Evaluation of the "Fresh Air Exhaust™" System to Reduce Carbon Monoxide Exposure during Motor Boating and Wake Surfing

(Lake Austin, TX)

David A. Marlow
Corina Guishard
Andrew Patterson
G. Scott Earnest, Ph.D., P.E., C.S.P.

REPORT DATE:
August 2004

REPORT NO.: 171-35a

MANUSCRIPT PREPARED BY:
Diana Campbell

U.S. Department of Health and Human Services
Public Health Service
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
Division of Applied Research and Technology
4676 Columbia Parkway, MS - R5
Cincinnati, Ohio 45226

Survey Sites: Lake Austin, Austin, Texas

SIC Code: N/A

Survey Dates: May 24 and 25, 2004

Employer Representatives Contacted: Larry Mann, owner
Fresh Air Exhaust

Employee Representatives Contacted: None

Manuscript Edited by: Diana Campbell

DISCLAIMER

EXECUTIVE SUMMARY

Under an interagency agreement with the United States Coast Guard, National Institute for Occupational Safety and Health (NIOSH) researchers evaluated carbon monoxide (CO) emissions and exposures on a 2001 Ski Natique recreational boat equipped with a carbureted, inboard engine and a Fresh Air Exhaust (FAE) emission control system. The Ski Natique's engine normally discharges the exhaust through two 4-inch openings at the stern of the boat, typically a few inches below the water line. The FAE system was retrofitted onto the exhaust discharge in order to route the separate exhausts to a single location and discharged approximately 14-inches downward directly behind the propeller wash area.

This investigation builds upon a series of recent studies to reduce CO exposures and poisonings on houseboats and other recreational boats. Epidemiologic studies have found that from 1990 to 2004, there have been approximately 540 CO poisonings associated with exhaust from gasoline-powered marine engines on recreational boats. Two hundred and twenty-five of the poisonings occurred on non-houseboats (other types of recreational boats).

This study was performed for the U.S. Coast Guard for three purposes: To serve as an independent evaluation of the FAE system, to gather additional data building upon previous studies related to CO concentrations and exposures near ski boats operating under various conditions, and to collect personal exposure data on an individual performing wake surfing. The ski boat was evaluated with and without the FAE system while stationary and moving multiple speeds, ranging from 2.5 to 20 miles per hour. CO concentrations were measured by multiple real-time instruments, placed at different locations on the boats and at various distances (10 to 60 feet) behind the boat while moving.

Study results indicated that CO concentrations on the boat were generally highest while the boat was stationary. CO concentrations tended to fall when the boat was underway and decreased as boat speed and distance increased. CO concentrations were highest closest to the water and fell as height above the water increased. The FAE system significantly reduced CO concentrations (by 60- 90%) on and behind the boat when operating at speeds of 10 mile per hour (mph) or greater. When the boat was stationary or operating the speeds below 10 mph (i.e. slow no-wake speeds) CO reductions were mixed. In some cases CO concentrations were reduced; however, in others there was an increase. Average personal CO exposures to a wake surfer (located approximately ten feet behind the boat and slightly off center) were approximately 17 ppm and the FAE system was able to reduce exposures to approximately 3 ppm (an 80% reduction).

The authors conclude that the CO concentrations measured 10 to 60 feet behind the boat appear to be relatively low with or without the FAE system. One particular area of concern relates to towed water sports activities were people could be near the boat, operating at slow speeds, and near the water (such as some tubing activities). The FAE system could be beneficial in helping to reduce CO exposures to individuals involved in a variety of towed water sports activities.

Further research is warranted to provide a better understanding of the CO reduction mechanisms.

BACKGROUND

On May 24 and 25, 2004, researchers from the National Institute for Occupational Safety and Health (NIOSH) conducted an evaluation of carbon monoxide (CO) emissions and exposures on a gasoline-powered, inboard ski boat that was equipped with a Fresh Air Exhaust™ (FAE)carbon monoxide control system. The FAE system is a recently developed device that can be used on inboard ski boats to reroute engine exhaust from directly behind the boat near the water surface to approximately 1.5 feet below the water directly behind the propeller. The manufacturer has collected data showing that this device effectively removes CO from the air in the vicinity of the stern of the boat, as well as at numerous distances behind the boat [Mann, 2004]. The current evaluations occurred on a ski boat operating on Lake Austin, Austin, Texas with and without the FAE system.

