Healthy Homes Issues:

Carbon Monoxide

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Office of Healthy Homes and Lead Hazard Control

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Healthy Homes Issues: Carbon Monoxide

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Preface

In 1998, Congress appropriated funds and directed the U.S. Department of Housing and Urban Development (HUD) to "develop and implement a program of research and demonstration projects that would address multiple housing-related problems affecting the health of children." In response, HUD solicited the advice of experts in several disciplines and developed a preliminary plan for the Healthy Homes Initiative (HHI). The primary goal of the HHI is to protect children from housing conditions that are responsible for multiple diseases and injuries. As part of this initiative, HUD has prepared a series of papers to provide background information to their current HHI grantees, as well as other programs considering adopting a healthy homes approach. This background paper focuses on carbon monoxide and provides a brief overview of the current status of knowledge on:

- The extent and nature of carbon monoxide hazards in the home;
- Assessment methods for carbon monoxide in the home;
- Mitigation methods for carbon monoxide in the home; and
- Information needs in the field of carbon monoxide research.

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Summary and Relevance to Healthy Homes Programs

Carbon monoxide (CO) is a poisonous colorless, odorless, and tasteless gas that is produced as a by-product of incomplete combustion of carbon-based fuels such as natural or liquefied propane (LP) gas, kerosene, oil, gasoline, wood, or coal. CO is responsible for hundreds of deaths and numerous non-fatal poisonings each year in the United States.

Many of the issues related to CO poisoning are familiar to those who have worked on childhood lead poisoning and other environmental health hazards. Questions arise about the health impact of low level exposures, the actual number of people affected, technologies for measuring levels in the environment or clinical specimens, and mitigation protocols. The literature supports the following findings regarding CO hazards in the home:

Health Impacts of CO:

- The severity of health effects from CO exposure depends on various factors, including the age and physical health status of an individual, the duration of CO exposure, and the CO concentration in the air.
- Those with certain pre-existing health problems (e.g., those with cardiac or lung conditions), the elderly, pregnant women, fetuses and infants are most susceptible to health effects from CO exposure.
- Both short-term exposures to high concentrations of CO and repeated longer-term exposures to lower concentrations of CO can result in serious health effects.
- Some research shows that repeated exposures to CO, even at levels previously believed to be low, are capable of producing numerous, and persistent, adverse physical, cognitive, and emotional health effects in humans.

Reducing CO Hazards in the home:

- Common sources of elevated CO levels in homes include placing portable generators inside living spaces or attached garages or outdoors and too close to windows, starting or leaving cars running in attached garages, and malfunctioning, improperly or inadequately vented gas heating systems.
- Preventing CO exposures requires responsible operation of combustion appliances and motor vehicles by home occupants as well as routine periodic maintenance to ensure that the fumes from combustion appliances are adequately vented.
- Assessment of potential CO sources, as well as behavioral hazards, can be accomplished by occupant surveys and visual inspections of homes.
- Elevated CO concentrations can be assessed, with differing levels of accuracy, through the use of research quality and professional CO detection and monitoring devices.
- Homeowners can purchase low-cost CO detectors that are designed to warn of elevated levels of CO in the home.

The following practical considerations are made to Healthy Homes programs and practitioners:

- A variety of field instruments are commercially available for investigation of residential CO levels, many available at a cost of less than $500. Currently, the assessment of CO levels in homes by researchers and professional investigators (e.g., from weatherization programs) is most often conducted using a commercial analyzer equipped with an active sampler and either a non-dispersive infrared (NDIR) absorption sensor, or an electrochemical cell sensor.

- For routine CO screening or in situations where the goal is to identify higher concentrations of CO that represent a health risk, palm-held electrochemical samplers/analyzers are most commonly used. However, regardless of the instrument or method employed, accurate results depend on appropriate training for those using the instrument as well as routine maintenance/calibration.
- Sensors used in home CO detectors are intended for the purpose of warning residents of potentially dangerous CO levels.
- Home CO detectors should be centrally located outside of each separate sleeping area in the immediate vicinity of the bedrooms and installed on the wall, ceiling or other location specified by the manufacturer in the installation instructions, as well as on each level of the home.
- Although there are no mandatory national standards in place for CO detectors, the quality of CO detectors available for purchase today is greatly influenced by voluntary industry performance criteria, which provide recommended performance requirements for detectors, as well as general criteria for their construction and testing. The U.S. Consumer Product Safety Commission (CPSC) recommends that consumers purchase home detectors that meet specifications established by Underwriters Laboratories (UL) Standard 2034 for CO detectors, "Single and Multiple Station Carbon Monoxide Detectors" or the Canadian Standards Association standard CAN/CSA 6.19-01, and the previous International Approval Services standard IAS 6-96.
- Electrochemical home CO detectors are designed to produce a current that is precisely related to the amount of CO in the atmosphere. The electrochemical cell used in these detectors has a highly accurate and linear output to CO concentration, requires minimal power when operated at room temperature, and has a long lifetime (i.e., usually five years).

Intervention methods for prevention of residential CO poisonings include:

- Education and outreach to consumers about CO poisoning symptoms and CO source control (including safe behaviors and proper maintenance of combustion appliances).
- Education and outreach to professionals about home CO poisoning, including symptoms and correct assessment of home conditions that pose potential or actual CO hazards.
- Installation of home CO detectors and implementation of standard protocols for detector response.
- Installing ventilation for, or improving existing ventilation of, combustion appliances.
- Replacing combustion with non-combustion appliances.
- Locating generators at least 20–25 feet from homes by means of a heavy duty extension cord and keeping them away from open doors, windows or vents.
- Yearly professional inspections of all fuel-burning home heating systems, including furnaces, boilers, fireplaces, wood stoves, water heaters, chimneys, flues and vents.
- Adherence to local statutes with respect to carbon monoxide detectors.

Residential Hazards: Carbon Monoxide

1.0 Health Impacts of Carbon Monoxide Poisoning

Carbon monoxide (CO) is responsible for hundreds of deaths and thousands of non-fatal poisonings each year in the United States (CPSC, 2004; CDC/MMWR, 2008). Short-term exposures to high concentrations of CO (acute exposure) and repeated longer-term exposures to relatively lower concentrations of CO (chronic exposure) can both result in serious health effects. People with certain pre-existing health problems (e.g., those with cardiac or lung conditions), the elderly, pregnant women, fetuses, and infants are most susceptible to health effects from CO exposure (EPA, 2011). Some research has found that repeated exposures to CO, even at levels previously believed to be low, are capable of producing numerous, and persistent, adverse physical, cognitive, and emotional health effects in humans (Donnay, 2005).

1.1 Prevalence of CO Poisoning

Fatal CO Poisoning. CO was the leading cause of poisoning fatality in the US between 1979 and 1988 and was cited as a contributing cause of death in 56,133 death certificates filed during the 10 year period. Unintentional CO deaths, about 1,155 annually account for 21% of total CO deaths (Table 1). Of unintentional deaths, 57% were associated with automobile exhaust. During the years 1999–2004, CO poisoning caused an average of 2,733 deaths per year of which 16% were unintentional and non-fire-related (Shochat and Lucchesi, 2010).

The U.S. Consumer Product Safety Commission (CPSC) tracks fatal CO poisonings not associated with fires or motor vehicles. Between 2005–2007, according to the CPSC, an average of 184 unintentional deaths occurred per year in the U.S. from CO. Of these deaths, 38% from heating

Table 1. Cause of CO-related deaths from death certificates (1979–1988, annualized)

Cause of Death	Annual Estimate	Average Percent
Suicides	2,589	46.1%
Burns or fires	1,552	27.7%
Unintentional	1,155	27.7%
Automobile exhaust	(655)	(56.7%)
Stoves and fireplaces	(120)	(10.4%)
Natural Gas	(58)	(5.0%)
Gasoline, acetylene, or utility gas	(47)	(4.1%)
Industrial processes	(19)	(1.6%)
Ships and aircraft	(12)	(1.0%)
Unspecified	(230)	(19.9%)
Homicide	21	0.4%
Other	296	5.3%
Total deaths	5,613	100.0%

Source: Shochat and Lucchesi, 2010

CO Fatalities from Motor Vehicle Exhaust Infiltration from Garage

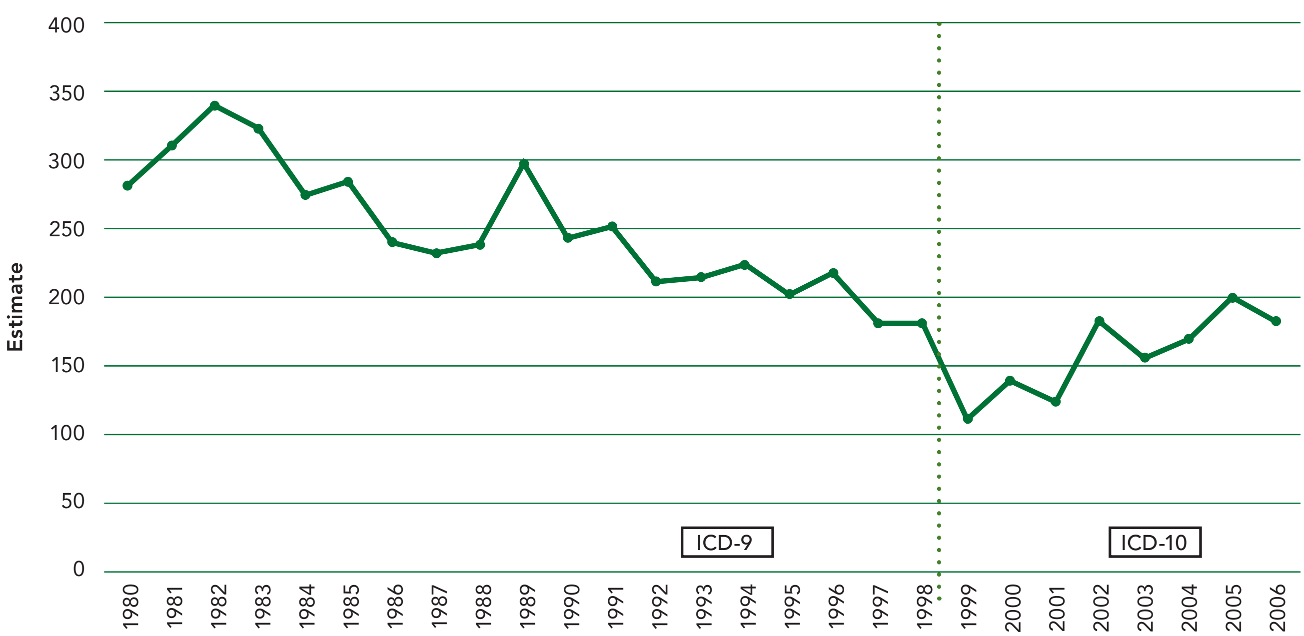
Beyond CO fatalities associated with consumer products, many additional unintentional deaths occur each year as a result of CO poisoning from motor vehicle exhaust, including some deaths in homes from motor-vehicle exhaust infiltration into the living space from an attached garage. The National Highway Traffic Safety Administration (NHTSA) estimated that, between 1995 and 1997, the total number of unintentional CO poisoning fatalities from stationary motor vehicles in residential settings was 397 (126 in 1995, 149 in 1996, and 122 in 1997) (NHTSA, 2000).[1]

[1]*NHTSA estimates based on analysis of National Center for Health Statistics (NCHS) 1995–1997 data.*

systems, and 38% from engine-driven tools, including generators. The majority (79%) of these deaths occurred in the home. The remainder occurred in temporary shelters (campers, seasonal cabins and trailers), automobiles, or motels. Figure 1 illustrates how CO non-fire, non-motor vehicle related poisoning fatalities declined in the 1980s and 1990s but increased somewhat since 2000 (CPSC, 2009b). Additional trend analysis in the 2000s is presented in CPSC, 2011.

Non-Fatal CO Poisoning. In addition to CO poisoning fatalities, it is estimated that approximately 15,000 people go to hospital emergency rooms for treatment of non-fatal, unintentional CO poisoning each year (CDC/MMWR, 2011). According to CPSC staff, it is not uncommon for CO incidents involving one or more fatalities to also result in one or more non-fatal CO poisoning injuries. It is estimated that over 20,600 persons with confirmed or possible unintentional non-fire-related CO exposure were treated annually in hospital emergency departments, with most (72.8%)

Figure 1. Estimated[1] Non-Fire and Non-Vehicle CO Poisoning Deaths Associated with Consumer Products, 1980–2006.



