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DEVELOPMENT OF A TECHNICAL BASIS FOR CARBON MONOXIDE DETECTOR SITING

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EXECUTIVE SUMMARY

The goal of this work was to develop a technical basis for carbon monoxide detector siting for use in general occupancies in support of the continued development and potential expansion of the scope of NFPA 720, Standard for the Installation of Carbon Monoxide (CO) Warning Equipment in Dwelling Units. The project included a review of the scientific literature with regard to non-fire CO poisoning statistics, CO source characterization, CO dispersion in buildings, and CO detector siting findings in the research literature. Simple analytical expressions for CO dispersion were sought for potential application in detector siting. The modeling and experimental results from the scientific literature were synthesized to develop simple prescriptive type siting rules.

Several types of non-fire CO poisoning statistical studies were identified in the literature: national level statistical analysis of general incident data, state level statistical analysis of general incident data, and national level statistical analysis of special CO sources/problems.

National level studies and analysis have been developed by the Center for Disease Control (CDC), the Consumer Product Safety Commission (CPSC), the Bureau of Labor Statistics (BLS) the UK Health and Safety Executive, and the National Fire Protection Association (NFPA). Among these studies the scope of coverage of the CO poisoning differed depending upon the scope of responsibility of the sponsoring organization. For instance the CPSC studies did not include motor vehicle exhaust, boats, or any work related exposures. The overall finding from the collective body of work is that in the US there are approximately 500 CO poisoning deaths per year and about 5000 individuals who receive treatment for CO poisoning.

The CO poisoning deaths and injuries have been steadily decreasing over recent decades. The steady decline has been attributed to improved motor vehicle emissions controls and general improvements in combustion devices. All the studies indicate that CO poisonings result from CO produced by combustion sources. Identified sources include furnaces, motor vehicles, ranges/ovens, stoves, water heaters, generators, engine-driven tools space heaters, and charcoal grills. Automobile incidents comprise about half the non-fire CO incidents and overwhelmingly involve idling vehicles. About ⅔ of all CO exposures occur in the home, with the remainder most often found in public areas and facilities, temporary shelters, and the workplace.

The statistical data does not indicate that the CO poisoning problem in dwellings is fundamentally different from in other occupancies. CO sources are combustion devices in all occupancies. CO exposures are not statistically linked to sleeping. CO exposures are highly seasonal with the highest rates in the winter months in cold climates. Fatalities in adults over 65 years of age are about twice the rate as the general population. While CO exposures are not gender-biased, there are two to three times more deaths for males than females.

State level studies have been reported from California, Colorado, West Virginia, Washington State, and New Mexico. These studies generally follow national trends but highlight climatic differences and automobile emissions regulation effects. A Washington State study focused on racial and ethnic differences in CO poisonings. This study identified Blacks and Hispanics as experiencing higher risks than the general population. A special study of non-dwelling CO incidents identified higher ratios of injuries to deaths than in the general statistics and also found portable combustion devices as the CO source in 1/4th of the incidents. Special studies of CO poisonings associated with natural disasters and power outages indicated that engine powered devices, especially electrical generators, were a significant hazards.

The World Health Organization (WHO), US Environmental Protection Administration (EPA), and the National Institute for Occupational Safety and Health (NIOSH) identify chronic CO exposures to have important health effects in all settings (work and home). The WHO identified workers involved with automobiles (driving, parking servicing, traffic police), warehouse operations, firefighting, cooking, construction work, as well as working in the steel nickel, coke, carbon black and petroleum industries as having higher levels of CO exposure at work. Overall, CO levels are lowest in homes, churches, and health care facilities. WHO, NIOSH, and EPA CO exposure guidelines are well below the alarm levels of current CO alarms for dwellings.

Carbon monoxide is a normal product of combustion from all combustion sources. However, CO production rates can be significantly increased by abnormal operating conditions including problems with the combustion device or the exhaust ventilation system. The production rate of CO varies widely with the combustion device and the operating conditions. The indoor release levels are further widened by large variations in the fraction of CO released within the building. Typical CO generation rates for gaseous and liquid fuels are 0.04 mg/kW of nominal input. Abnormal operations of these devices can be about ten times larger. Internal combustion engines and solid fuel appliances are generally larger CO sources than gaseous or liquid fueled appliances. Normally operating diesel engines produce about 2 mg/kW, wood burning appliances produce 1-8 mg/kW, industrial and marine gas engines produce 14 mg/kW, and small gasoline powered tools produce 100-220 mg/kW. A reasonable range of CO emissions rates is 1–1000 mg/s.

Carbon monoxide dispersion in buildings has been studied experimentally and computationally in single rooms and home size buildings. Indoor air quality (IAQ) studies using tracer gases have been performed in larger buildings as well. Studies can be divided into two classifications; studies of CO movement in and from the room containing the CO source, and studies examining distribution of CO from a source room. CO transport and dispersion occurs via two major mechanisms; forced convection via mechanical ventilation systems and free (or passive) dispersion by natural forces. Natural forces of importance include the buoyancy of the CO source itself, buoyancy due to other appliances, buoyancy due to solar heating, buoyancy due to wall heat transfer to or from out of doors, buoyancy due to stack effect, infiltration due to wind, and occupant movement. These forces are largely involved in the thermal performance of buildings. Where present mechanical or forced convection dominate CO dispersion and result in a well-stirred environment within the ventilation zone.

Dispersion by natural forces is generally dominated by buoyancy. Mixing within a home size floor occurs on the time scales of one to two hours. Flows to lower floors are generally very small and cannot be relied upon for timely detection. Flows to upper floors are generally effective when sufficient openings between floors exist. Closed doors generally are very effective in mitigating CO dispersion. As such, where natural forces dominate the dispersion, a closed door can prevent a CO detector from effectively protecting occupants closer to the source than the detector behind a closed door.

The dynamics of buoyant CO releases is well described by the same modeling principles developed for fire plumes in a room. The dynamics involve a buoyant plume and the development of a heated upper layer that progressively fills the room from the top down. Filling times are typically minutes to tens of minutes. Flows out of a room warmed by the buoyant CO source are well described by classical buoyant door flow equation. Natural forces tend to stir house size areas on the time scales of an hour or two.

Modeling of CO and other contaminants has been pursued using network models that treat a building as a network of well-stirred rooms with transfer between rooms via mechanical and natural forces. As such, they cannot provide guidance regarding the height of detector placement and are not suitable for large space compartments and corridors. The most effective models are those designed to deal with the thermal performance of buildings, as these models better capture the natural mechanisms for mixing and dispersion. Simple contaminant transport models that lack the thermal performance modeling aspects are most useful for assessing mechanical ventilation and stack effect only.

Modeling of CO and other contaminants has also been pursued using computational fluid dynamics (CFD) models. These models provide a higher level of detail in that they model the detailed flows within a room as well as room to room flows. However, these models tend to not include all the relevant natural forces that are important to dispersion where mechanical systems are not in use. Given that mechanical ventilation gives rise to well stirred building areas, there is little value in detailed modeling under these circumstances. Lacking adequate modeling of natural forces seriously limits the utility of existing CFD models in studying natural dispersion in buildings.

The literature review and analysis suggests a two prong approach to CO detection: 1) CO detectors in all rooms containing a combustion source to serve in the role of combustion safety devices (CSD); and 2) CO detectors located in occupied areas to provide monitoring of the indoor air quality (IAQ) with respect to CO, to provide protection from mobile sources, and to provide backup protection with respect to fixed sources.

Siting of CSD CO detectors should be in every room containing a combustion device. The detector should be placed high in the space due to the important role of buoyancy within the source room. If pre-stratification potential exists due to heat sources high in the space (e.g. heated pipes, solar heated roofing, etc), the detector should be lowered below the pre-stratification zone but no lower than nose level. If openings exist between the source room and the remainder of the building, the detector should be placed at the height of the opening or above to prevent CO dispersion to other spaces without detection in the source room.

For buildings with continuously operating HVAC ventilation systems, one IAQ detector should be provided per HVAC zone. The detector should generally be provided centrally within the zone and should not be located in a peripheral space behind a closed door.

For buildings where the HVAC system is not continuously operating, additional siting considerations apply. One IAQ CO detector should be installed per floor of the building. Where normally closed doors divide a floor area, one detector for each area defined by a closed door is needed. These same siting requirements apply to buildings without HVAC systems. IAQ detectors should generally be placed at nose level or above.

While ongoing progress in the reduction of CO emissions has had a significant safety benefit, there is an ongoing need for CO detection in buildings in general. Even as CO emissions are reduced, there are ongoing hazards associated with improperly installed or improperly operating combustion sources. Appropriate siting of CO detectors has benefits both for safety with respect to acute CO exposures and potentially in reducing health impacts of more chronic CO exposures.

If further work is to be conducted, the existing body of data is most lacking in large floor area spaces with a minimum of closed doors. These spaces would be typical of office areas where there are long corridors or other types of open areas. To date, most of the data is in smaller footprint buildings. It is recommended that experimental research in actual buildings be conducted. This would involve sources motivated by the findings of the current study. Gas sensors and temperature sensors should be distributed throughout the test area. CO or tracer gas sources could be utilized. Variables that should be included in the study include wind speed, solar heating conditions, HVAC operation, and door closures. Building leakage areas should be measured and documented via door fan methods and by tracer gas methods. These tests would provide additional data to evaluate the recommendations of the study and would provide a database of well-documented tests that could be used to develop and validate modeling methods in the future.