This evaluation was intended to:

1) Serve as an independent evaluation of the FAE system's ability to reduce CO exposures.
2) Provide a better understand of how CO concentrations change at various speeds, distances, and heights behind a ski boat, and
3) Provide personal CO monitoring for individuals performing wake surfing.

This evaluation was conducted under an interagency agreement between the U.S. Coast Guard's Office of Boating Safety and NIOSH to reduce CO emissions and exposures that occur on recreational boats used in the United States. This report provides background information and describes the NIOSH study methods, results, discussion, conclusions, and recommendations.

Prior Studies Looking at CO Exposure behind ski boats

NIOSH Studies

In spring 2002, working with the United States Coast Guard, NIOSH researchers analyzed the carbon monoxide 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.

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 20ppm in the interior of most boats. Cabin Cruiser measurements ranged from 800 to 1000 ppm on the lower deck and less than 15 ppm in the interior. (The upper limit for the ToxiUltra CO monitor is approximately 1,000 ppm and may have been exceeded at times.) CO concentrations were significantly lower when the boat was moving than when stationary. The highest concentrations were at the boats' stern and lowest in the interior of the boats. CO concentrations were lower on boats with cleaner burning outboard engines and with increasing boat and wind velocities.

Approximately 90% of the boats evaluated in this study had dangerously high CO concentrations. The authors recommended 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.

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 Bass Boat Hardbody equipped with two ToxiUltra CO detectors at two and five feet above the water.

The main test variables were boat speed and distance from the stern. Data were not collected when wind speeds exceeded 5mph. 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. Problems with survey measurements prevented taking data when boats speeds exceeded 10mph at distances less than 60 ft.

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 2ft compared to 5 feet 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 with the exception of great distances. At great distances the CO levels increased as the boat speeds increased. In general, highest CO concentrations were at the ski boat's stern seat at 2 ft above the water, and at distances of 20 feet or less. There was no need for concern at 5 feet above the water level at distances of 60 feet and beyond. CO concentrations at this level were low enough for the safe enjoyment of recreational water sport activities.

"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 Tiger 20i with a 351 CID throttle body fuel injected engine.

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

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, while at 10 mph measurements 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 Tiger 20i at 10 and 20 mph at distances 60' and 80' feet behind the transom consistently reported CO concentrations of 0 ppm.

The FAE manufacturer concluded that at 5mph, FAE greatly reduces the risk of CO exposure within and 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.

Towed Water Sports Activities

There are a variety of towed water sport activities in which CO exposures may occur. CO exposures are related to the distance behind the boat, height from the water, and operating speed. The most common of these sports, depicted in Figure 1, are tubing, teak surfing, water skiing, wakeboarding, wake surfing, and knee boarding. A brief description of these common towed water sport activities is provided below.

Tubing: The rider(s) sits in a rubber inner tube and is towed along by a rope that is attached to a vessel. For tubing the ideal tow rope is approximately 60 feet long. Tubing often consists of one or two persons riding simultaneously (each with a separate tube and tow rope).

Waterskiing: Waterskiing is similar to tubing except the rider wears skis and glides over the water in a standing position. The average tow rope length for waterskiing is about 70 to 75 feet. Water-ski ropes are generally made from polypropylene and under a normal skiing load the rope can stretch from 2 to 3 percent of the original length.

Wakeboarding: Wakeboarding is a form of waterskiing in which the rider's feet are bound to a board rather than attached to skis. The rider stands in an upright position on the board with both feet pointing off the side of the board. The average tow rope length is 70 to 75 feet.

Wake Surfing: In this sport the rider is initially towed by a rope of various lengths that is attached to a weighted vessel. Once the desired wave is created by the vessel and the rider is balanced on his/her surfboard, the tow rope is tossed into the boat or on the opposite side of the wave. The rider then proceeds to surf the wave often approximately 10 feet behind and slightly to the side of the boat.

Knee boarding: A sport similar to waterskiing except the rider kneels on a fiberglass board rather than standing on skis. The length of the average tow rope is approximately 60 to 70 feet.

