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Carbon Monoxide Dispersion in Residential Buildings: Literature Review and Technical Analysis

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ABSTRACT

Carbon monoxide (CO) detectors are being used increasingly in residential buildings to warn occupants about CO concentrations that could potentially cause acute health effects. While the use of CO detectors can decrease the likelihood of exposure to such CO levels, questions exist concerning the installation of these devices in residential buildings, primarily with regards to the location and number of detectors. Efforts to develop installation guidance and standards have been faced with these questions of location, and the availability of technical information to support the development of installation recommendations has been questioned. As the first task of a project to analyze the distribution of CO in residential buildings as it relates to the installation of CO detectors, a literature review and technical analysis was conducted to assess information on CO dispersion in residential buildings that could support the development of guidance on detector installation. The review covered a number of issues including CO concentration measurements in residential buildings, sources of indoor CO, mixing within and between rooms, tracer gas techniques for assessing building airflow, and computer models of air movement and contaminant dispersal in buildings. The material obtained in the literature review is discussed, and a technical analysis of the issues related to CO dispersion in residential buildings is presented.

Key words: building technology; carbon monoxide; exposure; indoor air quality; literature review; residential; ventilation

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1. INTRODUCTION

The acute health risks of CO exposure have been well established for the general population and for certain risk groups, such as people with heart disease, and discussions of these health concerns have included exposure to elevated indoor CO concentrations (Brennan and Ivanovich 1995; Caplan et al. 1986; Cobb and Etzel 1991; Colome et al. 1992; Coultas and Lambert 1991; EPA 1991). CO detectors, which provide building occupants an early warning of elevated CO levels, have become commercially available, and their use in residential buildings has been recommended in the popular press (Consumer Reports 1995; Marable 1996) and by government agencies (CPSC). A number of local jurisdictions have instituted requirements for their installation in new residential buildings (CPSC).

A properly-functioning CO detector will warn building occupants of elevated indoor CO concentrations so that they can respond before acute health effects occur. Standards for CO detector performance have been developed in the United States (UL 1992 and 1995) and in the United Kingdom (BSI 1996). These standards cover primarily performance issues of alarm levels, electrical and mechanical requirements, and interference from other airborne substances. However, these standards are limited in terms of requirements on detector installation in residential buildings. The UL standard does not cover detector location; the BSI standard contains a normative annex stating that a detector should be located in or near every room containing a fuel-burning appliance. If there are multiple appliances, but only one detector is available, then a number of considerations are given that relate to the locations of appliances and building occupants. The BSI standard recommends positioning the detector at least 1.5 m (5 ft) above floor level unless the manufacturer specifies otherwise, and at least 1.85 m (6 ft) from a fuel-burning appliance. The Consumer Product Safety Commission recommends in a consumer fact sheet, not a regulation, that CO detectors be installed on the wall or ceiling in sleeping areas, but outside individual bedrooms (CPSC). While acknowledging the need for more research, recommendations exist to place CO detectors near the ceiling based on the thermal plume produced by many CO sources (Rogers and Saffell 1996).

There have been suggestions and attempts to develop formal installation guidance in the form of model building codes and a proposed National Fire Protection Association standard. In discussions of these activities, the adequacy of the information to support specific installation recommendations has been questioned. Issues have included where the detector should be installed and at what height, and how many detectors should be installed. Relevant factors have been identified including the sources of indoor CO, the manner in which CO is released from these sources, room layout and other building characteristics, ventilation system type, and internal air mixing. This literature review and technical analysis has been undertaken in order to assess the available information on these issues, determine its adequacy for formulating installation guidance, and identify important areas where additional information is required.