1.0 INTRODUCTION

The NFPA Technical Committee (TC) on Carbon Monoxide Detection has drafted a revised NFPA 720 standard with a new scope that includes all occupancies, beyond the existing scope of only dwelling units, principally one- and two-family dwellings. This new draft is being developed in response to various users and organizations having to address requirements for the use of CO detection in non-dwelling occupancies. A number of states and jurisdictions reference the existing 2005 edition and past NFPA 720 documents despite the fact that 720 has not addressed non-dwelling occupancies. For dwelling occupancies, there is limited data that addresses the distribution of CO as it relates to CO alarm placement. Because of the similar molecular weight of CO relative to air and the typical origins of CO being relatively low momentum sources, the TC has allowed CO alarms to be mounted per manufacturer's instructions, which include ceiling and both high and low wall installations. In dwelling applications, generally the CO disperses uniformly from floor to ceiling, particularly as the distance from the source increases and with ventilation. NFPA 720 requires that CO alarms be centrally located outside each sleeping area in the immediate vicinity of the bedrooms to assure notification of a CO hazard to sleeping individuals.

In non-dwelling applications, there is even less in the CO literature regarding dispersion within buildings and siting requirements for detectors. In commercial and industrial occupancies, there is a broader range of potential building designs, operations, and ventilation systems that can influence the transport of CO. Due to these variables and the lack of established requirements, the NFPA 720 TC seeks a technical basis to develop prescriptive or performance-based requirements for the location of CO detectors in non-dwelling applications.

It is the objective of this report to develop a technical approach to the development of CO detector siting methodologies. In order to develop an approach, the scientific literature regarding CO incidents, CO sources, and CO transport are reviewed.

2.0 REVIEW OF CO POISONING STATISTICS

Understanding the nature of the carbon monoxide poisoning problem in the field is an essential part of developing mitigation strategies, including the development of siting recommendations. The available statistics can provide critical information as to where CO poisonings are occurring and what sources of CO are causing these poisonings. Further, the statistics can provide other demographic information that may prove valuable in understanding the CO poisoning problem. Studies have been done at the national and state levels. In addition, special purpose studies have been undertaken in response to specific CO poisoning problems.

A Center for Disease Control (CDC) study of unintentional non-fire related carbon monoxide exposures during the period 2001-2003 indicates that approximately 500 deaths occur per year and approximately 5000 individuals per year receive treatment in emergency departments of hospitals (Vajani and Annest, 2005). The nonfatal exposures were found to occur in homes in 64% of the cases and in public facilities and areas in 21% of the cases. Adults over 65 years of age accounted for 23% of the fatalities, while accounting for only 12% of the population. CO exposures were not gender biased, but deaths were highly biased toward males (2.3 times greater). Both fatal and nonfatal exposures were biased toward the winter months. Carbon monoxide sources were almost exclusively combustion sources, including furnaces, motor vehicles, stoves, water heaters, generators, space heaters, and machinery.

In an earlier study by CDC, Cobb and Etzel (1991) studied unintended CO deaths over the period of 1979-1988. The number of unintentional deaths decreased steadily from 1513 in 1979 to 878 in 1988. The highest death rates occurred in winter and among males, blacks, the elderly, and residents of northern states. Motor vehicle exhaust gas caused 57% of the deaths; with 83% of these associated with stationary automobiles. The authors attribute the favorable trend to improvements in automobile pollution control systems and improved safety of cooking and heating appliances.

The Consumer Product Safety Commission (CPSC) (Ascone and Marcy, 2005, Carolson, 2004, Vagts, 2003, Mah, 2001, Mah, 2000, Ault, 1999, Ault, 1998) finds that the unintentional deaths due to CO poisoning from consumer products has been decreasing steadily from over 300 in the early 1980s to less than 200 in the late 1990s through 2002. These estimates exclude fires, motor vehicle exhausts, boats, and any work-related exposures. The CO deaths in the CPSC studies are about 2/3 in homes, with about 1/4 in temporary shelter such as tents, recreational vehicles, vans, seasonal cabins and trailers. The CO sources found are combustion sources. Heating systems dominate the list which includes charcoal grills, water heaters, camp stoves/lanterns, ranges/ovens, and engine-powered tools. Like CDC, the CPSC studies show that males die disproportionately due to CO over females.

The Bureau of Labor Statistics (BLS) reports annual carbon monoxide fatalities in the workplace ranging from 18 to 45 during the period 1992–2005 (BSL 1992-2005). No injury data was reported and no breakouts of the data were provided. Janicak (1998) analyzed the BLS data for the period 1992-1996. He found that CO poisoning deaths were quite broadly distributed with most occurrences found in the service sector, primarily involving auto repair and parking. Other significant sectors included agriculture, manufacturing, and construction. The most common source was engine exhaust, followed by combustion powered equipment such as power saws, pumps, and space heaters. As such, occupational CO poisonings occur as a result of exposure to CO from combustion sources just as in other settings. However, furnaces seemed to be notably missing from the list of identified sources.

Hall (2005) studied long-term statistical trends in injuries and deaths due to non-fire exposure to gases. The analysis indicates that the statistics are dominated by carbon monoxide exposures. Based upon death certificate data, deaths due to CO were about 1200 per year in the early 1980s, gradually reducing to about 600 by the early 1990s. Over that same period, deaths due to CO poisoning involving consumer products were in the range 200–300 with a decreasing trend over time. Non-fire CO poisonings reported to emergency rooms ranged from 7,700 to 15,100 per year during the period 1993–1999. The death statistics indicate that individuals about 65 years of age are at higher risk than the general population.

Several state level studies of carbon monoxide poisonings have been reported. Baron et al. (1989a, b) studied unintended fatalities due to CO poisoning in West Virginia for the period 1978–1984. They reported 87 motor vehicle related CO poisoning deaths and 62 non-vehicular CO deaths. Motor vehicle related deaths were predominantly in stationary vehicles. The vehicles were most often outdoors and incidents were highly biased toward the cooler months. For non-vehicular CO fatalities, sources were almost always associated with heating or cooking appliances. About 80% of non-vehicular CO poisonings were in domestic situations and the remainder were in recreational settings (tents, vans). There was a strong male bias in the reported deaths (4:1).

Girman et al. (1998) studied unintentional deaths from CO poisoning in California over the period of 1979-1988. The overall low rates of CO poisoning deaths in California (second lowest in the country behind Hawaii) were attributed to the state's mild climate and stringent auto emissions requirements. They found a strong male bias in the reported deaths (2.5:1) and a strong bias toward winter months. Motor vehicles were the source for 30% of the deaths, while heating and cooking appliances were the source for 40% of the deaths. Charcoal grills, small engines, and camping equipment were also recorded as sources. A breakout of heating and cooking appliances yielded 17% by stoves, 9% by water heaters, 8% by furnaces, 38% by wall heaters, and 7% by floor heaters. While the majority of CO deaths occurred in single-family homes, all small engine source deaths occurred in other settings including mines, RVs, cabins, boats, a truck, and diving. Small engine deaths were caused primarily by generators.

Cook et al. (1995) studied unintended CO poisonings in Colorado over the period 1986-1991, including fires, vehicle exhaust and other sources which were each responsible for about ⅓of the fatalities. The other source categories included furnaces, space heaters, appliances, gas-powered motors, and fireplaces. Furnaces were responsible for 43% of all nonfatal injuries (fires: 7%, auto exhaust: 22%). They noted the same seasonal variations and male bias (2.6:1) found by others. They also found the elderly at high risk over younger people (3:1). Three percent of deaths and 15% of injuries occurred in occupational settings, which were caused by gas-powered tools in half the instances.

Ralston and Hampton (2000) studied racial and ethnic differences in CO poisoning in Washington State over the period 1987 to 1997. They found higher risks in the Black and Hispanic communities. Major sources of CO were charcoal, motor vehicles, fire, generators, forklifts, boats, furnaces, gas engines, and space heaters. Distributions of the CO source were quite different than in other studies with charcoal as the largest single source with generators, forklifts, boats and engines taking higher than normal percentages. The charcoal sources were predominately in the minority communities. Furnaces as a CO source was well down in the list compared to other studies for all populations.

Lofgren (2002) identified occupational CO poisoning hazards in Washington State through a review of OSHA inspection reports for the period 1994-1999. Sources most often identified were forklifts, compressors for respirators, auto/truck/bus, and temporary heating devices.

Moolenaar et al. (1995) studied carbon monoxide poisonings in New Mexico. They found half of the deaths resulted from heating equipment and 46% resulted from automobiles. Deaths were strongly seasonally biased toward winter months.

Yoon et al. (1998) studied non-fire CO poisoning fatalities in New Mexico over the period of 1980–1995 with the goal of assessing the potential value of CO detectors as a preventative measure. They found that 36% of fatalities were likely asleep when poisoned. CO victims in motor vehicles were awake in 82% of the incidences and in residences, 51% of victims had been awake. Seasonal bias was observed and residential fatalities were caused by heating equipment 46% of the time. Elderly were more vulnerable in residences and young people were more vulnerable in motor vehicles.