Teak Surfing: Teak surfing has been banned in many areas because it is extremely hazardous. In teak surfing or "platform dragging" there is no rope. The rider holds on to the swim platform of a vessel until the desired wake or wave forms. Once the desired wave has formed, the rider (or body surfer) releases the grip on the swim platform and proceeds to ride the wave on his/her stomach, within a few feet of the back of the boat.

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].

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

The NIOSH Recommended Exposure Limit (REL) for occupational exposures to CO 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

Description of the Evaluated Boat and Engineering Control

The boat used during this evaluation was a 2001 SkiNautique by Correct Craft with a 351 cubic inch Ford engine (carbureted Pleasurecraft, 5.7 liter). See Figures 2 and 3. This boat and engine normally discharge the exhaust through two 4-inch openings at the stern of the boat, just a few inches below the water line. The exhaust openings were spaced approximately 34-inches apart. The Fresh Air Exhaust (FAE) system was retrofitted onto the exhaust discharge. The FAE retrofit consisted of several 4-inch hose couplings and a formed 4-inch black pipe that routed the two exhausts together and discharged approximately 14-inches downward into the propeller wash area. Figures 4 through 7 depict the dimensions and configuration of the FAE device, and how it attaches to the boat's exhaust system.

Description of the Evaluation Equipment

CO concentrations were measured at various locations on and behind the boat (on a towed Hobie Cat sailboat) as shown in Figures 8 and 9. CO measurements were made using ToxiUltra Atmospheric Monitors (Biometrics, Inc.), equipped with CO sensors. CO and NO_2 concentrations were measured during wake surfing by a PhD Ultra Gas Detector (Biometrics, Ins.) ToxiUltra CO and PhD Ultra Gas Detector monitors were calibrated before and after use, according to the manufacturer's recommendations. These monitors are direct-reading instruments, having data logging capabilities.

The ToxiUltra monitors were operated in the passive diffusion mode, having a 30 second sampling interval. The ToxiUltra monitors have a nominal range, from 0 ppm to approximately 999 ppm. The PhD Ultra Gas Detectors operated the same as the ToxiUltra monitors except the air was drawn to the monitor by a pump calibrated at 1.5 liters per minute. During wake surfing sampling, tubing from the PhD monitor was extend out to the person who was wake surfing.

During air sampling, NIOSH researchers also measured wind velocity when the boat was stationary or underway, by using a VelociCalc Plus Model 8360 air velocity meter (TSI Inc., St. Paul, MN).

Description of Procedures

Air sampling for CO and wind-velocity measurements were collected at various locations and conditions. CO measurements were made while the boat was idling, traveling at speeds of 5, 10, 15 miles per hour (mph) towing a 16 ft. Hobie Cat sailboat at distances of 10, 20, 40, and 60 feet behind the boat. CO monitors were fixed to a vertical pole mounted on the sailboat at distances of 2, 3.5, and 5 ft. above the water. A PhD Ultra Gas detector was mounted along the stern of the boat. It was used to pump air through a small flexible tube that was held near the breathing zone of individuals that were wake surfing behind the boat (Figure 10). The boat was typically traveling at 10 mph or slightly less during wake surfing.

RESULTS

Results of Air Sampling with ToxiUltra CO Monitors

Monitors were placed at various locations on the boats, 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. Summary statistics for the data collected with the ToxiUltra CO and PhD Ultra Gas monitors are shown in Appendix A. For each sample location and condition, mean CO concentration, standard deviation, number of 30-second CO measurements, and peak CO concentration are shown.

ToxiUltra CO Samples While the Boat was Stationary

Table 1 provides the summary statistics for CO concentrations on the stationary boat with engine idling. Performance of the FAE system was mixed when the boat was stationary. The mean CO concentration at the front of the passenger compartment of the boat on the port side was 18 ppm without the FAE system and 15 ppm with the FAE system (a reduction of 14%). Mean CO concentrations in the middle of the boat on the starboard side were 14 ppm without and 17 ppm with the FAE system (an increase of 18%). At the stern of the boat, mean CO concentrations were 41ppm without and 55 ppm with the FAE system (an increase of 35%). Peak CO concentrations at the stern were 549 ppm without and 370 ppm with the FAE system.

