CARBON MONOXIDE POISONING
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EDITED BY
DAVID G. PENNEY
Dedication

I wish to dedicate this book first to my mother,
Gertrude Ellen (Goodhew) Penney,
always a source of support and encouragement,
to my grandchildren,
and to all of those victims of carbon monoxide poisoning
who sought but did not find professional help for their suffering.
Preface

*Carbon Monoxide Poisoning* is a new title covering further areas of the expansive field of carbon monoxide (CO) toxicology that were not covered in the first two books, *Carbon Monoxide* and *Carbon Monoxide Toxicity*, both edited by David G. Penney, PhD. Both were published by CRC Press, the first in 1996 and the second in 2000. This book is designed to be complementary to both earlier books, forging into new areas and following new themes.

The scope of this book is even broader than the earlier two. The first book took a very scholarly approach, presenting the latest basic and medical science of CO toxicology in 13 chapters. The contents of that book remain current. The second book was broader in its approach, and while extending presentations of basic and medical science, added discussions of human CO exposure under specialized conditions and in geographic locations other than the United States, in 23 chapters. It also presents a large body of new data on both acute and chronic CO poisoning. This present, third book, *Carbon Monoxide Poisoning*, further extends these presentations both to new areas such as the law, rehabilitation, personal experience with CO poisoning, education of the public about CO using the World Wide Web, and so forth, and adds further new data on chronic CO poisoning.

This book contains some unique features:

1. A critical look at the efficacy of hyperbaric oxygen therapy in decreasing the damage caused by CO poisoning
2. The use of exciting new scanning techniques in revealing damage from CO poisoning
3. The introduction of a handheld pulse-oximeter that reads COHb directly and noninvasively
4. New data showing the persistent health damage that can be caused by chronic CO poisoning
5. The dangers of CO poisoning possible in motor homes, recreational boats, and so on
6. The levels of ignorance regarding CO on the part of the general public

Interest in the effects of carbon monoxide on human health has grown rapidly during the past 20+ years. Governmental agencies, private groups, and the public are concerned. While an old and familiar poison, CO remains the number one “poison” in our environment in terms of its “brain-killing” potential, and its potential for overall immediate and long-term health harm. The public and the medical community need to obtain quality information about the risks from CO and need the means to identify and manage victims of CO poisoning successfully. It is hoped that this book, and its two previous companions, will in some way be of value in meeting these challenges.
David G. Penney, PhD, is a retired professor of physiology, who taught and conducted research on carbon monoxide at the School of Medicine, at Wayne State University, Detroit, Michigan. He was at one time adjunct professor of occupational and environmental health in the School of Allied Health Professions at Wayne State University. He is also a retired director of general surgical research at Providence Hospital in Southfield, Michigan, where for 12 years he directed the scholarly activities of surgical residents and attending surgeons.

Dr. Penney obtained his BSc degree from Wayne State University in 1963, and his MSc and PhD degrees from the University of California, Los Angeles, in 1966 and 1969, respectively. Before coming to Wayne State University in 1977, he was a faculty member at the University of Illinois, Chicago. With his wife, Linda Mae Penney, the couple have six children.

Dr. Penney’s professional interests have been focused on carbon monoxide for over 37 years, in both animal models and in humans. His special interests center around chronic CO poisoning, education of the public about the dangers of CO poisoning, the diagnosis and management of CO poisoning victims, and the medicolegal aspects of CO toxicology.

Dr. Penney has assisted many national and international government and non-government agencies in matters involving carbon monoxide. He was among the earliest consultants to the US Environmental Protection Agency (EPA) in setting CO standards for outside air. He assisted the World Health Organization (WHO) in the late 1990s in setting similar standards for the world. He has worked with the Australian Medical Association (AMA) and with other concerned groups in Australia to attempt to stem the tide of suicides involving CO. Currently, Dr. Penney assists Underwriters Laboratory (UL) as a medical expert on CO in establishing standards for CO alarms and other gas-monitoring equipment, and major gas distributing companies in educating the public about the dangers of CO poisoning.

Dr. Penney’s published works on CO include over 65 peer-reviewed research articles, several dozen other articles and abstracts, a number of review articles, book chapters, and three other books in print. At last count, Dr. Penney had more research articles and books published on the topic of CO toxicology than anyone else in the world. He has also published several other books on medical education and on Royal Oak history, and for some years wrote a column on local history for a hometown newspaper.
Acknowledgments

I wish to thank all the authors, former patients, and all who have contributed to this book. It has been a long road and at times it seemed impossible. Now it is done. Thanks to everyone.

I also wish to thank Wayne State University School of Medicine and my Department of Physiology chairman, Dr. Joseph Dunbar, for granting me the time off in 2005 to get the book off the ground.

I of course thank CRC – Taylor and Francis Publishers and all their employees who have been wonderful to work with these past 12 years, in developing my three books on carbon monoxide.

Finally, I wish to thank my wife Linda for her constant support in developing these books, hearing my complaints, providing inspiration and also some perspiration in getting the work done. I of course thank my mother, Gertrude, for her support, encouragement and even late night help with data entry.
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7.1 INTRODUCTION

Although carbon monoxide (CO) poisoning has been recognized since the earliest medical writings, CO exposure continues to be a major cause of death and illness. Many fatal and nonfatal exposures go undetected and unreported. The development of effective prevention programs is severely hampered by the absence of a centralized, coordinated surveillance system.

CO poisonings in the marine environment began receiving attention as early as 1984, with poisonings occurring inside living quarters (also referred to as the boat cabin) being recognized early on. In 1990 and 1991, the United States Coast Guard (USCG), responsible for regulating recreational boat manufacture, investigated issues related to intrusion of engine exhaust into boat cabins. CO poisoning associated with occupancy of cabins of recreational boats was first described in the scientific literature in 1995. Subsequently, the American Boat and Yacht Council (ABYC—a nonprofit membership organization that develops safety standards for boat building and repair) developed standards for CO detection systems for boats manufactured after July 31, 1998.

However, CO poisonings occurring outside the boat cabin were another matter. Reports of outdoor CO poisonings in any setting are scant. Published reports of boat-related CO poisoning outside of a boat cabin, in which the boat occupant was swimming behind a motorboat and behind a houseboat appeared in 1998.

The absence of data on outdoor CO poisonings confused National Park Service (NPS) Emergency Medical Services (EMS) providers on Lake Powell (within the Glen Canyon National Recreation Area—GCNRA) who had noticed a number of poisoning incidents involving boat occupants losing consciousness outdoors, beginning in the early 1990s. Through the early years of these poisonings, park officials sought evidence of other outdoor CO poisonings, but failed to find documentation of this problem elsewhere in the United States. When the first verified fatal marine CO poisoning occurred at Lake Powell in 1994, NPS EMS personnel had treated a total of 29 nonfatal CO poisonings associated with boats.
On an August evening in 1994, NPS officials at the GCNRA dispatch center received an emergency call from boaters requesting assistance regarding the possible drowning of a 12-year old boy. Three boys had been swimming near the rear of a houseboat while family members were inside the air-conditioned living quarters of the boat. One of the boys became ill, and parents took him inside the boat to rest, attributing his illness to the hot weather. The other two boys continued swimming. The victim (the second boy) was on the swim platform at the time and complained to his companion about his legs feeling funny. The third boy climbed onboard and went inside the boat, complaining to his mother that he, too, did not feel well. The victim remained on the swim platform at the rear of the boat while others attended to his companion. Nearly an hour later, the group discovered that the victim was missing and began to search for him, concurrently summoning NPS assistance. NPS divers recovered the boy’s body from 21 ft. of water more than 2 h later. During the course of their investigation of this drowning, NPS discovered that the onboard gasoline-powered generator had been operating when the boys were swimming, and communicated this information to the medical examiner. As a result, a carboxyhemoglobin (COHb) analysis was requested as part of the autopsy. The analysis, repeated due to the high initial concentration, revealed a COHb of 61% documenting that the boy’s drowning was secondary to CO poisoning, the source of which was the generator.12

Although NPS requested assistance from the USCG after this boy’s death, and again in 1998 when two CO-related drownings occurred within 12 days of each other behind houseboats of a similar design, active response was lacking. This changed in August 2000, when two brothers, Dillon and Logan Dixey (aged 8 and 11 years), swimming at the rear of their family houseboat on Lake Powell, died as a result of CO poisoning. Their deaths were quick, occurring within minutes of exposure to generator exhaust under the swim deck, and were strikingly similar to five previously recognized fatalities on this lake behind houseboats of the same design. The brothers’ deaths, combined with the growing body of evidence at Lake Powell, triggered an interagency, multidisciplinary investigation, the goal of which was to identify effective prevention strategies at this lake.13 The interagency investigation rapidly grew to cover similar poisonings nationwide, with a number of local, state, and federal governmental agencies, individual boat and equipment manufacturers, boat rental companies, trade organizations, nonprofit organizations representing consumers, and individual boaters joining the effort to identify poisonings and interventions.

