (ppm)

Experiment #	PAC III 355	PAC III 357
1	215	395
2	160	345
3	5	15
4	5	65
5	0	10
6	0	5
7	0	5
8	0	0
9	165	45
10	45	220

Table 8: Mean PAC III CO Values, Boat 2 (without catalyst).

All measurements are expressed in parts per million (ppm)

Experiment #	PAC III 355	PAC III 357
11	1906.56	677.18
12	1105.66	1186
13	1856.83	1742.83
14	469.54	385.45
15	217.85	265
16	480.23	340
17	501.78	434.64
18	2697.33	967.66
19	437.22	276.66
20	406.11	193.88

Table 9: Maximum PAC III CO Values, Boat 2 (without catalyst).

Above 50 ppm	
Above 200 ppm	
Above 1000 ppm	

All measurements are expressed in parts per million (ppm)

Experiment #	PAC III 355	PAC III 357
11	3940	2220
12	2780	2980
13	3860	4000
14	1300	1490
15	775	445
16	1050	695
17	3240	1810
18	5100	1590
19	1280	1070
20	535	280

Table 10: Ferret Emissions Analyzer Data Boat 1 vs. Boat 2

All measurements are expressed in parts per million (ppm)

	CO concentrations in ppm	
Time (sec)	Boat 2	Boat 1
10	14,000	12,500
20	14000	2,100
40	13000	500
60	10300	400
90	13000	1,100
120	12900	800
420	NS	300
450	NS	700
510	NS	800

NS: Not Sampled

Table 11: Reduction (%) vs. Time from Cold Crank Start

Time (sec)	% Reduction
10	10.71
20	85.00
40	96.15
60	96.12
90	91.54
120	93.80

Table 12: Detector Tube Readings, Boats 1 & 2.

Boat	Condition	Concentration (ppm)
Boat 1	5 mph, heading South	50
Boat 1	5 mph, heading North	40
Boat 1	10 mph, heading South	2
Boat 2	5 mph, heading South	3,000
Boat 2	5 mph, heading North	>5,000
Boat 2	10 mph, heading South	1,000
Boat 2	10 mph, heading North	> 3,000
Boat 2	15 mph, heading South	1,500

Table 13: Relative Wind Velocities, Boats 1 & 2.

Boat	Condition	Velocity (mph)
Boat 1	5 mph, heading South	5.31
Boat 1	5 mph, heading North	8.64
Boat 1	10 mph, heading South	8.61
Boat 1	10 mph, heading North	6.57
Boat 1	15 mph, heading South	7.84
Boat 1	15 mph, heading North	9.22
Boat 1	25 mph, heading South	9.28
Boat 1	25 mph, heading North	8.61
Boat 1	Open Throttle heading South	9.87
Boat 1	Open Throttle heading North	9.91
Boat 2	5 mph, heading South	2.69
Boat 2	5 mph, heading North	1.65
Boat 2	10 mph, heading South	2.32
Boat 2	10 mph, heading North	2.86
Boat 2	15 mph, heading South	2.63
Boat 2	15 mph, heading North	2.69
Boat 2	25 mph, heading South	3.33
Boat 2	25 mph, heading North	1.74
Boat 2	Open Throttle heading South	2.89
Boat 2	Open Throttle heading North	3.33