Gifford (2007) has collected incident data via clipping services to develop an understanding of the CO poisoning problem in non-dwelling occupancies. The data collected over the period 2004-2006 includes 15 deaths, 1024 hospitalizations, and 172 scene treatments without transport to hospital. This data indicates a greater ratio of hospitalizations to deaths than the general CDC statistics. The high ratio of hospitalization to deaths may reflect the larger population of non-dwelling units. In the Gifford data the average hospitalizations per incident was nearly ten individuals, while dwelling incidents would be expected to much less. Other studies are injury and fatality based and as such do not report the number of individuals injured per incident. The cause or source statistics indicate that half the incidents resulted from fixed sources (involving installation, engineering, and venting issues with furnaces, boiler, and appliance such as hot water heaters and clothes dryers), while 1/4 resulted from temporary or portable sources (e.g. idling trucks, forklifts, propane tools, and generators). Five percent of incidents involved pool heaters, and 16% of incidents had unidentified sources. This highlights the importance of temporary or portable sources in non-dwelling incidents.

Ross (1999a) reported on heating appliance CO poisoning incidents in the UK during the period 1985–1992. Heaters accounted for about 45% of fatalities from appliances, with boiler, water heaters, and cookers contributing to most of the remaining fatalities. Nonfatal accidents reported were about five times the fatal accidents. In statistics for the period 1990–1994 in the UK, CO was emitted into the room housing the combustion appliance in most incidents. Most fatalities (>80%) occurred in a living area of the home and not in bedrooms, suggesting that sleeping was not a primary contributor to CO fatalities.

In addition to these broad based inquiries, there have been a number of studies of CO poisoning due to specific equipment and under specific situations. CDC has studied the incidence of CO poisonings associated with hurricanes in which they identify that the use of generators led to CO poisonings as a direct result of hurricane damage and disruption (CDC 2005a, b). Similar studies of the consequences of a power outage were undertaken (CDC 2004, Hampson et al, 1993). A specific study of engine-driven devices as a CO poisoning source was undertaken by CPSC (Ascone and Marcy, 2005) which identified generators as a major source within this category.

Flynn (2007) studied fire department responses to non-fire CO incidents in 2005. The number of estimated responses for CO incidents was over 61,000, over an order of magnitude greater than the number of deaths and injuries. The response frequencies are seasonal, consistent with injury statistics. Response frequencies are highest during waking hours, with night time frequencies less than half the hourly frequencies at other times. Fire department responses are 90% to residential premises. This is much larger than the CDC injury data which indicates that only 65% of CO injuries occur in residences. It is not known what fraction of non-fire CO incidents attended by the fire department result from the operation of residential CO alarms. Since fire department responses are vastly in excess of actual injury rates (61,000 responses vs. 5,000 estimated injuries), it is unclear how often the operation of CO alarms results in notification of hazards before any injury results. Since fire department responses to non-fire CO incidents are increasing while injury rates by non-fire CO incidents are decreasing, the statistics may suggest that CO alarms are responsible for some of the reductions in CO injuries. Specific research is lacking in this area. For purposes of assessing CO poisoning risks, the CDC statistics must be regarded as a more direct measure of the problem than fire department responses.

The World Health Organization (WHO) (1999) confirms that CO is produced almost exclusively via combustion processes. There are industrial sources of CO, but these have not been compiled in any systematic manner. Major industrial sources include foundry work, and the production of charcoal and carbon black. The estimated total annual carbon monoxide emissions from the various source categories in the USA in 1990 was 60.1 million tons The majority, about 63%, of the carbon monoxide emissions total comes from transportation sources, 12% comes from stationary source fuel combustion, 8% comes from industrial processes, 3% comes from solid waste combustion and 14% comes from miscellaneous sources. CO production from vehicles was halved during the period 1970-1990 due to emissions control equipment on vehicles.

Marr et al. (1998) review the literature concerning automobile-related CO poisonings. The literature reflects a reduction in automobile related CO deaths during the period of 1979–1988 of 7% per year, with the death rate reaching 500 by 1988. California statistics indicate that deaths due to CO associated with automobiles overwhelmingly occur during idling, primarily indoors but also occurring in outdoor circumstances. It has been argued that the biggest benefit of current motor vehicle emission control programs has been the reduction in deaths due to CO poisoning.

The WHO considers the workplace an important setting for carbon monoxide exposure. In general, carbon monoxide exposures at work exceed exposures during non-work periods, apart from commuting to and from work. Average concentrations may be elevated during this period because workplaces are often located in congested areas that have higher background carbon monoxide concentrations than do many residential neighborhoods. Occupational and non-occupational exposures may overlay one another and result in a higher concentration of carbon monoxide in the blood. Certain occupations also increase the risk of high carbon monoxide exposure. These include those occupations involved directly with vehicle driving, maintenance and parking, such as auto mechanics; parking garage and gas station attendants; bus, truck or taxi drivers; traffic police; and warehouse workers. Some industrial processes produce carbon monoxide directly or as a byproduct, including steel production, nickel refining, coke ovens, carbon black production and petroleum refining. Firefighters, cooks, and construction workers may also be exposed to higher carbon monoxide levels at work.

Occupational exposures in industries or settings with carbon monoxide production also represent some of the highest individual exposures observed in field monitoring studies. The highest indoor non-occupational carbon monoxide exposures are associated with combustion sources and include enclosed parking garages, service stations and restaurants. The highest levels observed in one study were in an underground parking garage, which was found to be the source of elevated carbon monoxide within the building through transport via the elevator shaft (stack effect). This highlights the need both for ventilation in indoor spaces with portable CO sources and the need to provide protection from flow out of such spaces into ordinary occupied spaces. The lowest indoor carbon monoxide concentrations are found in homes, churches and health care facilities. WHO (1999) provides a review of CO exposure studies in the workplace, as well as the health effects and health risks of CO exposure. The WHO found that increased use of CO detectors should be encouraged.

WHO (1999) guidelines recommend a limit of 9 ppm over eight hours to maintain %COHb below 2.5% for the general public. For occupationally related exposures, WHO (1999) recommends a limit of 5% COHb. The US EPA limits are a one-hour standard of 35 parts per million and an eight-hour standard of 9 parts per million for the general public. The following occupational exposure limit levels are reported by OSHA (2007). The current Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for carbon monoxide is 50 ppm as an 8-hour time-weighted average (TWA) concentration. The National Institute for Occupational Safety and Health (NIOSH) has established a recommended exposure limit (REL) for carbon monoxide of 35 ppm as an 8-hour TWA and 200 ppm as a ceiling. The American Conference of Governmental Industrial Hygienists (ACGIH) has assigned carbon monoxide a threshold limit value (TLV) of 25 ppm as a TWA for a normal 8-hour workday and a 40-hour workweek. Between 1980 and 2006, the US national eight hour average CO concentration dropped from 9 ppm to 2 ppm (EPA, 2007a). All these standards reflect a public health concern for chronic CO exposures beyond the acute hazards that existing CO detectors are intended to protect.

In all CO poisoning studies, the sources were identified as combustion sources. These include fixed combustion sources (e.g. furnaces, water heaters, cooking equipment), and mobile combustion sources (e.g. road vehicles, non-road vehicles, space heaters, engine-driven tools and generators). None of these sources is unique to residential settings. The data indicates that hazards are associated with combustion sources wherever they exist. Poisonings are highly seasonal due both to energy use patterns and limited building ventilation in winter months. CDC reports that about 35% of non-fire related CO poisoning injuries occur outside of residential settings. Overall, non-fire related CO poisonings in the US are responsible for about 500 deaths per year and 5000 injuries per year that required emergency treatment. Among automobile CO poisonings, the vehicles are overwhelmingly idling and are primarily indoors.

Demographically, males are at far greater risk of death than females and the elderly are at higher risk relative to younger individuals. The sex linked risk factor has not been identified or explained. The higher risk to the elderly is likely due to preexisting health issues.

3.0 CO SOURCE CHARACTERIZATION

The hazard posed by CO is critically linked to the production rate of CO. CO is a normal product of combustion from all combustion sources. However, the levels of CO production can be significantly enhanced by abnormal conditions of operation. This can include problems with the combustion device itself or the exhaust ventilation system. Of course, the exhaust ventilation system for a combustion device is normally relied upon to assure that the CO produced is safely vented to the outside so as to prevent indoor exposure to CO. Failures of the ventilation system could cause all or part of the normally produced CO to remain in the building, or can even increase the production of CO by reducing the ambient oxygen concentration in the inlet combustion air. There is reasonable data available on the CO production for normal operations. There is very limited data on CO production for abnormal conditions and limited data on levels of impairment of exhaust ventilation systems. This section summarizes the state of knowledge.

CO emission sources can be categorized based on their CO emission rates and the buoyancy of the CO source. Emission rates have been extensively studied and regulated by the U.S. Environmental Protection Agency. They compile emissions factors for a wide range of sources (EPA 2007). A brief summary of categories of regulatory data for sources and fuels are shown below.

- Automobile Engines: 3.4 to 7.3 gram per mile;
- Small Gasoline Engines: 519 to 603 g/kW-hr;
- Marine Diesel Engines: 5.0 g/kW-hr;
- Small Gasoline Marine Engines: 50 g/kW-hr;
- Non-road Diesel Engines: 3.5 g/kW-hr to 8.0 g/kW-hr;
- Large Industrial Spark-Ignition Engines: 50 g/kW-hr;
- Bituminous and Sub-bituminous Coal Combustion: 753 lb/10^{12} Btu;
- Anthracite Coal Combustion: 0.015 kg per Mg of fuel;
- Fuel Oil Combustion: 1-10 lb/1000 gal oil;
- Natural Gas Combustion: 84-98 lb/10^6 scf;
- Liquefied Petroleum Gas: 2.1-3.6 lb/1000 gal;
- Wood Residue Combustion in Boilers: 0.60 lb/MMBtu;
- Lignite Combustion: 0.06–0.48 lb/ton;
- Residential Fireplaces: 126.3 g/kg;
- Residential Wood Stoves: 26-161 g/kg of fuels; and
- Waste Oil Combustion: 2-5 lb/1000 gal.