Source: CPSC, 2009b (updated in CPSC, 2011)

[1] Due to changes in the International Statistical Classification of Diseases and Related Health Problems (ICD) with the implementation of the Tenth Revision (ICD-10) in 1999, there are discontinuities in comparing the estimates of CO deaths associated with consumer products in 1999 and later to prior years' estimates.

occurring at home (CDC/MMWR, 2008). CO exposures can occur at any time of year but are more likely to occur in colder weather. About 41% occur in winter versus 20% in summer (CDC/MMWR, 2008 and 2011). Furthermore, some researchers suggest that CO poisoning may go unreported or be medically misdiagnosed because symptoms can be easily mistaken for other illnesses such as the flu (Penney, 2000; Hampson, 2000; Comstock et al., 1999) or chronic fatigue syndrome (Knobeloch and Jackson, 1999). Therefore, although there is no reliable method for estimating the number of individuals who suffer from symptoms of CO poisoning, it may be larger than reported.

Most unintentional automobile-related CO deaths in garages occur with garage doors or windows open, demonstrating the inadequacy of passive ventilation (Shochat and Luchessi, 2010).

1.2 Differences in Populations at Risk for CO Poisoning

Although adults, especially the elderly, are more like to *die* from CO poisoning, children, especially toddlers, are more likely to become nonfatal victims (Shochat and Luchessi, 2010). In 2000, the death rate for CO poisoning was 0.03 per 100,000 for children under 15 years compared to 0.06 per 100,000 for those 15 years and older (CPSC, 2009; US Census, 2010). For nonfatal CO poisonings, however, the rate was 11.6 out of 100,000 for children under 5 years but 3.6 for adults age 65 and older in 2004–2006 (CDC/MMWR, 2008). It should also be noted that the unborn fetus is also considered at increased risk from CO poisoning due to differences in fetal accumulation of CO relative to the mother (i.e., carboxyhemoglobin levels

Table 2. Average Carbon Monoxide Poisoning Deaths For Each Type of Consumer Product Reported, 2005 to 2007, Excluding Fire and Motor-Vehicle Related Deaths

Consumer Product	2005–2007 Average Estimate	2005–2007 Average Percent
Total Deaths	184	100%
Heating systems	57	35%
Unspecified gas heating	2	4%
LP gas heating	23	12%
Natural gas heating	21	11%
Coal/wood heating	1	1%
Kerosene/oil heating	5	2%
Heating systems, not	*	*
Specified	5	3%
Unspecified fuel	4	4%
Charcoal grills	8	3%
Gas water heaters	4	2%
Camp stoves, lantern	5	3%
Gas ranges, ovens	4	2%
Other/ multiple appliances	15	5%
Engine-Powered Tools	91	50%
Generators	79	41%
Other Engine-Driven Tools	13	9%

Source: CPSC, 2010
** No reports received by CPSC staff*

may be much higher in the fetus) (Abelsohn et al., 2002; Liu et al., 2003).

Ralston and Hampson (2000) found that the incidence of unintentional CO poisoning differs across racial/ethnic categories. Among 586 Washington state residents treated for severe CO poisoning from 1987 to 1997, black and Hispanic populations had higher relative risks for CO poisoning than white populations. In addition, the most common sources of CO poisoning differed by racial/ethnic category. For example, for Hispanic and black populations, about 67% and 40%, respectively, of poisonings were due to indoor burning of charcoal briquettes, while all boat-related CO deaths were in white populations. The researchers acknowledge that the observed “racial/ethnic” differences were likely due to socioeconomic differences, but that they did not collect socioeconomic information. CO poisoning is also higher among US immigrants who are non-English speaking among whom, the majority of the unintentional non-fire related CO deaths, 74%, are with males (Shochat and Lucchesi, 2010).

1.3 Human Health Effects

CO is poisonous primarily because it prevents the body from using oxygen. When inhaled, CO binds with hemoglobin approximately 250 times more avidly than oxygen, forming carboxyhemoglobin (COHb) in the bloodstream (Shochat and Lucchesi, 2010). This interferes with oxygen transport to the tissues and organs of the body and leads to adverse health effects (e.g., neurological impairment), particularly in sensitive organs such as the brain and heart. Eventually, at high enough levels, CO causes death by asphyxiation. The onset and severity of CO poisoning symptoms is influenced by the level and duration of reduced oxygen availability (hypoxia), as well as the sensitivity of the individual. It is possible for permanent injury, with resulting disability, to occur from a single, acute CO exposure. In addition, research indicates that CO has adverse health effects beyond those related to oxygen interference (Devine et al., 2002; Townsend and Maynard, 2002; Thom et al., 1999; Thom et al., 1997; Ryter et al., 2004).

Chronic and Acute CO Poisoning—General Symptoms. CO poisoning may occur as a result of both short-term (minutes to hours) exposures to high concentrations of CO (acute exposure) and longer-term exposures (repeated over days to months) to relatively lower concentrations of CO (chronic exposure). Acute CO symptoms include headache followed by dizziness and nausea. Other symptoms may include malaise (flulike symptoms), chest pain, lethargy, confusion, depression, hallucination, agitation, incontinence, and coma (Shochat and Lucchesi, 2010). Chronic CO poisoning involves lower levels of CO in the bloodstream and the same aforementioned symptoms but may present with gradual onset neuropsychiatric symptoms, or impairment of cognitive ability. Unfortunately, victims and/or physicians might not consider CO poisoning as the underlying problem. If CO poisoning is not diagnosed, the misdiagnosis will likely prolong the CO exposure, and could ultimately result in long-term health effects.

Although the neurotoxicant effects of CO were traditionally thought to be solely a result

Common CO Symptoms and Longer-Term Neurological Effects

Individuals who suffer exposures to elevated levels of CO may be unaware of the source of their health problems because moderate CO poisoning, both chronic and acute, can cause symptoms that vary over time and mimic common illnesses like the flu and other bacterial and viral infections. Symptoms of exposure can begin with a slight headache, subtle sensory-motor deficits, nausea, vomiting, impaired vision, fatigue, dizziness, and shortness of breath. If exposures continue, symptoms become more intense, progressing to a loss of consciousness. Survivors of CO poisoning may also have long-term neurological effects such as sensory abnormalities, personality changes, memory deficits, impaired judgment, poor concentration, and other intellectual impairments (Varon and Marik, 1997; Raub et al., 2000; EPA, 2000). In addition, after an initial apparent recovery from an acute CO poisoning incident, delayed neurological health effects may not appear until many days or even months after the exposure event (Townsend and Maynard, 2002).

of a lack of oxygen to the tissues (hypoxia) due to avid binding of CO to hemoglobin, recent studies of CO pathophysiology suggest that additional mechanisms beyond carboxyhemoglobin (COHb) formation are also involved, such as interference with biological pathways in cells and disruption of sensory nerve control (Devine et al., 2002; Townsend and Maynard, 2002; EPA, 2000; Thom et al., 1999; Thom et al., 1997; Ryter et al., 2004). Research (through 1999) reviewed by EPA (EPA, 2000), found a growing body of research on potential impacts of CO on vasomotor control, based on the fact that CO is continually produced by the human body as part of normal physiology and acts at very low levels as a neurotransmitter in the control of sensory nerves (EPA, 2000). EPA also found ongoing CO research focused on the ability of CO to cause disruption of intracellular and cellular level (e.g., mitochondrial) functions via free-radical-mediated changes (EPA, 2000). Although controversy exists over the role that other processes such as these may play in either acute or chronic CO poisoning, phenomena such as delayed neurological sequelae cannot be explained by hypoxia alone (i.e., after COHb levels have returned to normal and hypoxic stress is removed, symptoms would be expected to improve) (Townsend and Maynard, 2002). Other mechanisms of CO pathophysiology continue to be investigated.

Correlations Between CO Symptoms and Exposures Are Imprecise

The technical literature and authoritative medical texts, as well as many public outreach materials (e.g., instruction manuals that come with CO detectors), often include guidelines to specific CO poisoning symptoms that may be expected as a function of percent COHb measured in the blood and/or as a function of CO concentrations in the air. These guidelines should not be regarded as absolute discrete relationships between symptoms and either the ambient CO level or the COHb level—rather the CO poisoning symptoms are a continuum of health effects that can overlap the discrete tabular CO/COHb intervals. As noted, health effects of CO are dependent on the level and duration of exposure as well as individual inhalation rate and physical condition. Thus, the CO poisoning symptoms should be regarded as a contiuum of effects rather than discrete symptoms at each CO ambient level or % COHb level.

Diagnosis and Measurement of Severity of CO Poisoning. In general, determining the level of injury caused by CO poisoning is not always possible, and as discussed below, even confirmation of CO poisoning can be difficult. Acute CO poisoning can be assessed by measurement of COHb (see below), but this is only reliable if done within hours of exposure because CO has a biological half-life of 3 to 4 hours at room temperature, which is reduced to 30 to 90 minutes if 100% oxygen is administered (Shochat, 2010). A reliable biological marker for determining the severity of chronic CO poisoning has yet to be developed (Devine et al., 2002). For example, Devine et al (2002) identified some of the long-term health impacts of chronic CO poisoning only through extensive neurological and psychological testing.

Although there are many clinical tests that can be conducted on people with suspected cases of CO poisoning (and some recent advances have been made using non-invasive pulse oximetry as a screening tool (Suner et al., 2008; Coulange et al., 2008), currently the only test that measures CO directly is blood carboxyhemoglobin (COHb) saturation (Vreman et al., 2000). COHb can be determined by direct analysis of venous or arterial blood, or by measuring expired CO (in parts per million, ppm) with a breath analyzer and converting to COHb (Vreman et al., 2000). In a CO breath analysis study, Cunnington and Hormbrey (2002) found that breath analysis was rapid and results correlated well with recent CO exposure.

Measured COHb levels can be affected by a variety of factors (e.g., the time interval between removal from the CO source and blood sampling, interaction with other substances in the bloodstream such as administered oxygen, physiological differences among people), and not infrequently levels have been shown to correlate poorly with the signs and symptoms of acute CO poisoning (Raub et al., 2000). As a result, low COHb levels should never be solely relied upon to exclude a case of CO poisoning (Vreman et al., 2000; Penney, 2001; Cunnington and Hormbrey, 2002; Benignus et al., 1990; Raub and Benignus, 2002).

Baseline COHb concentrations, for nonsmokers, typically remain below 2% (EPA, 2000). Even though measured COHb levels may be poorly correlated with symptoms, COHb levels below 10% are usually not associated with symptoms (WHO, 1999; Shochat, 2010). EPA, however, also cites studies in their Air Quality Criteria for CO document that demonstrated adverse effects of CO at COHb levels as low as 2.9 to 3.0% in persons with coronary artery disease and chest pain (EPA, 2000). At higher COHb saturations of 10 to 30%, WHO states that neurological symptoms of CO poisoning can occur, such as headache, dizziness, weakness, nausea, confusion, disorientation and visual disturbances. Shortness of breath, increases in pulse and respiratory rates, and loss of consciousness are observed with COHb levels from 30% to 50% (WHO, 1999). When COHb levels are higher than 50%, coma, convulsions, and cardiopulmonary arrest may occur (WHO, 1999; Shochat, 2010). It should be emphasized that these ranges can only provide a rough idea of the potential effects of acute CO exposure, due both to the high variability in measurement of COHb and differences in individual susceptibility to CO toxicity. Low COHb levels do not necessarily exclude a case of CO poisoning (Vreman et al., 2000; Penney, 2001; Cunnington and Hormbrey, 2002; Benignus et al., 1990; Raub and Benignus, 2002).

Research has shown that COHb levels at which symptoms of CO poisoning begin to occur can vary widely with the individual (due to differences in factors such as metabolic rate, health status, smoking, or sensitivity) and the situation. For example, Sanchez et al. (1988) observed striking disparity in the symptoms of two children of similar age (27 and 28 months) exposed simultaneously to the same environment, resulting in similar COHb levels: a 27-month old child with a COHb level of 35.0% was flaccid and poorly responsive when brought to the emergency room, while a 28-month old with a COHb level of 33.6% was asymptomatic. Measured COHb levels can also be dissimilar in individuals with the same CO exposures (Sanchez et al., 1988). Even in known cases of CO poisoning, measured COHb may be unexpectedly low due to a long time interval between leaving the site of exposure and drawing blood for measurement, resuscitation attempts (i.e., administration of oxygen), or the presence of other substances (e.g., drugs) in the bloodstream (Penney, 2001). Therefore, although a high COHb level may confirm CO poisoning, low COHb cannot exclude it.