Figure 1: Typical Sample Locations

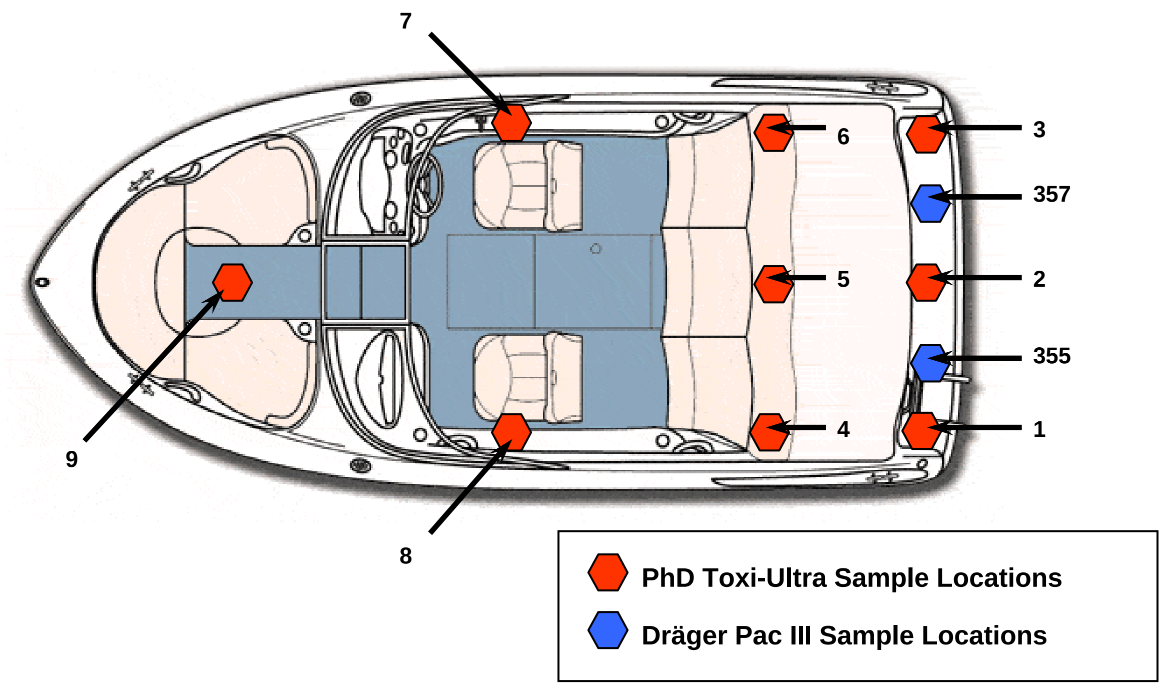

Figure 2: CO Distribution from Indmar Technology heading South

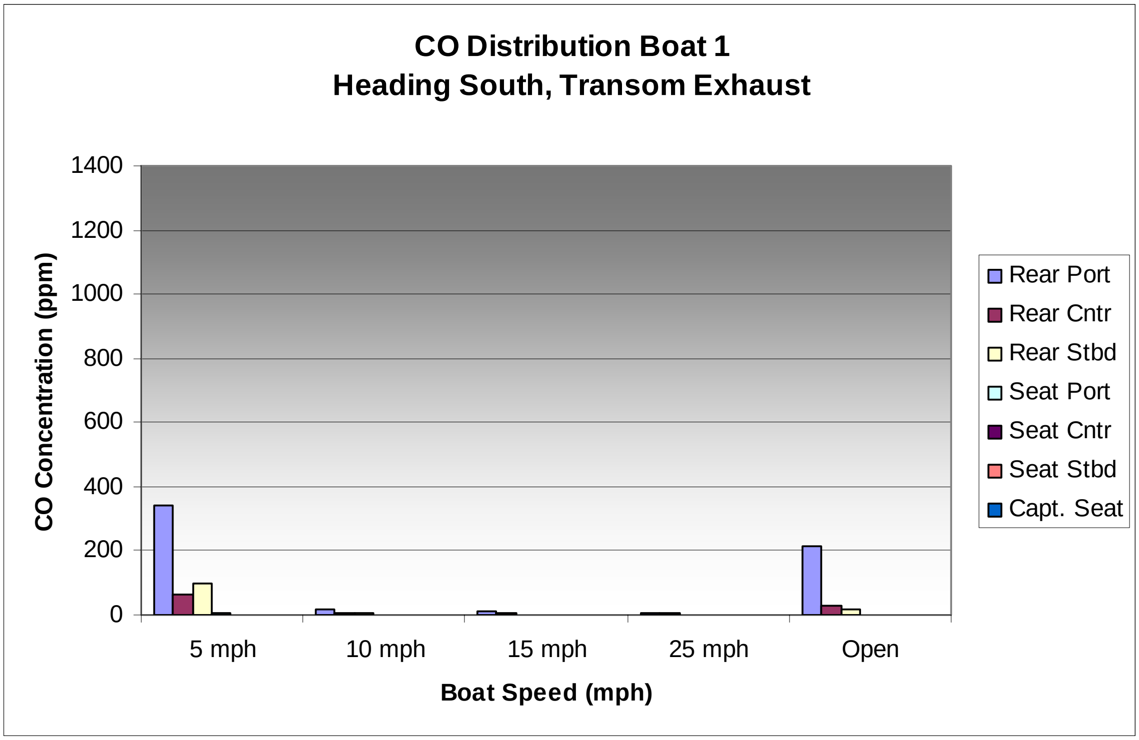