These emissions factors vary widely and reflect normal operating conditions. Clearly, small gas powered internal combustion engines are vastly more hazardous than larger internal combustion engines or natural gas or propane combustion devices under normal operations. Fireplaces and wood stoves are also notably efficient producers of CO.

The above CO production figures are not representative of CO production from combustion sources that are not operating as intended. This data also does not reflect where the CO is released and what fraction may be released within a building or other confined space. Note that large industrial spark ignition engines include industrial equipment such as forklift trucks.

Sources may range from small exhaust leaks to fully unvented operation. Exhaust problems may arise from exhaust path leakage or exhaust spillage caused by inadequate makeup air for vented combustion appliances. While larger sources may include measurable momentum, none of the source scenarios include sufficient momentum to cause significant stirring of an enclosure. The general trend is for large releases to be buoyant. The largest release rates tend to result from unvented combustion devices. Even these large sources will be buoyancy dominated very near the source. Jets from engine exhausts normally turn upward within a few feet of the exhaust point. As such, from an enclosure mixing perspective, the mixing of CO is determined by the buoyancy of the source and the general environmental mixing due to ventilation and heating systems.

Marr et al. (1998) reviewed CO emissions data for idling automobiles and found the range to be 0.17 mg/s to 17 mg/s. The high end of this range is dominated by very old vehicles (before emission control) and malfunctioning vehicles.

Lowrie, Hill, and Pool (2001) characterized the CO production from three UK gas appliances operating in room test chamber sized according to the minimum allowable room volume and at larger volumes. The appliances included a 53 kW heating boiler, a wall mounted 30 kW boiler, and a 15 kW wall mounted boiler. Field measurements of CO/CO_2 ratios indicated that normally operating appliances have ratios less than 0.004 and units with ratios above 0.008 had serious faults requiring maintenance attention. Tested units had CO/CO_2 ratios ranging from 0 to 0.05. The values varied with the unit tested and the test conditions. In general high CO/CO_2 ratios for a given unit corresponded to low oxygen concentrations (~19% vol). The variability among units and operating conditions indicates why literature values are not tabulated. Hill and Pool (2001a and 2001 b) further explored the performance of these units in a test house. Measurements were made, but no clear universal findings were obtained.

While no universal findings were obtained, the field measurements of CO/CO_2 ratio can be used to develop useful metrics of potential CO production from appliances. This can be done using the principles of carbon dioxide calorimetry (Tewarson 2002). The generation of CO is given by

$$\dot{m}_{CO} = \left(\frac{Q}{\Delta H_{CO2}}\right)\left(\frac{Y_{CO}}{Y_{CO2}}\right) \tag{1}$$

where Q is the energy consumption rate of the appliance, ΔH_{CO2} is the heat of reaction of CO_2 (approximately 14.6 kJ/g), and Y_{CO}/Y_{CO2} is the ratio of the CO yield to the CO2 yield (which is also the ratio of the CO concentration to the CO_2 concentration measured in the appliance exhaust). Using this approach, a normally operating 10 kW appliance with a CO/CO_2 ratio less than 0.004 (as suggested for gas appliances by Lowrie, Hill, and Pool (2001)) , would produce less than 2.7 mg/s of CO. This is well in excess of the EPA values for natural gas or propane (0.2-0.4 mg/s for a 10 kW device, see Table 1 below). Similarly, a very poorly operating 10 kW gas appliance with a CO/CO_2 ratio of 0.05 would produce 30 mg/s CO.

Brown (2006) measured CO production rates for four gasoline powered portable electric generators with rated loads from about 1–6 kW. He found that CO production rates varied with load, oxygen concentration, and ambient temperature. He measured CO generation rates per kW-hr from 340 to 780 g/kW-hr. This compares well with the EPA values of 519 to 603 g/kW-hr for small gasoline engines included in the EPA summary above. The highest CO generation rates were normally associated with high load, high temperature, and low oxygen. Oxygen concentrations were examined down to 18.6% and temperatures up to 37 C were employed. The CO production rate for the largest generator under adverse conditions was about 700 mg/s. This is vastly in excess of the UK data for gas appliances and is the greatest CO production rate identified in this review of the literature.

The WHO (1999) also noted that although it would be most useful to assess the impact of each of the sources on indoor concentrations of carbon monoxide by using models, the high variability in the source emissions and in other factors affecting the indoor levels does not make such an effort very useful. Such an estimate will result in predicted indoor concentrations ranging over several orders of magnitude, making them of no practical use, and may be misleading. WHO (1999) does provide a review of the available data for emissions from indoor sources.

Source characterization is the least developed component of CO hazard and risk analysis. While some additional work has been published, this finding is the same today as when Persily (1996) reviewed the literature. Based upon this review, CO leakage rates vary over many orders of magnitude, and range from 0 to 1000 mg/s. Table 1 gives a general indication of CO production rates in grams/second of CO per kW of rated power input from the results taken from the EPA (2007), Lowrie, Hill, and Pool (2001), and Brown (2006). Shading is used in the table to delineate classes of emissions sources.

Clearly, internal combustion engines are a very special case that should be examined separately due to the vastly larger CO generation rates. In particular, gasoline fueled internal combustion engines are the largest sources of CO. While wood burning appliances are also serious CO sources, the emissions are less likely to be insidious due to other irritating and odorous constituents of the combustion products.

The results tabulated in Table 1 and the combustion device sizes found in practice suggest the following broad characterization of CO emissions sources; Class A- up to 1 mg/s CO (typified by properly operating combustion appliances), Class B- up to 100 mg/s CO (typified by a poorly operating combustion appliance or a normally operating wood burning appliance), and Class C- up to 1000 mg/s CO (typified by a gasoline powered portable generator). This classification does not deal with the buoyancy of the source. For scoping purposes, heat outputs of 100 W to 1 kW seem to be representative values. This CO source classification system is clearly a vast oversimplification of the complexities of CO production and the wide range in combustion sources (fuel, power consumption, operating conditions, etc.). The system further ignores the entire question of what fraction of this CO output is exhausted into the building. The classification system is provided here only for purposes of defining the scope of CO emissions as an aid in understanding the overall problem. In its current form, it is not suitable for use as a design aid or basis for regulation. Clearly, additional study is required.

In Table 1, values are for normal operation unless otherwise identified. This table reflects production rates and does not address the fraction that may be released within a building. Shading is used to delineate classes of emission sources.

Table 1 – Summary of CO Production Rates from Combustion Sources

Source	CO Output (mg/s per kW of nominal input*)
Small Gasoline Engines (EPA)	140–170
Gasoline Powered Generators (Brown 2006)	100–220
Small Gasoline Marine Engines (EPA)	14
Large Industrial Spark-Ignition Engines (EPA)	14
Wood Burning Appliances (EPA)	1.4–8.7
UK Gas Appliances (Lowrie et al. 2001) (abnormal)	3.4
Non-road Diesel Engines (EPA)	2.2
Marine Diesel Engines (EPA)	1.4
UK Gas Appliances (Lowrie et al. 2001) (max normal)	0.27
Natural Gas Combustion (EPA)	0.041
Fuel Oil Combustion (EPA)	0.031
Liquefied Petroleum Gas (EPA)	0.017
UK Gas Appliances (Lowrie et al. 2001)	0.007-0.07

* mg/s per kW is equivalent to g/MJ

4.0 CO DISPERSION IN BUILDINGS

Carbon monoxide transport and dispersion occur in two major methods; forced convection due to mechanical ventilation systems installed in the buildings and free (or passive) dispersion due to natural forces. Under forced convection, the ventilation system in the building removes CO from the release room. The exhausted gases may leave the building or be circulated to other rooms. On the other hand, under the influence of natural convection within the space, the transport and dispersion of CO are more complex.

Many research projects have studied carbon monoxide transport and dispersion in enclosed spaces, utilizing both experiments and computational modeling methods. These have been reviewed by Persily (1996) with a focus on residential buildings. However, some findings regarding CO dispersion are applicable in a broader context.

Persily's findings indicated that without ventilation, CO concentrations are initially higher in the room of origin. Mixing within the floor of origin occurs on the time scales of an hour or two. Buoyant releases at floor level in closed rooms tend to give rise to fairly uniform CO concentrations vertically in the room after an initial period of stratification. Initial vertical gradients were generally found in the room of origin, but these were generally modest in other rooms. Movement of CO to lower floors is generally very modest, such that detection on lower floors cannot be relied upon. Upward flows to the floors above were notable with buoyant releases. Buoyancy was effective in mixing multiple rooms on the same level. In testing with a buoyant unvented kerosene heater, flows out of the room of origin ranged from less than 6 cfm (0.0028 m^3/s) with the door closed, 9–31 cfm (0.0042-0.0146 m^3/s) with the door open one inch, and 110–2000 cfm (0.052-0.94 m^3/s) with the door open. In ventilated cases, CO was well distributed within the structure within about one hour. The overall findings were that active ventilation gives rise to uniform CO concentrations. Buoyant flows dominate where active ventilation is not present. Mixing between connected rooms on a floor occurred with a time scale of an hour or two with doors open. Mixing between floors was very small in a downward direction and significant in an upward direction. Closed doors were effective in limiting CO dispersion in the absence of active ventilation.