7.2 IDENTIFYING MARINE CO POISONINGS

Data discussed in this chapter were derived from a variety of sources, and vary in level of documentation and detail available from the source. The most important thing to remember is that these are not all the poisonings that have occurred, but rather are the poisonings we know about from the sources discussed below. Case data are influenced by reporting bias (such cases were not recognized early on, recognition of cases has improved only slightly, awareness of reporting requirements is scant, and many cases
were reported because of increased news coverage); and misdiagnosis of disease and
dearth etiology (many deaths were and are classified as drowning that were actually
CO poisonings first).

7.2.1 IDENTIFICATION OF MARINE CO POISONINGS AT LAKE
POWELL

To date, nearly 1/3 of all recognized cases occurred at Lake Powell, and were iden-
tified through extensive case-finding research conducted jointly by the Centers for
Disease Control and Prevention’s (CDC), National Institute for Occupational Safety
and Health (NIOSH), the Medical Advisor for Prehospital Care at GCNRA, NPS
GCNRA staff, and the US Department of the Interior.

The isolation of the lake, and related centralization of NPS emergency response
and patient transport, resulted in early identification and thorough documentation of
fatal and nonfatal marine poisonings by Glen Canyon NPS medical and law enforce-
ment personnel. Computerized and hard copy records were abstracted to identify and
describe Lake Powell CO poisonings.14 These included: NPS GCNRA law enforce-
ment dispatch logs; NPS EMS response sheets; Page Hospital Emergency Department
treatment records; hospital discharge data; and medical examiner/coroner autopsy
reports.

7.2.2 IDENTIFICATION OF MARINE CO POISONINGS NATIONWIDE

In the United States, data related to boating accidents are collected through the USCG
Boating Accident Report Database (BARD), which provides vital information for
USCG regulation of the manufacture and recall of recreational boats and boating-
related equipment.

Data used to compile the BARD statistics come from two sources: (1) Boating
Accident Report data forwarded electronically to the USCG by recognized reporting
authorities, typically the state boating law administrator in each state; and (2) reports
of USCG investigations of fatal boating accidents that occurred on waters under
Federal jurisdiction.15

To obtain the most accurate data, BARD relies as much as possible on recreational
boating accident investigations conducted by local law enforcement personnel and
submitted to the USCG electronically by the recognized reporting authority. In the
absence of investigational data, information is collected from accident reports filed by
recreational boat operators, who are required to report boating accidents that involve
the vessel or its equipment.16

Included in the USCG database are recreational boat-related or equipment-related
accidents in which:

1. A person dies; or
2. A person is injured and requires medical treatment beyond first aid, that is,
treatment at a medical facility or by a medical professional other than at the
accident scene; or
3. Damage to vessels and other property totals $2000 or more or there is a complete loss of any vessel; or
4. A person disappears from the vessel under circumstances that indicate death or injury.

CO poisonings were specifically added to the listed USCG reporting guidelines in 2001, in response to confusion expressed among the reporting authorities as to whether recreational marine CO poisonings met the reporting requirements. Thus, a fraction of marine CO poisonings were reported to the Coast Guard prior to 2001.

7.2.3 ADDITIONAL CARBON MONOXIDE POISONING CASE IDENTIFICATION

Intense national news coverage of the poisonings at Lake Powell, as well as technical presentations and other information dissemination, resulted in the identification of additional cases by researchers closely identified with this issue. The pattern that emerged from collection of related records from these independently identified cases indicated a broader problem, and pointed to emerging problems nationwide related to the design of houseboats and swim platforms on other types of motorboats.

These randomly identified cases were added to those identified in the Lake Powell investigation and those contained in BARD to comprise a document now known as the National Case Listing. Data discussed below are derived from the January 2006 listing and analysis of the supporting database.

7.3 DESCRIPTIVE CHARACTERISTICS OF KNOWN MARINE CARBON MONOXIDE POISONINGS

7.3.1 DEMOGRAPHICS, DISTRIBUTION, AND OUTCOME OF POISONINGS

The National Case Listing contains detailed information about 607 US boat-related CO poisonings requiring medical treatment or emergency response occurring on water bodies in or adjacent to 32 states. Further information is described in publications by the CDC. One-hundred-twenty-two (20%) of the 607 people died as a result of the poisoning. Ninety-eight percent of the poisonings occurred between 1990 and 2005. Age was known for 432 (71%) of the cases: 42% of the 432 cases were children (aged 18 or younger). Gender was known for 393 (64%) of the cases, which was fairly evenly divided between males (204 or 52%) and females (189 or 48%). Figures 7.1 through 7.3 show the distribution of cases by year, month, and state.

The decline in cases in 2005, shown in Figure 7.1, is primarily an effect of the time lapse between the occurrence of the incident and reporting or verification of the case. (As of this writing, we have preliminary information regarding 13 additional cases for 2005.) Monthly distribution of marine CO poisonings is opposite that of
7.3.2 LOCATION OF THE VICTIM AND SOURCE OF CARBON MONOXIDE

Location (on the boat) was known for 546 of the cases. Two of every three victims (353/546) were documented to be inside the boat’s living quarters when poisoned.
These poisonings in the boat cabin occurred in 88 incidents primarily involving multiple victims (as many as 17 victims at a time). In contrast, 190 people were poisoned outside the boat cabin, in 149 incidents which were more likely to involve one to three victims. Thus, the higher number of incidents of poisoning occurred outside the boat.

The specific location of the victim was documented for 100 of the CO-related deaths, with 56 of the victims exposed to CO outside the boat’s living quarters, 44 exposed inside the living quarters or within a full boat canopy. Location on the boat was characterized for 446 of the 485 survivors of marine CO poisonings: 309 were exposed to CO inside the boat cabin in 69 incidents; 134 were exposed outside a boat cabin in 103 incidents; and 3 people (1 incident) were characterized as having been at various locations inside and outside. Again, although more poisoning survivors were inside boats when poisoned, more incidents occurred outside boat cabins.

The specific source of CO exposure was documented for 487 of the 607 poisonings. Exhaust from onboard gasoline-powered marine generators used to produce electricity for onboard appliances (air-conditioners, televisions, refrigerators, etc.) was the most common source, linked to 302 of the 480 poisonings. Gasoline-powered propulsion engine exhaust was linked to 168 poisonings. Twelve people were exposed to exhaust from both types of engines (generators and propulsion engines) when they were poisoned. Source was undifferentiated (e.g., the record said “engine exhaust” or “exhaust fumes” but did not clearly define which engine) or unspecified for 120 cases. At this point, there are no poisonings known to have been associated with marine diesel-powered engines of either type.
7.4 MEDICAL CHARACTERISTICS OF THE CASES

Medical characteristics of marine CO poisonings to be discussed here include COHb as an indicator of exposure, death and loss of consciousness (LOC) as indicators of exposure severity, and Glasgow Coma Scale (GCS—a scale that assesses the degree of brain function) as a measure of victim status when EMS personnel arrived on the scene.

7.4.1 CARBOXYHEMOGLOBIN MEASUREMENT LIMITATIONS

Many boat-related CO poisonings occur while the victim is swimming near the boat. In such incidents, the victim loses consciousness, sinks into the water or lays face down in the water, ultimately drowning as a result of the poisoning. As such, COHb concentrations are often lower than those typically associated with CO-related fatalities. As is true with all CO poisonings, there is no consistency regarding timing of the COHb measurement. Reported COHb concentrations must be viewed as indicators of exposure, because of the many factors impacting that measurement (i.e., oxygen therapy duration, number of half-lives that have passed since the CO exposure ended, activity level of the victim between exposure cessation and COHb measurement, etc.).

COHb analysis related to fatal boat-related poisoning may be complicated by the fact that victims who are poisoned and subsequently drowned sometimes are submerged for extended periods before their bodies are found. In such cases, body decomposition, and related degradation of blood cells, may impact the ability to accurately measure COHb.

7.4.2 BOAT-RELATED CARBON MONOXIDE POISONINGS RESULTING IN DEATH

COHb concentrations were available for 50 of the 122 marine CO-related fatalities. Six of those 50 people received oxygen therapy prior to blood analysis.

Reported COHb concentrations for people that were poisoned outside the cabin ranged from 1.9% (after 440 min of oxygen treatment by intubation) to 100%. The related estimated CO exposure duration for these victims was surprisingly short, ranging from 30 s to 30 min.

Most (47) of the 56 people who died as a result of poisoning outside the boat’s living quarters were in the water when they were exposed to CO, likely losing consciousness and sinking. Reported duration of submersion for those that drowned as a result of the poisoning ranged from 5 min to 13 days. Six people that died outside the living quarters were on the boat, either sitting in the rear seat or rear section of the boat, or leaning over the transom. Specific location of the victim was unknown for three people.

