CARBON MONOXIDE EMISSIONS AND EXPOSURES ON RECREATIONAL BOATS UNDER VARIOUS OPERATING CONDITIONS

(Lake Mead, NV, and Lake Powell, AZ)

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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) exposures on over ten recreational boats in the United States, including ski boats, cabin cruisers, deck boats, fishing boats, and personal watercraft. Most of the evaluated boats were speed boats or cabin cruisers, ranging in age from new to 25 years old. These boats had gasoline-powered, propulsion engines, and the evaluated cabin cruisers used gasoline-powered generators to provide electricity.

This investigation grew from a series of recent studies to reduce CO exposures and poisonings on houseboats. Epidemiologic investigations found that from 1990 to 2000, 111 CO poisonings occurred on Lake Powell, near the Arizona and Utah border. Seventy-four of the poisonings occurred on houseboats and 37 poisonings occurred on other types of recreational boats. NIOSH researchers are aware of 106 nationwide CO poisonings associated with recreational boats (non-houseboats).

This study was performed for the U.S. Coast Guard to better understand how CO poisonings can occur on recreational boats and to identify the most hazardous conditions. Boats were evaluated while stationary and at multiple speeds, ranging from 2.5 to 25 miles per hour. CO concentrations were measured by multiple real-time instruments, which were placed at different locations on the boats and at various distances behind the boat while moving.

Study results indicated that stationary conditions were generally the most hazardous; however, many boats while moving had elevated CO concentrations near the rear deck. Most of the evaluated boats generated hazardous CO concentrations: peak CO concentrations often exceeded 1,000 parts per million (ppm), while average CO concentrations were well over 100 ppm at the stern (rear). Two boats—one with a 150-horsepower (hp), 2-stroke, direct-fuel injected Evinrude Ficht outboard engine, and the other with a 40-hp, 4-stroke Johnson outboard engine—had dramatically lower CO concentrations than any of the other evaluated boats. Peak and average CO concentrations for these two outboard engines were an order of magnitude lower than engines on most of the other evaluated boats. These two new engines depended on recently developed technologies to burn cleanly and comply with the EPA regulations for outboard marine engines.

Greater use of gasoline-powered marine engines having engineering controls to lower CO emissions could dramatically reduce the likelihood of CO poisonings related to recreational boating. Development and use of emission control technologies such as catalytic converters and emission control devices (ECDs), and greater use of cleaner-burning drive engines and generators could minimize the future number of CO poisonings in the marine environment.

BACKGROUND

On April 22 through 25, 2002, researchers from the National Institute for Occupational Safety and Health (NIOSH) evaluated carbon monoxide (CO) emissions and exposures on a variety of recreational boats at Callville Bay Marina on Lake Mead, Nevada, and at Wahweap Marina on Lake Powell, near Page, Arizona. This evaluation was conducted under an interagency agreement between the U.S. Coast Guard's Office of Boating Safety and NIOSH to become more fully aware of the types of CO emissions and exposures that were occurring on recreational boats used in the United States today. A similar NIOSH survey occurred at Lake Norman, North Carolina, and the results of that survey are described in a separate report. In both of these surveys, a cross-section of recreational boats were evaluated, including ski boats, cabin cruisers, deck boats, fishing boats, and personal watercraft. Each of the evaluated boats were propelled by gasoline-powered engines, and the evaluated cabin cruiser had a gasoline-powered generator to provide electrical power for onboard appliances. This report provides background information and describes the NIOSH study methods, results, discussion, conclusions, and recommendations.

The current investigation of CO exposures on recreational boats, grew out of a series of studies related to CO exposures and poisonings on houseboats. Initial investigations involving CO exposure and poisonings on houseboats began at Lake Powell in September and October 2000. During these investigations hazardous CO concentrations were measured on numerous houseboats [Hall and McCammon 2000; McCammon and Radtke 2000]. Epidemiologic investigations have discovered that from 1990 to 2000, 111 CO poisoning cases had occurred on Lake Powell. Seventy-four of the poisonings occurred on houseboats, and 37 poisonings occurred on other types of recreational boats [McCammon, Radtke, et al. 2001; CDC 2000].

A great deal of work has already been performed to evaluate engineering controls for CO on houseboats, but less effort has been given to understanding the extent of the CO hazard on other types of recreational boats. The question remained, how and why did 37 CO poisonings occur on nonhouseboats and how typical is this of other U.S. bodies of water? Overall, 106 CO poisonings are known to have occurred on or near recreational boats (non-houseboats). Forty-two of these poisonings occurred at Lake Powell and 64 occurred on other waters.

The severity and extent of these poisonings (described below) led to a number of questions such as:

- Where is it safe on the boat?
- Is it safe to pull my children (grandchildren) behind the boat in a tube?
- How long should the rope be?
- Is it safe to sit in the rear seat and under what conditions?

The current study was intended to provide a better understanding of the CO exposures that occur on recreational boats and to identify the most hazardous conditions. Collection of environmental data was vital to this effort, by testing the variability between different kinds of boats, engines, and design features. This data will be used to develop mathematical models to more fully answer some of the above questions.

CO Poisonings Outside the Cabin Area of Recreational boats (Non-houseboats)

At Lake Powell, since 1990, 3 deaths and 22 non-fatal poisonings have occurred outside of any enclosure on (non-houseboat) recreational boats, such as ski boats and cabin cruisers. The first person died while sitting in the driver's side transom seat, near the exhaust ports, and pulling a personal watercraft at about 10 miles per hour (mph), for approximately 45 minutes. The second fatal poisoning was an 18-year-old ski-boat passenger who died while "teak surfing"—a common water activity where a passenger, grasping boat handles and resting the upper torso on the boat's teakwood platform, is pulled behind the speeding boat [McCammon 2001]. In this case, after only one to two minutes, one of three teak surfers lost consciousness, sank beneath the surface, and died. An autopsy revealed a carboxyhemoglobin (COHb) level of 57%, and NIOSH calculated that his exposure concentration ranged from 9,000 to 27,000 parts per million (ppm). The third fatal poisoning was a 9-year-old girl playing in shallow water, at the rear of a cabin cruiser, near the terminus of a gasoline-powered Kohler 5 Kilowatt (Kw) generator [McCammon, 2002].