Figure 3: CO Distribution from Indmar Technology heading North

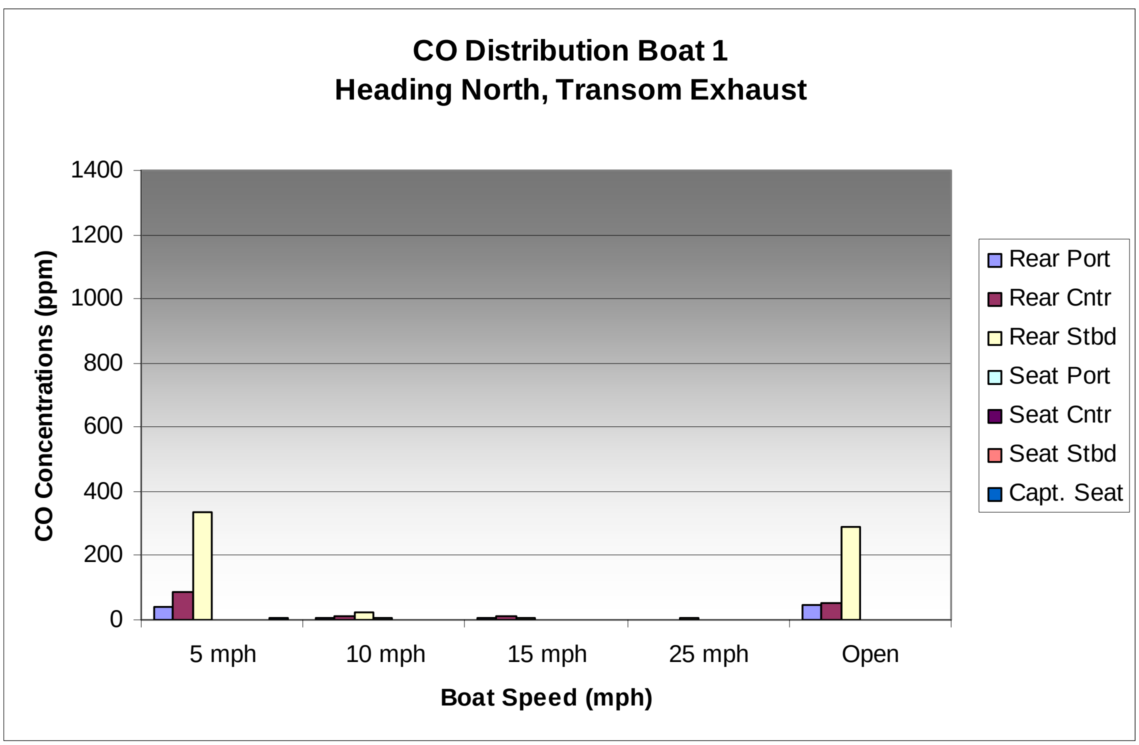

Figure 4: CO Distribution from Standard Technology heading South

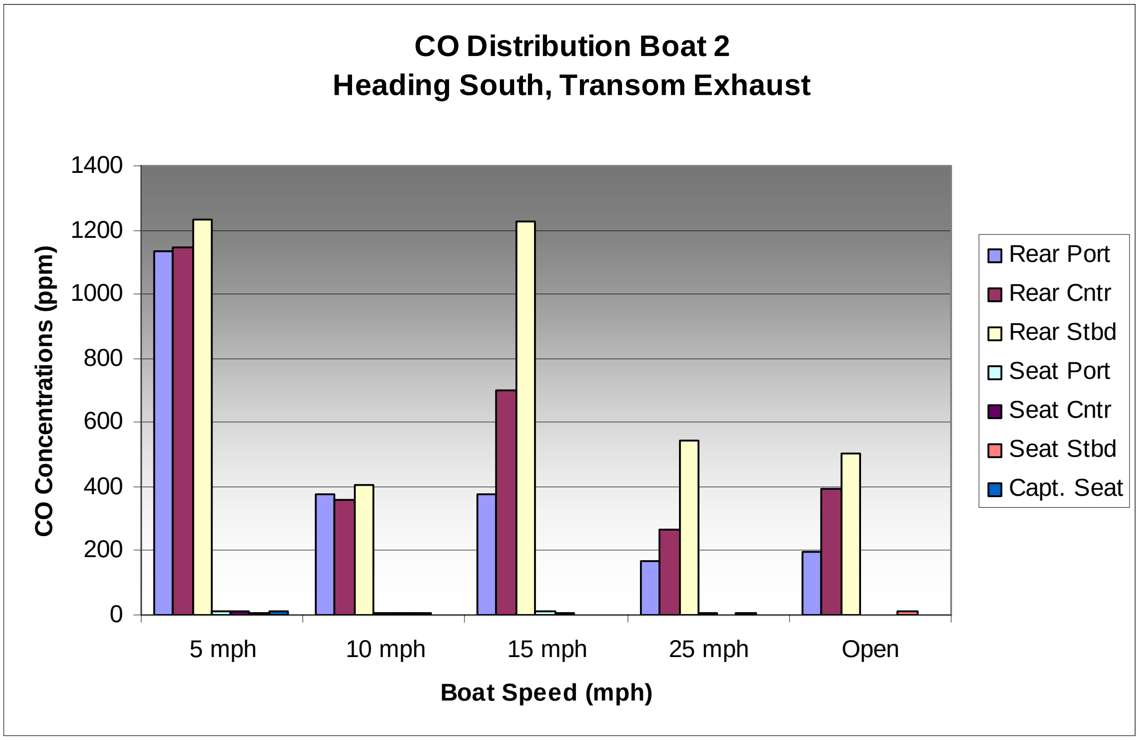