COHb concentrations for deaths that occurred inside the cabin or a full canopy ranged from 27% to 77%. With one exception, the people that died in the cabin of boats had gone there to sleep or watch videos, and were found dead the following morning when someone had noticed them missing, or when someone noticed the boat adrift. The exception to this is an incident in which four children were found...
unconscious (one of which was dead) in the rear area of a cabin cruiser boat that was covered with a full canopy (see Figure 7.4). The children were using a shower device that drew heated water from the operating propulsion engine’s cooling system. They unzipped a panel in the canopy and stood on the swim platform to use the shower hose. About 45 min after they had gone to the boat to shower, two of the boys were found unconscious on the bed in the boat cabin, and two (one of which died) were found unconscious in the area covered by the canopy. CO from the operating propulsion engine had apparently entered the canopied area and cabin. The COHb of the boy who died was 46.6%.

7.4.3 Carbon Monoxide Exposure as a Drowning Risk Factor

To assess the proportion of drownings and boat-related drownings for which CO poisoning was a contributing or primary cause of death, drownings that occurred on Lake Powell from 1994 to 2004 were identified.14 (The starting point was based on the year of the first confirmed CO-related drowning at Lake Powell.) Seventy-two people died of unintentional drowning within GCNRA during that time period. Seventeen percent (12 of the 72 people) of all drownings were CO-related. Twenty-five of the 72 people drowned in BARD-reportable boat-related accidents. This meant that nearly half (12/25) of all the boat-related drownings at Lake Powell were CO-related. These surprising numbers indicate that CO exposure may be a factor in many more drownings on other open water bodies than are currently recognized. This under-recognition is likely to continue unless COHb analyses are routinely included in autopsy protocols and hospital emergency room patient care procedures.
To assess under-reporting of these cases, researchers examined the Coast Guard surveillance system (BARD) data and found that one of three Lake Powell boat-related drownings were absent from BARD, and that CO-related and non-CO-related drownings were missing in similar proportions.

### 7.4.4 Non-Fatal Boat-Related Carbon Monoxide Poisonings

As mentioned earlier, 485 people are known to have survived marine CO poisoning that required at least emergency medical treatment. It is important to remember that these patients did not always have easy access to transport (because they are out on a lake, river, or ocean), and that transport to a local hospital where blood is drawn (or equipment for breath analysis is available) often takes a while. These delays impact the COHb result significantly, especially if oxygen is being delivered to the patient during a lengthy transport.

COHb concentrations were available for 128 of these poisoning victims, of which nearly half (i.e., 63) were treated with oxygen prior to COHb analysis (ranging from 10 to 645 min in duration). Measured COHb ranged from 1.9% to 47.8%. Information about LOC was available for 250 of the 485 survivors of poisoning, and just over half (i.e., 130) of the 250 were documented to have lost consciousness.

GCS ratings were available for 112 of the survivors, with assessment ratings ranging from 3 (unconscious and unresponsive to deep pain) to 15 (indicating normal mental status at the time of EMS response and assessment). It was striking to note that 85 of the 112 GCS-rated patients were assessed as having normal mental status (GCS of 15), despite the fact that nearly 40% (33) of those patients reported profound LOC during their exposure to CO. Half of these patients (17/33) were evaluated by EMS personnel within 10–35 min of experiencing LOC, indicating that CO poisoning etiology can be easily missed if emergency response personnel do not know that CO exposures outside of an enclosure can result in rapid, serious poisoning.

### 7.5 Boats and CO Sources Related to Marine Poisonings, with Case Study Presentations

Types of boats involved in marine poisonings are categorized as follows: ski boats; cabin cruisers; houseboats; other pleasurecraft (fishing boat, personal watercraft, etc.), or unspecified. The distribution of poisonings by boat is shown in Table 7.1, and are discussed below.

#### 7.5.1 Ski Boats

Ski boats are typically a high-performance craft designed for speed and agility. They vary in size, but are typically about 21 ft. long and about 8 ft. wide. Ski boats associated with the outside poisonings (shown in Figures 7.4–7.6) are typically equipped with a high horsepower (310–400 hp) gasoline-fueled inboard direct-drive propulsion
TABLE 7.1
Distribution of Marine Carbon Monoxide Poisonings by Boat Type

<table>
<thead>
<tr>
<th>Boat Type</th>
<th>Fatal Inside Cabin</th>
<th>Fatal Outside Cabin</th>
<th>Fatal Unknown Location</th>
<th>Nonfatal Inside Cabin</th>
<th>Nonfatal Outside Cabin</th>
<th>Nonfatal Unknown Location</th>
<th>Total by Boat Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ski</td>
<td>0</td>
<td>23</td>
<td>0</td>
<td>0</td>
<td>45</td>
<td>3</td>
<td>71</td>
</tr>
<tr>
<td>Cabin cruiser</td>
<td>31</td>
<td>3</td>
<td>4</td>
<td>102</td>
<td>14</td>
<td>4</td>
<td>158</td>
</tr>
<tr>
<td>Houseboat</td>
<td>2</td>
<td>23</td>
<td>0</td>
<td>177</td>
<td>54</td>
<td>1</td>
<td>257</td>
</tr>
<tr>
<td>Other or unknown</td>
<td>11</td>
<td>7</td>
<td>18</td>
<td>30</td>
<td>21</td>
<td>34</td>
<td>121</td>
</tr>
<tr>
<td>Total by outcome</td>
<td>44</td>
<td>56</td>
<td>22</td>
<td>309</td>
<td>134</td>
<td>42</td>
<td>607</td>
</tr>
</tbody>
</table>

FIGURE 7.5  Ski boat transom, platform, exhaust, and propeller configuration.

engine, the propeller of which is under the belly of the boat and thus removed from close proximity to the victim and thought by many to be out of harm’s way. Most of these boats have a water level rear platform (see Figure 7.5) used to facilitate easy access to the water and donning of ski and wakeboard gear. Engine exhaust is dual piped, exiting the boat hull just below the rear platform.

All fatal and nonfatal poisonings associated with ski boats occurred outside of any enclosure, and were caused by exposure to propulsion engine exhaust (this class of boat is not typically equipped with a generator). The details of these incidents are strikingly similar: 45 (63%) of 71 people poisoned on this type of boat were sitting on or holding onto the swim platform; 18 of the 45 people died and 27 of them survived poisoning (19 of whom experienced LOC). The ages of victims occupying the swim platform ranged from 2 to 23 years. Five people were poisoned, four of whom lost consciousness, while occupying the padded sunning deck at the rear of ski boats.
Much media, legislative, and educational attention has centered on a thrill seeking activity that has been labeled as “teak surfing” or “dragging” (shown in Figures 7.6 and 7.7), in which the person holds onto the rear swim platform (which is often made of teakwood, thus the term “teak surfing”) until the boat reaches a speed (typically 10–12 mph) and orientation that allows them to briefly release their grasp and be pulled forward by the displacement wave directly behind the boat. Five of the poisonings associated with platform occupancy (three fatal and two nonfatal) occurred during teak surfing. The predominance of incidents associated with platform occupancy actually occurred when the boat was moving at idle speed (5 mph) through the water, while the victim was being pulled from here to there, or was sitting on the platform dangling his/her feet in the water. In addition, one person who died on the platform and eight survivors were sitting there while the ski-boat was not moving at all, but the propulsion engine was idling. One of the later incidents involved the poisoning of a 4-year-old girl exposed to propulsion engine exhaust while she sat on the swim platform, playing with a shower device that is fed hot water by the operating engine. (This is the same device previously mentioned in Section 7.4.2)

Case 1. In June 2001, an 18-year-old passenger of a ski-boat drowned in Lake Powell as a result of CO poisoning. Three of the ten boat passengers were being
pulled behind the boat, teak surfing. Approximately 2 min after they began, one of the teenagers was unable to maintain her hold on the platform. She was reported as having “jerky arm movements” and difficulty in communicating. She was pulled into the boat by the passengers. Not recognizing the cause of her symptoms, another teen took her position on the platform, and they began teak surfing again. Approximately 1–2 min later, one of the three teens began to experience a severe headache and weakness. This teen pulled herself up onto the swim platform while the boat continued to move forward. The third surfer, still positioned for teak surfing, suddenly lost consciousness and released his hold on the platform. He sank beneath the surface. His body was retrieved from the water 3 days later. His COHb on autopsy was 57%.

*Case 2.* In July 2000, a 15-year-old girl survived CO poisoning while she was lying on the rear padded sunning deck of a ski-boat on Lake Minnetonka in Minnesota. Boat occupants were waiting for a fireworks display, with the propulsion engine operating to power the onboard music system. Other occupants thought the girl was sleeping until they tried unsuccessfully to awaken her. She had stopped breathing. Her COHb measured upon transport to the local hospital was 30%.