The scope of this literature review includes studies of CO concentrations and distribution in residential buildings, sources of CO in these buildings, air mixing within and between rooms, tracer gas techniques for measuring airflows in buildings, and models for predicting airflow and contaminant dispersal in buildings. This information has been collected and analyzed for its relevance to the question of how CO disperses in residential buildings and the information that it contains concerning the installation of CO detectors, particularly their location in a building and their height. Following the literature review and the technical analysis of the information obtained, the adequacy of this information to develop technically-sound installation guidance was assessed and a list of research needs was developed to obtain additional information to develop such guidance. Subsequent phases of this project may be pursued in which some of these research needs are addressed. While the literature review covers both single and multi-family residential buildings, the technical analysis and the discussion of research needs cover only single-family buildings. It is important to note the issues that are not covered in this literature review and will not be addressed in future phases of this effort. Issues that will not be covered include sensitivity and accuracy of CO sensors, appropriate alarm levels, and interference from other airborne substances. Also, the project is concerned only with indoor CO generated in non-fire situations.

Recently, a study has been initiated at the Building Research Establishment (BRE) on the location of CO detectors in residential buildings. The study is being undertaken to investigate the movement of CO within a room in which a boiler is spilling combustion products and the subsequent movement of CO through the rest of the house. Both experimental and modeling work will be used in this study, and a literature review has been completed (Ross et al. 1996). This review covered relevant research and standard requirements for siting of CO, natural gas and smoke alarms. Much of the review was focused on modeling approaches, specifically computational fluid dynamics modeling, and on experimental work on the flow of buoyant gases. The conclusions of the review include an enumeration of the factors related to the location of CO detectors in a room. These include: the fastest buildup of CO may be expected at ceiling height, but there may also be vertical stratification at the source height; horizontal variations may be important close to the source and surfaces; there may be boundary effects close to surfaces such as walls, floors and ceilings; CO may be lower in regions close to ventilation openings; objects (e.g., curtains and furniture) may impede the transport of CO; there may be pockets of air at intermediate and floor heights with little CO; if there is a separate source of temperature stratification, then it may be difficult for CO to reach the ceiling; CO distribution may be affected by surfaces which are much warmer or colder than the rest of the room; and, airflow will be very dependent on source conditions, e.g. temperature, position, velocity, volume, and angle of orientation. A number of factors are also presented that are related to the room in which a CO detector should be located. These include: alarms need to be located in or near every room with a combustion appliance; if there is more than one appliance but only one detector, then one should consider putting the detector in a bedroom or an often-used room with an appliance; the detector needs to be located where it can be easily heard; CO may be readily transported and mixed with accessible areas on a single floor; and, CO may be readily transported and mixed with accessible areas on upper floors, but there may be less penetration to floors below. While the BRE work is relevant to the present study, it is focused on boiler spillage as the CO source. In addition, residential buildings in the UK can be quite different from US homes, primarily in size, airtightness and not having forced-air systems. Almost all of the sources cited in the BRE literature review are incorporated in this report.

While this literature review, and the subsequent phases of this project, will not address the issue of CO concentrations at which detectors should and should not alarm, some discussion of CO concentration guidelines are appropriate as a point of reference. The EPA National Ambient Air Quality Standard for CO is 10 mg/m^3 (9 ppm) over an 8-h averaging period and 40 mg/m^3 (35 ppm) for a 1-h average (EPA 1991). The threshold limit value (TLV) for CO promulgated by the American Conference of Governmental Industrial Hygienists is 29 mg/m^3 (25 ppm) and is applicable to occupational exposures (ACGIH 1995). This value is a time-weighted average for an 8-h workday and a 40-h workweek. While no standards exist for residential occupancies, guideline values of 29 mg/m^3 (25 ppm) averaged over 1 h and 12.6 mg/m^3 (11 ppm) over 8 h have been issued in Canada (Canada Department of National Health and Welfare 1987) The health effects of CO exposure are generally described in terms of the level of carboxyhemoglobin (COHb) in the blood, which is a function of the time history of CO exposure (EPA 1991). Relationships have been developed between the time of exposure to a particular CO concentration and the COHb level, and these relationships serve as the basis of alarm levels in CO detector standards (BSI 1996, UL 1992 and 1995). Both of these standards require that the detector alarm at CO exposures corresponding to about 10% COHb.