Carboxyhemoglobin Saturation from Cigarette Smoking

COHb levels may also become elevated for reasons other than exposure to CO from appliances and vehicles. For example, in individuals smoking one to two packs of cigarettes a day, baseline COHb concentrations average 4%, with a usual range of 3% to 8% (EPA, 2000). COHb concentrations as high as 15% have been reported in chain smokers (EPA, 2000).

In addition, CO that is formed during the normal course of metabolism contributes to baseline COHb levels, including CO produced endogenously through heme degradation; metabolism of drugs; and degradation of unsaturated fatty acids, inhaled solvents, and other xenobiotics (EPA, 2000). Baseline COHb levels have also been observed to be higher in certain groups, such as untreated asthmatics and critically ill patients (EPA, 2000; Omaye, 2002).

Research on Health Effects of Chronic and Low Level Exposures. There is no clear consensus in the literature regarding the definition of a "low level" CO exposure. In general, low level ambient CO exposure for the general population can reasonably be characterized as exposure to an air concentration of CO that is less than EPA's current National Ambient (outdoor) Air Quality Standards of 9 ppm (8-hr average) or 35 ppm (1-hr average). However, a low level COHb (≤ 5%) could arise from a brief exposure to high ambient CO or sustained CO of approximately 35ppm.

Slight reductions in maximal exercise duration and performance in healthy adults, and decreased exercise tolerance and increased chest pain in individuals with coronary artery disease, have also been associated with brief high level CO exposure (EPA, 2000).

Potential Effects of Prolonged, Repeated Low Level CO Exposures

Though not universally accepted, some research has found that prolonged repeated exposures to CO, even at levels previously believed to be low, are associated with numerous persistent, adverse physical, cognitive, and emotional health effects in humans (Penney, 2000; Devine et al., 2002; Liu et al., 2003). For example, Ritz and Yu (1999) investigated the potential adverse physical effects of low-level CO exposures by looking at the relationship between outdoor ambient exposure during the last trimester of pregnancy on the frequency of low birth weight among neonates (125,573 children) born 1989-1993 to women living in the Los Angeles, California area. Results of the analysis showed that exposure to ambient CO in the range of 5.5 to 7 ppm during the last trimester of pregnancy was associated with a significantly increased risk for low birth weight. In a similar study, Liu et al. (2003) reported an association between preterm birth and ambient CO exposures during the last month of pregnancy in Vancouver, Canada between 1985 and 1998. Devine et al. (2002) also observed mild, but persistent (17 and 29 months after exposure), symptoms of nervous system dysfunction in a case study of one woman chronically exposed to low level CO over the course of at least one year.

EPA's Air Quality Criteria for Carbon Monoxide (EPA, 2000) reviews research related to effects of low level exposure to CO (Sheppard et al., 1999; Norris et al., 1999). EPA found that physiological mechanisms for CO exacerbation of asthma are unclear and epidemiologic observations on the relationship between short-term low levels of CO exposure and the frequency of respiratory disease cannot yet be interpreted with confidence (EPA, 2000). In a later study of 133 children (5–13 years of age) with asthma residing in the greater Seattle, Washington, area, Yu et al. (2000) observed a population average 30% increase in the odds of asthma symptoms for a 1-ppm increment in CO. The authors hypothesized that CO may either be a marker for other combustion products which exacerbate asthma, or may be associated with an increased susceptibility to CO that asthmatics experience with exercise induced airflow limitation (Sheppard et al., 1999; Norris et al., 1999).

Associations Between Traffic-Related CO Exposures and Respiratory Symptoms

More recent studies (Hwang et al., 2005; Estrella et al., 2005), have observed associations between ambient (traffic-related) CO exposures and respiratory symptoms. Hwang et al. (2005), conducted a nationwide cross sectional study of 32,672 Taiwanese school children in 2001 that compared risk of childhood asthma with air pollution monitoring data for sulfur dioxide (SO_2), nitrogen oxides (NOx), ozone (O_3), CO, and particles with an aerodynamic diameter of 10 micron or less (PM_{10}). They found that the risk of childhood asthma was positively and significantly associated with CO, as well as O_3 and NOx; supporting the hypothesis that long term exposure to traffic related outdoor air pollutants increases the risk of asthma in children. In contrast, the risk of childhood asthma was weakly or not related to SO_2 and PM_{10}.

2.0 Carbon Monoxide Hazards in the Home

Based on the sources and likelihood of significant exposure, the primary residential hazards and conditions associated with CO exposure and poisoning are:

- Properly functioning consumer products can pose a CO hazard when they are operated incorrectly, including
  - Portable generators located within 25 feet of homes and open windows.
  - Charcoal/gas grills or hibachis used indoors or in confined spaces

- Gasoline-powered electric generators used in confined spaces
- Gasoline-powered vehicles started or left idling in attached garages, even with the garage door open

• Malfunctioning or inadequately vented gas, oil, or wood burning appliances, including:
  - Water heaters
  - Central heating appliances including furnaces and boilers
  - Dryers
  - Fireplaces and woodstoves
  - Vented space heaters

• Malfunctioning or improperly operated unvented appliances including:
  - Kerosene heaters
  - Unvented space heaters
  - Ranges and ovens

• Housing design
  - Lack of proper ventilation in attached garages (e.g., 100 cubic feet per minute (cfm) of continuous exhaust ventilation according to section 403.3 of the International Mechanical Code)
  - Conditions which create back drafting
  - Lack of maintenance and yearly professional inspection of gas, oil, or wood burning appliances and their vent systems
  - Lack of CO detectors

• Behavior (e.g., operating generators in appropriate locations, i.e., inside attached garages or living spaces; idling automobiles in attached garages; using gas ovens for space heating; misuse of heating and combustion appliances; cigarette smoking)

2.1 Potential Residential Carbon Monoxide Sources

Figure 2 illustrates common potential sources of CO in the home. In situations where elevated CO levels are detected in a home (e.g., via a CO detector alarm sounding), the source, or sources, may be difficult to isolate, especially because many CO problems are intermittent in nature (Greiner and Schwab, 2000).

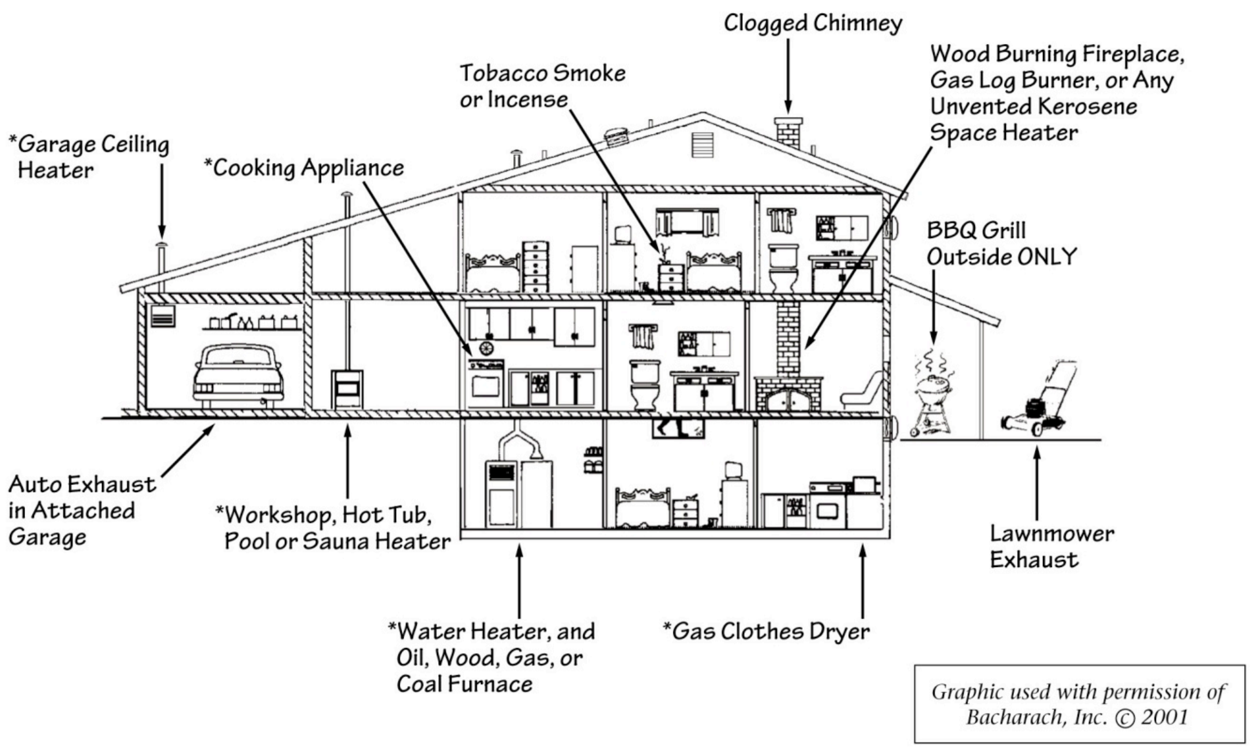
Tobacco smoke can also contribute to CO levels in indoor air, although, unless other sources are present, the increase in CO levels associated with tobacco smoke is typically insufficient to cause CO detector alarms to sound (EPA, 2000).

Back drafting. CO levels can become elevated in buildings where back drafting is occurring. Back drafting occurs when the air pressure within a home is lower than the air pressure outside, a phenomenon known as house depressurization. When these conditions exist, flue combustion gasses (CO, CO2, NO2, etc.) can reverse direction, spilling into the living area of a home instead of traveling up a vent or chimney.

Vented Combustion Appliances. The contribution to CO in the indoor environment from vented combustion appliances (furnaces, hot water heaters, and gas clothes dryers) is generally negligible unless the unit or ventilation system is malfunctioning, leaking, or back drafting (EPA, 2000). Dangerous levels of CO have been noted in cases where the venting system became disconnected or leaked (e.g., deteriorating vent systems or chimneys), was improperly installed or designed (e.g., vents too short or at improper angles), or was otherwise malfunctioning due to factors such as blockages caused by bird nests or leaves or the occurrence of back drafting (as discussed above). According to CPSC staff estimates for 1999–2001, some form of venting problem was noted in about 17 percent of the annual average total CO poisoning deaths and 29 percent of fatalities associated with heating systems (CPSC, 2004). In follow-up investigations of selected incidents, CPSC staff found that specific venting problems included: detached or improperly installed or maintained vents; deteriorating or collapsing chimneys; outdoor debris, birds' nests, or small animals in the chimney or flue pipe creating a blockage; blockage by soot caused by inefficient combustion (which in turn may have been caused by several factors, such as leaky or clogged burners, an over-firing condition, or inadequate combustion air); or improperly

Figure 2. Potential Residential Sources of Carbon Monoxide Indoors (used with permission of Bacharach, Inc. ©2001)

Potential Household Sources of Carbon Monoxide Indoors



Remember there are many more possible sources of carbon monoxide and factors affecting exposure:

- **Lack of adequate ventilation**
- **Backdrafting — e.g., bathroom and clothes dryer exhausts vented to outside in an airtight home can interfere with other vented appliances and cause CO to enter the home**
- **Lack of maintenance and inspection of gas, oil, or wood burning appliances**
- **Behavior — e.g., warming the car engine in a closed garage, misuse of combustion appliances**

*All common household combustion appliances normally produce Carbon Monoxide, but this does not usually pose a risk to household occupants unless the appliance is malfunctioning or not vented properly.

Note: The figure is missing a portable generator—the single product most associated with more residential CO deaths.

Back drafting Causes—Difficult to Diagnose

Buildings with a relatively tight envelope (few sources for air to enter) and high exhaust capacity are especially prone to depressurization. Appliances with passive ventilation via a draft hood (e.g., water heaters) may also be particularly susceptible to back drafting. Back drafting may be triggered by a constricted or poorly functioning chimney, improperly designed or maintained venting systems, or suction created by the operation of household equipment such as exhaust fans, clothes dryers and fireplaces (Nagda et al., 1996; CMHC, 1998). Because of the sporadic nature of some of these triggers, back drafting is often difficult to diagnose. A simple change in wind speed or direction, turning off an exhaust fan, or opening a door or window may be enough to alleviate the depressurization and allow flue gasses to rise. Visual clues like soot on cobwebs and excess moisture can indicate a back drafting problem. Condensation on windows and other moisture problems result from the water vapor that is produced when burning most fuels. Nagda et al. (1996) reviewed literature devoted to this subject and found that, while the causes of house depressurization and back drafting are well understood, additional research is needed on the frequency, duration, and severity of depressurization-induced spillage events in a broad cross-section of houses.

functioning exhaust fans. Less frequently, other conditions related to furnaces included cracked heat exchangers, filter door or covers that were removed or not sealed, and dirty filters.