*Case 3.* In July 2005, a 21-year-old woman drowned as a result of CO poisoning. The woman was boating on the Gulf of Mexico with her husband and a group of friends in a 21 ft. ski boat. She and her husband were floating in the water, holding on to the swim platform of the stationary boat. The boat operator started the engine and began moving at about 5 miles per h when the woman slipped from the platform and sank. Her husband was unable to locate her. Several hours later, her body rose to the water’s surface and was discovered. Her COHb upon autopsy was 67%.
7.5.2 Cabin Cruisers

A cabin cruiser is generally a large motorboat that has a cabin, and plumbing and other conveniences necessary for living onboard. The hull of a cabin cruiser (see Figure 7.8) is shaped like a conventional motorboat. Many modern cabin cruisers are equipped with air-conditioning and other electrical appliances that necessitate the use of an onboard generator for power.

Most (31) of the 44 deaths inside a boat of any kind occurred in a cabin cruiser. Source of CO was known for 24 of the 31 deaths occurring in cabin cruisers: 18 of these deaths were associated with generator exhaust that infiltrated into the cabin; 5 from propulsion engine exhaust; and 1 from emissions from both types of engine. Four deaths occurred outside cabin cruisers, with the source being generator exhaust in three of the deaths and propulsion engine exhaust in the remaining incident.

Case 4. In June 2005, a 36-year-old man and his 35-year-old wife died of CO poisoning while inside a cabin cruiser. The couple’s boat was moored at Lake George Inlet, Florida near two other boats; all three boats’ generators were operating to power the air-conditioners. When the victims’ generator ran out of gas at about 10:00 a.m., friends opened the door and found the occupants’ bodies. When emergency workers entered the cabin, they found high concentrations of CO. It was unclear if the CO was from the boat on which the couple died, or from the combined exhaust of all three generators. Autopsy results revealed that the husband’s COHb was 75.2%; the wife’s COHb was 77.2%.
Case 5. In September 2001, a 62-year-old man was swimming near his cabin cruiser boat on Shasta Lake, California, talking with his wife who was on the boat. The boat was not moving, but the propulsion engine was operating at the time, charging the boat batteries. The man went to the swim platform at the rear of the boat to rest. While resting for approximately 1–3 min, he started splashing water at his wife. His eyes then became fixed, and he lost consciousness. His wife tried to pull him from the water, but couldn’t. She moved his body to a nearby island. Although the medical examiner initially listed his cause of death as a heart attack, this was changed upon receipt of forensic toxicological test results two months later indicating that his COHb concentration was 89.3%. The test was repeated, this time indicating a COHb concentration of 80.8%.

Case 6. In August 2002, two 9-year-old girls were poisoned outside of a moored cabin cruiser on Lake Powell. One girl died and one survived. They were observed playing in shallow water (about 30 in. deep) near the rear of the boat very near the exhaust terminus of the operating generator. One girl was called into the boat by her parents, and when she climbed out of the water onto the swim platform, she stumbled and fell onto the floor. She was thought to be suffering from dehydration. The other girl was discovered to be missing about 15–30 min later. She was found lying on the bottom of the lake. Attempts to resuscitate her were unsuccessful. The survivor’s COHb was 15.1% after more than 70 min of oxygen therapy. The girl who died had a COHb of 39% after more than 40 min of resuscitative efforts, including CPR and intubation.

7.5.3 Houseboats

A houseboat typically looks a bit like a house trailer mounted on a large floating barge (referred to as a monohull) or pontoons. Houseboats vary substantially in size, with some reaching 90 ft. in length and 16 ft. in width, dependent upon the requirements of the purchaser, restrictions of the water body on which the boat will be placed, transport restrictions, and so forth. Many of the fatal poisonings associated with houseboats (and all of the fatal houseboat poisonings on Lake Powell) were related to a specific design, shown in Figures 7.9 through 7.11.

This design incorporates a monohull structure with an attached extended swim deck at the rear of the boat. The rear deck structure creates a cavity or air space between the hull and the water level swim platform. Exhaust of both propulsion engines, and sometimes that of the gasoline-powered generator, is directed into this air space, which came to be referred to by many as the “Death Zone” (a designation that will be used throughout this chapter for ease of reference). When the engines or the generator are operating, the build-up of CO in this cavity is so high that it creates an imminent danger of death for anyone who enters the cavity. Exhaust lingers in this cavity for an extended period following deactivation of either type of engine. CO poisonings have also been associated with the very high CO concentrations measured on or near the swim platform of houseboats. The common practice of continuous generator operation to provide power for air-conditioning, entertainment centers, and electronic suites while the houseboat is moored has exacerbated the problem.
FIGURE 7.9  Houseboat design associated with fatalities.

FIGURE 7.10  Cavity beneath the extended deck (showing one of two propulsion engine outdrives and rear-directed generator exhaust location) - commonly referred to as “the Death Zone”.
Poisonings outside of houseboats were typically attributed to exposure to generator exhaust (15 fatalities and 44 nonfatal poisonings). In other incidents, the source of CO was a combination of generator and propulsion engine exhaust (two deaths and one nonfatal). Five people were poisoned by propulsion engine exhaust only (two deaths and three nonfatal).

All poisonings that occurred inside the living quarters of houseboats (2 fatalities in 1 incident; 177 nonfatal poisonings in 27 incidents) were attributed to generator exhaust infiltrating the cabin.

**Case 7.** In July 2004, a 34-year-old woman drowned and two others lost consciousness as a result of CO poisoning on Perry Lake, Kansas. A group of women were swimming behind several tethered (rafted) houseboats on which one or more generators were operating. There was little wind when the incident occurred. Two of the women were found unconscious. One of the women was not breathing, but was revived, and the second was unconscious and unresponsive. A few minutes later, someone noted that the third woman was missing. Her body was recovered approximately 30 min later. On autopsy, her COHb was 45%.

**Case 8.** In September 2002, a 42-year-old man entered the airspace beneath the extended rear deck of a houseboat on Lake Powell shortly after the propulsion engines were deactivated. Just prior to the incident, the boat occupants were attempting to moor the boat during windy weather. As they maneuvered the boat, the anchor ropes became entangled in one of the engine propellers. Just after the engines were deactivated (estimated to be more than 3, but less than 5 min), the victim entered the air space beneath the stern deck to remove the lines from the propeller. He was wearing
a personal floatation device (PFD) at the time. After his first entry into the airspace
(estimated to have lasted about 2 min), he emerged and removed the PFD because he
was unable to access the propeller. After approximately 2 min, he entered the space
again, and stayed there about 2 min. He emerged for 2 min, and then re-entered the
space a third time. After about 2–3 min elapsed, he no longer responded to questions
from the boat occupants and failed to emerge from the space. His overall time of
exposure was thought to have been 6 min, with a total of approximately 15 min tran-
spiring before he was no longer heard from. Although divers made many attempts to
find him, they were unsuccessful. His body floated to the surface 3 days later. Autopsy
results indicated that his COHb was 51%.

**Case 9.** In June 1998, a 4-year-old girl was swimming at Lake of the Ozarks,
Missouri with a group of children behind the rear deck of a houseboat. She was
wearing a PFD, and was under the direct supervision of adult swimmers. She
swam to the swim platform, held on to the ladder while her mother applied sun-
screen to her face, and then swam away. Within moments she was observed floating
face up on the water, unconscious, and rigid. She was quickly brought into the
boat where her mother, a registered nurse, checked her for respirations and pulse.
She appeared pale and stiff at that time, was unresponsive with poor respiratory
effort. After 2–3 min of aggressive stimulation, the child began responding with
grunts but was described as disoriented and sleepy. Paramedics were called and
arrived 10–15 min later. They administered oxygen and transported the child to
the nearest hospital emergency department within 30–45 min. Her COHb level at
the hospital after approximately 1 h of oxygen therapy was 22.2%. Upon examin-
ing the houseboat during their next visit to the lake, the child’s parents discovered
that the exhaust terminus for the onboard generator that was operating at the time
of this poisoning was located at the edge of the swim platform, in the center of
the rungs of the ladder that the child was holding onto when the sun screen was
applied.

**Case 10.** In June 2000, 15 people, ages ranging from 16 to 47 years, were over-
come by CO on two rented houseboats on Lake Cumberland, Kentucky. The boats
were tied together and anchored in a cove. Both boats had gasoline-fueled generators;
the generator on one of the boats had a side-directed exhaust terminus. The exhaust of
one of the generators seeped into the adjacent boat through an open bathroom window.
CO was circulated through the full interior of the boat by the central air-conditioning
system. A few boat occupants awoke at about 5:00 a.m. with headaches and nausea.
Realizing they had a problem, the group radioed the marina and ambulances met the
boats at the shore. The water patrol officer that responded to the emergency witnessed
that two occupants were unconscious when he arrived, and others were drifting in
and out of consciousness. All 15 people were treated at the emergency department of
a nearby hospital; 3 were admitted as hospital inpatients for further treatment. There
were six CO detector/alarms on this boat, but none were properly connected when
the boat was inspected after the poisoning incident.
7.6 AIRBORNE CARBON MONOXIDE CONCENTRATIONS MEASURED ON AND NEAR BOATS

7.6.1 METHODS FOR MEASURING, ANALYZING, AND EVALUATING CO IN AIR

Four methods, each with different upper range of measurement capability, were used for collecting CO air samples in the investigations discussed below.