The organization of this report reflects a distinction between what is known that is relevant to the issue of CO dispersion in residential buildings and what tools are available to obtain more information. Sections 2 through 5 cover a number of topics that reflect what is known, with

Section 2 covering studies of CO concentrations in residential buildings, including investigations and discussions of the factors that affect CO concentrations in buildings, studies involving the measurement of indoor CO concentrations at multiple points in residential buildings, and the results of large field studies of indoor air quality in single-family buildings. In section 3, the various sources of CO in residential buildings are discussed, including measurements of emission rates from combustion sources. Section 4 discusses studies of the mixing of air and contaminants within and between rooms. Surveys of ventilation rates in residential buildings are discussed in section 5, along with information on the volumes of residential buildings, in order to assess the information available concerning these important determinants of indoor CO levels. The next two sections discuss some of the tools that may be useful for learning more about how CO disperses in residential buildings. Tracer gas measurement techniques for determining building airflow rates are discussed in section 6, with particular attention given to techniques for determining interzone airflow rates. Airflow and contaminant transport models are discussed as a means of predicting building ventilation rates and indoor contaminant levels in section 7, with a focus on multizone models that predict interzone airflow rates and contaminant concentrations in multizone building systems. The findings of this literature review are summarized and discussed in section 8. Section 9 discusses the technical analysis that was performed based on the results of this literature review, and the last section presents a discussion of research needs based on the technical analysis.

2. CO CONCENTRATIONS IN RESIDENTIAL BUILDINGS

There have been a number of studies involving measurements of CO concentrations in residential buildings, with most of these performed in single-family residences. These studies include CO exposure studies in which personal exposure monitors were used to determine CO concentrations associated with various activities and microenvironments. There have also been a number of indoor air quality surveys of large numbers of residential buildings in which multiple indoor pollutants were sampled, including CO. While these surveys have generally employed only a single CO sampling location in each building, they provide information on indoor levels and the sources associated with indoor CO. A limited number of studies have involved multi-point sampling of CO. Finally, there have been a number of investigations of the factors that impact CO concentrations and the spatial and temporal variation in these concentrations. While not all of the studies indicate where, and at what height, the CO concentration was measured, this information is provided when it is available.

2.1 CO Exposure Studies and Residential CO Measurements

There have been a number of studies designed to determine the levels of human exposure to CO. These studies have included personal monitoring studies in which occupants wore personal exposure monitors for 24 hours or more and recorded their activities and locations in diaries (Akland et al. 1985; Nagda and Koontz 1985). These studies have provided information on CO exposure as a function of activity and microenvironment, such as parking garages, motor vehicles, outdoors, and residential buildings. Some studies have focused on CO exposure in buildings, and in some cases on exposure in specific locations within buildings. One of these studies focused on men with ischemic heart disease, in which they wore personal CO monitors that recorded one-minute average CO concentrations (Colome et al. 1992). The study participants also maintained written diaries of their activities, locations and symptoms. In addition to information on health symptoms, the results of this study include information on CO exposure as a function of occupant activity and location. The highest personal exposures were associated with driving automobiles and using small gasoline appliances for lawn care or cutting wood, and CO concentrations are reported for a number of indoor spaces including residential buildings by room type, e.g., kitchen, living room, and bedroom. In residential buildings, mean one-minute CO exposures ranged from 4 mg/m^3 to 4.6 mg/m^3 (3.5 ppm and 4.0 ppm) in family rooms, kitchens, dining rooms and living rooms, from 2.4 mg/m^3 to 3.4 mg/m^3 (2.1 ppm and 3.0 ppm) in bedrooms, bathrooms and laundry rooms, and 4.5 mg/m^3 (3.9 ppm) in garages or enclosed carports. However, maximum concentrations were above 100 mg/m^3 (87 ppm) in family rooms, kitchens and garages/carports.

A relatively recent study, discussed in more detail in section 2.4, focused specifically on the factors that affect indoor CO levels in residential buildings (Colome et al. 1994; Wilson et al. 1993 and 1995). In this study, 48-h and 8-h average CO concentrations were monitored in about 300 homes in California and were related to a number of variables including the concentrations of other pollutants, house characteristics, ventilation rates, appliance types, and occupant activities. Statistical analyses were performed to determine the relationship between indoor CO concentrations and these variables. Of the 277 homes for which CO was reported, 13 had 8-h average concentrations above 10 mg/m^3 (9 ppm), and one house had a 1-h average of about 40 mg/m^3 (35 ppm). These two values correspond to the EPA ambient air quality standard. The findings of this study include that indoor CO levels are correlated with outdoor levels, and that high indoor CO is associated with cigarette smoking, gas fuel for cooking, wall furnaces and smaller houses. Some high levels were also associated with using gas ranges for heating and with attached garages.