Unvented Combustion Appliances. In contrast to vented appliances like furnaces, some combustion appliances (e.g., kerosene- and propane-fueled space heaters, some gas-fueled log sets, and gas cooking ranges and ovens) are not designed to vent directly outdoors. Although the use of unvented combustion heating appliances is common throughout the United States, the percentage of adults using these devices is higher in the South, among low-income groups, blacks, and rural residents (CDC/MMWR, 1997).

Assessing the potential impact of unvented gas cooking ranges and ovens as a significant source of CO is difficult. According to an EPA report, because unvented gas cooking ranges and ovens are used intermittently for cooking purposes, it is not likely that their use would result in substantial increases in CO over long periods of time, except possibly in households where gas ovens are being used improperly as a primary or secondary source of heat (EPA, 2000). However, some researchers have expressed concern over the potential for high concentrations of CO for even short periods of time resulting from either extended cooking or poor burner performance, or due to practices such as covering oven floors with aluminum foil (Tsongas, 1995). Short-term peak CO concentrations of 1.8 to 120 ppm have been associated with the use of unvented gas stoves for cooking (EPA, 2000). The current American National Standards Institute (ANSI) oven flue standard for CO does not address these concerns (Greiner and Schwab, 2000) (see Table 2). However, of larger concern is the improper use of gas ranges and ovens as a primary or secondary source of heat (Slack and Heumann, 1997).

The use of unvented space heaters can pose risks for elevated CO levels in indoor environments with inadequate ventilation (EPA, 2000). NHANES data indicate that an estimated 13.7 million adults used unvented combustion space heaters between 1988 and 1994 (CDC/MMWR, 1997). This includes an estimated 13.2% of the adult population in the southern United States (CDC/MMWR, 1997). Dutton et al. (2001) observed significant CO accumulations indoors when unvented gas fireplaces were used for extended periods of time. Other unvented sources can also be a hazard when used improperly in an enclosed or partially enclosed environment—such sources can include charcoal or gas grills, hibachis, or gasoline-powered tools or engines, such as portable generators, pumps, or power washers. When generators are used in garages or in living areas of homes CO concentrations can rise to much greater than 1000 ppm in a very short time.

Of particular concern is CO exposure resulting from the use of portable generators during the widespread electrical outages caused by ice storms or hurricanes. Between 2004 and 2008, Hurricane Katrina and six other hurricanes resulted in 21 fatal and 321 nonfatal CO exposures. Portable generators were determined to be the cause in 82% to 98% of the cases (CDC/MMWR 2005; CDC/MMWR 2005b; CDC/MMWR 2006; CDC/MMWR 2009). Few of the homes had functioning CO detectors. In several fatal cases, generators were located inside the home. In many nonfatal incidents, generators were located within seven feet of the home and near windows.

Although the amount of CO entering the home is minimized by placing the generator farther away, Wang and Emmerich (2009) noted that many manufacturers recommend using extension cords "as short as possible, preferably less than 15 feet long" to prevent voltage drop and the possibility of wires overheating, although an acceptable alternative would be to use heavy duty extension cords. In their study modeling the effects of generators on indoor CO levels, Wang and Emmerich concluded that placing the generator within 15 feet of an open window can cause excessive CO entry into the home. To adequately minimize peak CO levels, they found generators should be placed 25 feet from the house.

Risk of CO Exposure from Use of Gas Stoves or Ovens for Supplemental Heat

Data from the National Health and Nutrition Examination Survey (NHANES) indicate that, of 83.1 million adults surveyed who used gas stoves or ovens for cooking during the years 1988 to 1994, 7.7 million had used the stoves for supplemental heating at least one time during the previous year (CDC/MMWR, 1997). Improper use of the stove or oven as a heating device was more common among rural than among urban residents, and higher among adults in the South than in any other region. In all regions, the use of stoves or ovens for heating in low-income households was approximately twice that in high-income households (CDC/MMWR, 1997).

Further research has also reported associations between extreme weather, such as ice storms leading to prolonged losses of power, and cases of CO-poisoning related to the use of alternative heating and cooking sources (Ghim and Severance, 2004; Broder et al., 2005; Hampson and Zmaeff, 2005; CPSC, 2011).

Automobiles in Attached Garages. CO can also potentially be drawn into a house from any combustion source being operated in an attached garage, including motor vehicles, lawn mowers, or grills. Even if the garage doors are open, CO can seep into the house, particularly in situations where back drafting is occurring (e.g., CO seepage into homes from attached garages during cold winter months due to pressure differentials).

Ambient levels of CO from automobile exhaust decreased approximately 90 percent between 1965 and 1992 due to progressively tighter motor vehicle emission controls and the introduction of the catalytic converter in 1975 (EPA, 2000; Mott et al., 2002). Subsequent tiered emission standards have been phased in after 1994. First, cars and then, in 2009, light trucks (SUVs, pickup trucks, and minivans) had to further restrict emissions of CO and other exhaust emissions (http://www.epa.gov/tier2/). However, even new and well-tuned engines will produce large concentrations of CO for the first minute or two of operation. Catalytic converters do not work efficiently until they are warmed up (to about 300 °C), which usually takes one to three minutes after starting a cold engine (ISU, 1998; Burch et al., 1996). While a properly

Speed of CO Seepage from Garage to Living Space

In an Iowa State Study, researchers found that after only two minutes of warming-up an automobile in an opened garage, CO concentrations in the garage rose to 575 ppm (ISU, 1998; Greiner and Schwab, 1998). Within one minute, measurable levels of CO seeped into the house and after only 45 minutes the level in the house rose to 23 ppm. Eight hours later CO concentrations still remained above 9 ppm (ISU, 1998).

working catalytic converter typically reduces the concentration of CO in automobile exhaust to fewer than 100 ppm, the CO concentration released by a cold or otherwise non-working converter can be much higher (ISU, 1998). As a result, many acute CO poisoning episodes continue to occur from exposure to automobile exhaust. CDC also reports that some motor-vehicle-related CO deaths in garages have occurred even though the garage doors or windows have been open, suggesting that passive ventilation may not be adequate to reduce risk in semi-enclosed spaces (CDC/ MMWR, 1996).

CO researchers at Iowa State University recommend installation of exhaust fans in attached garages to prevent CO from entering the house and speed the removal of CO from the garage, but also emphasize that even with a garage exhaust fan (or with the garage door open) it is not safe to operate any sort engine in the garage (ISU, 1998). Standards such as those included in the International Mechanical Code (ICC, 2003), which require attached residential garages to have 100 cfm of continuous exhaust per bay (Section 403.3), have been established to help prevent buildup of toxics like CO in these situations; however, standards such as these have not been consistently adopted or implemented across the country at this time.

2.2 Behavioral Hazards and Lack of Prevention

Many unintentional CO poisonings in the home are the result of occupant behavior and lack of knowledge about potential sources of CO (e.g., using ovens for secondary heating sources), preventive measures (e.g., use of detectors, furnace maintenance), and the proper response to a suspected problem. Common behavioral hazards include:

- Improper placement of generators (placement within the house or an adequate distance from the house).
- Improper use of propane, natural gas or charcoal barbecue grills, portable generators, or any gasoline-powered tool (i.e., using indoors or in an attached garage);
- Unsafe behaviors where attached garages are present (e.g., starting a vehicle in a closed garage, idling the car in or near an attached garage (i.e., car should be pulled out immediately onto the driveway, then the garage door closed to prevent exhaust fumes from being drawn into the house);
- Improper use, cleaning, and maintenance of gas ranges and ovens (e.g., blocking secondary air ports with aluminum foil, using range burners or ovens to heat the home, not turning on exhaust ventilation prior to turning on oven or range top burners);
- Lack of regular cleaning of the clothes dryer and other ductwork and outside vent covers for blockages such as lint, snow, or overgrown outdoor plants;
- Lack of CO detectors, or improper use, placement, or maintenance of CO detectors;
- Lack of regular chimney flue cleaning, regular inspection and maintenance (by a professional when necessary) of gas or other fuel-burning appliances, etc.
- Lack of mechanical exhaust ventilation in attached garage and kitchen, as required by Section 403.3 of the International Mechanical Code.

A questionnaire-based study of 1003 respondents representing households in the continental United States found that although most respondents reported having a smoke detector (97%), only 29% had a CO detector (Runyan et al., 2005).

CO Victims' Use of Alcohol and Recreational Drugs

In 2001 an estimated 18 percent of CO fatalities were noted as having used alcohol or recreational drugs during the time period surrounding the incident (CPSC, 2004). Alcohol and recreational drug use can act as a central depressant causing dulled reactions, potentially impairing a person's ability to react appropriately to a CO hazard (CPSC, 2004).

3.0 Methods Used to Assess Carbon Monoxide Hazards in the Home

A variety of methods are available for assessing CO hazards in the home. Assessment of potential CO sources, as well as behavioral hazards, can be accomplished by occupant surveys and visual inspection. Elevated CO concentrations can be assessed, with differing levels of accuracy, through the use of various CO monitors (e.g., research quality and professional CO monitoring devices). Homeowners can also purchase low-cost CO detectors that warn of serious, potentially lethal levels of CO.

3.1 Surveys and Visual Inspection

Occupant surveys and visual inspection can be used to evaluate housing conditions, as well as behavioral factors, that contribute to CO hazards. For example, in addition to visually inspecting combustion equipment, first responders to CO detectors may survey occupants about the activities occurring in the house at the time the alarm sounded.

Surveys and inspections are also used to identify inappropriate use of equipment (e.g., cooking ranges used for heating, space heaters in violation of codes, etc.) or other occupant behavior that might affect CO exposure, such as idling a vehicle or operating a generator in an attached garage. Commonly recommended points for homeowner education regarding CO hazards and behavior are discussed under mitigation methods in section 4.1 below.

3.2 Analytical Methods for Assessing CO

Field Monitors and Research Instruments. A variety of field instruments are commercially available for investigation of residential CO levels, many available at a cost of less than $500. Currently, the assessment of CO levels in homes by researchers and professional investigators (e.g., from the gas utility) is most often conducted using a commercial analyzer equipped with an active sampler and either a nondispersive infrared (NDIR) absorption sensor, or an electrochemical cell sensor.

Assessment of Housing Conditions

Housing conditions assessed through surveys and visual inspections may include housing design (e.g., the presence of an attached garage), installation of appropriate ventilation devices, presence of appliances that may contribute to CO exposure, or visual evidence of problems with equipment, chimneys, flues, vents, or ventilation. For example, visual evidence of the back drafting of combustion gases includes soot, scorched surfaces, and melted fittings near the vent (CMHC, 1998). Observations such as excess condensation on windows, and practices such as lining gas ovens with aluminum foil are also visual indications of possible CO problems. Recommendations for regular professional inspection of equipment and relevant housing conditions are discussed under mitigation methods in section 4.2 below. Checklists help ensure that all potential sources are investigated.

The NDIR method, which is generally accepted as the most reliable, continuous method for measurement of CO in ambient air, is based on the specific absorption of infrared radiation by the CO molecule and is extremely sensitive over wide concentration ranges. The most sensitive, commercially available analyzers using NDIR technology are able to detect minimum CO concentrations of about 0.02 ppm (EPA, 2000). The EPA-designated reference methods for collecting CO measurement data for National Ambient Air Quality Standards (NAAQS) are automated methods using NDIR technology (EPA, 2000). Portable analyzers using NDIR technology are available for home assessments with the capability of measuring extremely low-levels of ambient CO (i.e., down to ppb). However, they are expensive (e.g., up to tens of thousands of dollars) and are typically used only in research settings where the extra sensitivity is needed.

Although the electrochemical sensor technology, which is based on the measurement of electrical currents generated as a result of chemical reactions that occur in the presence of CO, is less sensitive and more susceptible to interferences (from water vapor and other gases) than NDIR technology, it is less expensive (e.g., typically a few hundred dollars) and sufficiently sensitive (some down to 1ppm) for the identification of CO poisoning hazards[2]. Therefore, for routine CO screening, or in situations where the goal is to identify higher concentrations of CO that represent a health risk, palm-held electrochemical sampler/analyzers are most commonly used. Electrochemical sensors are also used in certain types of home CO detectors. Upper-end (e.g., up to a few thousand dollars) electrochemical sensor analyzers are available that, with frequent recalibration, can exhibit sensitivities comparable to NDIR. The normal performance range expected for automated CO analyzers is 0 to 1,000 ppm, with some instruments available that offer higher or lower ranges for specific uses. Sensors used in home CO detectors are intended for the purpose of providing warning of potentially dangerous CO levels (generally above 70 ppm) and therefore do not need such a large range.