*Method 1:* Direct-reading infrared instruments, more conventionally used to measure CO directly in engine emissions, were used to analyze air samples of very high CO concentrations (i.e., collected in the “Death Zone” and on swim platforms) from houseboats and ski boats. Emissions analyzers are capable of measuring CO in the ranges of percentages (1% CO equals 10,000 ppm) as high as 100%, and also measure oxygen concentration.

*Method 2:* Direct-reading instruments with electrochemical sensor technology were used to measure CO in concentrations between 0 and 1000 ppm. These sensors can be damaged when exposed to excessive CO concentrations for extended periods.

*Method 3:* Detector tubes (a glass tube filled with media that changes color when CO in air is passed through it) capable of measuring 30,000–70,000 ppm were used primarily to confirm ranges of measurement, and to indicate which technology could be safely used in different locations of measurement.

*Method 4:* A laboratory analytical method was used to confirm very high CO concentrations measured by direct-reading instruments. Grab samples were collected using glass air-evacuated containers, which were then shipped to a laboratory for analysis. The sample inside each vial was then analyzed for a number of components, including CO and oxygen. This method was capable of analyzing 0–100% CO, as well as oxygen concentration.

How much CO is too much? The answer to this question involves both duration of exposure (minutes, hours, days, etc.) and air concentration. Units of measure for CO concentration in air are parts of CO per million parts of air (ppm). Exposure to CO concentrations (in ppm) results in a rise in CO in the blood, referred to as COHb—expressed as percent saturation.

Various health and safety agencies recommend or require limits for CO in air. Table 7.2 shows the limits for general populations and for workers. These limits are presented as evaluation criteria to help the reader understand the hazard associated with the air sampling data presented below.
### TABLE 7.2
Evaluation Criteria for Carbon Monoxide

<table>
<thead>
<tr>
<th>Agency</th>
<th>Intent of the Limit</th>
<th>Limit (in parts of CO per million parts of air)</th>
<th>Time Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>US Environmental Protection Agency</td>
<td>Established to protect the most sensitive members of the general population by maintaining increases in COHb to less than 2.1%(^77)</td>
<td>35</td>
<td>1 h</td>
</tr>
<tr>
<td>World Health Organization</td>
<td>Recommendations established to protect the general population by maintaining increases in COHb to less than 2.5% when a normal subject engages in light or moderate exercise(^78)</td>
<td>9</td>
<td>8 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>87</td>
<td>15 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>52</td>
<td>30 min</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26</td>
<td>1 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9</td>
<td>8 h</td>
</tr>
<tr>
<td>National Institute for Occupational Safety and Health</td>
<td>The 8-h limit is recommended to protect workers from health effects associated with COHb levels in excess of 5%. The IDLH (Immediately Dangerous to Life and Health) limit is recommended as a concentration at which an immediate or delayed threat to life exists or at which an individual’s ability to escape unaided from a space would be compromised. The ceiling limit is recommended based on acute effects of exposure(^79)</td>
<td>1200</td>
<td>IDLH value</td>
</tr>
<tr>
<td></td>
<td></td>
<td>200</td>
<td>Ceiling limit—never to be exceeded 8 h</td>
</tr>
<tr>
<td>American Conference of Governmental Industrial Hygienists</td>
<td>The 8 h limit is recommended to protect workers from increases in COHb levels in excess of 3.5%. The agency similarly recommends a Biological Exposure Index (BEI) of 3.5% COHb for end of shift exhaled breath analysis in nonsmoking workers(^80)</td>
<td>35</td>
<td>Excursion limit (5 times the 8-h standard)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>Occupational Safety and Health Administration</td>
<td>Required limit to protect workers from health effects associated with a COHb of 8–10%(^81)</td>
<td>25</td>
<td>8 h</td>
</tr>
<tr>
<td></td>
<td></td>
<td>50</td>
<td>8 h</td>
</tr>
</tbody>
</table>
7.6.2 Carbon Monoxide Concentrations Associated with Boat-Related CO Poisonings

7.6.2.1 Ski Boats

In June and July 2001, CO air samples were taken as part of the investigation of the Lake Powell death of an 18-year-old boy that succumbed to exposure to CO while “teak surfing” (see Section 7.5.1, Case 1). CO concentrations as high as 23,800 ppm in the unobstructed airspace above the swim platform (where the teak surfer’s face and upper body would be during the activity) were measured. When the airflow above the platform was obstructed by a form simulating the shape of the upper torso of a person with extended arms (like a “teak surfer”), CO concentrations above the platform were consistently between 10,000 and 26,700 ppm, despite the fact that engine maintenance had been conducted.

In an August 2001 Connecticut incident, a 15-year-old boy who was teak surfing for an estimated 10–15 min, released the platform, floated briefly, lost consciousness, and sank. His COHb measured during the autopsy was 56%. An investigation involving air sampling for CO was later conducted on the boat. (The upper limit for equipment used to measure CO in air for this investigation was 1000 ppm.) CO concentrations exceeded 1000 ppm on the swim platform (and in what would be the breathing zone of simulated swimmers/teak surfers) at varying engine speeds, and whether the platform was obstructed or unobstructed. The operator of the boat was exposed to as high as 410 ppm during idle, depending on the wind direction. Average concentrations consistently exceeded 200 ppm during the entire sampling event when the boat was operating.

7.6.2.2 Cabin Cruisers

In response to reported incidents that identified a potential safety problem involving CO for recreational boater occupants inside cabins, the USCG contracted a study to evaluate intrusion of CO into the passenger areas of gasoline-powered recreational cabin cruiser boats. Tests results reported in 1991 showed that under certain conditions, CO accumulated in the passenger spaces at a rate of about 1 ppm per minute, posing a health and safety threat to occupants. In areas at the rear of the boat (on the transom, in the rear deck passenger area, etc.) peak CO concentrations as high as 400 ppm, and 30 min average concentrations as high as 272 ppm, were measured. The authors concluded: “It is apparent that the potential exists for a serious health and safety problem for power boaters.”

Results of an interagency investigation of a fatal and nonfatal CO poisoning that occurred near a cabin cruiser were reported in 2002. (See Section 7.5.2, Case 6 for details of the incident.) CO concentrations as high as 41,600 ppm, and oxygen concentrations as low as 12%, were measured in the open air within inches of the boat’s generator exhaust terminus (approximately where the poisoned children were exposed). In addition, CO concentrations consistently exceeded the upper limit of the air monitors placed on the swim platform and at locations one and five ft. from the exhaust terminus, indicating that the CO concentration at these locations were
somewhere between 1000 ppm and the maximum value measured at the exhaust terminus (41,600 ppm). Concentrations as high as 570 ppm were measured 10 ft. away from the exhaust terminus.

7.6.2.3 Houseboats

Unless otherwise specified, all data discussed below pertain to houseboats designed similarly to those in Figures 7.9 through 7.11.

In 1995, a 43-year-old man died in Florida as a result of a 5-min CO exposure within the airspace under the extended rear deck of a houseboat. The boat’s electrical power generator, which released exhaust into the airspace, was activated just before he entered; propulsion engines were not operating. Approximately 5 min after he entered the airspace, he was observed unresponsive floating face down in the shallow water; he subsequently died. His COHb measured in the hospital 2 h after exposure, and after more than an hour of oxygen therapy, was 29.7%. A forensic toxicologist estimated that the man’s COHb was greater than 70% when he collapsed. CO concentrations measured as part of the investigation of this death were reported in legal proceedings. Inspection and testing of the houseboat revealed that CO concentrations in that airspace would reach 4,000–10,000 parts per million (ppm) within 2–5 min after the generator was activated.

As part of the initial investigation of the death of two young brothers exposed to generator exhaust in the airspace under the rear deck of their family houseboat at Lake Powell in August 2000, the NPS conducted air sampling to define the incident circumstances. CO concentrations at water level below the rear deck of three similar houseboats exceeded 2000 ppm (which was the maximum CO concentration the instrument could measure) approximately 10 min after generator activation. CO measurements collected above the swim platforms of the three boats were 800, 100, and 1156 ppm. Two of the people conducting the test began to experience headache, mild nausea, and weakness while conducting this air sampling.