There have been a number of other studies in which CO concentrations were measured in residential buildings, some of which have addressed the impact of specific sources on indoor CO concentrations. In a study in manufactured houses less than 10 years old, CO exposure was monitored at a single location in each house during portable kerosene heater operation (Williams et al. 1992). The sampling locations were about 0.5 m (1.6 ft) above the floor and about 2 m to 4 m (7 ft to 13 ft) from the heaters. The measurements showed that three of the eight houses studied had 8-h average concentrations above or near 10 mg/m^3 (9 ppm), the EPA 8-h ambient air quality standard. Seven of the houses had significant increases in indoor CO levels during heater operation, and one routinely had levels of 34 mg/m^3 to 57 mg/m^3 (30 ppm to 50 ppm) for prolonged periods.

In one of the few studies of CO in multifamily buildings, concentrations were monitored in 60 small apartments with kitchen ovens operating continuously (Tsongas and Hager 1994). CO was monitored every 5 min over the oven exhaust port, in the kitchen, and in adjacent rooms, until the concentrations reached steady state, which in some cases took more than one hour. The sampling locations in the kitchen were about 1.5 m (5 ft) above the floor, and about 0.9 m (3 ft) above the floor in adjacent rooms. In about half of the kitchens, the steady-state CO levels were above 10 mg/m^3 (9 ppm). With respect to the maximum steady-state levels at any measurement location in each apartment, about 15% were above 40 mg/m^3 (35 ppm), 5% were above 230 mg/m^3 (200 ppm) and the highest concentration was 400 mg/m^3 (350 ppm). A similar study was conducted in 87 randomly-selected households in Chicago (Conibear et al. 1995). About one-half of the sites were single-family residences, half were apartments, and three were townhouses. In this study, indoor CO was monitored during the operation of various combustion appliances including ovens, stoves, furnaces, boilers, water heaters, clothes dryers and space heaters. Initial peak and steady-state CO concentrations were analyzed. The results revealed that 89% of the initial readings were below 1.1 mg/m^3 (1.0 ppm) and all were below 17 mg/m^3 (15 ppm). Of the steady-state levels, with all appliances operating, 48% were below 1.1 mg/m^3 (1.0 ppm), 92% were below 11 mg/m^3 (10 ppm), and all were below 25 mg/m^3 (22 ppm).

In a study of ventilation and indoor air quality in multifamily buildings, Parker (1986) measured CO in three apartments in a two-story, four-unit building. CO concentrations were measured in the main living area of each apartment, away from windows and outside doors. The measured CO concentrations were all 1 mg/m^3 (0.9 ppm) or less except when there was cigarette smoking, in which case they were below about 5 mg/m^3 (4 ppm). Another study of air movement and indoor air quality in several multifamily buildings in Canada, ranging from four to twenty-one stories, included CO measurements. The measured levels were generally below 5 mg/m^3 (4 ppm) (Gulay et al. 1993). Levels above 5 mg/m^3 (4 ppm), up to 13 mg/m^3 (11 ppm), appeared to be associated with underground parking garages. The report on this study did not include much detail on the measurements, such as the sampling duration and location.

These studies of CO levels in residential buildings have shown that indoor concentrations are generally low compared to ambient and occupational standards, which are based on averages over several hours. However, under some circumstances and in a relatively small number of buildings, these average values and short-term peak values can be significantly above the values in these standards.

2.2 CO Levels in Residential IAQ Surveys

There have been a number of residential indoor air quality surveys in which the concentrations of various pollutants were measured at a single sampling location in a large number of residences. While the results of these surveys do not provide information on the distribution of CO in residential buildings, they are included for the sake of completeness and because they provide some indication of the impact of various sources and building factors.