Other Common Methods for Assessing CO Levels

Other methods also commonly used to assess CO levels include gas chromatography/canister sampling methods for measuring low level background CO levels, and passive samplers (e.g., badges and spot detectors) used to monitor personal exposure to CO. Regardless of which method is used, and as with all field instrumentation, accurate results are dependent on appropriate training for those using the instrument, as well as routine maintenance/calibration of the instrument. Badges and spot detectors provide measurements of exposure based on color change, and can't be calibrated or reset to zero after exposure since they offer no digital display. Using multiple instruments with differing vulnerabilities to interference is one method of verifying suspect readings.

CO Concentrations Indoors. CO concentrations in the indoor environment vary based on the source emission rate, use pattern (i.e., intermittent or constant use), ambient outdoor CO concentration, air exchange rate, building volume, and air mixing within the indoor compartments (EPA, 2000). Generally, all-electric homes have lower CO readings than homes that have combustion appliances, although even all-electric homes may still contain several potentially hazardous sources of CO (e.g., fireplaces, electric ovens in self-cleaning mode, and attached garages). Average indoor CO levels typically vary from 0.5 to 5 ppm (Wilson et al., 1993). Studies conducted by Wilson et al. (1993) investigated a random sample of residences in California for the purpose of estimating a statewide distribution of indoor CO concentrations. Based on this analysis, the estimated 95th percentile value of 48-hour average CO concentrations in California residences was 5.8 ppm. The estimated 95th percentile value for the maximum 10-minute exposure was 18.6 ppm. These values provide some context for determining when an indoor CO concentration is abnormally high in comparison to average levels.

Available Criteria for Comparison to Measured CO Concentrations. CO hazard levels are typically expressed as airborne concentrations in parts per million (ppm) and duration of exposure. Table 3 shows available standards and guidelines for comparison to measured CO

Difficulty Detecting CO Levels from Intermittent Sources

Transiently elevated CO levels in homes caused by intermittent sources, such as appliances used only occasionally or down drafting, may be difficult to detect. For example, although average long-term concentrations of CO from gas cooking stoves are not expected to be significant due to their intermittent use, short-term peak CO concentrations up to 120 ppm have been associated with these stoves (EPA, 2000).

[2] *For example, available automated data logging CO analyzers include: PocketCO (accuracy +/- 10% of reading), http://www.quantumfields.com/Pocketco.html; HOBO CO Datalogger (accuracy +/- 7% of reading, no digital display), www.onsetcomp.com/Products/Product_Pages/Other_HOBOs/co_data_logger.html; Gasman II (with digital display and datalogging options that can be set by user), http://www.ceainstr.com/pdf_datasheets/gasman2_Info.pdf.*

Table 3. Selected Standards and Guidelines1 for Carbon Monoxide

Criterion	Agency & Purpose
9 ppm	• EPA's National Ambient (outdoor) Air Quality Standard—8-hr average
	• World Health Organization's outdoor air limit—8-hr average
≤ 11 ppm	• Health Canada's Exposure Guideline for Residential Indoor Air—acceptable short-term exposure range, 8-hr average
≤ 25 ppm	• Health Canada's Exposure Guideline for Residential Indoor Air—acceptable short-term exposure range, 1-hr average
30 ppm	• Lowest CO level that UL and CSA allow home CO detectors to display, must not alarm in less than 30 days
35 ppm	• EPA's National Ambient (outdoor) Air Quality Standard—1-hr average
50 ppm	• OSHA's 8-hr time-weighted average exposure for workers
	• EPA's Significant Harm Level for ambient CO per 8 hr time-weighted average
70 ppm	• UL and CSA false alarm resistance point at 60 minutes (1 hr) of exposure
	• Level at or above which UL and CSA home CO detectors must go off when exposed for 60–240 minutes (1–4 hrs)
75 ppm	• EPA's Significant Harm Level for ambient CO per 4 hr time-weighted average
125 ppm	• EPA's Significant Harm Level for ambient CO per 1 hr
150 ppm	• Level at or above which UL approved CO detectors must go off within 10–50 minutes of exposure
200 ppm	• NIOSH ceiling concentration for workers at which immediate evacuation is recommended
	• (Air free) Level of CO allowed inside water heater flue by ANSI standard
400 ppm	• Level at or above which UL approved CO detectors must go off within 4–15 minutes of exposure
	• (Air free) Level of CO allowed inside furnace flue by ANSI standard
800 ppm	• (Air free) Level of CO allowed inside oven flue by ANSI standard

[1] *For comparison: Average indoor CO levels typically vary from 0.5 to 5 ppm (Wilson, et. al., 1993). During smog episodes, atmospheric levels of CO, both indoors and outdoors can climb to 5 to 10 ppm (EPA, 2000).*

ANSI = American National Standards Institute; CSA = Canadian Standards Association (refers to CSA Std. 6.16-01); NIOSH = National Institute for Occupational Safety and Health; OSHA = Occupational Safety and Health Administration; UL = Underwriters Laboratories (refers to UL Std. #2034, Second Edition, dated October 29, 1996, with revisions through June 28, 2002).

levels, although it should be noted that each of these was created for purposes other than assessing residential CO levels.

Ambient Carbon Monoxide Standards. Under the Clean Air Act, EPA issued a CO standard for outdoor air of 9 ppm averaged over 8 hours and 35 ppm averaged over 1 hour (EPA, 2011). These National Ambient Air Quality Standards (NAAQS) for outdoor air are intended to be protective for all segments of the population (including sensitive populations). Areas that fail to meet the NAAQS two or more times in a year must implement special air pollution control measures. These standards are also used as the basis for EPA's Air Quality Index. Ambient CO levels that exceed the Index trigger warnings to those most sensitive to CO: "People with cardiovascular disease, such as angina, should limit heavy exertion and avoid sources of CO, such as heavy traffic." Warnings increase with increasing CO levels. If outdoor CO levels reach three- to five-fold the standard (an extraordinarily unusual finding), Air Quality Index warnings are extended to members of the general public who are advised to avoid heavy exertion. EPA has also defined Significant Harm Levels (SHL) for ambient CO as 50 ppm/8h average, 75 ppm/4h average, and 125 ppm/1h (40 CFR part 51.151). SHL are ambient pollutant concentrations that EPA defines as levels that cause significant and imminent harm to the general public. There is no EPA standard for CO in indoor air.

Occupational Standards for Carbon Monoxide. In contrast to EPA's standards that apply to more vulnerable members of the general public, occupational standards and guidelines pertain to healthy adult workers. The Occupational Safety and Health Administration (OSHA) standard for exposure to CO prohibits worker exposure to no more than 50 ppm, averaged over an 8-hour workday (29 CFR 1910.1000, Table Z-1; OSHA, 2002). The National Institute for Occupational Safety and Health (NIOSH) recommends that CO levels to which workers are exposed should not exceed a ceiling concentration of 200 ppm (NIOSH, 1972).

Carbon Monoxide Detector Standards. Although there are no mandatory national standards in place for CO detectors, the quality of CO detectors available for purchase today is greatly influenced by self-imposed industry performance criteria, which provide recommended performance requirements for detectors, as well as general criteria for their construction and testing. The U.S. CPSC recommends that consumers purchase home detectors that meet specifications established by Underwriters Laboratories (UL) 2034 standard for CO detectors, "Single and Multiple Station Carbon Monoxide Detectors" or the Canadian Standards Association CAN/CSA 6.19-01, and the previous International Approval Services IAS 6-96. All three organizations are well respected standards developers and their standards are equally acceptable to the CPSC staff.

The current UL 2034 standard is the third edition, dated February 28, 2008 (UL, 2008). The UL specifications require detectors to sound before an active individual would experience an estimated dose causing 10% COHb. Because COHb levels are a function of both the level of CO in the air and the duration of exposure, among many other factors, specifications for CO detectors are defined by the CO level in air and the amount of time the level is maintained. As shown in Table 3, under UL Standard 2034 alarms must sound within 60–240 minutes (1–4 hours) if 70 or more parts per million (ppm) CO are present; within 10–50 minutes if 150 or more ppm CO are present; and within 4–15 minutes if 400 or more ppm are present.

Limiting CO Detector False Alarms

In order to limit false alarms, home detector specifications also identify levels at which CO alarms must not sound. These performance criteria were established in response to incidents like the one in Chicago in December 1994 in which thousands of home CO alarms sounded simultaneously during a smog episode and the ensuing calls to fire companies overwhelmed the 911 system. Detectors from the early 1990's alarmed at levels of concern for those with cardiovascular disease or other risk factors for CO effects, but, given the unintended consequences on the 911 system, were considered unacceptable for the general population. In response, under the revised UL Standard 2034, detectors must be exposed to a minimum of 30 ppm CO for at least 30 days before they may sound.

These alarm criteria are consistent with the use of CO detectors to warn residents of serious, life threatening levels of CO. The criteria, however, are purposefully not designed to warn of unhealthy ambient conditions addressed by EPA's Air Hazard Index or compliance with occupational standards and ceiling recommendations. Currently manufactured CO detectors that meet the UL standard must not display the CO concentration below 30 ppm, and starting in 2007 will only be required to be accurate within 30 percent of the actual CO concentration. CO detectors are not designed for low-level CO monitoring and are not appropriate for that use.

3.3 Carbon Monoxide Detectors

Along with regular inspection of combustion appliances, properly working CO detectors can provide home occupants with warning when indoor CO levels reach dangerous levels. (See below for types of carbon monoxide detectors.) For example, in a study of unintentional CO poisoning deaths in New Mexico (1980 through 1995), Yoon et al. (1998) found that 49% of residential CO deaths occurred when the occupants were sleeping, and estimated that (of the victims without the presence of alcohol in their blood) approximately half (78) of the deaths could have been prevented if audible CO alarms were used and functioned properly. Donnay (2005) however, questions whether the UL CO detector standards are protective enough (e.g., in light of NIOSH recommendations for workers that recommend immediate evacuation of workers above 200 ppm), especially for sensitive groups such as those with cardiac and pulmonary health problems, and pregnant women.

Clifton et al. (2001), using a novel method that involved analysis of national media clipping data, studied CO exposures in the US and the role of CO detectors in prevention of CO-related deaths. Comparing nonfatal outcomes attributable to the presence of CO detectors and case fatality rates among cities with and without CO detector ordinances, the researchers found that cities with CO detector ordinances showed lower case fatality rates as reported in the media than those cities without ordinances ($P<0.001$). There were 1,008 (24.2%) survivors who attributed their survival to the presence of a CO detector. The authors also note that despite its limitation, the use of a media clipping service may provide insight into CO poisoning demographics.

Investigating the Effectiveness of a CO Detector Ordinance

CDC, in coordination with local emergency physicians and fire department authorities, conducted an investigation of the effectiveness of a CO detector ordinance in Mecklenburg County, North Carolina (2002 population: 722,367) after a 2002 ice storm caused 78.9% of county households to lose power (CDC/MMWR, 2004). The ordinance, adopted in September 2000, requires a CO detector in the majority of residences; all-electric residences without attached garages (35.4% of all homes) were exempt. The CDC investigation found that of the 124 cases of symptomatic CO poisoning reported over a period of nine days, 96.2% of the severe poisonings occurred in homes with no reported functioning CO detector. As a result of these findings, on October 8, 2003, Mecklenburg County officials amended the ordinance to require detectors with battery back-ups in all residences. The CDC researchers note that officials in other communities should consider enacting such detector ordinances to prevent CO poisonings (CDC/MMWR, 2004).

According to the Home Safety Council's State of Home Safety in America 2004 report, approximately two-thirds (67%) of respondents used gas, wood, kerosene, coal, or fuel oil as their major household heating source, and 51 percent of homes had some sort of gas appliances. However, less than one-third (29%) of all homes surveyed for the report reported having a carbon monoxide detector. The respondents to the survey who used gas, wood, kerosene, coal or fuel oil as their primary household heating source, or whose homes had gas appliances of some sort, were slightly more likely (35%) than the overall average to have a carbon monoxide detector in their home (Home Safety Council, 2004).