The door flows noted above are consistent with buoyant flows expected through openings from the room. Following Drysdale (1999),

$$\dot{m}_{door} = 2/3 C_d \rho_a \sqrt{2g} W H^{3/2} \left(\frac{(\rho_a - \rho_r)/\rho_a}{\left[1 + (\rho_a/\rho_r)^{1/3}\right]^3} \right)^{1/2} \tag{2}$$

where C_d is the discharge coefficient (~0.6-0.7), g is the acceleration due to gravity (9.8 m/s^2), W is the width of the door opening (m), H is the height of the door opening (m), ρ_a is the ambient air density (kg/m^3), and ρ_r is the gas density in the room (kg/m^3). The final density term, R, in equation (2) is a function of the room temperature and for an ambient temperature of 20^{o}C.

$$R = \left(\frac{(\rho_a - \rho_r)/\rho_a}{\left[1 + (\rho_a/\rho_r)^{1/3}\right]^3} \right)^{1/2} \tag{3}$$

Figure 1 below shows the final density term. Using room temperatures up to 15 C above ambient, yields flows consistent with the flows above noted by Persily (1996) for closed interior doors (taken as 1 cm side edge gap), one inch open doors, and fully open doors.

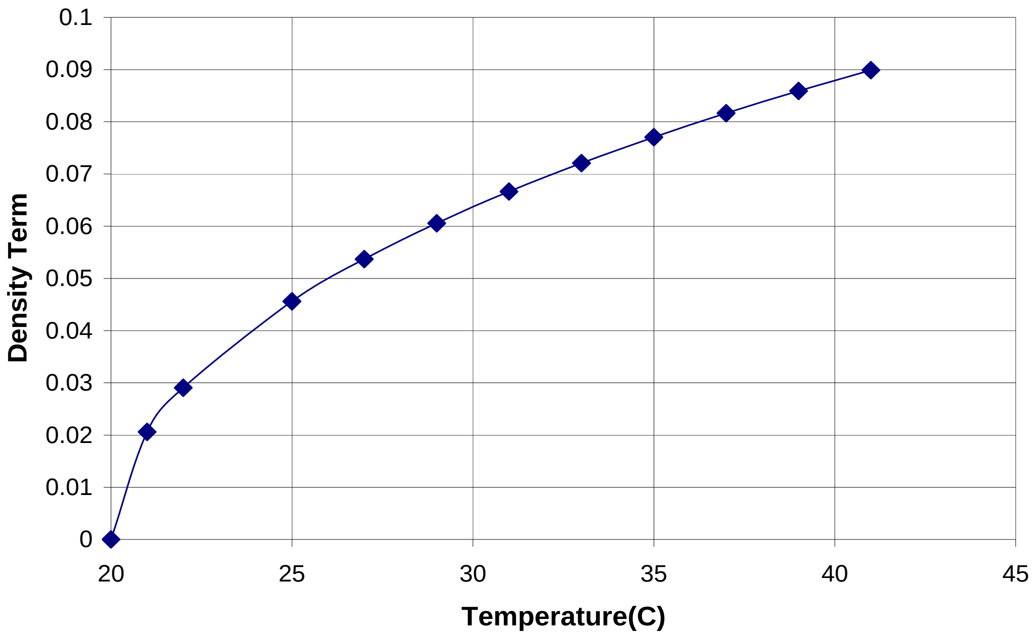

Figure 1 – Temperature dependence of door flows.

The increase in CO concentration outside of the room of release depends upon the openings present and the volume of the connected spaces. Treating the connected spaces as a well stirred volume, the evolution of the CO concentration is defined by the time constant of the connected space, t_c, which is given by the volume of the connected space divided by the volumetric flow rate into the connected space via the door opening. For a constant CO concentration and temperature (and therefore a constant door flow) in the release room we have the following evolution of the CO concentration in the adjoining spaces.

$$C_{CO,cs}(t) = C_{CO,r}\left(1-\exp\left(-\frac{t}{\tau_c}\right)\right) = C_{CO,r}\left(1-\exp\left(-\frac{t}{V\rho_a/\dot{m}_{CO}}\right)\right) \tag{4}$$

where $\tau_c = V\,\rho_{air}/\ \dot{m}_{CO}$ and $C_{CO,r}$ is the CO concentration in the room of origin. For a connected space of 1000 m^3 and an open door, the time constant is a fraction of an hour. For the same space size and a closed door, the time constant is measured in tens of hours. These time scales indicate why openly connected spaces have relatively uniform CO concentrations and why closed doors are effective in limiting CO distribution.

The above analysis ignores infiltration and other air exchange. For a well stirred but ventilated volume with a constant CO source, the evolution of CO is given by

$$CO(ppm) = \frac{\dot{m}_{CO}}{\rho_a \dot{V}}\left(1-\exp\left(-\frac{\dot{V}t}{V}\right)\right)\frac{MW_a}{MW_{CO}}\times 10^6 \tag{5}$$

where $\dot{m}_{CO}$ is the CO addition rate (either via door flow from the CO source room or from a source within the room), $\dot{V}$ is the volumetric air exchange rate, V is the volume of the space, and other variables are as before. For residential buildings Marr et al.(1998) report data by Murray and Burnmaster (1995) who found a mean air exchange rate of 0.76 air changes per hour (ACH) and a range of 0.1 to 10 air changes per hour ($\dot{V}$ /V). The latter ACH is remarkably high and higher values are unlikely in any occupancy. From other studies, Marr et al. (1998) found that residential garages had air exchange rates in the range of 1 air change per hour (ACH). It is likely that the range of 0.1–10 air changes per hour is a suitable range for considering a broader range of building uses as well. Since the reciprocal of the air exchange rate is the time constant for the development of the CO concentration, this translates into time constants of 6 minutes for the highest exchange rate to ten hours for the lowest exchange rate. Of course, for the highest exchange rates and the same CO source, the ultimate steady concentrations are comparative very low.

Marr et al. (1998) considered the effects of automobiles inside garages on occupants of the garage and the residence as a whole assuming well stirred spaces with infiltration. For post-1975 vehicles, they found risks of death in the range of 2–16% in the garage and 0–3% in the residence. This analytical study used distributions of CO production and distributions of air exchange to predict CO concentration histories using Monte Carlo methods, with subsequent analysis of CO uptake via the Coburn, Foster, Kane equation.

From the above analysis for buildings with infiltration, it is apparent that there are potential CO sources that could produce CO that is never detected. The UL test method is designed to prevent CO detectors from operating at or below 30 ppm which would yield an equilibrium %COHb of about 5%. At the same time, the WHO (1999) guidelines recommend a limit of 9 ppm over eight hours to maintain %COHb below 2.5%. For occupationally related exposures, WHO (1999) recommends a limit of 5% COHb. The US EPA limits are a one-hour standard of 35 parts per million and an eight-hour standard of 9 parts per million. The following occupational exposure limit levels are reported by OSHA (2007). The current Occupational Safety and Health Administration (OSHA) permissible exposure limit (PEL) for carbon monoxide is 50 ppm as an 8-hour time-weighted average (TWA) concentration. The National Institute for Occupational Safety and Health (NIOSH) has established a recommended exposure limit (REL) for carbon monoxide of 35 ppm as an 8-hour TWA and 200 ppm as a ceiling. The American Conference of Governmental Industrial Hygienists (ACGIH) has assigned carbon monoxide a threshold limit value (TLV) of 25 ppm as a TWA for a normal 8-hour workday and a 40-hour workweek. Between 1980 and 2006, the US national eight hour average CO concentration dropped from 9 ppm to 2 ppm (EPA, 2007a).

Using Equation 5 at steady state and recognizing that the volumetric exchange rate is the product of the ACH and the compartment volume, compartment volumes can be determined that would produce 30 ppm CO over the range of ACHs found in practice (0.1 to 10 1/hr.). For a 1 mg/s CO source (typical of a normally operating appliance), the range of enclosure volumes found is about 10 to 1000 m^3. This range of enclosure sizes is entirely realizable, indicating that a normally operating but unvented appliance can be expected to give rise to undetectable (<30 ppm) but chronic CO exposures. This shows the potential value of providing CO concentration displays in CO alarms. Chronic exposures could be mitigated and potentially dangerous conditions could be averted through remediation measures because of occupant actions resulting from CO concentration readouts below alarm thresholds.

Hill and Pool (1997) performed 28 experiments to study the dispersion of CO in a two-story house. Some tests used a single closed room and others used multiple connected compartments. CO sources included unvented and partially vented appliances; a gas fire (6.45 kW), a combi-boiler (35.4 kW), a boiler (15.4 kW), and a sink water heater (11.6 kW). The CO sources were all strong thermal sources and no mechanical ventilation was employed. Within the room of origin, CO stratification occurred in most of the tests, but the lower portions of the space had CO concentrations typically about 1/2 of the values near the ceiling. Outside the room of origin stratification within rooms was not generally observed and CO moved effectively to the floor above via the stairs. No temperature measurements were reported and the CO production was strongly time dependent, apparently related to the changing oxygen concentration. The extent of flue blockage changed CO production strongly, indicative of changes in stoichiometry from lean to rich. CO concentrations in the source flow ranged from 10 ppm to a percent by volume.