ToxiUltra CO Samples while the Boat was Underway (5 mph)

Air sampling data were collected while the boat was underway to simulate towed water sport activities. Summary statistics for CO concentrations with and without the FAE system operating at a speed of 5 mph are shown in Table 2 and comparisons of some of the data are shown in Figures 11 and 12. Generally, the performance of the FAE system at this speed was mixed. The mean CO concentration at the front of the passenger compartment of the boat on the port side was 8.1 ppm without the FAE system and 10 ppm with the FAE system (an increase of 23%). For CO measurements in the middle of the boat on the starboard side, mean CO concentrations were 19 ppm without and 16 ppm with the FAE system (a reduction of 19%). At the boat's stern, the mean CO concentration was 47 ppm without and 25 ppm with the FAE system (a reduction of 46%). Peak CO concentrations measured at the boat's stern were reduced from 1,137 ppm to 267 ppm by the FAE system (a reduction of 76%).

As shown in Figure 11, CO concentrations behind the boat generally fell with distance from the boat and height above the water, although there were some deviations. Figure 12 shows that the FAE system generally reduced CO concentrations behind the boat, but under certain conditions (at 10 and 60 feet behind the boat) there were minor increases. For mean CO concentrations measured 2 ft. above the water reductions of 6%, 6%, and 28% were measured at distances of 10, 20, and 40 ft. behind the boat, respectively, when the FAE system was used. For mean CO concentrations measured 3.5 ft. above the water, reductions of 25%, 18%, and 23% were measured at 20, 40, and 60 ft. behind the boat, respectively, when the FAE system was used. For mean CO concentrations measured 5 ft. above the water reductions of 62%, 26%, and 40% were measured at 20, 40, and 60 ft. behind the boat, respectively, when the FAE system was used. The peak CO concentration measured on the Hobie Cat with the FAE system off was 90 ppm 2 ft. above the water and 10 ft. behind the boat. The peak CO concentration measured on the Hobie Cat with the FAE system on was 54 ppm 2 ft. above the water and 10 ft. behind the boat.

ToxiUltra CO Samples while the Boat was Underway (10 mph)

Summary statistics for CO concentrations with and without the FAE system for the boat traveling at 10 mph are listed in Table 3. The Hobie Cat could not be towed in the centerline 10 ft. behind the boat at 10 mph due to wake turbulence. Comparing the results from Tables 2 and 3 showed that higher speeds reduced the CO concentrations. The mean CO concentration at the front of the passenger compartment of the boat on the port side was reduced 50% with the FAE system (from 4.2 to 2.1 ppm). Mean CO concentrations measured in the middle of the boat on the starboard side were reduced by 40% with the FAE system. At the stern of the boat the mean CO concentration was 5.4 ppm without and 3.7 ppm with the FAE system for a reduction of 32%. Peak CO concentrations were measure at the stern of 147 ppm without and 126 ppm with the FAE system.

As was the case with CO measurements made at 5 mph, Figure 13 shows that the CO concentrations measured on the Hobie Cat while traveling 10 mph decreased with distance from the boat and height above the water. At 10 mph all CO measurements were much lower than at 5 mph. Percent CO reductions behind the boat due to the FAE ranged from 59-87%. For mean

CO concentrations measured 2, 3.5 and 5 ft. above the water and at 20, 40, and 60 ft. behind the boat, reductions in CO concentrations ranged between 59 and 87% when the FAE system was used. The peak CO concentration measured on the Hobie Cat while traveling at 10 mph with the FAE system off was 49 ppm 2 ft. above the water and 20 ft. behind the boat. The peak CO concentration measured on the Hobie Cat with the FAE system on was 30 ppm 2 ft. above the water and 40 ft. behind the boat.