Figure 5: CO Distribution from Standard Technology heading North

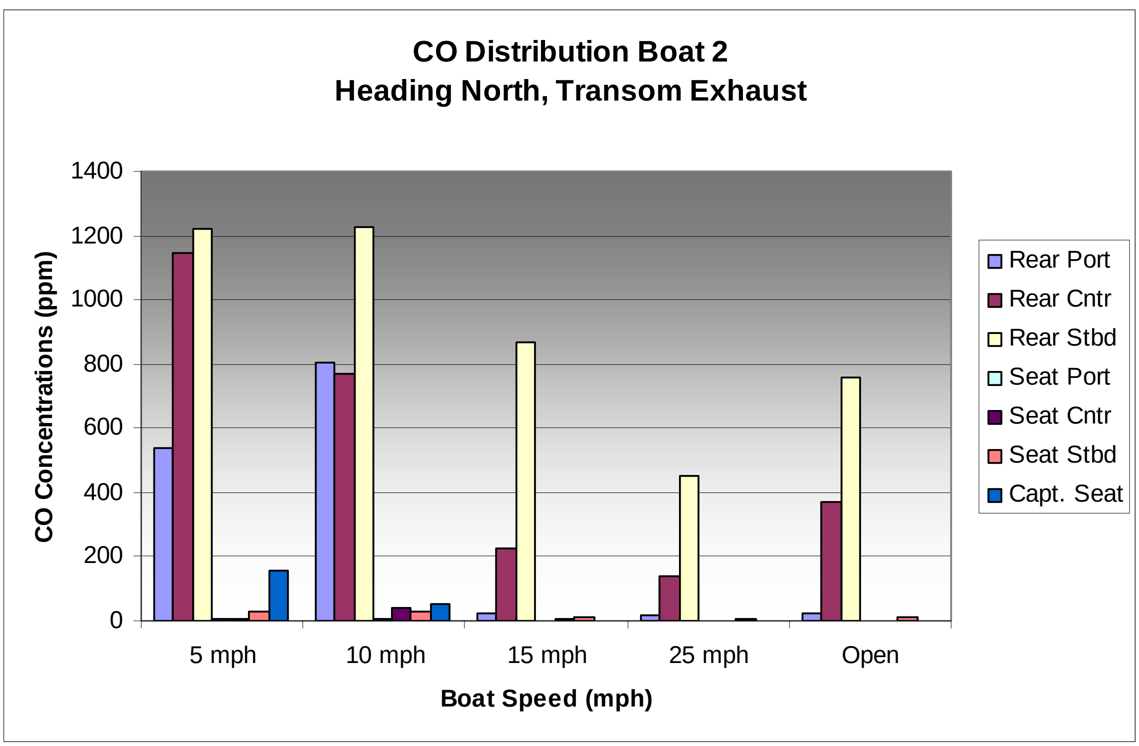

Figure 6: Comparison of CO Distribution from PAC III Data heading South