In the late 1990s, an extensive research program on CO detection in domestic premises was conducted by the Building Research Establishment (BRE) with funding from the Health and Safety Executive (HSE). The work included a literature review, experimental studies, modeling studies, and resulted in recommendations. The work was summarized by Ross (1999b). Following is a summary of that effort with a focus on CO dispersion.

Ross, Smith, Spearpoint, Smith, and Colwell (1999) reviewed the literature concerning dispersion of CO within domestic premises. They reviewed work with CO spillage from a water heater, a gas cooker, an unvented space heater, and tobacco smoking (with and without an auxiliary 500 W heat source, and with strong solar radiation from a window onto the floor). In most of these investigations the CO environment was highly stratified in the release room, forming a layer at the ceiling due to the strong buoyancy associated with the CO source. In the tests with tobacco, the degree of circulation was dependent upon the size of the buoyant source. The heater stirred the enclosure well and the solar radiation onto the floor was very effective in creating circulation in the room. They did note that buoyancy independent of the CO source could pre-stratify the environment and prevent CO from reaching the ceiling. They also reviewed CFD modeling of these flows and found that while the technology seemed capable, experimental validation was still needed.

Ross, Smith, and Sullivan (1999) performed an experimental and computational study of CO dispersion within a single room (floor area- 14.4 m^2, height- 2.4 m). Motivated by the character of spillage gases from gas appliances, they used a 100 C source with flow rates in the range of 0.85-6 liters/second flow of 3% by volume CO (24 to 170 mg/s CO and heat output of 70–470 W) from a 12.5 cm diameter pipe located within one meter of the floor. These were intended to represent appliances with input ratings of 1.7 to 12 kW with the exhaust flue fully blocked. The CO flow was designed to yield an average compartment CO concentration of about 250 ppm at the end of the one hour experiment. Two 0.21 by 0.13 m operable vents were located 0.73 m and 1.88 m from the floor. Temperatures and CO concentrations were measured throughout the 14.4 square meters by 2.4 m tall room. Thermally, the room stratified with about a 6 C temperature rise at the ceiling and near ambient temperatures at the floor. CO concentrations were much less stratified with concentrations reaching near 300 ppm at the ceiling and more than 200 ppm at the floor after an hour. They found the results insensitive to the source temperature over the range of 75–150 C. They also found little effect of the pipe discharge height (raising it 0.57 m), the pipe orientation (horizontal vs. vertical upward), or reducing the source flow rate (0.85 l/s to 6 l/s). Opening vents reduced the CO concentrations as expected, but did not lead to greater stratification. The door opening did enhance stratification such that differences in CO concentration with height were observed. Concentrations were not reduced at head height relative to the ceiling height. Other tests evaluated the effects of objects in the room, wall openings for fixtures, and additional room heat sources. None of these had effects upon CO distributions in the room. The heaters used were always near ground level and tended to stir the compartment rather than stratify the compartment. Tests with an actual gas boiler and gas heater yielded similar dispersion characteristics as the test CO source, though CO concentrations were quite low as would be expected for normal operating conditions. Comparisons of the CFD model and the experiments yielded good agreement. Numerical experiments were done to evaluate the effect of doubling the ceiling height to 4.8 m, using a room heat source, changing the source flow rate (1.2 vs. 6 liters/s), doubling the room floor area while introducing an internal partition (large soffited opening), adding a sloped ceiling, and adding cold external walls. These numerical experiments yielded differences in CO dispersion, but none that specifically effected the report recommendations.

Ross, Smith, Khan, and Cripps (1999) conducted an experimental and computational investigation of CO dispersion in a two story home. Approximately 90 experiments were conducted. Their testing with sources on the first floor gave rise to stratification in the room of origin with more uniform but reduced concentrations elsewhere on the floor. CO did move to the upper story. Sources on the second floor lead to CO dispersion over the second floor rooms, but little CO on the first floor. In all cases closing a door essentially prevented CO dispersion via that route. They used the same CO source used by Ross, Smith, and Sullivan (1999) (described above). Testing with a non-buoyant CO source yielded more well-stirred conditions in the room of origin, though the detailed distributions were unpredictable. Modeling CO dispersion in the home was performed using a single zone (network) model in which each room is treated as well mixed control volume and transport between rooms is calculated. Comparisons between measured and predicted concentrations were shown for the base case and the agreement was good. The model was used extensively to study the effects of wind direction, wind speed, window openings, and external temperature for a range of building leakage levels. Results were present for the CO dose (concentration time integral) for each room over the one hour simulation period. Wind speed and direction had the greatest impact on CO dispersion in the home.

Ross, Palmer, and Khan (1999) performed experiments in the same home used by Ross, Smith, Khan, and Cripps (1999) with the intention of validating CO detector siting recommendations. They used the same house and CO source used by Ross, Smith, Khan, and Cripps (1999). The study confirmed dispersion findings from the earlier work with buoyant CO sources. The study used commercial CO alarms and reported the alarm times for all devices and tests. No assessment was performed to establish the acceptability of the performance of the alarms or assessment of the potential COHb values for occupants in different spaces up to the time of various alarms.

Gant et al. (2006) reviewed the general literature regarding indoor dispersion and identified the following factors that impact dispersion (Table 2).

Table 2 – Summary of Factors Affecting Contaminant Dispersion

Feature	Factor
Doors	door opening, door swing pumping effect
Windows & walls	thermal effects, radiation, infiltration
Occupants	heat output, movement, breathing, flow blocking effects, spatial resolution
Equipment, lights & furnishings	heat output, flow blocking effects
Air flow	turbulence, humidity, supply terminals
Contaminants	physical properties, electrostatic charge, source location, contaminant models

These factors give rise to two major classifications of dispersive flows, momentum controlled flows and buoyancy controlled flows. While Gant et al. (2006) identifies a wide range of dimensionless numbers that characterize the flow, many of these are effectively the same in that they characterize the relative importance of momentum vs. buoyancy (Froude, Richardson, and Archimedes numbers).

$$\mathrm{Fr} \sim (\text{inertia/buoyancy})^{1/2}, \quad Fr = \sqrt{\frac{\rho_o U^2}{\Delta\rho g H}} \tag{6}$$

where U is the velocity of the active ventilation, H is the enclosure height, ρ is the density, and $\Delta\rho$ is the density defect of the buoyant source that can be calculated as the difference of ambient density and the buoyant source density (ρ_o- ρ_{bs}). In addition, ratios of length scales arise in fully characterizing the enclosure (enclosure dimensions, buoyant source dimensions, vent dimensions). Ratios of these forces relative to viscous dissipation are also involved in complete description (Reynolds and Grashof). Gant et al. (2006) also reviewed considerations in CFD modeling. They draw no conclusions about the type of CFD model that is best for this application, but do note the importance of radiation and humidity that is most often ignored in these models.

Gadgil et al. (2000) observed that airflow in large spaces is driven primarily by mechanical ventilation, and thermal buoyancy caused by surface temperature differences and heat sources. Natural ventilation and infiltration are negligible or secondary effects in most circumstances. They note that whether the mixing is dominated by mechanical or buoyancy forces, that the flows are generally highly turbulent. They explored experimental and CFD methods for studying contaminant dispersion in large spaces.

Jayaraman et al. (2004) compared a simple control volume model, COMIS, with a CFD model, for pollutant transport in a seven-room suite with active ventilation. They found that the exposures (the integrated contaminant exposure) determined with the control volume model were within a factor of two of the CFD computation. This illustrates the relative effectiveness of simple control volume models where active ventilation is employed.

Finlayson et al. (2003) compared small-scale water tank simulations of an atrium with RANS CFD predictions for the same space. They found concentrations predicted by the CFD code to be within a factor of two of the measured values at breathing height in the compartment. Mora et al.(2003) compared coarsely meshed RANS CFD predictions to velocity data for mechanically ventilated enclosure experiments and found good agreement.

Gadgil (2003) compared a RANS CFD model with data from experiments using a closed mechanically stirred isothermal room with an instantaneous discharge of CO. The comparisons with data were good. The calculated mixing times in the compartment were within 30% of the measured mixing times, which ranged from 2 to 42 minutes. The mixing times were correlated with the average air speed with a 42-minute mixing time for an average speed of 1 cm/s and 2 minutes for an average speed of 16 cm/s. The ventilation rates spanned the normal range of indoor ventilation.

Inkster (2004) reported the results of modeling CO dispersion and CO uptake in a residential setting to assess the impact of a gasoline-powered generator operating in the basement. The detailed layout of the home was not reported but appeared to be a two story home with a basement. The CO dispersion was modeled using EPA's RISK Indoor Air Modeling program and the CO source term was determined from the testing of Brown (2006). CO uptake was modeled using the Coburn, Foster, Kane equation. Carboxyhemoglobin percentages (%COHb) were calculated for an occupant in each room of the house at activity levels from resting to moderate activity. The home was modeled with and without the HVAC operating. The UL sensitivity requirements for CO alarms is essentially consistent with a %COHb of 10% for heavy work activity (UL 2001). As such, the time to 10% COHb at moderate activity can be used as an estimate of the alarm operation time. The results indicate alarm times of 0.25 hours in the basement, 0.75–1.25 hours in the living areas and 2.5 hours in the bedrooms for the no HVAC case. Notably, fatal conditions developed in the living areas of the home before detection levels were reached in the sleeping areas. For the HVAC case, all rooms other than the basement had the same exposure history with alarm levels in 1.25 hours, compared to 0.25 hours in the basement. For both HVAC modes, fatal conditions developed in the basement before detection levels were achieved in the living or sleeping areas. These results confirm the important role of HVAC systems and the need for detection proximate to the CO source to assure safety to occupants throughout the home.