Eichner and Morris (1983) studied 173 homes to investigate the impact of residential energy conservation measures on indoor air quality and found small but detectable amounts of carbon monoxide in more than half of the homes surveyed. CO levels were higher in homes with unvented kerosene or gas space heaters and homes with smokers present. Hawthorne et al. (1986) conducted a one-year survey of 40 homes in Tennessee. The CO levels were usually less than 2 mg/m^3 (1.7 ppm), with some exceptions when gas stoves or kerosene heaters were operating or when a car was running in an attached garage.

Carbon monoxide was measured over one-week periods in a study of thirty houses in upstate New York, in addition to measurements of air change rates and several other pollutants (Traynor and Nitschke 1984; Nitschke et al. 1985). Most of the houses had combustion-related indoor pollution sources, including smokers, unvented space heaters, gas-fired ranges, coal-burning stoves, wood-burning stoves and fireplaces. Carbon monoxide concentrations were generally low, 1 mg/m^3 or less, however, one residence with an attached garage had an average indoor carbon monoxide level of 10 mg/m^3 (9 ppm). Another survey of 400 homes included indoor CO measurements and focused on the indoor air quality impacts of combustion sources (RTI 1989). In this survey, CO was sampled from 0.9 m to 1.7 m (3 ft to 5.6 ft) above the floor and about 0.15 m (0.5 ft) from the walls. Based on a statistical analysis of the measured concentrations, gas stoves and kerosene heaters were associated with increased CO levels. In general, fireplaces and wood stoves did not increase CO levels and were sometimes associated with decreased levels.

2.3 Multipoint CO Measurements

There have been a number of studies in which CO was monitored at multiple points in residential buildings, providing some information on CO distribution. While several of the CO exposure studies cited earlier provide information on CO levels in different rooms of residential buildings, the studies discussed in this section involved continuous monitoring at multiple locations in a building. As in many other residential CO studies, these investigations have tended to focus on combustion sources. The operation of mixing fans, either forced-air distribution system fans or fans used during the test for mixing a tracer gas, appears to be critical to the extent of uniformity of the multipoint measurements. Unfortunately, not all of the studies report on the existence or operation of such fans.

Some of the studies involving multipoint CO monitoring were designed to investigate the impacts of specific combustion appliances on CO levels in different rooms, while others were more general investigations of indoor air quality in residential buildings. The latter category includes a study of the indoor air quality impacts of house tightening for energy efficiency in 400 homes that was cited in the previous section (RTI 1989). In these homes, CO was monitored at a single location, but in a subset of 13 homes CO was monitored continuously in the primary living area and in the space containing the CO source. The reported CO concentrations were similar in the source and living areas, but in many cases the source was in the living area. For cases in which the source was a gas stove, and the source and living areas were clearly not the same, there was still little difference in the CO levels between the two areas. The RTI study did not describe the houses in terms of their air distribution systems, that is, whether they had forced-air systems and whether they were operating during the measurements. In a survey study of 78 homes in Winnipeg, CO was monitored in the living room, bedroom and basement (Yuill and Comeau 1989). The CO concentrations measured over a period of only a few hours were similar in these three spaces. Little information was provided on the houses or the CO sources.

In a study by Moschandreas and Zabransky (1982), CO levels were measured in twelve residential buildings for about two weeks in order to gain some insight into the selection of air sampling locations in indoor air quality studies. The CO sources in these houses included gas cooking and heating, cigarette smoking, fireplaces and wood-burning stoves. There were concentration differences between rooms in houses with gas cooking, but the kitchen was not always the zone with the maximum concentration. The differences that did exist were only on the order of 1 mg/m^3 or 2 mg/m^3 (0.9 ppm and 1.7 ppm). An early study of the relationship between indoor and outdoor pollutant concentrations included measurements of CO in two residential buildings in the kitchen and living room and at a living room window (Yocom et al. 1971). Higher levels were seen in the kitchen relative to the living room at some times, but the paper contains little information on the CO sources or the houses.