Another fatal poisoning occurred in a recreational boat, enclosed by a canvas roof and side walls, but having an open back. The victim was driving his boat and towing a second. After approximately 10–30 minutes, all four occupants lost consciousness. The boat eventually beached itself upon running out of gas, and twelve hours later, the three passengers awoke to find the driver dead. Autopsy results indicated that the COHb concentration for the victim was 53%.

Of the 22 non-fatal CO poisonings occurring outside the cabin area of recreational boats, 11 resulted in loss of consciousness. All but one of the 22 outdoor recreational boat poisonings were associated with exposures to emissions from gasoline-powered propulsion engines: ten passengers were riding in the back of a moving boat; four were in a boat being towed by another boat; three were teak surfing (two of these involved the teak surfing fatalities described above); one lost consciousness as he occupied the swim platform; one was on the swim platform playing with a shower device that drew water from the operating propulsion engine; and two were in the water. Exposure duration was documented for fourteen of these cases: three were exposed to engine exhaust for less than ten minutes; five were exposed for ten to 60 minutes; and six were exposed for greater than 60 minutes.

On other bodies of water, 38 boat-related CO poisonings (18 fatal and 20 non-fatal) have been reported outside the cabin area of recreational boats (non-houseboat). Investigative and/or medical records were collected for 37 of these cases. Four of the outdoor poisonings occurred on or near cabin-cruisers and 32 occurred on or near ski boats. Twenty-three of the 38 poisonings occurred while the boat was underway (again, outside any enclosure), and 12 occurred while the boat was stationary.

Twenty-seven of the 38 poisonings were related to occupancy of the swim platform or swim step at the rear of the boat. Five of these people were swimming behind stationary recreational boats when poisoned, and six were seated on the transoms or in the rear seats of the boats.

CO Poisonings Inside the Cabin Area of Recreational boats (Non-houseboats)

Indoor CO poisonings have long been recognized as a problem on boats, in automobiles, and buildings. Since 1990, a total of 84 CO poisonings have been reported as occurring inside the enclosed cabin area of recreational boats. Seventeen of these poisonings resulted in death (1 at Lake Powell and 16 on other water bodies). Nineteen non-fatal poisonings inside recreational boats at Lake Powell and 48 on other water bodies have been reported. The U.S. Coast Guard has records of additional watercraft indoor poisonings in their database.

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) because occupational standards do not provide the same degree of protection as they do for the healthy worker population. 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) have 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

Air sampling for CO, ventilation, and wind-velocity measurements were collected on 11 different recreational boats built by various manufacturers, including Carver, Four Winns, Polaris, Outboard Marine Corporation (OMC), SeaRay, Glastron, Bayliner, and Crownline. Photos of the evaluated boats are shown in Figures 1 through 11. The evaluated boats ranged in age from 27 years old to new. Drive engines and generators on the boats also had a wide range of ages. Drive engines used on the evaluated boats were manufactured by Pleasurecraft, Volvo, Evinrude, Polaris, Johnson, Mercury, and Ford. The two evaluated cabin cruisers also had generator sets. One generator was manufactured by Onan and the other by Westerbeke. Data was collected to evaluate the CO emissions of gasoline-powered engines and CO exposures on and near the boats, operating under various conditions.

A description of the boats, the drive engines, and generators is provided below. Boat engines are classified, in part, depending on where on the boat they are installed. On inboard engines, the engine and drive train are permanently mounted near the center of the boat's hull, and the propellor shaft penetrates beneath the hull. Stern drives are located near the back of the boat and in the hull. Stern drives also have permanently mounted engines; however, the drive train penetrates the transom of the vessel. Outboards are attached via a bracket to the back of the boat or transom. Typically, boats less than 16 feet (ft) long use outboard motors, boats between 16 and 30 ft can use outboard or stern drive units, and boats over 30 ft long use inboard motors. There are some exceptions to this general principle.

Description of the Evaluated Recreational Boats

<u>Boats evaluated on Lake Mead</u>

1. **Carver Model 3607, 36-foot Aft cabin Cruiser, 1983**
   Engines: 2, Pleasure craft, 454 cubic inch (ci)-330 horsepower (hp)
   Generator: 6.5 Kw Onan, 4 cylinder, 4 stroke, 1,800 revolutions per minute (rpm)
   Approximate dimensions of boat: 36 by 13 ft
   Exhaust Configuration: 1) Drive engine exhaust through propellor hub and 2) generator exhaust through hole on aft port side.

2. **Sun Country Marine Deck Boat**
   Engines: Volvo Penta 4.3 GL PEFS
   Generator: None
   Approximate dimensions of boat:
   Exhaust Configuration: Exhaust through propellor hub

3. **Four Winns 180 Horizon**
   Engines: Evinrude Ficht®, 2000 Ram injection, 150 hp outboard
   Generator: None
   Approximate dimensions of boat: 18 by 8 ft
   Exhaust Configuration: Exhaust through propellor hub

4. **Four Winns 200 Horizon**
   Engines: Volvo Penta 2001 Stern Drive, deep vee
   Generator: None

Approximate dimensions of boat: 20 by 8 ft, 5 in.
Exhaust Configuration: Exhaust through propellor hub

5. **Polaris Virage Personal Watercraft 2000**
   Engines: 95-hp, twin cylinder, 700 engine
   Generator: None
   Approximate dimensions of boat: 10 by 4 ft.
   Exhaust Configuration: Exhaust through rear jet

6. **Outboard Marine Corporation (OMC) aluminum boat group Model 1880**
   Engines: 1998, Johnson outboard, 40 hp, 2-stroke, Model J40PLEEA
   Generator: None
   Approximate dimensions of boat: 18 ft.
   Exhaust Configuration: Exhaust through propellor hub