Inkster (2004) also reviews the Coburn Foster Kane equation for CO uptake and points out the direct effect of respiration rate on CO uptake by humans. Inkster reflects that the time constant for CO uptake by resting/sleeping adults is greater than four hours, while for highly active adults the time constant reduces to about one hour. This is generally consistent with the

CO uptake equation for a constant CO concentration exposure provided in Annex B of NFPA 720, which has a time constant of just less than 100 minutes for a working individual. A slight simplification of the NFPA 720 equation which ignores pre-exposure %COHb cast in terms of a time constant, τ, yields

$$\%COHb = \frac{CO(ppm)}{6.04}\left(1 - \exp\left(\frac{-t}{\tau}\right)\right) \tag{7}$$

This expression is a linear form of the Coburn, Foster, Kane equation. The linearized expression is consistent with the equilibrium values found in the work of Peterson and Stewart (1975) for CO concentrations of 100 ppm or less. For higher CO concentrations the results diverge from the full Coburn, Foster, Kane equation. Note that the linearized equation can yield %COHbs above 100%. The linear version of the Coburn, Foster, Kane equation is only valid for small values of %COHb. The nonlinearity effects the equilibrium values as well as the time apparent time constant. The NFPA 720 Annex B equation and associated graph utilize the equation outside its applicable range. If, however, we seek to utilize the equation only for detector response at 10% COHb, the errors present little concern. Of course, the equation is only correct for constant CO exposure concentrations to adult individuals engaged in the prescribed level of activity.

The development of the environment within the compartment of origin as determined from the literature reviewed above is much the same as the development of the environment in a compartment with a fire source. The development of a stratified environment with the warm gas layer filling the compartment over time is the essential feature of the problem. This filling problem due to a buoyant source has been widely studied and the results are summarized by Cooper (2002). Here we will confine ourselves to steady sources, though generalizations are available.

For weak sources that do not result in significant changes in gas density, the problem can be solved analytically. Note that in this formulation the layer depth does not develop below the source height. This assumption can be relaxed via a more generalized version of the theory. The layer interface height relative to the source height, Z_i, evolves over time as follows:

$$\begin{aligned} &\frac{Z_i}{H} = \left[1 + 0.21(2/3)\tau\right]^{-3/2} \\ &where \\ &\tau = \left(\frac{\dot{Q}}{\rho_a c_p T_a}\right)^{1/3} \frac{H^{2/3} g^{1/3}}{A} t \end{aligned} \tag{8}$$

where H is the ceiling height above the source, $\dot{Q}$ is the heat output of the source, ρ_a is the ambient density of air, c_p is the heat capacity of air, T_a is the ambient temperature, g is the acceleration due to gravity (9.8 m/s^2), A is the floor area of the compartment, and t is the time from the start of the release. The carbon monoxide concentration in the layer is given by

$$CO(ppm) = \frac{\dot{m}_{CO} t}{H\left(1 - Z(t)/H\right)A\rho_a} \frac{MW_a}{MW_{CO}} \times 10^6 \qquad (9)$$

where $\dot{m}_{CO}$ is the release rate of carbon monoxide, MW_a is the average molecular weight of air (29 g/gmol), MW_{CO} is the molecular weight of carbon monoxide (28 g/gmol). This same equation can be used for the well stirred case by taking Z=0.

The significance of this description of the filling process is to establish the time scales for filling. For CO release sources, the heat source is typically modest with heat outputs typically in the range of 10 W to 1000 W, with resulting room temperatures of 0-10 C above ambient. Carbon monoxide release rates are generally in the range of 1 mg/s to 1 g/s. Typical room floor areas are in the range of 10–100 square meters and typical ceiling heights are in the range of 2–4 meters. These are crude estimates based upon the literature review results that are provided only for scoping purposes.

As would be expected, this filling time can vary widely depending upon the inputs. For a large generator (1 kW thermal output and 1 g/s CO) in a small room (10 m^2 by 2 m high), times to half fill the space are only a few minutes and CO concentrations can reach 10,000 ppm in only a few minutes. This must be regarded as a serious but far from typical situation. Simply moving the generator into a two car garage size space or basement (100 m^2 by 3 m high) extends the time to half fill to ten minutes with CO concentrations of several thousand ppm. Substituting an unvented water heater similar to sources used by Ross, Smith, and Sullivan (1999) (500W, 100 mg/s CO source) in a space 100 m^2 by 3 m high yields a half filling time of 15 minutes and with CO concentrations in the hundreds of ppm. Moving further into the range of moderate sources (100W, 10 mg/s CO source) in a space 100 m^2 by 3 m high yields a half filling time of 25 minutes and with CO concentrations around one hundred ppm. From these examples it is clear that stratification and filling times are significant for very large CO sources like generators. For more moderate sources, the filling times are longer, but the CO concentrations are sufficiently slowly developing so as to make stratification less significant.

The available research indicates that CO sources are generally buoyant releases and the filling of the compartment with CO is dominated by buoyancy-induced layering as is found for fire sources. During the initial period of release, the compartment is well stratified with the layer filling the space after that period.

The flows via doors due to buoyancy are well described by the classical vent flow equations used in fire dynamics. The findings from the experimental and analytical work show that closed doors are indeed effective in limiting the dispersion of CO. Open doors give rise to significant flows which support a relatively well stirred group of enclosures. Where a forced ventilation system is in operation, this mechanism dominates CO dispersion. Concentrations within a ventilation zone are quite well stirred. These findings have a significant impact upon our general understanding of CO dispersion and will have important implications for detector siting.

While the experimental data on CO dispersion in buildings is generally limited to small buildings, the analytical methods included in this section have broad applicability over a wide range of scales. The equations have, in many instances, been validated and applied to very large-scale spaces and buildings. In addition, the expressions are well founded in scaling laws developed in the fluid mechanics and fire protection engineering fields.

The analysis of enclosures with infiltration indicate that steady CO concentrations below detectable levels (>30 ppm) but above EPA and WHO limits for exposures are realizable for some of the CO sources identified in this review.

5.0 CO DETECTOR SITING FINDINGS IN THE RESEARCH LITERATURE

Based upon single room testing, Ross, Smith, and Sullivan (1999) recommended placement of CO detectors on ceilings. Based upon testing in a test house, Ross, Smith, Khan, and Cripps (1999) observed that while stratification is much less pronounced in rooms away from the release room, nonetheless, CO concentrations near the ceiling are at least as high as those recorded at other heights.

Ross (1999a, b) recommended that CO detectors be placed in rooms that contain combustion appliances and in rooms where occupants spend the most time. In rooms with detectors, Ross recommends ceiling placement at least 300 mm from any wall. If the detector is located on a wall, he recommends that it be placed as high as possible (but not within 150 mm of the ceiling) and that the detector be placed higher than doors and windows. The detector should be located within one to three meters horizontally from the appliance. With sloped ceilings, the detector should be on the high part of the ceiling. In rooms without a combustion source, Ross recommends placement within the breathing zone for that room. The recommendations are very vague and combine considerations with respect to detection and with respect to the alarm function.

Bullman, Hill, and Pool (2001) reviewed 80 CO dispersion experiments in single and multi-room enclosures to assess the siting of domestic CO alarms. This study introduced alarm effectiveness as a quantification of the time to reach alarm level when alarm siting parameters were varied. Evaluations with alarm thresholds in the 50–150 ppm range indicated relative insensitivity to the threshold chosen. The alarm effectiveness is the ratio of the time to reach the threshold concentration at the ceiling of the release room to the time to reach the threshold at alternate locations. Within the release room results indicated that the wall locations showed some time delay compared to the center of the room close to ceiling level. These alarm effectiveness values were also determined at other location within the house. The study showed that within the release room, the alarm effectiveness values found anywhere in the primary room were 80 % to 97 %. The highest alarm effectiveness was 70% in the adjacent room. The study suggested that at locations remote from the release room, times to reach the thresholds increased by a factor of about two. This only considered spaces connected by openings. These metrics provide some indication of detector performance remote from the release room. The optimal vertical mounting location was recommended to be on the release room wall not more than 0.8 m from the ceiling or on the ceiling of the release room. In spaces remote from the release, the height did not affect the performance of the detector. This study only included highly buoyant releases in home settings. While alarm effectiveness is a reasonable indicator of the relative performance of detectors at different locations, the measurement has no basis in actual performance characteristics related to the protection of people from harm. As such, the metric does little or nothing to determine how many detectors are needed and where they need to be located.

6.0 DISCUSSION

It is clear that the sources of carbon monoxide are combustion sources and that these sources are in no way uniquely associated with residences. Sleeping has little or nothing to do with the onset of CO hazards or injuries/deaths due to CO. The characteristics of residences and other occupancies do not directly indicate clear differences in CO production and dispersion. As such, siting rules for CO detectors are not expected to be occupancy dependent per se.