A number of other studies included multipoint CO measurements in conjunction with the operation of gas cooking appliances, including two early studies of the impacts of gas cooking on indoor CO levels (Wade et al. 1975; Sterling and Sterling 1979). The first study involved four homes in which CO was monitored in the kitchen over the stove and 1 m (3.3 ft) from the stove, and in the living room and bedroom. The paper contains plots of CO over one or several days at these locations, along with the schedule of oven and range operation. In one of the houses, the concentrations in the kitchen were as much as twice as high as the rest of the house, while other houses exhibited much more uniform concentrations. Some differences in concentration uniformity were attributed to layout and size differences between the houses, but the paper contains no discussion of air distribution system effects. The latter study took place in nine residences and included CO measurements in kitchen, living room and dining areas in an investigation of the impact of fan hood operation and window opening. A plot of CO concentration versus time for these three rooms shows that the concentration differences between the kitchen and the rest of the house are significantly reduced about one hour after turning off the stove. A table of CO concentrations in the living and dining room in the nine residences shows some small concentration differences when the stove stops operating, but these differences decrease within 30 min and are almost gone in 90 min. Again, the existence and impact of a forced-air fan are not discussed.

A more recent study in a townhouse showed that CO emitted from a kitchen stove was rapidly mixed throughout the first story, but that transport to the upstairs was slower (Davidson, Osborn and Fortmann 1984). In this study, CO was monitored in the kitchen, living room and bedroom over 6 h, but the impact of mixing in the house due to the existence of a forced-air system was not described. A study of two bi-level houses with gas ranges operating on a preset schedule showed that with the forced-air circulation fan off, CO tended to stay upstairs on the kitchen level due to the buoyancy of the gas emitted from the range (GEOMET 1985). The average difference between the upstairs and downstairs concentrations over two weeks of testing was 7 mg/m^3 (6 ppm). When the forced-air fan was operating, however, the upstairs and downstairs concentrations were within 1 mg/m^3 (0.9 ppm) of each other. Another study of gas range operation investigated the effects of infiltration, whole house ventilation and spot ventilation on indoor pollutant levels (Traynor et al. 1982b). In this study of a one-story research house, CO was monitored 1.5 m (4.9 ft) above the floor in the kitchen only when the range was operating and in the kitchen, bedroom and living room after the range was turned off. During the post-operation CO decay, the living room, which was adjacent to the kitchen, was at a slightly lower CO concentration than the kitchen, and the bedroom at the opposite end of the house was well below the kitchen concentration. After about 30 to 45 min, the concentrations were all fairly uniform, without any mixing fans operating. Goto and Tamura (1984) also made multipoint measurements of CO in a single-family residential building with a gas stove in operation. In this study, CO was sampled 1.6 m (5.2 ft) off the floor. The forced-air circulation fan was in operation during the tests to promote tracer gas mixing, and the measured CO concentrations were very uniform in the kitchen, living room and bedroom. A small number of tests were conducted with the furnace fan off, and the concentrations were still quite uniform.

A study of 12 homes in the Holland examined the impacts of unvented gas appliances on indoor CO concentrations, focusing primarily on ranges and instantaneous gas-fired water heaters (Lebret et al. 1987). In this study CO was monitored in each house for periods of about 5 to 10 days in the kitchen, living room and bedroom. Short-term peak concentrations were seen in the kitchen corresponding with the use of gas appliances. These peaks were also reflected in the other rooms, though at lower concentrations. The peak concentrations over 1 min and 1 h were about twice as high in the kitchen, but the overall mean concentrations were similar in all three sampling locations. In a study of 14 homes in the UK, CO was monitored for one week in the kitchen, living room and bedroom of each house (Ross 1996). In this study, CO was measured at a height equal to or greater than the height of the CO sources in each room. This study focused on the impact of range hoods and kitchen exhaust fans. Peak concentrations were generally higher in the kitchens, and hoods were seen to be more effective in controlling peak concentrations than fans because the hoods tended to remove combustion products before they could mix with the room air.