As other agencies joined in the investigation of past and ongoing CO poisonings at Lake Powell, air sampling on houseboats continued. In September 2000, air sampling in the airspace beneath the rear deck on similar houseboats documented the following maximum CO concentrations: 13,000 ppm when one propulsion engine operated; 30,000 ppm when the generator operated (with concurrent oxygen deficiency, 13% measured); and 20,000 when both the propulsion engines and generator operated. CO concentrations exceeding 1200 ppm above and around the water level swim platform were also measured. Repeat testing in November, 2000 confirmed these very high concentrations of CO in the “Death Zone” of similar boats, as well as on the upper rear deck and swim platform.

Further testing was conducted on houseboats at Lake Cumberland in Kentucky, with results reported in December, 2000. This study again documented that CO concentrations near and under the rear deck of houseboats were very high (4,078 ppm measured near water level off the back of the swim platform when the gasoline-powered generator operated, and 10,224 ppm measured at the same location when the generator and propulsion engines operated). These measurements confirmed that there was significant potential for poisonings on houseboats on lakes other than Lake...
Powell. This study was the first to characterize emissions of diesel generators—with a maximum CO concentration of 10 ppm measured when the diesel generator operated near the exhaust terminus and at the back of the boat. However, when the gasoline motors were in operation, CO concentrations increased considerably, with 455 ppm measured on the swim platform.

In March, 2003, an interagency group collected air sampling data as part of a supplemental investigation of a fatal poisoning at Lake Powell.26 (See Section 7.5.3, Case 8 for a description of the death.) The purpose was to provide further information about clearance of propulsion engine exhaust from the “Death Zone” airspace. (Previously reported data documented that the CO concentration in that airspace decayed to 0 ppm within 8 min following deactivation of the generator and propulsion engines.27) In repeated tests conducted on two boats in the 2003 study, rates of decay varied widely—with initial CO concentrations as high as 88,200 ppm decaying to 2 ppm in widely varying time periods (from 10 to 30 min), indicating that CO clearance times in that airspace are unpredictable, and could feasibly be much longer than documented in these tests.

7.6.2.4 Carbon Monoxide Exposure in Areas of Congested Boat Traffic (Lake Havasu Study)

During summer holiday weekends, as many as 700 boats collect in the Bridgewater Channel of Lake Havasu at any given time, some moored to the shoreline of the channel and many cruising slowly through it (see Figure 7.12). The City of Lake Havasu estimates that about one-third of the boats in the channel have engines operating, representing exhaust roughly equivalent to that of 40,000 automobiles.

As a result of initial reports of poisonings occurring in an area congested with boats at Lake Havasu, Arizona, CO exposures among municipal employees and visitors at the Bridgewater Channel were evaluated through air sampling and expired breath measurements. Air sampling was conducted during summer holidays in 2002 and 2003, when boat traffic within the channel was congested.28 Initial sampling documented that CO concentrations in channel air exceeded all short-term exposure criteria listed in Table 7.2; and 4 of 12 boating patients reporting to a local hospital emergency department for any cause (injury, LOC, etc.) had COHb levels of 9.4–28.3%.

In response to these findings, an interagency investigation of CO concentrations in the channel was conducted during Memorial Day weekend (May), and during June–September, 2003. These surveys documented excessive CO exposure and confirmed the health risk among vacationers and employees working in the channel near crowded motorboat gatherings, with a trend of higher exposures later in the day. Sixty-nine percent of monitored workshift exposures of 36 municipal employees involved short-term CO exposures that exceeded the NIOSH ceiling limit of 200 ppm. Overexposures were confirmed by postshift measurements of exhaled breath: 67% of sampled workshifts resulted in estimated COHb levels equal to or greater than the recommended limit of 3.5%,29 with the average COHb among nonsmoking employees increasing from 1% in the morning to 6% in the afternoon (maximum was 13%). Among 46 nonsmoking vacationers that volunteered for exhaled breath
measurements, the estimated COHb increased from a mean of 1% in the morning to 11% in the afternoon (maximum was 23%).

7.7 PREVENTION EFFORTS

7.7.1 U.S. COAST GUARD REGULATION OF BOAT MANUFACTURING/RECALL AUTHORITY

The USCG Recreational Boating Product Assurance Division of the Office of Boating Safety is responsible for such things as developing and enforcing federal safety standards and investigating consumer complaints. Specific responsibilities of the division includes inspecting and testing recreational boats for compliance, and issuing recalls of recreational boats and associated equipment. For this reason, boats are excluded from the jurisdiction of the US Consumer Product Safety Commission.

After the August 2000 deaths of two brothers at Lake Powell (and related subsequent data collection), the Coast Guard determined that the houseboat design shown in Figures 7.9–7.11 (specifically a houseboat with an extended rear deck, water level swim platform, and rear-directed generator exhaust terminus that empties into the air space beneath the rear deck) was defective and fell within their recall jurisdiction. The agency contacted 71 houseboat builders, informing them about data documenting a deadly combination of generator exhaust and houseboat swim platforms on boats of this design. As a result of this and following mailings,
six manufacturers agreed to a voluntary recall.\textsuperscript{31} Initially, it was estimated that more than 2000 boats would have to be retrofitted with the new design suggested by manufacturers (rerouting rear-directed generator exhaust terminus from within the cavity to the side of the boat outside of the cavity), but that number was adjusted downward to 1087 boats. Manufacturers self-certified that over 800 boats were retrofitted as a result of the voluntary recalls.\textsuperscript{32} Side exhaust was seen as an improvement in design, but not a solution, as there had been poisonings associated with water level exhaust outside of any enclosure (such as the one formed by the cavity beneath the deck). In addition, the common practice of “rafting” several houseboats together raised concerns about side exhaust that would now be directed towards the next boat when the generator operated.

The Coast Guard also acted to prevent poisonings associated with the use of a shower system at the back of the boat that draws heated water from the operating propulsion engine (thus exposing the user to propulsion engine exhaust). This device was associated with two poisoning incidents (one fatal and four nonfatal poisonings). In December 2005, the Coast Guard notified the manufacturer of the system that there were CO and other safety hazards for recreational boaters who use the shower system directly connected to the operating propulsion engine. The manufacturer responded with assurances that the system installation would be changed to eliminate connection to an operating propulsion engine, and that they would provide additional CO warnings in printed materials.\textsuperscript{30}

\textbf{7.7.2 ENVIRONMENTAL PROTECTION AGENCY REGULATION OF MARINE ENGINE EMISSIONS}

The Clean Air Act directs Environmental Protection Agency (EPA) to regulate non-road engines, a classification that includes marine propulsion engines and marine generators. Initial EPA regulations for gasoline-powered marine engines, published in 1996, pertained to outboard engines and personal watercraft only. These standards, phased in from 1998 to 2006, achieved approximately a 75\% reduction in hydrocarbons (HC) and oxides of nitrogen ($\text{NO}_x$) from new engines. Although a cap in CO emissions was proposed in these regulations, none was finalized. However, some of the methods used to reduce outboard engine HC emissions also result in a reduction in CO emissions.\textsuperscript{33}

In 2001, the California Air Resources Board adopted emission standards for new gasoline-powered sterndrive and inboard marine engines that are expected to require use of catalytic converters beginning in 2007.\textsuperscript{34}

There are currently no federal standards for emissions from gasoline-fueled sterndrive and inboard marine propulsion engines. Consequently, while these engines remain uncontrolled, calculations conducted by Sonoma Technology, Inc. indicated that an average marine engine emits the same amount of CO as 188 automobiles\textsuperscript{35} EPA gave notice of its intent to develop a proposal for these engines in 2002.\textsuperscript{34}

EPA regulates new gasoline-powered marine generators under 2 sets of rules. Rules for small generators ($\leq 19$ kW) vary depending on size of the engine, include limits for HC, $\text{NO}_x$, and CO, and were phased in from 1997 to 2005. Regulations
relevant to large gasoline-powered marine generators (>19 kW) were effective in 2004, with substantial reductions in HC, NO\textsubscript{x}, and CO required for 2007 models.\textsuperscript{34}

### 7.7.3 State Legislative Action

The National Association of State Boating Law Administrators (NASBLA) provides model language for individual state legislation related to boating safety. In 2003, NASBLA approved language related to marine CO poisoning, with revisions approved in 2005.\textsuperscript{36} The model act, referred to as the Safe Practices for Boat-Towed Watersports Act, and aimed at the practice referred to as “teak surfing”, included the following provisions:

**[Requirements.]**

a) No person shall operate a motorboat or have the engine of a motorboat run idle while a person is teak surfing, platform dragging, or body surfing behind the motorboat.

b) No person shall operate a motorboat or have the engine of a motorboat run idle while a person is occupying or holding onto the swim platform, swim deck, swim step, or swim ladder of the motorboat.

**[Exemptions.]**

The provisions of this act do not apply when a person is occupying the swim platform, swim deck, swim step, or swim ladder while assisting with the docking or departure of the motorboat, while exiting or entering the motorboat, or while the motorboat is engaged in law enforcement activity.