7. **OMC aluminum boat group Model 1880**
   Engines: 2001 Johnson outboard, 40 hp, 4-stroke, Model J40PL4SN
   Generator: None
   Approximate dimensions of boat: 18 ft.
   Exhaust Configuration: Exhaust through propellor hub

Boats evaluated on Lake Powell

1. **SeaRay, 1986, 18-foot**
   Engines: 4.3 liter Mercruiser V6, Alpha 1 stern drive
   Generator: None
   Approximate dimensions of boat: 18 by 7 ft, 6 in.
   Exhaust Configuration: Exhaust through propellor hub

2. **Glastron 225 Bal Harbor, 1975, 22-foot Cuddy Cabin Cruiser**
   Engines: V8 351 Ford Stern Drive
   Generator: None
   Approximate dimensions of boat: 22 by 8 ft.
   Exhaust Configuration: Exhaust above the propellor (in the water)

3. **Bayliner 32-foot Flybridge Cruiser, 1988**
   Engines: 2 V8 350 Volvo engines inboard, I/O drive
   Generator: 3.5 kw Westerbeke Generator
   Approximate dimensions of boat: 32 by 11 ft, 6 in.
   Exhaust Configuration: Exhaust through propellor hub

4. Crownline 18-foot, Bowrider 1996

Engines: 350 OMC Cobra Drive, carbureted
Generator: None
Approximate dimensions of boat: 18 by 7 ft, 8 in.
Exhaust Configuration: Exhaust through propellor hub

Two primary differences between automobile engines and marine engines used on recreational boats relate 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 to mix water with exhaust gases 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.

For the two generators, the hot exhaust gases from the generators were injected with water, near the end of the exhaust manifold, in a process commonly called "water-jacketing." Water-jacketing is used for exhaust cooling and noise reduction. Because the generator sits below the waterline, the water-jacketed exhaust passes through a lift muffler, which further reduces noise and forces the exhaust gases and water up and out through a hole beneath the swim platform.

Description of the Evaluation Equipment

Emissions from the generator and drive engines were characterized by a Ferret Instruments (Cheboygan, MI) Gaslink LT Five Gas Emissions Analyzer and a KAL Equipment (Cleveland, OH) Model 5000 Four Gas Emissions Analyzer. Both analyzers measure CO, carbon dioxide (CO_2), hydrocarbons, and oxygen. The five gas analyzer also measures nitrogen oxides (NO_x). All measurements are expressed as percentages, except for hydrocarbons and NO_x, which are ppm. (One percent of contaminant is equivalent to 10,000 ppm.)

CO concentrations were measured at various locations on the houseboat by ToxiUltra Atmospheric Monitors (Biometrics, Inc.), equipped with CO sensors. ToxiUltra CO monitors were calibrated before and after use, according to the manufacturer's recommendations. These monitors are direct-reading instruments, having data logging capabilities. The instruments were operated in the passive diffusion mode, having a 15–30 second sampling interval. The instruments have a nominal range, from 0 ppm to approximately 999 ppm.

CO concentration data was also collected with detector tubes (Draeger A.G. [Lubeck, Germany] CO, CH 29901– range 0.3% [3,000 ppm] to 7% [70,000 ppm]) in the areas below and near the rear swim deck. Having a bellows–type pump, detector tubes drew air 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 Mine Safety and Health Administration (MSHA) 50–mL glass evacuated containers. These samples were collected by snapping open the top of the glass container and allowing the air to enter. Then, containers were sealed with wax–impregnated MSHA caps. The samples were then sent by overnight delivery to the MSHA laboratory in Pittsburgh, PA, where a HP6890 gas chromatograph, equipped with dual columns (molecular sieve and porapak) and thermal conductivity detectors, was used to analyze them for CO.

During air sampling, researchers took wind velocity measurements when the boat was stationary or measured air velocity with respect to the boat when it was underway, by using either an omnidirectional (Gill Instruments Ltd., Hampshire, U.K.) ultrasonic anemometer or a VelociCalc Plus Model 8360 air velocity meter (TSI Inc., St. Paul, MN). The ultrasonic anemometer is based on a basic time-of-flight operating principle that depends upon the dimensions and geometry of an array of transducers. Transducer pairs alternately transmit and receive pulses of high frequency ultrasound. The time-of-flight of the ultrasonic waves are measured and recorded, and this time is used to calculate wind velocities in the X-, Y-, and Z-axes. This instrument is capable of measuring wind velocities of up to 45 meters per second (m/sec) and take 100 measurements per second. The air velocity meter measured wind speeds based upon the heat transfer to the air from a heated probe.

Description of Procedures

Evaluations were conducted on various boats and involved teams of two or three people. Each team consisted of a person from the collaborating organization to steer the boats, start the engines, and provide mechanical assistance when necessary. Evaluations were conducted over several days. Following each day of data collection, NIOSH researchers downloaded data and recalibrated instruments. Two to four boats were typically evaluated per day. For small ski boats, evaluations progressed quickly, requiring only one or two hours. For larger cabin cruisers, having a generator and drive engines, evaluations required more time. Most of the evaluations included both stationary and underway conditions. During these evaluations of the larger boats, the generator alone was operated for approximately 30 minutes, followed by both drive engines and the generator set to an operating mode for another 15 minutes. Cold start emissions were also evaluated during the stationary tests.

Underway boat emissions were evaluated at three or four different speeds for each of the 11 boats except the Carver Cabin Cruiser and Polaris PWC. The gathered data is of particular importance to ski boats and others that pull people behind boats in the water. Boat speeds typically included idle speed, one or two midrange speeds, and open throttle. Boat speed was measured by a Magellan Global Positioning System. When boats were underway, researchers oriented the wind monitors' North heading in the direction that the boat was moving. Because of this configuration, wind directions were measured relative to the boat's heading. Researchers gathered CO samples at various locations on the boat and behind the boat, using ToxiUltra monitors, which were connected at three locations on a long pole (see Figure 12). Monitors extending over the water were partially wrapped in plastic to protect them from splashes. The emissions analyzer was used to measure CO concentrations near the boats' sterns.