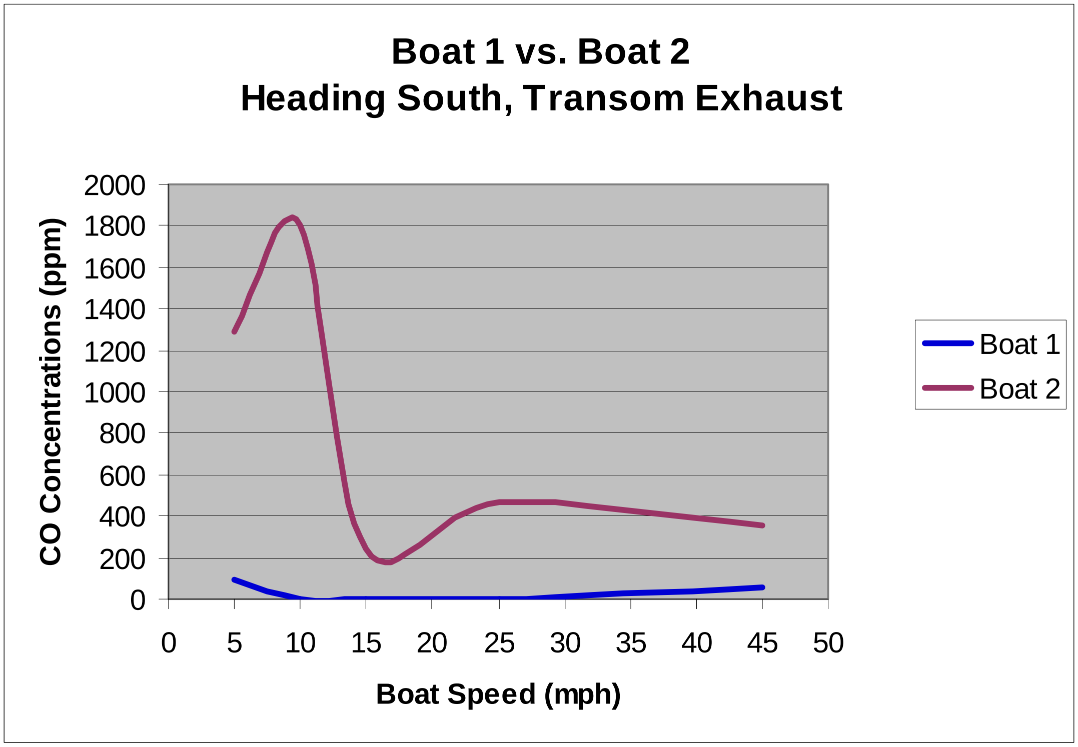

Figure 7: Comparison of CO Distribution from PAC III Data heading North

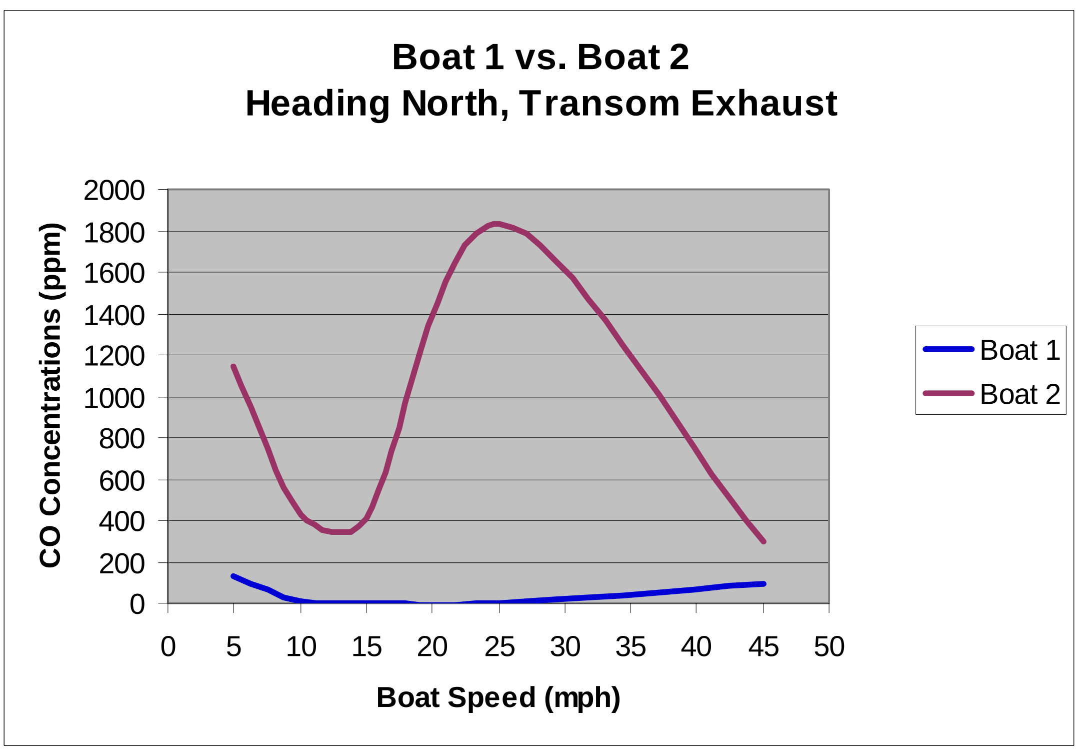

Figure 8: Ferret Data Measured Directly Into the Exhaust Opening