ToxiUltra CO Samples while the Boat was Underway (15 mph)

Summary statistic for CO concentrations with and without the FAE system while the boat was traveling 15 mph are listed in Table 4. The Hobie Cat could not be towed as close as 10 ft. or 20 ft. behind the boat at 15 mph. CO concentrations were all lower with the increase in speed from 10 to 15 mph. The mean CO concentration at the front of the passenger compartment of the boat on the port side was 2.8 ppm without the FAE system and 3.86 ppm with the FAE system for an increase of 50%. For the CO measurements collected in the middle of the boat on the starboard side the mean CO concentration was 4.3 ppm without and 2.3 ppm with the FAE system for a reduction of 46%. At the stern of the boat the mean CO concentration was 4.0 ppm without and 2.0 ppm with the FAE system for a reduction of 50%. Peak CO concentrations were measured at the stern of 134 ppm without and 7 ppm with the FAE system.

For the CO concentrations measured on the Hobie Cat, Figure 14 shows that mean CO concentrations generally decreased with distance from the boat and height above the water. Reductions in mean CO exposures at distances of 40 and 60 ft. behind the boat and 2, 3.5, and 5 ft. above the water were between 71 and 90% with the FAE emission system (Figure 15). The peak CO concentration measured on the Hobie Cat with the FAE system off was 66 ppm 2 ft. above the water and 40 ft. behind the boat. The peak CO concentration measured on the Hobie Cat with the FAE system on was 11 ppm 2 ft. above the water and 40 ft. behind the boat.

ToxiUltra Personal CO Samples while Wake Surfing (10 mph)

Summary statistics for CO concentrations with and without the FAE system at various locations on the boat and on individuals who were wake surfing are listed in Table 5. The boat typically travels at approximately 10 mph to produce the desired wake size for surfing. The mean CO concentration at the front of the passenger compartment of the boat on the port side increased 15% with the FAE system for 7.7 ppm without the FAE system and 8.8 ppm with the FAE emission system. For the CO measurements collected in the middle of the boat on the starboard side the mean CO concentration was reduced by 53% (from 19 ppm to 8.7 ppm) with the FAE system. At the stern of the boat the mean CO concentration was 45 ppm without and 23 ppm with the FAE system for a reduction of 49%. Peak CO concentrations were measure at the stern of 509 ppm without and 388 ppm with the FAE system. The mean CO exposure measured on a wake surfer with the FAE system off was 17 ppm and 3.3 ppm with the system on, for a reduction of 80% when using the FAE system. The peak CO exposure to the wake surfer was 78 ppm without and 16 ppm with the FAE system.

Environmental Measurements

Ambient air temperature and relatively humidity measurements were periodically taken throughout the two days of CO monitoring. During two days of sampling the mean ambient air temperature was 34°C and ranged from 29 to 37 °C. Average relative humidity was 30% and ranged from 20 to 40%.

DISCUSSION AND CONCLUSIONS

The mean CO concentrations measured on or behind the evaluated ski boat were similar to results from previous evaluations by Echt et al. 2003, Earnest et al. 2003, the U.S. Coast Guard (USCG/ABYC 2003), and Mann (Mann 2004). Peak CO concentrations at the stern of the idling boat were 549 ppm without and 370 ppm with the FAE emission system. Peak CO concentrations at the stern of the boat while traveling at 5 mph were 1,137 ppm (and higher) without and 267 ppm with the FAE emission system. All of these values exceed the NIOSH REL of 200 ppm ceiling.

At boat speeds of 10 and 15 mph, CO concentrations on and behind the boat were significantly reduced when the FAE system was used. The FAE system reduced CO exposures to wake surfers by approximately 80%; however, in general the wake surfer exposures were fairly low even without the FAE system (mean = 17 ppm). The data in this report demonstrates the need to better understand the extent of CO exposures for all towed water sports. Perhaps the best method to assess CO exposures during towed watersports would involve biological monitoring of participants using exhaled breath analysis. NIOSH researchers plan to conduct this type of study in the future. CO concentrations measured while the boat was idling and traveling at 5 mph (inside the boat and behind the boat) were mixed depending on whether the FAE system was on or off (falling in some cases and increasing in others).

Mean CO concentrations measured behind the boat show that at all speeds and distances from the boat the CO concentrations decreased with height above the water surface. This finding seems reasonable because the exhaust gasses on typical inboard boats exit above the waterline into the air, yet near the surface of the water. The FAE system injects the exhaust gasses into the water, nominally 12 to 18 inces below the waterline. None of the mean CO concentrations measured at various distances from the boat exceeded the World Health Organization (WHO) guideline of 87 ppm for 15 minutes.