The National Fire Protection Association reported that in 2005, U.S. fire departments responded to an estimated 61,100 non-fire CO incidents in which carbon monoxide was found, or an average of seven such calls per hour. That represents an increase of 18 percent from 2003, when 51,700 incidents were reported. The NFPA cites the use of CO detectors as the most likely reason for the increase (NFPA, 2007).

Types of Carbon Monoxide Detectors

Exposure to moderate concentrations of CO over several hours can be as dangerous as exposure to higher CO levels for a few minutes. Therefore, while CO detectors are designed primarily to provide early warning of potentially dangerous high-level exposures, they also offer some protection against lower levels by monitoring CO levels over time.

Evolution of Home CO Detectors/Detectors

There are many different types and brands of CO detectors available on the market today for home use (Kwor, 2000; Clifford and Dorman, 1996). Improvements in CO detector technology have helped produce detectors with greater sensitivity and reliability. As opposed to early designs that relied on a visual warning system based on chemical reactions, today's detectors use audible alarms and are capable of measuring CO concentration over time to mimic the uptake in the body, thereby reducing false alarms. Combination smoke detectors and CO detectors are now available, as well as interconnected CO detectors for large homes.

Opto-Chemical Sensors. These detectors contain a colorimetric reagent, in which a change in the color of a gel-coated disc sounds an alarm. The biomimetic (gel cell) sensor works with a synthetic hemoglobin that darkens in the presence of CO, and lightens without it. Opto-chemical detectors only provide a qualitative warning of the gas. While they are the lowest in cost, they offer the lowest level of protection. The devices last about 10 years. These products were the first to enter the mass market but have now largely fallen out of favor.

Metal Oxide Semiconductor (MOS) Sensors. Thin wires of the semiconductor tin dioxide on an insulating ceramic base provide a sensor monitored by an integrated circuit (Kwor, 2000; Clifford and Dorman, 1996). This sensing element needs to be heated to approximately 400 degrees Celsius in order to operate. Oxygen increases resistance of the tin dioxide, but carbon monoxide reduces resistance therefore by measurement of the resistance of the sensing element means a monitor can be made to trigger an alarm. The power demands of this sensor means that these devices can only be powered by electric mains although a pulsed sensor is available that has a limited lifetime (months) as a battery powered detector. The superior performance of electrochemical cell technology is beginning to displace this technology.

Electrochemical Sensors. This is a type of fuel cell that instead of being designed to produce power, is designed to produce a current that is precisely related to the amount of the target gas (CO in this case) in the atmosphere (Kwor, 2000; Clifford and Dorman, 1996). Measurement of the current gives a measure of the concentration of carbon monoxide in the atmosphere. The electrochemical cell consists of a container, 2 electrodes, connection wires and an electrolyte—typically sulfuric acid. Carbon monoxide is oxidized at one electrode to carbon dioxide while oxygen is consumed at the other electrode. The electrochemical cell has advantages over other technologies in that it has a highly accurate and linear output to CO concentration, requires minimal power as it is operated at room temperature, and has a long lifetime (typically commercial available cells now have lifetimes of 5 years or greater). Until recently, the cost of these cells and concerns about their long term reliability had limited uptake of this technology in the marketplace, although these concerns are now largely overcome.

A simplified overview of selected properties and the relative performance of the three primary CO sensor technologies currently used in home CO detectors is presented in Table 4. This overview serves as only a very general comparison of sensor technologies available for home use. Research has indicated that brand-to-brand variation in CO detector performance is not conclusively related to the particular sensing technology used, whether colorimetric, semiconductor or electrochemical (Clifford and Siu, 1998; Kwor, 2000). All three sensor technologies are capable of meeting UL

Electrochemical Detectors Have the Best Overall Cost and Performance

According to Kwor (2000), colorimetric and metal oxide type sensors dominated the home consumer market until about 1997, when the market share of electrochemical CO detectors began to grow rapidly. The colorimetric detectors tend to have the lowest cost, and the MOS detectors have the longest life. The review by Kwor (2000) concludes that the electrochemical detectors "exhibit the best overall combination of cost and performance". Other established technologies for CO detection, such as gas chromatography, mass spectrometry, ion mobility spectroscopy, and NDIR absorption sensors used for research and professional monitoring, are currently not available for low-cost home use.

Need for Longer-Term Evaluations of Home CO Detectors

Longer-term field evaluations of CO detectors (models available at the end of 1999), including sensitivity testing over time, are ongoing by organizations such as UL. UL research suggests that, regardless of the sensor technology used, most detectors perform within UL standards, and all provide effective signaling protection (Patty, 2001, personal conversation; Moloney, 2001). Based on current information, the major questions that remain unanswered concern how long CO detectors can actually remain in use in the field and the performance characteristics for different types of CO detectors after several years of use.

requirements. There is no recommendation as to which technology the detector must use to meet the standard.

UL specifications for CO detectors address not only CO exposures that trigger alarms, but also problems with interference and concerns about reliability. Because many detector technologies are also susceptible to interference from pollutants commonly found in indoor environments, UL 2034 standards specify minimum allowable interference levels for methane, butane, heptane, ethylacetate, isopropyl alcohol, carbon dioxide, ammonia, ethanol, toluene, trichlorethylene and acetone. Two studies identified some problems with CO detectors not meeting the UL specifications for sensitivity and selectivity (Clifford and Siu, 1998; Kramer and Tikalsky, 2000), but there is no widespread indication of problems with CO detectors fulfilling their intended use – to warn of potentially dangerous CO levels, generally above 70 ppm. With respect to maintenance of long-term performance, UL specifications require certain levels of performance for 3000 hours of operation.

Protocols for CO Detector Response and Evaluation. If a CO detector sounds, most residents call their local emergency service or utility company for assistance. Professionals who respond to CO alarms generally use field monitors that feature digital displays of CO levels to investigate the cause of the alarm sounding and to advise residents about the hazard posed by the levels of CO found. With no generally recognized standards for acceptable levels of CO in indoor air, advice to residents often reflects the professional judgment of the individual responding to the alarm.

Guidelines and protocols for responding to CO detectors have been developed by several groups including federal agencies (CPSC, 2003a; see Appendix A), trade associations (e.g., Building Performance Institute or BPI), municipal first response teams, and private industry (Scott Instruments, 2002). Although not identical, these protocols share many similarities. CPSC recommends that, in the event of a CO detector activation, the residents should go outdoors or to a neighbor's house immediately and not ventilate the house (to allow for identification of the CO source), unless someone is unconscious or cannot leave. Emergency responders (911) should be called immediately. As with any hazardous substance emergency, first responders need to follow protocols for safe entry once on the scene. Field instruments, as well as visual clues and occupant survey, are used to evaluate conditions.

Carbon Monoxide Detector Ordinances/ Regulations. Increased recognition of the importance of detection of high levels of CO in

Table 4. Selected Properties of the Primary Sensor Technologies for Residential CO Detectors

Sensor Property	General Performance of Sensor Type[a]		
	Colorimetric	Metal Oxide Semiconductor	Electrochemical
Basic Operation Principles			
	Gel-coated discs darken in the presence of CO; color change sounds an alarm	Heated metal (tin oxide) reacts with CO to determine the levels of CO; must connect to house power	Chemical reaction with CO creates an electrical current, setting off an alarm
Durability			
Lifetime	> 5 years (Data being collected)	5 - 10 years	> 5 years (Data being collected)
Short-term stability	Unknown; difficult to assess	Fair	Good
Performance			
Resolution and Accuracy[b]	Fair	Fair	Good
Sensitivity drift	Unknown	Moderate	Moderate
Response time	Fair	Fair	Good
Immunity to false alarms[c]	Fair	Good	Good
Immunity to false negatives[d]	Good	Good	Good
Temperature and humidity dependence	Fair	Fair	Good (humidity) Fair (temperature)
Selectivity[e]	Good	Good	Good
Immunity to poisoning[f]	Good	Good	Good
Consumer Preferences			
Power consumption	Low	High	Low
Sensor cost	Low	Low	Low
Primary advantages	Simple, lowest cost	Long-life, extensive performance data available (longest history of field usage)	Reasonable cost, low power consumption, good performance
Primary disadvantages	Interference (temperature, humidity, other gases), difficult to reset quickly after CO exposure, rarely equipped with digital displays, early models had shorter lifetimes	High input power, interference (temperature, humidity), inaccuracy	Temperature and humidity dependence, lack of long-term sensitivity data (relatively recently developed technology)

[Table adapted from Kwor, 2000 and Clifford and Dorman, 1996]

[a] There are commercial detectors available that meet UL-2034, CAN/CGA-6.19-M93 and CAN/CSA 6.19-01 requirements for all three sensor technologies. The U.S. Consumer Product Safety Commission (CPSC) recommends that consumers purchase and use a detector that meets the latest requirements of the UL or CAN/CSA or CGA standard. There is no recommendation as to which technology the detector must use to meet the standard. [b] Resolution and accuracy=reflects the detection limit and how close the measured value is relative to the true CO level. [c] False alarm=detector alarms even though CO level is low. [d] False Negative= detector fails to alarm when CO level is high. [e] Selectivity=ability to distinguish between CO and other gases. [f] Immunity to poisoning=resistance to interference from other substances or pollutants in indoor air.

preventing CO exposures has led many states and jurisdictions to require installation of CO detectors, especially in new homes and rental properties. As of January, 2010, twenty-five states have statutes requiring installation and maintenance of CO monitors. Appendix B lists the requirements by state and provides a summary of the requirements (National Conference of State Legislatures, 2010).

Important considerations for code authorities are itemized in UL's "Carbon Monoxide Alarm Considerations for Code Authorities" (UL, 2009). Considerations include UL listings; installation location and procedures, power supplies, maintenance, and testing requirements.

4.0 Methods Used to Mitigate Carbon Monoxide Hazards in the Home

Intervention methods for prevention of residential CO poisoning include:

- Education and outreach to consumers about CO poisoning symptoms and CO source control (including safe behaviors and proper maintenance of combustion appliances).
- Education and outreach to professionals about home CO poisoning, including symptoms and correct observation of home conditions that pose potential or actual CO hazards.
- Installation of home CO detectors and implementation of standard protocols for alarm response.
- Installing ventilation for, or improving existing ventilation of, combustion appliances.
- Replacing combustion with non-combustion appliances.
- Locating generators at least 25 feet from homes by means of a heavy duty extension cord.

4.1 Education and Outreach to Home Occupants

Education of home occupants regarding the potential sources of CO, actions to take to avoid CO exposure, and the proper response to a suspected problem are primary means of reducing CO hazards in the home. For example, as most acute CO poisoning episodes occur from exposure to automobile exhaust, residents need to be educated about the risk posed by starting and idling vehicles in unvented garages attached to the home. This risk can be substantially reduced by installing continuous mechanical exhaust ventilation (an exhaust fan) as required by Section 403.3 of the International Mechanical Code.

CPSC Recommendations to Consumers to Prevent CO Poisoning

At the household level, CPSC urges consumers to take the following steps to prevent CO poisoning (CPSC, 2009):

- Have your home heating systems (including chimneys and vents) inspected and serviced annually by a trained service technician.
- Never use portable generators inside homes or garages, even if doors and windows are open. Use generators outside only, far away from the home.
- Never bring a charcoal grill into the house for heating or cooking. Do not barbeque in the garage.
- Never use a gas range or oven for heating.
- Open the fireplace damper before lighting a fire and keep it open until the ashes are cool. An open damper may help prevent build-up of poisonous gases inside the home.
- Install battery-operated CO detectors or CO detectors with battery backup in your home outside separate sleeping areas.
- Know the symptoms of carbon monoxide poisoning: headache, dizziness, weakness, nausea, vomiting, sleepiness, and confusion. If you suspect CO poisoning, get outside to fresh air immediately, and then call 911.

4.2 Education and Outreach to Professionals

In addition to home occupants, the education of health care providers (e.g., visiting nurses),

Consumer Education Materials and Press Releases on CO

In an effort to reduce injury and deaths associated with CO poisonings, numerous federal agencies (EPA, CDC, CPSC, USDA) as well as private and non-profit groups, have created educational materials to increase awareness of the symptoms and sources of CO poisoning. Commonly recommended points for homeowner education regarding CO hazards and behavior include those focusing on proper use and maintenance of propane, natural gas, or charcoal equipment (appliances, grills, generators, etc.) or any gasoline-powered tool; safety where attached garages are present; the importance of regularly cleaning the clothes dryer and other ductwork and checking outside vent covers for blockages; proper use, placement, and maintenance of CO detectors; and the need to have all gas or other fuel-burning appliances and chimneys inspected and maintained regularly by a professional. Other outreach efforts include timely press releases and reminders issued by CPSC to consumers about CO hazards posed from bringing grills, hibachis, and gasoline-powered generators into the home or garage during storms or other events that cause power outages.

professionals who respond to CO detectors or conduct home inspections (e.g., utility company inspectors), and professionals who service combustion appliances (e.g., heating contractors) regarding home CO poisoning is also essential. These groups can both serve as effective conveyors of risk information to home occupants and serve important roles in diagnosing CO problems in a home, for example, through early recognition of symptoms of CO poisoning in home occupants or correct observation of home conditions that pose potential or actual CO hazards.