To date, five states have promulgated legislation or regulations intended to prevent marine CO poisonings, most using the model language proposed by NASBLA. Pennsylvania was the first state to revise boating regulations related to unacceptable boating practices in 2003.\textsuperscript{37} In 2004, the California State Legislature passed Assembly Bill (AB) 2222, the Anthony Farr and Stacy Beckett Boating Safety Act of 2004.\textsuperscript{38} This bill added to the NASBLA language by:

1. Requiring that all state-sponsored or approved boating safety courses include information about the dangers of CO poisoning at the stern of a motorized vessel and how to prevent that poisoning;
2. Requiring that any new or used motorized vessel, when sold, bear warning stickers as to the danger of CO poisoning on boats; and
3. Requiring that boat registration materials include similar informational about the dangers of CO poisoning and boats.

Nevada followed in 2004\textsuperscript{39} Oregon in 2005\textsuperscript{40} and Washington state\textsuperscript{41} and Utah\textsuperscript{42} in 2006, each state adopting and embellishing the NASBLA model language.
7.7.4 EFFECTIVENESS OF MARINE CARBON MONOXIDE DETECTOR/ALARMS IN PREVENTION

7.7.4.1 Case-Based Data

Investigative records related to Lake Powell CO poisonings that occurred in the living quarters of houseboats were evaluated with regard to CO detector/alarm presence and function. From 1990 to 2004, 80 people survived poisonings inside houseboats in 15 incidents.\(^{14}\) Fifty of the eighty people were poisoned in boats that were known to have had CO detectors in the living quarters. However, in only one incident (four people poisoned) did the alarm sound alerting the occupants to the hazard. Twenty people were poisoned in three separate instances involving disarmed or “broken” detectors. Twenty-two people were poisoned in four instances involving functional detectors that failed to sound during the poisoning incident. Ten people were poisoned in a houseboat that was not equipped with CO detectors. Twenty people were poisoned in houseboats in which the record failed to document the absence or presence of detectors.

In May 2005, an analysis of boat-related CO poisonings conducted by the National Marine Manufacturers Association (NMMA) pointed out that documentation was available regarding CO detectors in 12% (66) of 506 cases they analyzed, and for half of these cases (33), the exposure occurred with the CO detector disconnected.\(^{43}\) In 11 of the 66 cases (17%), the CO detector malfunctioned, and in only 1 of 66 poisonings did a CO detector sound.

The failure of onboard CO detectors in the living quarters of houseboats on Lake Powell, as well as data related to detectors elsewhere, raises concern about the impact of such devices in CO-poisoning prevention. Improving the effectiveness of these devices is complex, as there were four types of problems identified, each indicating a different corrective strategy. (Identified problems included: failure to alarm; alarming when they shouldn’t; disarmed or dysfunctional detector; and absence of detectors.) Failure of functional detectors to warn occupants of high CO concentrations and the sounding of alarms for no discernable cause are related to detector sensor technology. A likely explanation of disabling of detectors by boaters is that the detectors are sounding frequently and the boater either cannot identify a cause for the alarm (also a detector technology issue) or cannot resolve the issue that is causing CO to enter the cabin (an issue related to boat design, technology, and boater education).

7.7.4.2 Marine Carbon Monoxide Detector Evaluation

In 2004, the USCG Office of Boating Safety Recreational Boating Product Assurance Division released a contracted study of CO detector performance in the marine environment.\(^{44}\) The purpose of the study was to evaluate the reliability of CO detectors that, in 2002, were advertised as being suitable for marine environments. About 90 detectors (five different products) were evaluated; 54 had metal-oxide sensors, 18 had electrochemical sensors, and 18 had biomimetic sensors. The goal was to determine the impact of one or more factors (humidity, salinity, temperature
variants, or out-gassing of new boat construction materials) on detector performance, using the Underwriter Laboratories, UL 2034 standard for CO alarms on recreational boats, as evaluation criteria. The study also included data on performance of detectors following nonpowered storage, as is common with boats that have seasonal use.

Results and related recommendations included:

1. Future studies should be performed over two season extremes. This was based on results of the study that indicated the detectors may be affected by seasonal changes.

2. The effect of long-term exposure of sensors to volatile compounds resulting from out-gassing of vessel construction materials and related impact on sensor functionality should be investigated. This was based on the data characterizing new and increased existing volatile organic compounds over time when ambient temperatures rise, and when the boat is in a “closed condition” as would be the case during storage in nonuse seasons.

3. The recovery time of the sensors used and the time required for the sensor to reach a stable operating condition should also be investigated. This was based on results of nonpowered detector testing of the metal-oxide sensors, documenting that prolonged storage in a nonpowered condition (as is the case during storage of the boat or periods of nonuse) can affect sensor performance. Instructions from the sensor manufacturer stated that these conditions may require a longer preheating period to stabilize the detector before use, and recommends storing the sensor in a sealed bag containing clean air and nothing else (as in, no silica gel). No other manufacturer provided any information regarding the proper or recommended storage practices when the detector is not in use and not under power.

4. Detectors should be installed on various types of vessels and a portable test chamber testing capability should be developed to allow for testing detectors in a real world setting.

7.7.5 ENGINEERING CONTROL RESEARCH AND DEVELOPMENT

By the time data from the investigation of boat-related CO poisonings at Lake Powell were published in December, 2000, work was already underway to develop controls to reduce the CO hazard. Initial efforts were directed towards houseboat generators, primarily based on Lake Powell data. (Of the 111 poisonings identified at Lake Powell at that time, 74 were on houseboats, and 64 of these were associated with exposure to generator exhaust. In addition, 7 of 11 deaths there had occurred near houseboats of the design shown in Figures 7.9 through 7.11, and 5 of the deaths were associated with generator exhaust only.)

In May 2001, the USCG Office of Boating Safety cosponsored the first of what became a series of workshops to focus on ways to reduce marine CO hazards, bringing together boat manufacturers, control innovators, and government agencies. The initial meeting focused primarily on controls for houseboat generators, and spawned a number of research and development projects.
FIGURE 7.13  Generator exhaust terminus—side exhaust (marked by arrow).

Houseboat generator control alternatives developed and evaluated since then included

1. Rerouting generator exhaust to the side (as shown in Figure 7.13)\textsuperscript{46,47}
2. Rerouting generator exhaust through a hybrid wet/dry vertical stack exhaust system with an exhaust terminus several feet above the upper deck (Figure 7.14)\textsuperscript{27,47−57}
3. Retrofitting generators with an emission control device (Figure 7.15)\textsuperscript{45,46,49,57}
4. An electrical interlock device to deactivate the generator when conditions indicated that boat occupants were swimming (lowered swim ladder, open gates, etc.),\textsuperscript{48} and finally,
5. New manufacture of emission-controlled generators\textsuperscript{55,58}

Control directly at the source is the preferred and most effective intervention. In February, 2004, Westerbeke was the first manufacturer to introduce a series of reduced-emission gasoline-powered marine generators, reporting a 99% reduction in CO emissions. This reduction was confirmed through Coast Guard-sponsored field testing of two generators (14 and 20 kW) installed and used on houseboats.\textsuperscript{55} Final results for the second round of tests, designed to assess longevity of effectiveness of the emission controls after 2300 and 1300 h of use (calculated to be equivalent to 92,000 and 52,000 miles of use for an average automobile) indicated little or no deterioration in the effectiveness of the controls.\textsuperscript{58} In 2005, Kohler
FIGURE 7.14  Stacks directing generator exhaust upward (marked by arrows).

FIGURE 7.15  Emission control device for retrofit of generators.
also announced a new line of marine generators reported to reduce CO emissions by 99%.59

By 2002, focus shifted towards control of propulsion engine emissions. The Coast Guard and ABYC began semiannual meetings to discuss the progress of research and development of all marine engineering controls. These are held in conjunction with the International Boatbuilders Exposition meetings, and minutes of the meetings are available through ABYC.

These periodic CO workshops have greatly facilitated the exchange of both technical information among manufacturers and the public, and also the sharing of accident information, and a general rising of awareness in the industry, government, and the public. The workshops have also served to accelerate other mitigating technologies, including diesel engines as viable alternatives for recreational boats.60 The result has been to highlight a much broader scope of research by adding express cruisers, towed activities, etc. The workshops have also served as a catalyst for revision of ABYC TH-23 (Design, Construction, and Testing of Boats in Consideration of CO),61 and addition of dry stack exhaust considerations to ABYC P-1.62

Concurrent with the workshops, the Coast Guard sponsored evaluations of CO emissions on recreational boats.63,64 Safe distances from the boat were evaluated to address the issue of potential CO exposures for those being towed on water “toys” behind the boat (tubers, wake surfers, etc.).65,66 Evaluations of the effectiveness of devices designed to reroute the exhaust of ski-boat engines were also conducted.67,68

Prototype catalyzed propulsion engines were introduced at the International Boat Builders Exposition in February 2005, and evaluations of the catalyzed engines continued.69–71 In March 2006, Indmar introduced the first production inboard propulsion engine with controlled emissions to be available on 2007 model year boats.72

Most recently (January 2006), results of a Coast Guard sponsored study of CO emissions and exposures on a class of cabin cruiser boat known as express cruisers were reported.73 The study was performed to better understand how CO poisonings may occur on express cruisers, identify the most hazardous conditions, and begin the process of identifying controls to prevent/reduce CO exposures. Many of the evaluated boats generated hazardous CO concentrations: peak CO concentrations often exceeded 1100 ppm, while average CO concentrations were well over 100 ppm at the stern (rear). Two boats with a combined exhaust system (exhausting at the sides and underwater) had dramatically lower CO concentrations than any of the other evaluated boats (about 40% lower).