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 monitors are shown in Tables 1 through 11 of the Appendix. These tables are organized so that the sample location is designated along the left-hand column and the operating conditions are listed across the top row. For each sample location and condition a CO mean, standard deviation, sample number and peak concentration is reported. Each CO mean and standard deviation is rounded to the nearest whole number. CO concentrations exceeding approximately 1,000 ppm in Tables 1 through 11 indicate that the upper limit of the instrument was reached and the exact CO concentration and duration is uncertain. Graphs depicting some of the data in Tables 1 through 11 of the Appendix for selected boats and conditions are shown in Figures 13 through 17.

ToxiUltra CO Samples While the Boats were Stationary

CO concentrations measured on stationary boats were generally high. Peak CO concentrations commonly reached and exceeded the upper limit of the ToxiUltra CO monitors of around 1,000 ppm. The mean CO concentrations measured near the stern of many boats ranged from 500 to 1,000 ppm. There were some exceptions to these fairly high values. For example, mean CO concentrations measured near the sterns of the Fourwinns 180 Horizon, which had a 150-hp, direct fuel-injected, 2-stroke, Evinrude Ficht outboard engine (Appendix, Table 3) and of the OMC aluminum fishing boat, having a Johnson 40-hp, 4-stroke (Appendix, Table 7) outboard engine, were considerably less than those measured on most other evaluated boats.

CO concentrations measured inside stationary boats were much lower than CO concentrations measured near the stern. One of the most dramatic differences was found on the Carver aft cabin cruiser (Appendix, Table 1). Although mean CO concentrations measured on the lower rear deck of the Carver ranged from approximately 800 to 1,000 ppm, the mean CO concentrations measured in the interior of the boat were less than 15 ppm. Most of the boats had mean CO concentrations measured at interior locations of less than 20 ppm. There were a few boats that had higher interior concentrations. For example, some of the mid-sized boats that had large engines, such as the 18' SeaRay with a Mercruiser V6 engine (Appendix, Table 8), the Glastron Cuddy Cruiser with Ford V8 (Table 9), and the 18' Crownline Bowrider with a 350 Cobra engine (Appendix, Table 11) had interior mean CO concentrations ranging from 25 to 116 ppm.

ToxiUltra CO Samples while the Boat was Underway

Air sampling data was collected while the boats were underway, resulting in generally lower concentrations than those measured while the boats were stationary. CO concentrations measured on the boats tended to fall as the boats began to move and as speed increased. CO concentrations were measured in three areas:

- On or near the rear deck of the boat
- Inside of the boat
- On a pole at various distances eight to twelve feet behind the boat

CO concentrations measured on or near the sterns and rear decks of the boats were considerably higher than those measured either on the pole behind the boat or inside of the boat. For example, the Fourwinns 200 Horizon with Volvo Penta engine (Appendix, Table 4) had mean CO concentrations near the rear deck, of approximately 1,000 ppm or more, at speeds of approximately 1–2 mph. These values compare to mean CO concentrations that ranged from 26–417 ppm, 8–12 ft behind the boat, and from 1–60 ppm in the interior of the boat. Under most conditions, it appears that the concentrations measured eight to twelve feet behind the boat were slightly higher than the CO concentrations measured inside of the boat.

As boat speeds increased, CO concentrations at all locations tended to fall. However, this observed trend did not occur all of the time, as can be seen by taking a close look at Table 1 through 11 in the Appendix. A summary of average CO concentrations for four different boats is provided in Figures 13 through 17. Figure 13 presents data for a Fourwinns 200 Horizon with Volvo Penta sterndrive engine. Figure 14 provides data for the 18-ft Crownline Bowrider, having a 350 c.i. Cobra engine, and Figure 15 provides data for the Glastron Day Cuddy Cruiser, having a Ford V8 engine. Figures 16 and 17 provide mean CO concentrations for the 32-ft Bayliner cabin cruiser, having two V8 Volvo engines and for the Fourwinns 180 Horizon with 150-hp Evinrude Ficht drive engine, respectively. When these figures are reviewed closely, several trends become apparent.

- Mean CO concentrations are typically highest across the boats' stern.
- Mean CO concentrations measured behind the boat and in the boat interior are much less than those at the stern of the boat.
- Mean CO concentrations measured at all locations tend to fall as the velocity of the boat increases.
- Mean CO concentrations measured on boats having the cleaner burning outboard Evinrude Ficht engine were dramatically less than concentrations on the other evaluated boats.

Gas Emissions Analyzer, Detector Tubes, and Evacuated Container Results

Gas emissions analyzers, detector tubes, and glass evacuated containers were primarily used to characterize CO concentrations in and near the exhaust. These instruments were used because they are capable of reading higher CO concentrations than the ToxiUltra CO monitors, which have an upper limit of approximately 1,000 ppm. Because of the exhaust configurations on the evaluated boats (below or near the water line in constricted areas), measurements were not made directly in the engine exhaust. Rather, emissions were typically measured approximately six to twelve inches behind the boats' sterns near the water.

Summaries of the detector tube and evacuated container air sampling results are shown in Tables 1 through 4. Table 1 shows that CO concentrations measured with detector tubes at Lake Mead varied greatly depending upon location and operating condition. Several measurements above the IDLH 1,200 ppm limit were made when boats were stationary. A concentration of 500 ppm was measured behind the Fourwinns 200 Horizon, having a Volvo Penta engine, while it moved at 5 mph. The lowest CO concentrations were measured on the Fourwinns 180 Horizon, having a 150 hp Evinrude Ficht engine, and on the OMC aluminum boat, having a Johnson, 40-hp, 4 stroke engine. The detector tube results in Table 2 are similar to those found in Table 1. The Table 2 results again show fairly high CO concentrations being measured while the boats are stationary or moving at 5 mph or less.