Outreach to Health Care Providers about CO Poisoning Symptoms and Prevalence. Studies on the misdiagnosis of patients with CO poisoning demonstrate the need for outreach to medical professionals on CO poisoning (Comstock et al., 1999). Because of the relatively non-specific flu-like symptoms of CO poisoning (e.g., headache, nausea, lethargy, confusion, dizziness, agitation, etc.), it often may be misdiagnosed (Comstock et al., 1999).

Another target area for professional assessment is the potential for backdrafting problems, particularly in tight homes that are especially susceptible to backdrafting due to house

Misdiagnosis of Occupational CO Poisonings

In an investigation of 34 (45%) of 75 manufacturing plant employees that experienced symptoms of CO poisoning (i.e., primarily headaches) while at work, failure to diagnose illness correctly in the first employees evaluated resulted in some CO-intoxicated employees being sent back to work and further exposure and in continued exposures to other workers at the plant (Comstock et al., 1999). Of ten ill employees evaluated at three local emergency departments, CO poisoning was initially diagnosed (and then later dismissed as erroneous) in only three workers (Comstock et al., 1999). Grand rounds (i.e., lectures at hospitals for physicians and others) have been an effective tool for educating medical providers about other environmental health hazards. Reliable data on the prevalence of CO-related morbidity could also be a useful tool for demonstrating the need for medical providers to educate themselves about the dangers of CO.

Outreach to Home Inspection Professionals: Guidance on Assessing Appliance, Ventilation, and Back drafting Problems. Numerous organizations, such as the CPSC and the Canada Mortgage and Housing Corporation (CMHC), as well as several commercial organizations, provide guidance to professionals who conduct overall CO investigations in the home, including emergency response and routine preventive inspections. In November 2003, CPSC published the following guidance, "Responding to Residential Carbon Monoxide Incidents: Guidelines for Fire and Other Emergency Response Personnel" (see Appendix A).

depressurization. If a backdrafting problem is suspected, a professional heat contractor should check the house and heating systems. Small temperature-sensitive strips called "Backdraft Indicators" can be attached to the draft diverter (which regulates the flow of air in HVAC systems) to detect backdrafting of exhaust gases (ISU Extension Publication, 1996). A chimney flow test may also be conducted by holding a smoke indicator (such as an incense stick) near the draft hood of a gas furnace or water heater, and watching the direction of smoke movement at the draft hood or damper, both with and without exhaust fans and other exhaust equipment in the house turned on (CMHC, 1999). If the smoke moves into the house, a spillage problem may be present. Ways to reduce house depressurization (i.e., reducing indoor and outdoor pressure differences) include shutting off exhaust fans or avoidance of running several simultaneously, sealing return ducts or closing return registers in the basement, opening supply registers in the basement, opening doors between rooms, closing fireplace dampers, and where a furnace or water heater is enclosed in a small separate room, allowing air to move freely between the furnace room and the rest of the house. The only fail-proof way to eliminate backdrafting of combustion gases, however, is to install direct vent appliances that do not have open draft diverters.

Various guidance documents with suggested protocols for conducting safety testing of combustion appliances, including spillage and CO emissions, have been developed, including:

- ASTM Standard E1998-99, "Standard Guide for Assessing Depressurization-Induced Backdrafting and Spillage from Vented Combustion Appliances";
- Section H of the National Fuel Gas Code (ANSI Z223.1/NFPA 54);
- ASHRAE 62.2 Appendix A, Checking the Venting of Combustion Appliances; and
- Canada General Standards Board- 51.71-95, "The Spillage Test Method to Determine The Potential for Pressure Induced Spillage from Vented, Fuelfired, Space Heating Appliances, Water Heaters and Fireplaces";
- Iowa State University, Agricultural and Biosystems Engineering Extension, provides

What Professionals Should Look for When Investigating CO in Homes

According to the CPSC, inspections of homes by a professional (e.g., heating contractor or Gas Company) should include a careful look at the following sources of CO:

- **Furnaces, water heaters, boilers, and stoves.** If they burn natural gas, heating oil, wood or other kinds of fuel, these appliances are potential sources of CO. Typical appliance (e.g., furnace, stove, fireplace) problems that cause the release of CO in homes, many of which are hard for a homeowner to identify, include: cracked heat exchangers; insufficient air for proper combustion; and maladjusted burners.
- **Chimneys, flues, and vents.** Flues and chimneys should be inspected before each heating season for leakage and for blockage by creosote or debris. Creosote buildup or leakage could cause black stains on the outside of the chimney or flue. These stains can mean that pollutants are leaking into the house. (Specific methods for assessing back-drafting are described below). All vents to furnaces, water heaters, or boilers should be checked to make sure they are not blocked, loose, or disconnected. Snow and ice also create the potential for vent blockages. Owners and residents should know where all of their vents exhaust and be aware of those areas where heavy snow or ice can impact proper operation.
- **Improper ventilation.** Fuel burning appliances require adequate ventilation. A supply of fresh air is important to help carry pollutants up the chimney, stovepipe, or flue, and is necessary for the complete combustion of any fuel.
- **High Temperature Plastic Venting (HTPV) pipes.** Consumers should have the vent pipes on their natural gas or propane heating systems inspected for the presence of HTPV pipes. The HTPV pipes could crack or separate at the joints and leak CO into the home. In 1998, virtually the entire furnace and boiler industry, together with the manufacturers of HTPV pipes, joined with CPSC to announce a vent pipe recall program.

numerous factsheets on combustion appliance inspection, as well as other information on CO hazards (see, for example, "Carbon Monoxide Poisoning - Checking for Complete Combustion," ISU Extension Pub # AEN-175, available at http://www.abe.iastate.edu/human_house/aen175.asp).

5.0 Current Research and Information Gaps

Prevalence of CO poisoning

While detailed information is available on CO-related fatalities, no nationwide studies have been conducted to determine the prevalence of elevated CO exposures in the general population.

Topics of consideration for future research in this area include:

- Current CO poisoning prevalence among groups with greater sensitivities to CO;
- Current CO poisoning prevalence among patients with flu-like symptoms;
- Relationship between CO exposure and behavioral hazards and lack of prevention.

CO Sources, Exposures and Health Effects

The following are some topics on which additional research would be of value to better understand and ultimately, further reduce current residential exposures.

- Research on health effects associated with chronic exposures to low levels of CO or intermittent exposures to medium or higher levels of CO;
- Research regarding current CO exposure models and accurate prediction of high-level and low-level CO exposures;
- Research on the contribution of nonambient sources to total human exposure to CO;
- Data on actual CO levels founds in homes with various types of CO sources (to better inform HHI grantees about the range of CO levels they may encounter);
- Investigative information after combustion appliance failures and other CO poisoning accidents (i.e., the source of CO, the reason(s) CO entered the structure, the health outcome of the exposure, measures needed to correct the problem, the magnitude of the problem);
- Research/survey information on the prevalence of excessive CO emissions from combustion equipment and the primary cause of exposure (i.e., is it improper design, installation, maintenance, or use?);
- Information on the frequency and cause of vent failure (e.g., failure of the owners to have the vent maintained, failure of professionals to inspect and repair, etc?);
- Cost-effective options for venting currently unventilated garages and kitchens and information on the benefits of such ventilation; and
- Research into the incidence and severity of delayed neurological sequelae in individuals with confirmed CO poisoning.
- Research into sources of CO poisoning should include houseboats, a focus of some NIOSH research.

Home CO Detectors

- Evaluation of the overall performance of CO detectors, including reliability both at the time of purchase and throughout their lifetime;
- Evaluation of the performance of CO detectors in response to cumulative lifetime exposures to other indoor air contaminants that may compromise their functioning;
- Evaluation of the length of time consumers should retain a CO detector;
- Continued research into various sensing technologies that may be employed in CO detectors;
- Cost-benefit analyses of CO detector use and other intervention options from a public health program perspective.

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Appendix A. Additional Internet Resources

In addition to the references and links appearing in the reference list above, the following table provides selected links with additional information on carbon monoxide and associated issues.

Sponsoring Organization/Topic	Internet Web Site Address
American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.	http://www.ashrae.org/
Canada Mortgage and Housing Corporation (Healthy Housing & Sustainability Projects) (Combustion Gases Link)	http://www.cmhc-schl.gc.ca/en/index.cfm (http://www.cmhc-schl.gc.ca/en/imquaf/hehosu/index.cfm) (http://www.cmhc-schl.gc.ca/en/burema/gesein/abhose/abhose_ce02.cfm)
Canadian Standards Association (CSA)	http://www.csa.ca/
Carbon Monoxide Headquarters	http://www.coheadquarters.com/CO1.htm
Centers for Disease Control and Prevention	http://www.cdc.gov/
Environmental Health Watch	http://www.ehw.org/
Gas Technology Institute	http://www.gri.org/
Health Canada's Exposure Guidelines for Residential Indoor Air Quality	http://www.hc-sc.gc.ca/ewh-semt/pubs/air/exposure-exposition/index_e.html
HUD's Office of Healthy Homes and Lead Hazard Control	http://www.hud.gov/offices/lead/
International Approval Services (IAS)	http://www.approvals.org/
Iowa State University Extension	http://www.abe.iastate.edu/human_housing.asp
Home Safety Council	http://www.homesafetycouncil.org/
NIOSH Criteria for a Recommended Standard: Occupational Exposure to Carbon Monoxide	http://www.cdc.gov/niosh/73-11000.html
National Fire Protection Association	http://www.nfpa.org/
National Safety Council Indoor Air Program	http://www.nsc.org/ehc/indoor/iaq.htm
Occupational Safety and Health Administration	http://www.osha.gov/SLTC/healthguidelines/carbonmonoxide/index.html
Safer Child, Inc.—Indoor Pollution and Home Safety	http://www.saferchild.org/indoor.htm
Underwriters Laboratories (UL)	http://www.ul.com/
U.S. Consumer Product Safety Commission	http://www.cpsc.gov/
U.S. EPA Indoor Air Quality Home Page	http://www.epa.gov/iaq/
U.S. EPA Air Quality Criteria for Carbon Monoxide	http://www.epa.gov/ncea/coabstract.htm
U.S. EPA Tier 2 Vehicle and Gasoline Sulfur Program	http://www.epa.gov/tier2/
U.S. Fire Administration	http://www.usfa.fema.gov/

Appendix B. Carbon Monoxide Detectors State Statutes

State	Citation	Summary
Alaska	Alaska Stat. § 18.70.095—Smoke And Carbon Monoxide Detection Devices	Relates to the devices, including carbon monoxide detection devices, required in dwellings; provides that such devices must be installed and maintained in all qualifying dwelling units in the state; provides that smoke detection devices must be of a type and installed in a manner approved by the state fire occupancy. Requires marshall; provides that carbon monoxide detection devices must have an alarm and be installed and maintained according to manufacturers' recommendations; includes rentals.
Colorado	Colo. Rev. Stat. § 38- 45-101 To - 106—Carbon Monoxide Alarms	Requires any existing single-family dwelling or dwelling unit of an existing multi-family dwelling offered for sale or transfer on or after a specified date, that has a fuel-burning heater or appliance, a fireplace, or an attached garage to have an operational carbon monoxide alarm installed within a specified distance of each room lawfully used for sleeping purposes; applies a similar requirement on new residential construction.
Connecticut	Conn. Gen. Stat. § 29-292—Fire Safety Code. Carbon Monoxide And Smoke Detection And Warning Equipment. Certificate Of Occupancy.	Requires the installation of carbon monoxide detectors in new residential buildings; protects individuals and families from carbon monoxide poisoning in their homes; includes new residential buildings meant to be occupied by one or two families.
Florida	Fla. Stat. § 553.885—Carbon Monoxide Alarm Required;	Requires that every building for which a building permit is issued for new construction on or after July 1, 2008, and having a fossil-fuel-burning heater or appliance, a fireplace, or an attached garage shall have an approved operational carbon monoxide alarm installed within 10 feet of each room used for sleeping purposes.
	Fla. Stat. § 509.21—Safety Regulations	Requires that every enclosed space or room that contains a boiler regulated under chapter 554 which is fired by the direct application of energy from the combustion of fuels and that is located in any portion of a public lodging establishment that also contains sleeping rooms shall be equipped with one or more carbon monoxide sensor devices that bear the label of a nationally recognized testing laboratory and have been tested and listed as complying with the most recent underwriters laboratories, inc., Standard 2034, or its equivalent, unless it is determined that carbon monoxide hazards have otherwise been adequately mitigated as determined by the division. Such devices shall be integrated with the public lodging establishment's fire detection system.