7.7.6 Innovations in EMS Medical Management

With the support of the USCG, in 2003 NPS EMS personnel at Lake Powell began using equipment that allowed noninvasive estimation of COHb concentration from analysis of exhaled breath samples for more effective triaging of patients. The decision logic shown in Figure 7.16 is used to guide medics in acting upon results of the analysis. A decision logic for use of a new noninvasive blood pulse-oximeter has also recently been published74 and is discussed in another chapter of this book.
**CARBON MONOXIDE POISONING**

The micro CO meter is to be used on anyone who has been or you suspect has been exposed to or poisoned by carbon monoxide (CO).

Consider scene safety for rescuers and patients. Rapid extrication from hazardous environment PRN. (1)

Address airway issues.

**Micro CO meter immediately available?**

- **YES**
  - Administer high flow oxygen via non-rebreather mask

- **NO**
  - Obtain exhaled CO measurement

**Obtain exhaled CO measurement**

- **YES**
  - Patient is pregnant, has abnormal cerebellar testing, COHb level of 25% or greater, exhibits cardiovascular dysfunction, continued abnormal mental status or had any of loss of consciousness or seizure?

  - **YES**
    - Consider rapid transport to hyperbaric facility (3)

  - **NO**
    - Patient exhaled COHb level > 20%

  - **YES**
    - Transport to nearest medical facility for continued evaluation, treatment, and monitoring (2)

- **NO**

**Is patient symptomatic?**

- **YES**
  - Consider field treatment with no transport. Continue treatment with oxygen until COHb is <5% (or 10% in smoker) (2)

- **NO**

**Consider field treatment with no transport.**

(1) Rescuers will be equipped with SCBA for extricating patients from hazardous environment.

(2) Continue measuring exhaled CO with Micro CO meter Q 15–30 minute intervals.

(3) Initiate preplanning with receiving facility. Refer to transfer guideline: Hyperbaric oxygen therapy for acute carbon monoxide poisoning.

**FIGURE 7.16** Glen Canyon NPS decision logic for patient triage.

### 7.8 SUMMARY AND FUTURE DIRECTIONS

On the positive side, in a span of just over 5 years, many agencies, companies, and individuals have joined to improve identification of marine CO poisoning, characterize risks, develop and evaluate control technologies, and launch a plethora of prevention programs. The resulting developments are impressive: (1) two manufacturers successfully developed low-emission marine generators that are on the market; (2) two major manufacturers developed and participated in testing of catalyzed inboard propulsion engines, with one introducing it in production engines; (3) devices for rerouting generator and propulsion engine exhaust were developed and tested; and (4) several states passed safe towing legislation or regulations.
So what is left to do? We must remember that there are more than 12.8 million boats registered for use on US waters, more than 12 million of which are propelled by outboard, inboard, or sterndrive engines. The only engines that have emission controls are newly manufactured outboard engines and one inboard engine model. Thus, a large proportion of the gasoline-powered marine engines in use have no emission controls. Thus, even if EPA increases the scope of emission standards by regulating inboard and sterndrive engines, a lot of boats will continue to emit a lot of CO for a long time.

EPA regulation of CO emissions for all marine engines is vital for prevention of marine CO poisonings. A reduction in automobile-related CO poisonings followed the EPA Clean Air Act regulations requiring emission control on automobiles. The same would likely follow similar requirements for marine engines.

The key to improved prevention of boat-related CO poisonings lies in improved recognition and reporting. Until there is more comprehensive testing for COHb by physicians and those involved in death investigation, CO poisoning cases will continue to be missed. This results in inadequate or incorrect treatment of cases, related increased morbidity, inaccurate assignation of cause of death, and related failures in prevention. Development of standardized autopsy protocols, combined with more extensive training of the responding medical and law enforcement personnel to facilitate collection and transfer of adequate incident detail are needed for improved recognition.

Adequately recognized poisonings must then be reported so that the full scope of the problem can be defined for prevention programs. Reporting of marine CO poisonings is low. This can be easily examined by comparing Lake Powell data for fatal and nonfatal boat-related CO poisonings, identified, and documented through extensive searches of EMS records, against Coast Guard data for reported CO poisonings. From 1990 through 2002, there were 13 fatal boat-related CO poisonings and 151 nonfatal boat-related CO poisonings requiring medical attention documented at Lake Powell (thus a total of 164 boat-related CO poisonings at that one lake). In that same period, Coast Guard data documented 170 injuries and 62 deaths related to CO reported from incidents across the entire country. Clearly, marine CO poisonings are not extensively reported to the Coast Guard.

State Boating Law Administrators (the recognized reporting authority) should be encouraged to develop liaisons with other state-based surveillance efforts (i.e., state-based child fatality review boards, vital records departments, injury surveillance efforts), as well as Federal surveillance systems, to enhance identification and reporting of boat-related CO poisonings reporting. In addition, more extensive training of municipal law enforcement officers and first responders is needed, so that they can better understand the need to report CO poisonings.

While developments in control have been impressive, implementation of new controls and retrofitting existing boats remains problematic, as evidenced by recent poisonings (not included in the 607 cases analyzed here). Recent Coast Guard data identified two new poisonings (one fatal + one nonfatal) related to entry into the “Death Zone”. Newspaper reports and related autopsy results document a June, 2006 death associated with ski-boat platform occupancy (COHb = 51%). The list of marine CO poisonings continues to grow.
Boat manufactures must assess and address design features that attract occupancy at the back of the boat, redesigning to eliminate hazards. Consumer education, vital to the success of retrofit programs, must continue and increase. If boat owners don’t understand the problem, they won’t be motivated to go to the trouble of complying with recalls and consumer advisories.

Failure of onboard CO detector/alarms raises concern about the impact of such devices in CO poisoning prevention. Improving the effectiveness of these devices is complex, as there were four types of problems identified, each indicating a different needed corrective strategy. Failure of functional detectors to warn occupants of high CO concentrations and the sounding of alarms for no discernable cause are related to much needed improvements in detector sensor technology. A likely explanation of disabling of detectors by boaters is that the detectors are sounding frequently and the boater either cannot identify a cause for the alarm (also a detector technology issue) or cannot resolve the issue that is causing CO to enter the cabin (an issue related to boat design, technology, and boater education).

As has been documented here, quick death can and does occur from exposure to CO in the marine environment, even in the open air. Acceptance of this possibility remains difficult for technical audiences as well as consumers. Anecdotal accounts of medical examiners and hospital emergency departments failing or refusing to order COHb analyses related to incidents on boats continue. The need for increased awareness of the problem was recently underscored in the following quote by a family dramatically impacted by a teak surfing death:

*Unfortunately, widespread understanding of the issue among the boating public remains elusive. We still see kids teak surfing between wake boarding runs. Most people we talk to are surprised at the severity of the CO risk behind a boat. In spite of all our efforts, most seem not to realize the potential peril. I recently talked to two families from Canada who said they teak surfed all the time and were amazed when I told them it could be deadly. This risk is just not self-evident and consequently more kids die unnecessarily every year.*

*Our family, the Dixey family, and people like us that have lost loved ones certainly know the costs of not knowing about or under-estimating this hazard. We who have now been warned have the responsibility to sound the dangers for others. By lifting our voice in warning, we can do our part to make sure that great kids don’t continue to die.*

This quote certainly applies to all types of gasoline-powered marine engines, all boaters, and to all deaths from this preventable cause of CO poisoning.

### 7.9 ACKNOWLEDGMENTS

Much of the work described in this chapter, including initial recognition of the problem and call for engineering changes, would not have happened without my colleague and good friend, Dr. Robert Baron. I am grateful for his guidance, wisdom, and partnership. Thanks to Claire Babik, who has worked so hard for prevention in honor of the brother she lost. In addition, gratitude is owed to Tim Radtke; to National Park
Service Rangers, Divers, Emergency Medical Technicians (EMTs), and Medics at GCNRA; and to the researchers at the National Institute for Occupational Safety and Health. All of these fine public servants have devoted many hours to the cause of identifying and preventing marine CO poisonings. I pay respect to the families that have lost so much to this unnecessary cause. And to my own family, I want to say thanks for everything.

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