Evacuated container results in Tables 3 and 4 are similar to the CO concentrations measured with detector tubes. For example, in Table 3 CO concentrations ranged from a high of 12,500 ppm for a stationary cold-start of the Sun Country Deck boat's Volvo Penta 4.3 GL engine to concentrations below 5 ppm near the 6.5 Kw Onan generator on the Carver Aft cabin Cruiser and near the Johnson 40-hp, 4 stroke outboard on the OMC aluminum fishing boat. In addition to the 12,500 ppm measured near the Sun Country Deck boat engine, other fairly high CO concentrations of 3,400 ppm, 2,600 ppm, and 4,000 ppm were measured near the two 454 Pleasurecraft drive engines on the Carver Aft cabin Cruiser, the Polaris Virage Personal Watercraft, and the SeaRay, having a 4.3 liter V6, respectively.

Data collected with the Ferret Instruments five gas emissions analyzer generally supported the CO data collected by other methods. In general, CO concentrations were fairly high in the open air near the stern of the boats during stationary cold-starts. It was not uncommon to measure instantaneous CO concentrations ranging from 500 to 5,000 ppm or higher when the engines were started. Following a cold-start, as the engines operated for short periods (typically a few minutes), the CO concentrations began to fall. CO concentrations measured at the stern of most of the underway boats varied widely. Average CO concentrations ranged from nondetectable to over 2500 ppm and peak CO concentrations exceeded 5000 ppm for certain boats and conditions.

Wind Velocity Measurements

Wind velocity measurements were taken by several instruments, including an ultrasonic anemometer and rotating vane anemometer while CO sampling data was gathered. In many cases, data was gathered while the boats were stationary and underway. Tables 5 and 6 provides boat speed and average relative wind velocities and standard deviations for various boats and test conditions. Table 5 contains data gathered at Lake Mead and Table 6 contains data gathered at Lake Powell. Boat speeds ranged from stationary to up to 20 mph. Relative wind velocities were typically within 5 mph of the boat speed. At Lake Mead relative wind speeds ranged from a low of 0.78 mph while stationary to 25.77 mph while the Four Winns 180 Horizon was moving at 20 mph. At Lake Powell relative wind speeds ranged from a low of 2.59 mph while the 32-ft Bayliner was moving at 5 mph to 25.38 mph while the same boat was moving at 20 mph. Most of the relative wind conditions were slightly higher than the speed of the boat; however, in a few cases, relative wind speed was less than the boat speed indicating a tail wind.

DISCUSSION

The current study has shown that hazardous CO concentrations occur on and near many U.S. recreational boat models and makes. This problem results from both old and new boats and engines. CO concentrations, as measured by three separate methods (i.e., real-time instruments, evacuated containers, and detector tubes), indicated concentrations approaching or exceeding the NIOSH IDLH value of 1,200 ppm for many boats. These high CO exposures are affecting the boating public, too, rather than being limited to just healthy adult marina workers. The general public, including young children and the elderly, may be more susceptible to CO health risks than the typical worker. In addition, many of these exposures occur to people who are in the water, or people who have been using alcohol, where the combination of dangerously high CO concentrations with a potential for drowning compounds the risk. Exposures to high CO concentrations on recreational boats are the result of many factors, including an individual's location, type and make of boat, relative wind speeds, engine size and design, and the influence EPA regulations have had on engine designs. Many of these issues are discussed in more detail below.

Sample Location, Boat Speed, and Wind Conditions

CO concentrations are highest during cold starts and during operation of gasoline-powered engines when the boat is stationary. At these two times in particular, people swimming or located near an exhaust terminus of an operating drive engine or generator can potentially experience CO poisoning possibly leading to death. In general, high CO emissions from gasoline-powered generators cause the most concern because they frequently are operated while boats are stationary. Drive engines are less problematic because they usually operate while boats are moving and, thus, individuals avoid getting near the operating drive engines for fear of a propellor strike. These reasons may explain why much of the initial surveillance and epidemiological CO poisoning data have involved houseboats. Many houseboats have fairly large gasoline-powered generators. Similarly, many cabin cruisers also have gasoline-powered generators.

For any given engine under stationary conditions, measured CO concentrations were directly related to the CO sensor's proximity to the engine's exhaust. CO concentrations near the boat's stern were typically the highest, and the CO concentrations measured inside the boat and on the pole behind the boat were substantially less. On a calm day, proximity to the exhaust terminus is the critical factor influencing exposure levels. As the wind speed increases, CO exposures on or near the boat tend to fall. The one notable exception to this rule can occur if a slight, sustained tailwind blows engine exhaust directly toward individuals on or near the boat.

The CO data for boats underway show that hazardous exposures may occur under certain conditions. For example, if a boat is operated at 5 mph or less, fairly high CO exposures (near the NIOSH ceiling of 200 ppm) can occur within 10 ft of the boat's stern. These results are produced by circumstances similar to those found during an engine cold start or idling. Typically, as the speed of a boat increases, the CO exposures decrease.

Our research showed that as a boat's speed increased, the CO sensors (which substituted for people on a boat or participating in water sports behind a boat) spent less time near the highest CO concentrations. At speeds of 20 mph or more, individuals at the bow (front) of the boat are not likely to be exposed to any CO while individuals near the stern or behind the boat may be exposed to higher CO concentrations but for relatively short periods. Individuals near the stern of the boat can be exposed to hazardous CO concentrations during such activities as teak-surfing or wake boarding. Generally, the closer the individual's breathing zone is to the engine exhaust and the slower the boat's speed, the more potentially hazardous the situation becomes. This is due in part to the boat's slow operating speed creating exhaust eddies (circular movements of air) which may cause high CO concentrations to recirculate behind the moving boat.