Similar to the studies with gas-cooking appliances, a number of studies employing multipoint CO measurements have been performed in conjunction with the operation of unvented space heaters. In a study of 14 residences (13 with kerosene space heaters and one without), CO was monitored in two locations (Hoen et al. 1984). One location was in the room with the heater, and the other was in a bedroom. While the peak concentrations of reactive gases, that is NO_2 and SO_2, were generally higher in rooms with heaters, the levels of CO and other nonreactive gases were generally uniform in both indoor locations. These results suggest good mixing within the homes, however, no information is given on the houses or the existence of mixing fans. In a study of unvented gas space heaters, CO was monitored in the master bedroom, living room, and a downstairs living area with the forced-air fan running continuously (Nagda et al. 1985a; Koontz et al. 1988). In these tests, the heater was operated in different locations in the house, and CO concentrations were reported as a function of time and of heater location. With the heater located upstairs, higher concentrations were measured in the living room and master bedroom than downstairs, and the concentrations at these two upstairs locations were nearly identical. With the heater operating downstairs, the concentrations were fairly uniform upstairs and downstairs. The authors explain that this difference is due to buoyancy effects, with the warmer gas from the heater much more likely to move upstairs than down.

Multipoint monitoring of CO was employed in a study of the impact of various combustion sources on pollutant levels in a one-story research house (Leslie et al. 1989). The sources included a gas range and oven, a gas water heater and clothes dryer, and unvented space heaters. The results showed uniform pollutant concentrations throughout the house when the furnace fan operated continuously. When the furnace was off for extended periods, sources on the first floor did not impact the basement. For sources on the first floor in the kitchen or living room, the bedroom concentrations were somewhat lower than the rest of the house when the furnace fan was off, indicating only partial mixing on the first floor. Other experiments were conducted in this house with tracer gases to investigate mixing, and these are discussed in section 4.

In a recent study of 137 homes, one-week average NO_2 concentrations were measured in kitchens, bedrooms and outdoors (Spengler et al. 1993). While this study did not involve CO measurements, it provides some insight into intra-room concentration variations. In the 112 homes in the study with gas stoves, the concentrations in the kitchens were about 30 $\mu g/m^3$ (16 ppb) higher than the bedroom concentrations. Another study of residential NO_2 levels presents concentration measurements in kitchens and bedrooms of California homes (Wilson et al. 1986). In these tests of several hundred homes in various regions of the state, the weekly-average kitchen concentrations were generally higher than in the bedroom by as much as a factor of two, but generally less than that. This study also looked at the impacts of the presence of gas cooking and furnace type (forced-air, wall and floor) on NO_2 concentrations in kitchens and bedrooms.

2.4 Factors Affecting CO Levels in Residential Buildings

One of the most comprehensive reports on CO exposure is the EPA criteria document that presents the scientific basis for the National Ambient Air Quality Standard for CO (EPA 1991). This report notes the importance of indoor exposure and describes the factors affecting indoor CO levels: source and source-use characteristics, building features, ventilation rates, air mixing between and within building compartments, the existence and effectiveness of contaminant removal systems, and outdoor concentrations. Based on a number of exposure studies, the report identifies important residential sources including vented and unvented combustion appliances, attached garages and environmental tobacco smoke, and discusses the impacts of these sources on indoor concentrations. The report points out that the available data on spatial and temporal variability of indoor CO levels as a function of microenvironments and sources are not adequate to properly assess exposures.

A relatively recent study focused specifically on the factors that affect indoor CO levels in residential buildings (Colome et al. 1994; Wilson et al. 1993 and 1995). This study, described as a pilot effort, involved 300 homes in California in which 48-h and 8-h average CO concentrations were related to a number of variables including the concentrations of other pollutants, house characteristics, ventilation rates, appliance types, and occupant activities. Statistical analyses were performed to determine the relationship between indoor CO concentrations and the variables studied. The measured concentrations were generally low compared to ambient CO standards. Outdoor CO concentrations, pilot lights on cooking ranges, wall furnaces and cigarette smoking were all identified as influencing indoor concentration variations. Based on case studies of homes with higher indoor concentrations, the authors speculate that heating with gas ranges, malfunctioning gas appliances, improperly operated gas appliances, and automobile exhaust from attached garages were possible causes of higher indoor concentrations. While the outdoor concentration was the single most important factor in determining the indoor concentration, at higher indoor concentrations the observed concentration appears to be independent of outdoors. A mass balance model of the indoor CO concentrations revealed that the important variables in determining these concentrations were the outdoor level, the building ventilation rate, the source strength, and the house volume, which in turn were dependent on house characteristics and appliance type. For example, houses with gas-fired wall furnaces tended to be small, have gas ranges with standing pilots and be located in areas with elevated outdoor CO concentrations. In subsequent analysis of the results, a parameter related to the indoor source strength was calculated for each home. At the median level of this source-strength parameter, homes with gas cooking and heating had higher values of this source parameter than electric houses. Above the 90th percentile, the electric appliance homes had source parameters as high as in gas homes, suggesting that potential sources of higher emissions are not related to cooking or heating but may include automobile exhaust from attached garages, fireplaces and other combustion sources. CO concentrations in homes with smokers were about 0.6 mg/m^3 (0.5 ppm) higher than in homes without smokers.