The mechanism(s) responsible for CO reductions behind the boat is(are) unclear; however, the effect of the FAE system was strongest at speeds of 10 mph or greater. There are several plausible explanations for this result including some or all of the following: the CO was chemically scrubbed by the water, the CO was dissolved into the water, and/or the CO was diluted and dispersed away from the stern of the boat by the prop wash.

During scrubbing, the gas undergoes a chemical reaction with the water. Scrubbing has been the primary focus of the FAE manufacturer. CO is 2% to 2.5% soluble in water at recreational use lake temperatures, requiring approximately 40 to 50 times the water to the volume of the exhaust gases (Mann, 2004). Free oxygen in the water combines with the CO to form CO_2. Industries, such as commercial shipping or power/chemical plants use scrubbers to remove hazardous NO_x, SO_x, hydrocarbons (HCs), and soot from exhaust streams. There is a great deal of published research on catalysts and scrubbing technologies for NOx, SOx, HCs, and soot; however, there is relatively little in the literature on scrubbing of CO which makes it difficult to evaluate this claim.

CO could also be dissolving in the water much like carbon dioxide in a carbonated beverage. CO has a low solubility in water (see below), especially when compared to other exhaust gases. The low solubility of CO in water indicates that this mechanism plays a small role in reducing CO concentrations behind the boat. For a slightly soluble compound to dissolve, fairly long contact times are required between gas and water which is unlikely to occur as the gas bubbles to the surface. Research on exhaust gases dissolving in water has been inconclusive (Clark, 1998).

Volume of gas (reduced to STP) that can be dissolved in 1 volume of water at the temperature (°C) indicated. (Perry 5th ed.)

Gas	0°	10°	20°	60°
carbon dioxide	1.713	1.194	0.878	0.359
carbon monoxide	0.03537	0.02816	0.02319	0.01488
nitrogen dioxide	0.07381	0.05709	0.04706	0.02954
sulphur dioxide	79.789	56.647	39.374	--------

Microbubbles and disengagement provide an alternative explanation for the reduction in CO concentrations. The CO might be bonding with or getting trapped in the water for a brief time before freeing itself and bubbling to the surface. During the FAE field evaluation, the engine exhaust was observed forming a distinct cone in the water behind the boat which did not appear to disperse. When the FAE system was not installed the noticeable exhaust cone disappeared. The delay before the CO is detected in the air could be compounded by the formation of microbubbles which, according to the Navier-Stokes equations, would take significantly longer to reach the surface (McCabe 3rd ed, Perry 5th ed).

Stokes Equation for Bubbles with a Reynolds' Number < 0.3:

$$u_t = \frac{a_e D_p^2 (\rho_p - \rho)}{18\mu}$$

Intermediate Approximation for Bubbles with a 0.3 < Reynolds' Number < 1000

$$u_t = \frac{0.153 a_e^{0.71} D_p^{1.14} (\rho_p - \rho)}{\rho^{0.29} \mu^{0.43}}$$

Newton's Approximation for Bubbles with a Reynolds' Number > 200,000

$$u_t = 1.75\sqrt{\frac{a_e D_p(\rho_p - \rho)}{\rho}}$$

Where:

u_t = Terminal velocity (ft / s)
a_e = Acceleration (ft / s)
D_p = Particle diameter (m)
ρ_p = Density of bubble (lb / ft^3)
ρ = Density of water (surroundings) (lb / ft^3)
μ = Dynamic viscosity of water (surroundings)

The curves in Figure 16 seem to correlate well with the measurements found during this study (Mann, 2004). The very large bubbles (centimeters) would surface almost immediately (<20 feet) and there were concentrations of CO detected in that range. Between 20 and 40 feet there should be a peak in the CO concentration because some of the largest bubbles moving according to Stokes' law (approximately 0.0005 m) and the large bubbles (>0.8 cm) would reach the surface at that distance. However, many of the bubbles, those between approximately 0.0005 m and 0.004 m, would take much longer to reach the surface, likely behind the detectors (> 80 feet). It may be possible that the exhaust gases trapped in the small bubbles have sufficient time to dissolve more completely into the surrounding water so that when the bubble surfaces there is a lower concentration of gas released.