Wind conditions are also important because CO exposures tend to decrease as wind speeds increase. For a boat underway, induced wind and ambient wind are additive. In the current study, the additive effect was accounted for by measuring the relative wind velocity on the boat. For example, when a boat moves at 10 mph under completely calm wind conditions, the relative wind is approximately 10 mph from the bow toward the stern. If a boat moves at 10 mph into a head wind of 5 mph because the effect is additive, the relative wind condition is 15 mph. Under this condition, the two wind effects, (ambient and induced) tend to reduce CO exposures. However, if a boat moved at 10 mph under a tail wind of 8 mph, the relative wind condition would be just 2 mph toward the stern of the boat. For this scenario, the ambient tail wind would tend to increase the CO exposure as compared to the same condition with no ambient wind. The data in Tables 5 and 6 show that for all of the underway tests, the average relative wind velocity was toward the rear of the boat. Similarly, in most of the test conditions, the average relative wind velocity was greater than the boat speed indicating that the wind tended to reduce CO exposures.

Engine design

When large gasoline-powered engines operate as designed and have no catalytic converter or other pollution control devices, dangerously high CO concentrations are commonly emitted into the atmosphere. Exhaust gases released from a gasoline engine may contain from 0.1% to 10% CO (1,000 to 100,000 ppm). Engines operating at full-rated hp produce exhaust gases having approximately 0.3% CO (3,000 ppm) [Heywood 1988].

The relative CO concentrations produced by gasoline-powered engines depend upon engine design, operating conditions, and most importantly the fuel/air equivalence ratio [Plog 1988]. The fuel/air equivalence ratio is the actual fuel to air ratio, divided by the stoichiometric fuel to air ratio. Generally, an engine running rich will tend to produce higher concentrations of CO than the same engine running lean. Simeone predicted CO concentrations exhausted from marine engines as a function of air inlet and several other parameters [Simeone 1990]. Any restrictions that may exist on air inlets and exhaust ports for marine engines can potentially increase CO concentrations in the exhaust. As observed, in this study many factors influence the CO concentration exhausting from marine engines.

The current study showed dramatic differences from the CO produced by one gasoline-powered marine engine to another. For example, the 150-hp, fuel-injected Evinrude Ficht and the 40-hp, 4-stroke Johnson outboards produced dramatically less CO and other air pollutants than most of the other evaluated boat engines. Outboard engines have been regulated by the EPA since 1998. These outboard engines reduce CO and other air pollutants by tightly controlling the combustion process. The outboard engine manufacturers accomplished cleaner emissions by using a direct fuel injection process (Evinrude Ficht) or by converting from 2-stroke to 4-stroke design (Johnson). Besides the emission benefits, these engines typically use less gas (35%-50%), less oil (50%), are quieter, have quicker throttle response, and are easier to start. In addition to the Evinrude and Johnson outboards, Mercury, Yamaha, Suzuki, and Honda also produce low-emitting outboard engines that comply with EPA regulations. Unfortunately, the EPA regulations that apply to small gasoline-powered generators (<19 Kw) used on recreational boats and inboard and stern drive marine engines are much less stringent than the outboard regulations (as described below).

Environmental Protection Agency Regulations

Environmental Protection Agency (EPA) regulations for recreational boat drive engines and generators were intended to control hydrocarbon and nitrous oxide emissions rather than CO. The EPA estimates that recreational marine engines contribute the second highest average quantity of hydrocarbon exhaust emission only behind lawn and garden equipment. (EPA 1996) Under the Clean Air Act, EPA regulations apply specifically to new engines, rather than to the millions of engines currently used on U.S. recreational boats.

EPA regulations for the recreational boating industry can be divided into three categories:

1. Regulations for outboard spark-ignition marine engines and personal watercraft
2. Regulations for inboard and stern drive engines
3. Regulations for large (> 19 Kw) and small (< 19 Kw) generators

EPA regulations that apply to outboard spark-ignition marine engines and personal watercraft were passed in 1996 under 40 CFR, Part 91. This regulation is currently being phased in between 1998 and 2006. It is intended to reduce hydrocarbon and nitrous oxide emissions by a factor of four. Although this regulation is not directed at CO, the current evaluation shows that there are CO benefits. The primary emission reduction technologies under this regulation are replacement of conventional two-stroke engines by four-stroke engines, or by electronic direct fuel-injected two-stroke engines.

The other class of recreational boat drive engines are the inboard and stern-drive spark-ignition engines. EPA has recently published a notice to regulate inboard and stern-drive marine engines. These engines are often, but not always, larger than outboard engines and have higher horsepowers. Many of these types of engines have automotive origins. Inboard and stern drive engines could potentially reduce emissions by using feedback electronic air-fuel control, electronically controlled exhaust gas recirculation, and three-way catalytic converters. The Southwest Research Institute is currently conducting work in this area for the EPA.

The final class of engines that are used on recreational boats are generators. Generators are not addressed under Marine engine rules. Rather they fall under small equipment and large spark-ignition rules, depending upon their size. Large generators are classified as those producing 25-hp or 19-Kw or more. These regulations become effective by 2004 and require catalysts to control hydrocarbons and nitrous oxides, requiring a 95% reduction in CO by 2007. All of the generators evaluated during the NIOSH field surveys for recreational boats were smaller than 19-Kw, thus falling under small equipment rules, which are directed at residential lawn and garden tools. Because these rules are primarily concerned with hydrocarbon emissions, CO has not been an issue. Today, it is common to see new, large gasoline-powered generators, which produce 5 grams of CO per Kw/hour and small gasoline-powered generators, having a mass CO production rate that is 100 times greater (500 grams of CO per Kw/hour). The CO cap, which shall not be exceeded, for small equipment under EPA regulations is 610 grams of CO per Kw/hr. The differences in CO emission rates between large and small gasoline-powered generators is primarily related to economic issues and industry concerns rather than technological feasibility.