This literature review and analysis suggests a two-prong approach to CO detection. The first approach is to associate a CO detector with any know combustion source. These devices serve the role as a combustion safety device (CSD) and act to detect, actuate an alarm, and potentially to turn off the combustion device. While such detectors can effectively protect building occupants from CO hazards from known combustion sources, there is ample evidence that CO can enter the building from outdoor sources and that combustion sources can be brought into buildings by occupants which can create CO hazards that may not be detected by a CO detector sited as a CSD. The second approach to CO detection is the use of a CO detector that acts as an indoor air quality monitor (IAQ) within the occupied portions of the building. These CO detectors are located to monitor the general occupiable areas of a building and provide data concerning the IAQ and activate an alarm when hazardous conditions arise. The IAQ type of CO detector serves both as a non-source specific means of protecting building occupants from acute CO hazards and as a general purpose, IAQ monitors to minimize chronic CO exposures.

Siting of CSD CO detectors should be proximate to every installed combustion device within a building. Based upon the filling phenomenon due to buoyancy seen in experiments and reflected in the filling calculations, the location of a detector low in the same space as the combustion source can lead to delays in detection relative to detectors placed high in the space. This effect is especially pronounced for large CO sources. If the room containing the combustion source is well isolated from occupied spaces, the delay associated with low detector placement may not be large. However, where openings between the combustion source room and occupied spaces is both large and located above the detector, serious exposures before detection can result.

Pre-stratification by thermal sources without CO can delay or prevent CO detection near the ceiling. This would typically occur where there are heat sources near the ceiling or where roof decks are heated by solar radiation and no suitable mechanical ventilation is provided. If such pre-stratification potentials are present, then placement of the CO detector at head height would be indicated. Delays associated with this detector siting can be accessed using the filling analysis (Equations 7, 8).

One strategy to protect against combustion sources is to integrate CSD CO detection as part of the combustion appliance. This potentially should be done for all combustion devices which could be brought into a building as misuse of mobile combustion devices seems to be a definite problem, especially due to gasoline powered devices after natural disasters, power outages, etc and also seems to be commonplace in many workplaces even absent these unusual conditions. Lee (2006) recognized the value of this approach. He further recognized that CO detection could either be integral to the combustion device or remotely located in an occupied space. He demonstrated a remote CO detector which automatically shut-off a generator in a space (like a garage) based upon CO detection within the occupied portion of the home. There is no commercially available CO detector that operates as Lee (2006) describes, and there are no commercial CO detectors that could be used in a flue environment. The commercially available equipment can be used in the room containing the combustion device to act as a CSD CO detector.

Time constants in the CO poisoning problem vary substantially. Time constants for air exchange range from 0.1–10 hours, time constants for CO uptake by people are in the range of one to four hours. Mixing times range from minutes to an hour or two in openly connected spaces. Times to develop detectable CO hazards range from minutes to hours. This in part results from the very large range of CO release rates which spans a range from below 1 mg/s to 1000 mg/s. However, except for continuously operating Class B sources in small enclosures and Class A sources in moderate size enclosures, CO hazards develop on the time scale of hours.

Beyond CSD CO detection associated with combustion devices, there may be a need to provide general IAQ CO detector coverage. The IAQ CO detectors provide non-source specific means of protecting building occupants from acute CO hazards and as a general purpose IAQ monitors to minimize chronic CO exposures. Based upon the review of CO poisoning statistics (Section 2), it is clearly that CO poisoning is a hazard that has both acute and chronic elements. The health effects of chronic low level exposure involve significant personal health and economic consequences. Siting of these IAQ CO detectors is discussed in the following paragraphs.

In modern buildings, HVAC units are ubiquitous and one IAQ CO detector per HVAC zone is an appropriate level of protection, since the HVAC system will stir the zone and provide relatively uniform concentrations throughout the zone. Whenever a ventilation system is present and operating, it will dominate the flows in the building. However, some consideration of unventilated conditions is required unless the ventilation system is designed to operate continuously. The likelihood of ventilation not being active is very seasonal, with lowest ventilation associated with moderate outdoor temperatures.

With the CO incidents biased toward winter conditions, it is reasonable to assume that an operating ventilation system is the most common scenario. Nonetheless, since ventilation use is cyclic and seasonal, consideration of detector siting in the absence of ventilation is important. It is important to deal with seasons of the year where heat and cooling ventilation systems are lightly utilized though other combustion devices (like hot water heaters) may still be in use. In addition, some buildings do not have HVAC system, but rather rely upon hot water type heating systems. CO dispersion in these buildings will generally be dominated by buoyancy and other secondary flows. Stack effect may be significant in tall buildings.

The literature on CO dispersion indicates that within a floor, CO dispersion will be relatively effective via buoyancy and other secondary flows except via closed doors that will significantly mitigate CO dispersion. Such closed doors may provide some protection to occupants in the absence of forced ventilation. More importantly, closed doors between the CO source and the CO detector will prevent the detector from providing timely detection.

CO dispersion to lower floors cannot be relied upon for detection. CO dispersion to upper floors does occur reasonably effectively if there are open stairways for buoyant flows to the upper floor. This suggests that IAQ detectors could be provided on the upper floor of an openly connected two-floor space if one detector per floor were judged to be a burdensome requirement.

7.0 CONCLUSIONS

The CO poisoning problem is dominated by CO produced by combustion sources. The statistical evidence is that there is an ongoing reduction in injuries and deaths due to non-fire CO poisonings, due to the reduced emissions from combustion devices resulting from environmental regulation. This regulation arises out of concern for public health effects of combustion products pollution, but has had significant safety benefits as well.

The literature review and analysis of CO production and dispersion suggests a two-prong approach to CO detection. The first approach is to associate a CO detector with any know combustion source. These devices serve the role as a combustion safety device (CSD). They act to detect, actuate an alarm, and potentially to turn off the combustion device. While such detectors can effectively protect building occupants from CO hazards from known combustion sources, there is ample evidence that CO can enter the building from outdoor sources and that combustion sources can be brought into buildings by occupants which can create CO hazards. The second approach to CO detection is the use of a CO detector acting as an indoor air quality monitor (IAQ) within the occupied portions of the building. These CO detectors are located to monitor the general occupiable areas of a building and provide data concerning the IAQ and activate an alarm when hazardous conditions arise. The IAQ type of CO detector serves both as a non-source specific means of protecting building occupants from acute CO hazards and as a general purpose, IAQ monitors to minimize chronic CO exposures.

The magnitude of CO release rates vary from zero to 1000 mg/s. CO production from normally operating combustion appliances is typically up to 1 mg/s. Poorly operating combustion appliances and normally operating wood burning appliances can have CO production rates up to 100 mg/s. Small gasoline powered engines can produce up to 1000mg/s when operating normally. Time constants in the CO poisoning problem vary substantially. Time constants for air exchange range from 0.1 to 10 hours, time constants for CO uptake by people are in the range of one to four hours. Mixing times range from minutes to an hour or two in openly connected spaces. Times to develop detectable CO hazards range from minutes to hours. This in part results from the very large range of CO release rates. While hazardous conditions can be produced in minutes for large CO sources in small or moderate enclosure sizes, most CO hazards develop on the time scale of hours.

CSD CO detectors should be sited proximate to the combustion device with the detector located high in the space containing the combustion device. Pre-stratification effects of heat sources high in the space or by heated roof decks should be considered. Where such effects could prevent operation of the CO detector, placement of the CO detector at around nose height or at the height of openings to other spaces may be indicated. For substantial CO sources, detectors placed at or near the floor may result in detection delays of concern with respect to potential pre-alarm CO exposures.

IAQ CO detectors should be sited throughout the occupied portions of a building. These detectors should be located in relatively open areas. Where HVAC systems are in continuous use, the ventilation rates will stir the HVAC zone to create fairly uniform CO concentrations. In these circumstances, location of on IAQ CO detector per HVAC zone is indicated.

However, some buildings do not use HVAC systems or the operation of HVAC systems is limited to seasons and times when heating or cooling is called for by a thermostat. Buoyancy and other secondary flow mechanisms are generally effective in mixing openly connected rooms on a single floor. Closed doors are effective in limiting CO dispersion such that placement of a CO detector behind a closed door will not provide effective protection. Flow of CO to floors below the floor of origin cannot be relied upon to operate CO detectors. However, upward flow of CO to a second floor is relatively effective when the two levels are openly connected.

Based upon these findings, for IAQ CO detectors should be located on every floor and detectors should be provided in each area of a floor defined by normally closed doors. Where an HVAC system is present, at least one CO detector per HVAC zone should be provided. Where HVAC operation is continuous, relaxation of CO detector siting requirements with respect to floor and area defined by closed doors can be allowed.

While ongoing progress in the reduction of CO emissions has had a significant safety benefit, there is an ongoing need for CO detection in buildings in general. Even as CO emissions are reduced, there are ongoing hazards associated with improperly installed or improperly operating combustion sources. Appropriate siting of CO detectors has benefits both for safety with respect to acute CO exposures and potentially in reducing health impacts of more chronic CO exposures.

If further work is to be conducted, the existing body of data is most lacking in large floor area spaces with a minimum of closed doors. These spaces would be typical of office areas where there are long corridors or other types of open areas. To date, most of the data is in smaller footprint buildings. These large area spaces are not well addressed by network models. The important non-HVAC fluid mechanical forces are not well addressed by CFD models. As such, it is recommended that experimental research in actual buildings be conducted. This would involve sources motivated by the findings of the current study. Gas sensors and temperature sensors should be distributed throughout the test area. Variables that should be included in the study include wind speed, solar heating conditions, HVAC operation, and door closures. Building leakage areas should be measured and documented via door fan methods and by tracer gas methods. These tests would provide additional data to evaluate the recommendations of the study and would provide a database of well-documented tests that could be used to develop and validate modeling methods in the future.

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