It is difficult to say whether or not CO can be successfully scrubbed from exhaust. The low solubility in water and the short contact time suggest that it is unlikely that CO is actually dissolved into the water. It is more likely that there is more time before the bubbles containing CO reach the surface and dilute. NIOSH researchers plan to cunduct a controlled laboratory study to more fully understand and address this issue.

REFERENCES

ACGIH (1996). Documentation of Threshold Limit Values and Biological Exposure Indices. Cincinnati, OH, American Conference of Governmental Industrial Hygienists.

CARB (1998). Evaluation of Unlimited Technologies International, Inc.'s Series SA090 New Aftermarket Three-way Catalytic Converter for Exemption From the Prohibitions in Vehicle Code Section 27156, and Title 13 California Code of Regulations Section 2222(h). El Monte, CA, State of California Air Resources Board: 6.

CDC (1988). MMWR 37, supp (S-7) NIOSH Recommendations for Occupational Safety and Health Standards. Atlanta, GA, Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

CDC (2000). MMWR 49, Houseboat-Associated Carbon Monoxide Poisonings on Lake Powell— Arizona and Utah, 2000. Atlanta, GA, Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

CFR (1997). 29 CFR 1910.1000, Chapter XVII - Occupational Safety and Health Administration. Code of Federal Regulations, Table Z-1, Limits for Air Contaminants. Washington, DC: U.S. Federal Register.

CFR (1997). 29 CFR 1910.1000, Code of Federal Regulations. Washington, DC: U.S., Government Printing Office, Federal Register.

Dunn, K. H., G. S. Earnest, et al. (2001). Comparison of a Dry Stack with Existing Generator Exhaust Systems for Prevention of Carbon Monoxide Poisonings on Houseboats. Cincinnati, OH, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health: 30.

Dunn, K. H., R. M. Hall, et al. (2001). An Evaluation of an Engineering Control to Prevent Carbon Monoxide Poisonings of Individuals on Houseboats at Somerset Custom Houseboats. Cincinnati, OH, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health: 35.

Earnest, G. S., K. H. Dunn, et al. (2001). An Evaluation of an Engineering Control to Prevent Carbon Monoxide Poisonings of Individuals on Houseboats. Cincinnati, Oh, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health: 35.

Earnest, G. S., R. L. Mickelsen, et al. (1997). "Carbon Monoxide Poisonings from Small, Gasoline-Powered, Internal Combustion Engines: Just What Is a "Well-Ventilated Area"?" Am. Ind. Hyg. Assoc. J. **58**(11): 787-791.

Earnest, G. S., A. Echt, et al. (2003). Carbon Monoxide Emissions and Exposures on Recreational Boats under various Operating Conditions. Lake Mead, Nevada and Lake Powell, Arizona. USDHHS, PHS, CDC, NIOSH, Cincinnati, Ohio, EPHB No. 171-05ee2.

Echt, A., G.S. Earnest, et al. (2003). Carbon Monoxide Emissions and Exposures on Recreational Boats under various Operating Conditions. Lake Norman, N.C. USDHHS, PHS, CDC, NIOSH, Cincinnati, Ohio, EPHB No 171-31a.

Ehlers, J. J., J. B. McCammon, et al. (1996). NIOSH/CDPHE/CPSC/OSHA/EPA Alert: Preventing Carbon Monoxide Poisoning from Small Gasoline-Powered Engines and Tools, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

Envirolift (2001). Envirolift Product Literature. Charlotte, NC.

EPA (1991). Air Quality Criteria for Carbon Monoxide. Washington, DC, U.S. Environmental Protection Agency.

EPA (1996). Environmental Fact Sheet: Emission Standards for New Gasoline Marine Engines. Ann Arbor, Michigan, Environmental Protection Agency: 4.

Forbes, W. H., F. Sargent, et al. (1945). "The Rate of CO Uptake by Normal Man." Am Journal of Physiology **143**:594-608.