State	Citation	Summary
Georgia	Sec. R313.4.1 Of The Ga. State Minimum Standard One And Two Family Dwelling Code (International Residential Code For One- And Two-Family Dwellings With Georgia State Amendments) Adopted Pursuant To Ga. Code Ann. § 8-2-20.	Requires carbon monoxide detectors be installed in general sleeping areas in all new one- and two-family homes and townhomes of three stories or less.
Illinois	430 Ill. Comp. Stat. § 135/—Carbon Monoxide Alarm Detector Act	Requires that every dwelling unit shall be equipped with at least one approved carbon monoxide alarm in an operating condition within 15 feet of every room used for sleeping purposes. Every structure that contains more than one dwelling unit shall contain at least one approved carbon monoxide alarm in operating condition within 15 feet of every room used for sleeping purposes.
Maine	Me. Rev. Stat. Ann. Tit. 25, § 2468—Carbon Monoxide Detectors	Requires that all single-family dwellings and multi-apartment buildings, newly constructed single-family dwellings and rental units have smoke detectors and at least one carbon monoxide detector in an area within or giving access to a bedroom; requires the detectors in multifamily dwellings and newly constructed single family dwellings to be powered by both the electrical service in the building and by battery.
Maryland	Md. Code Ann., Pub. Safety § 12- 1101 To 1106—Carbon Monoxide Alarms Md. Code Ann., Pub. Safety § 10-702—Single Family Residential Real Property Disclosure Req.	Requires the installation of carbon monoxide alarms outside of each sleeping area or within a certain distance of carbon monoxide-producing equipment within certain dwellings; prohibits a person from disabling a carbon monoxide alarm; clarifies that this does not prevent a local entity from enacting more stringent requirements; provides that a vendor of a single family dwelling shall disclose if the property relies on fossil fuel combustion for heat and whether carbon monoxide alarms are installed. The disclosure form shall include a list of defects, including latent defects, or information of which the vendor has actual knowledge in relation to the following...if the property relies on the combustion of a fossil fuel for heat, ventilation, hot water, or clothes dryer operation, whether a carbon monoxide alarm is installed on the property.

State	Citation	Summary
Massachusetts	Mass. Gen. Laws Ann. Ch. 148, § 26f1/2 Mass. Gen. Laws Ann. Ch. 148 §27a	Requires that every dwelling, building or structure occupied in whole or in part for residential purposes that contains fossil-fuel burning equipment or incorporates enclosed parking within its structure shall be equipped by the owner with working, approved carbon monoxide alarms. No person shall shut off, disconnect, obstruct, remove or destroy, or cause or permit to be shut off, disconnected, obstructed, removed or destroyed, any part of any sprinkler system, water main, hydrant or other device used for fire protection or carbon monoxide detection and alarm in any building owned, leased or occupied by such person or under his control or supervision, without first procuring a written permit so to do from the head of the fire department of the city or town wherein such building is situated, which permit such head is hereby authorized to issue subject to such terms and conditions as, in his judgment, protection against fire and the preservation of the public safety may require.
Michigan	Mich. Comp. Laws Ann. § 125.1504d	Requires newly constructed boarding houses, hotels, motels and other residential buildings where occupants are primarily transient in nature to install an operational carbon monoxide device in each area where a mechanism is present that provides a common source of heat from a fossil-fuel-burning furnace, boiler or water-heater.
	Mich. Comp. Laws Ann. § 125.1504f	Authorizes the director of the department of consumer and industry services to provide for the installation of at least one carbon monoxide device in the vicinity of bedrooms within newly constructed or renovated single-family or multifamily dwellings.
Minnesota	Minn. Stat. § 299f.50 To .51—Carbon Monoxide Alarms	Requires that every single family dwelling and every dwelling unit in a multifamily dwelling must have an approved and operational carbon monoxide alarm installed within ten feet of each room lawfully used for sleeping purposes.
Montana	Mont. Code Ann. § 70- 20-113	Provides for a notice about the presence of a carbon monoxide detector upon the sale of a residence.
	Mont. Code Ann. § 70- 24-303	Requires carbon monoxide detectors in each dwelling unit rented by a landlord and limits landlord liability for failure of a detector.
New Hampshire	N.H. Rev. Stat. Ann. § 150:10-A	Requires the installation of carbon monoxide detectors in rental units and in single and multi-family dwellings built or substantially rehabilitated after January 1, 2010.

State	Citation	Summary
New Jersey	N.J. Stat. Ann. § 52:27d- 133.3 To 133.5—Carbon Monoxide Sensor Device Required For Issuance Of Certificate Of Occupancy	Requires installation of carbon monoxide detectors in single and two-family homes upon initial occupancy or change of occupancy.
	N.J. Stat. Ann. § 55:13a-7.17 —Carbon Monoxide Sensor Device Required In Hotel, Multiple Dwelling.	Requires every unit of dwelling space in a hotel or multiple dwelling be equipped with one or more carbon monoxide sensor devices unless it is determined that no potential carbon monoxide hazard exists for that unit.
	N.J. Stat. Ann. § 55:13b-6.1 —Rooming And Boarding Houses	Requires every unit of a rooming or boarding house be equipped with one or more carbon monoxide sensor devices unless it is determined that no potential carbon monoxide hazard exists for that unit.
New York	N.Y. Exec. Law § 378—Standards For New York State Uniform Fire Prevention And Building Code.	Requires New York fire prevention and building code to adopt standards for installation of carbon monoxide detectors requiring that every one- or two-family dwelling constructed or offered for sale after July Thirtieth, Two Thousand Two, any dwelling accommodation located in a building owned as a condominium or cooperative in the state constructed or offered for sale after July Thirtieth, Two Thousand Two, or any multiple dwellings constructed or offered for sale after august ninth, two thousand five shall have installed an operable carbon monoxide detector of such manufacture, design and installation standards as are established by the council. Carbon monoxide detectors required by this section are required only where the dwelling unit has appliances, devices or systems that may emit carbon monoxide or has an attached garage.
North Carolina	N.C. Gen Stat. § 143- 138 —North Carolina State Building Code	Authorizes adoption of provisions requiring the installation of either battery-operated or electrical carbon monoxide detectors in every dwelling unit having a fossil-fuel burning heater or appliance, fireplace, or an attached garage.
	N.C. Gen Stat. § 42-42 To 42-44—Landlord And Tenant Articles—Residential Rental Agreements	Requires landlords to provide one operable carbon monoxide detector per rental unit per level. A landlord that installs one carbon monoxide detector per rental unit per level shall be deemed to be in compliance with standards under this subdivision covering the location and number of detectors. The landlord shall replace or repair the carbon monoxide detectors within 15 days of receipt of notification if the landlord is notified of needed replacement or repairs in writing by the tenant. The landlord shall ensure that a carbon monoxide detector is operable and in good repair at the beginning of each tenancy. Unless the landlord and the tenant have a written agreement to the contrary, the landlord shall place new batteries in a battery operated carbon monoxide detector at the beginning of a tenancy, and the tenant shall replace the batteries as needed during the tenancy. Failure of the tenant to replace the batteries as needed shall not be considered as negligence on the part of the tenant or the landlord. This subdivision applies only to dwelling units having a fossil-fuel burning heater or appliance, fireplace, or an attached garage. Provides for penalties.

State	Citation	Summary
Oregon	Or. Rev. Stat. § 90.320	Deems a rental dwelling unit uninhabitable if it lacks a carbon monoxide alarm when that dwelling unit or the structure that the dwelling unit is a part contains a carbon monoxide source.
	Or. Rev. Stat. § 90.325	Prohibits tenants from removing or tampering with carbon monoxide alarms. Requires tenants to test carbon monoxide alarms at least once every six months and replace batteries as needed.
Rhode Island	R.I. Gen. Laws § 23- 28.1-2—Purposes	Requires Rhode Island fire safety code provide reasonable standards for the installation of smoke and carbon monoxide detectors in private dwellings occupied by one (1), two (2), and three (3) families; provided, further, that after July 1, 2008, three (3) family dwellings shall be equipped with hard wired or supervised interconnected UL approved wireless smoke and carbon monoxide detectors, in accordance with standards established by the fire safety code board of appeal and review. The code adopted pursuant to this legislation, the Rhode Island uniform fire code (RIUFC), requires carbon monoxide detectors in all apartment buildings, dormitories, lodging and rooming houses, one-, two- and three-family dwellings and child day-care facilities (http://www.fsc.ri.gov/documents/rhodeislandfiresafetycode.pdf)
Texas	Tex. Hum. Res. Code Ann. § 42.060—Carbon Monoxide Detectors.	Requires that qualifying day-care centers, group day-care homes, and family homes must be equipped with carbon monoxide detectors.
	Tex. Health & Safety Code Ann. § 766.003—Information Relating To Fire Safety And Carbon Monoxide Dangers	Requires the state prepare information relating to the availability of carbon monoxide detectors, their use in preventing carbon monoxide poisoning; and the need to properly use and maintain fossil fuel-burning appliances.
Utah	Utah Admin. Code § R156-56-802(16)	Requires carbon monoxide alarms on each habitable level in new residential structures regulated by state residential code that are equipped with fuel burning appliances.
	Utah Code Ann. § 10-8-53.5	Prohibits a municipality from enforcing any ordinance, rule or regulation requiring the installation or maintenance of carbon monoxide detectors in a residential dwelling against anyone other than the occupant of the dwelling. Does not affect building permit applicants where building code requires the installation of carbon monoxide detectors as part of new construction.
	Utah Code Ann. § 17-50-327	Prohibits a county from enforcing any ordinance, rule or regulation requiring the installation or maintenance of carbon monoxide detectors in a residential dwelling against anyone other than the occupant of the dwelling. Does not affect building permit applicants where building code requires the installation of carbon monoxide detectors as part of new construction.

State	Citation	Summary
Vermont	Vt. Stat. Ann. Titl. 9 § 2881 To 2883—Smoke Detectors And Carbon Monoxide Detectors	Requires that a person who constructs a single-family dwelling shall install one or more smoke detectors, and one or more carbon monoxide detectors in the vicinity of any bedrooms in the dwelling in accordance with the manufacturer's instructions. In a dwelling provided with electrical power, detectors shall be powered by the electrical service in the building and by battery. Statute says that nothing in this section shall require an owner or occupant of a single-family dwelling to maintain or use a smoke detector or a carbon monoxide detector after installation.
	Vt. Stat. Ann. Tit. 20, § 2729—Fire Safety Division General Provisions	Requires any condominium or multiple unit dwelling using a common roof, or row houses, or other residential buildings in which people sleep, including hotels, motels, and tourist homes, excluding single family owner-occupied houses and premises, whether the units are owned or leased or rented, to contain one or more carbon monoxide detectors.
Virginia	Va. Code Ann. § 55- 248.16—Tennant To Maintain Dwelling Unit.	Prohibits the tenant from removing or tampering with a carbon monoxide detector installed by a landlord.
	Va. Code Ann. § 55- 248.18—Tenant Obligations	Authorizes tenant to install carbon monoxide detection devices that the tenant may believe necessary to ensure his safety.
Washington	Wash. Rev. Code Ann. § 19.27.530—Carbon Monoxide Alarms	Requires carbon monoxide alarms to be installed in dwelling units built or manufactured in the state; requires the seller of any owner-occupied single-family residence to equip the resident with carbon monoxide alarms before the buyer or any other person may legally occupy the residence; allows the building code council to exempt categories of residential buildings if it determines that requiring carbon monoxide alarms are unnecessary to protect the welfare of the occupants.
Wisconsin	Wis. Stat. Ann. § 101.149—Carbon Monoxide Detectors	Requires installation of carbon monoxide detectors in certain areas of residential buildings (defined as a tourist rooming house, a bed and breakfast, or any public building that is used for sleeping or lodging purposes). Sets forth installation requirements, obligations and liabilities for owners of such residential buildings.

Notes