CONCLUSIONS AND RECOMMENDATIONS

The following recommendations are provided to reduce CO concentrations on and around recreational boats, particularly in the stern area, and provide a safer and healthier environment to boaters:

1) All manufacturers/owners/users of recreational boats with gasoline-powered engines should be aware of and concerned about the potential for CO poisoning. There are approximately 17 million recreational boats used in the United States, and based upon the results of current and previous NIOSH studies, it is very likely that many of these gasoline-powered engines produce hazardous CO concentrations. The data collected in the current evaluation show that nearly 90% of the evaluated boat engines produced hazardous CO concentrations, and CO poisonings could occur from use of these engines under certain conditions.

2) Additional work should be conducted using the data collected during this survey and computational fluid dynamics modeling to identify the most hazardous conditions. Stationary operations and operating a speeds less than 5 mph near the stern of the boat appear to be most hazardous. A model could

potentially be developed to more clearly define how the various factors such as engine type and size, boat speed, distance behind boat, and relative wind conditions interrelate.

3) The role of engineering control technologies to prevent CO poisonings on marine vessels should continue to be investigated. Previous studies have shown that CO hazards from houseboat generators can be reduced by engineering control systems [Dunn, Hall, et al. 2001; Earnest, Dunn, et al. 2001]. For example, the vertical stack, emission control devices (ECD), or other types of ventilation options for generator exhaust could potentially be applied to cabin cruisers. Boat manufacturers should investigate whether engineering control systems used to control CO on houseboats could be effectively used for other types of recreational boats.

4) The role of cleaner burning engines and emission control technologies in reducing the CO hazard should be more fully investigated. It is clear from data gathered in the current study on modern outboard engines that cleaner burning engines, which comply with EPA regulations, will reduce CO concentrations and exposures. This ongoing NIOSH-Coast Guard partership is evaluating the long-term performance of ECDs to reduce CO emissions. Engineers from the Southwest Research Institute are studying catalytic converter technologies to reduce CO emissions from inboard and stern-drive engines. Each of these technologies should be considered as a possible way to reduce the CO hazard on recreational boats.

5) The issue of oxygen deprived marine engines should be systematically investigated. It is possible that marine engine compartments may have been designed too tightly. This can result in air flow restrictions on modern marine engine inlet and exhaust ports that deprive the engine of much needed oxygen. Lack of adequate oxygen during the combustion process will cause CO concentrations in the exhaust to dramatically increase. It would be useful to study the extent of this problem as well as the likelihood of reducing the generated CO concentrations by increasing air flow to the engines.

6) Governmental and consensus standard setting bodies should carefully examine existing standards to determine if they adequately address the potential CO hazard from many types of recreational boats. For example, the EPA has an existing standard that is being phased in for outboard marine engines. The outboard marine engine standard will substantially reduce engine emissions. EPA personnel should evaluate how their existing and future standards for inboard marine engines and small marine generators can best address the CO poisoning problem. Similarly, the American Boat and Yacht Council (ABYC) has recently modified their standard for acceptable exhausting from marine engines to include a vertical exhaust stack. Attention should be given to whether or not ABYC standards could adequately apply to other types of recreational boats in reducing the potential CO hazard.

7) The educational campaign related to CO and houseboats should continue and expand to include other types of recreational boats and boat-related CO hazards. These materials may include warning signs, hand-out materials, newspaper articles, videos, and public service announcements, as described in previous NIOSH Health Hazard Evaluation Reports on CO poisonings and recreational boats. Public education efforts should be continued to inform and warn all individuals (including boat owners, renters, and workers) of potential exposures to CO hazards. The USNPS has launched an awareness campaign to inform boaters on their lakes about boat-related CO hazards. This Alert included press releases, flyers distributed to boat and dock-space renters, and verbal information included in the boat checkout training provided users of concessionaire rental boats. These and other educational materials are available at the following web site: http://safetynet.smis.doi.gov/COhouseboats.htm.

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—Arizon 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.

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.

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.

Table 1

Detector Tube Results for Boats Evaluated on Lake Mead.

Evaluated Boat	**Detector Tube Location and Results**
1. 36-foot Carver 1983 Aft cabin cruiser 2- 454 Pleasurecraft drive engines 6.5 Kw Onan generator	Cold start, boat stationary, center swim deck > 2,800 ppm Boat stationary, center swim deck > 3,000 ppm Boat stationary, center swim deck = 0.3 %
2. Sun Country Deck Boat Volvo Penta 4.3 GL	Cold start, boat stationary, center swim deck > 3,000 ppm
3. Four Winns 180 Horizon; 150 hp Evinrude 2000 Ficht® Drive Engine	Cold start, boat stationary, center swim deck = 0 ppm
4. Four Winns 200 Horizon; Volvo Penta 2001 Stern Drive	Cold start, boat stationary, center swim deck = 3,000 ppm Moving 5 mph, center swim deck = 500 ppm Moving 7 mph, center swim deck = 10 ppm
5. Polaris 2001 Virage PWC Jet drive, 95 hp	Cold start, stationary, center near exhaust = 500 ppm Cold start, stationary, center near exhaust = 500 ppm
6. OMC aluminum boat, 1999, Johnson 40-hp, 2 stroke	Cold start, stationary, center near exhaust > 100 ppm
7. OMC aluminum boat, 2001, Johnson 40-hp, 4-stroke	Cold start, stationary, center near exhaust = 5 ppm

Table 2

Detector Tube Results for Boats Evaluated on Lake Powell.