Hall, R. M. (2000). Letter of December 18, 2000 from Ronald M. Hall, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services and to Rice C. Leach, Commissioner, Cabinet for Health Services, Department of Public Health, Commonwealth of Kentucky. Cincinnati, OH, NIOSH: December 18, 2000.

Hall, R. M. and J. B. McCammon (2000). Letter of November 21, 2000 from Ronald M. Hall and Jane B. McCammon, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services and to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, Arizona. Cincinnati, OH, NIOSH: November 21, 2000.

Heywood, J. B. (1988). Internal Combustion Engine Fundamentals. New York, New York, McGraw-Hill Inc.

Kales, S. N. (1993). "Carbon Monoxide Intoxication." American Family Physician 48(6):1100-1104.

Kovein, R. J., G. S. Earnest, et al. (1998). CO Poisoning from Small Gasoline-Powered Engines: A Control Technology Solution, U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health.

MariTech (2001). Conversation between Dr. G. Scott Earnest of EPHB, DART, NIOSH, and Keith Jackson, President of MariTech Industries, July 24, 2001. Anderson, California.

Mann, L.W. (2004). Carbon Monoxide Exposure While Operating an Inboard Boat and Related Water Sports Activities. http://www.FreshAirExhaust.com.

McCammon, J. B. and T. Radtke (2000). Letter of September 28, 2000 from J. McCammon, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services and T. Radtke, U.S. Department of the Interior, to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, Arizona. Denver, CO, NIOSH.

McCammon, J. B., T. Radtke, et al. (2001). Letter of February 20, 2001, from J. McCammon, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services, T. Radtke, U.S. Department of the Interior, and Dr. Robert Baron Prehospital Medical Care, Glen Canyon National Recreation Area, to Joe Alston, Park Superintendent, Glen Canyon National Recreation Area, Page, Arizona. Denver, CO, NIOSH.

McCammon, J. B. (2001). Letter of July 31, 2001 from J. McCammon, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services, to Kayci Cook Collins, Assistant Park Superintendent, Glen Canyon National Recreation Area, Page, Arizona. Denver, CO, NIOSH, Denver Field Office: 39.

McCammon, J. B., T. Radtke, et al. (2002). Letter of December 3, 2002 from J. McCammon, National Institute for Occupational Safety and Health, Centers for Disease Control and Prevention, Public Health Service, U.S. Department of Health and Human Services, T. Radtke and D. Bleicher, U.S. Department of the Interior, to Kitty Roberts, Park Superintendent, Glen Canyon National Recreation Area, Page, Arizona. Denver, CO, NIOSH: 28.

NIOSH (1972). Criteria for a Recommended Standard: Occupational Exposure to Carbon Monoxide. Cincinnati, OH, National Institute for Occupational Safety and Health.

NIOSH (1977). Occupational Diseases: A Guide to their Recognition. Cincinnati, OH, National Institute for Occupational Safety and Health.

NIOSH (1979). A Guide to Work Relatedness of Disease. Cincinnati, OH, Department of Health Education and Welfare, Public Health Service, Centers for Disease Control, National Institute for Occupational Safety and Health.

NIOSH (2000). Pocket Guide to Chemical Hazards and Other Databases: Immediately Dangerous to Life and Health Concentrations, DHHS (NIOSH).

Plog, B. A. (1988). Fundamentals of Industrial Hygiene. Chicago, Illinois, National Safety Council.

Proctor, N. H., J. P. Hughes, et al. (1988). Chemical Hazards of the Workplace. Philadelphia, PA, J.P. Lippincott Co.

Simeone, L. F. (1990). A Simple Carburetor Model for Predicting Engine Air-Fuel Ratios and Carbon Monoxide Emissions as a Function of Inlet Conditions. Cambridge, Massachusetts, U.S. Department of Transportation, Research and Special Programs Administration: 11.

Westerbeke (2001). Conversation between Dr. G. Scott Earnest of EPHB, DART, NIOSH, and Carlton Bryant, Vice-President of Westerbeke Corporation, February 21, 2001. Avon, Massachusetts.

Westerbeke (2001). Unpublished Data: Engine exhaust emission test results. Taunton, MA: 2.

WHO (1999). Environmental Health Criteria 213 - Carbon Monoxide (Second Edition). Geneva, Switzerland, World Health Organization.