Evaluated Boat	**Detector Tube Location and Results**
1. SeaRay, 1986, 18 foot, 4.3 ltr, Mercruiser V6	Stationary, rear of boat, center of swim deck = 0.3 - 0.5 % Moving 2 mph, rear of boat, center of swim deck = 0.5 % Moving 5 mph, rear seat on boat = 10 ppm Moving 10 mph, rear of boat, center of swim deck = 100 ppm Moving 10 mph, rear of boat, center of swim deck = 10 ppm
2. Glastron 225 Bal Harbor, 1975 Ford Stern drive 351 V8	Moving 5 mph, rear of boat, center of swim deck > 3,000 ppm Moving 5 mph, rear of boat, center of swim deck = 0.5 % Moving 10 mph, rear of boat, center of swim deck = 3,000 ppm Moving 10 mph, rear of boat, center of swim deck = 0.5% ppm Moving 10 mph, driver's seat = 10 ppm Moving 20 mph, rear of boat, center of swim deck > 100 ppm
3. Bayliner, 32-foot Flybridge Cruiser, 1988 2-350 V8 Volvo engines 3.5 Kw Westerbeke gen.	Moving 3 mph, rear of boat, center of swim deck = 600 ppm Moving 5 mph, rear seat on boat = 100 ppm Moving 10 mph, rear of boat, center of swim deck > 100 ppm Moving 20 mph, rear of boat, center of swim deck = 100 ppm
4. Crownline, 18-foot Bowrider, 1996 350 OMC Cobra drive	Moving 4 mph, rear of boat, center of swim deck > 100 ppm Moving 5 mph, rear of boat, center of swim deck = 1,000 ppm Moving 10 mph, rear of boat, center of swim deck = 100 ppm

Table 3

Evacuated Container Results for Boats Evaluated on Lake Mead.

Evaluated Boat	**Evacuated Container Location and Results**
1. 36-foot Carver 1983 Aft cabin Cruiser 2- 454 Pleasurecraft drive engines 6.5 Kw Onan generator	Cold start, boat stationary, center swim deck = 5 ppm Boat stationary, center swim deck = 3,400 ppm Boat stationary, 1-foot from generator exhaust = ND Boat stationary, 1-foot from generator exhaust = 38 ppm
2. Sun Country Deck Boat Volvo Penta 4.3 GL	Cold start, boat stationary, center swim deck = 12,500 ppm
3. Four Winns 180 Horizon; 150 hp Evinrude 2000 Ficht® Drive Engine	Cold start, boat stationary, center swim deck = 59 ppm
4. Four Winns 200 Horizon; Volvo Penta 2001 Stern Drive	Cold start, boat stationary, center swim deck = 60 ppm Moving 5 mph, rear seat = 354 ppm Moving 5 mph, center swim deck = 159 ppm
5. Polaris 2001 Virage PWC Jet drive, 95 hp	Cold start, stationary, center near exhaust = 2,600 ppm Cold start, stationary, center near exhaust = 124 ppm
6. OMC aluminum boat, 1999, Johnson 40-hp, 2 stroke	Cold start, stationary, center near exhaust = 74 ppm
7. OMC aluminum boat, 2001, Johnson 40-hp, 4-stroke	Cold start, stationary, center near exhaust = 2 ppm

Table 4

Evacuated Container Results for Boats Evaluated on Lake Powell.

Evaluated Boat	**Evacuated Container Location and Results**
1. SeaRay, 1986, 18 foot, 4.3 ltr, Mercruiser V6	Moving 2 mph, rear of boat, center of swim deck = 21 ppm Moving 5 mph, rear of boat, center of swim deck = 4,000 ppm
2. Glastron 225 Bal Harbor, 1975 Ford Stern drive 351 V8	Cold start, boat stationary, center swim deck = 1,600 ppm Moving 5 mph, rear of boat, center of swim deck = 112 ppm Moving 10 mph, rear of boat, center of swim deck = 681 ppm Moving 20 mph, rear of boat, center of swim deck = 54 ppm
3. Bayliner, 32-foot Flybridge Cruiser, 1988 2-350 V8 Volvo engines 3.5 Kw Westerbeke gen.	Moving 10 mph, rear of boat, center of swim deck = ND Moving 20 mph, rear of boat, center of swim deck = 102 ppm
4. Crownline, 18-foot Bowrider, 1996 350 OMC Cobra drive	Moving 10 mph, rear of boat, center of swim deck = 24 ppm Moving 10 mph, rear of boat, center of swim deck = 240 ppm

Table 5

Boat Speed and Average Relative Wind Speed for Boats Evaluated on Lake Mead.

Boat Description	**Boat Speed (mph)**	**Average Relative Wind Speed (mph) and Standard Deviation**
Sun Country Deck Boat Volvo Penta 4.3 GL	1	4.8, 0.92
	5	6.85, 2.47
	8	11.76, 1.60
	15	14.55, 0.26
Four Winns 180 Horizon; 150 hp Evinrude 2000 Ficht® Drive Engine	stationary	2.80, 0.93
	5	4.86, 1.13
	10	8.06, 0.35
	15	25.27, 0.51
	20	25.77, 0.71
OMC aluminum boat, 1999, Johnson 40-hp, 2 stroke	stationary	0.78, 0.56
	1	6.83, 1.30
	5	10.14, 0.73
	10	11.44, 4.16
OMC aluminum boat, 2001, Johnson 40-hp, 4-stroke	stationary	1.68, 0.31
	1	5.01, 1.90
	5	8.27, 2.12
	10	6.44, 1.86

Table 6

Boat Speed and Average Relative Wind Speed for Boats Evaluated on Lake Powell.

Boat Description	Boat Speed (mph)	Average Relative Wind Speed (mph) and Standard Deviation
1. SeaRay, 1986, 18 foot, 4.3 ltr, Mercruiser V6	1	3.41, 1.24
	5	4.22, 1.63
	10	9.31, 2.42
	20	21.19, 3.14
2. Glastron 225 Bal Harbor, 1975 Ford Stern drive 351 V8	2.5	2.56, 1.30
	5	3.12, 0.85
	10	8.41, 3.99
	20	20.56, 4.25
3. Bayliner, 32-foot Flybridge Cruiser, 1988 2-350 V8 Volvo engines 3.5 Kw Westerbeke gen.	3	3.18, 1.05
	5	2.59, 0.96
	10	5.01, 3.31
	20	25.38, 2,30
4. Crownline, 18-foot Bowrider, 1996 350 OMC Cobra drive	3	3.61, 1.20
	5	2.97, 1.31
	10	4.46, 2.10
	20	24.98, 5.58