As noted in the previous paragraph, consideration of a single-zone mass balance model, discussed in detail in section 7.2, reveals that the primary factors affecting CO levels are outdoor concentrations, ventilation rate, source strength, and house volume. A number of studies have focused on how some of these factors affect CO concentrations in buildings, in many cases focusing on combustion sources. Traynor (1987 and 1989) describes the parameters affecting combustion-related concentrations and exposures, and uses a single-zone mass balance model to quantify the influence of some of them. Various combustion sources are listed, along with the factors affecting emission rates of sources associated with space heating and non-space heating sources such as cigarettes and cooking stoves. A more detailed description of the single-zone modeling approach within the context of combustion sources is presented in Traynor et al. (1989).

Single-zone modeling has been used to examine the impacts on indoor CO levels of a number of parameters, in particular infiltration, whole house ventilation and local exhaust ventilation (Lambert and Colome 1984). Experimental work has also been used to examine the issue of ventilation as a means of controlling indoor CO levels (Goto and Tamura 1984; Koontz and Nagda 1984; Nagda et al. 1985a and 1985b, Traynor et al. 1982b and 1988). These studies tend to show that range hoods vented to the outdoors are an effective means of removing pollutants from gas-fired ranges, in some cases more effective than an open window or door (Nagda et al. 1985b).

3 Sources

This section discusses studies of the various non-fire sources of indoor CO, including the measurement of CO emission rates. The importance of some of these sources, in terms of acute health effects, has been studied nationally by Cobb and Etzel (1991) and by Girman et al. The sources that have been identified in this literature review are as follows:

- Unvented combustion appliances
  - Gas-fired ranges and ovens
  - Gas, propane and kerosene-fired unvented space heaters
  - Gas-powered refrigerators
  - Portable generators
  - Charcoal grills
- Vented combustion appliances
  - Wood-burning stoves
  - Gas dryers
  - Fireplaces, wood and gas-fired
  - Gas and oil furnaces
  - Gas water heaters
  - Gas wall heaters
- Tobacco smoke
- Attached garages
- Outdoor air

This section is organized by these source categories. One unusual source which does not fit into these categories was CO emitted by an explosive used in a sewer construction project (Dougherty et al. 1990). In this incident, high gas pressures within the bedrock led to the migration of large quantities of explosion gases into nearby residences and indoor CO levels as high as 3600 $\mu g/m^3$ (2000 ppm).

CO sources associated with vented and unvented combustion appliances have received the most attention in the literature. A comprehensive overview of combustion sources is available in Mueller (1989). This report discusses the various combustion-based sources of CO and the factors that affect these emissions, and summarizes the available emission rate data, some of which is discussed in more detail below. Traynor (1987 and 1989) discusses the factors affecting the emissions from combustion sources, as well as the factors that determine the subsequent indoor pollutant levels. The factors that affect emissions include appliance type, fuel consumption rate, use pattern, and condition of the appliance. The latter category includes cleanliness, tuning of burners and other internal adjustments. The impact of some of these operational factors on emission rate measurements in chambers has been examined by Billick et al. (1984). Traynor (1987 and 1989) also discusses other factors that affect the emission rates from sources associated with space heating. These factors include the indoor-outdoor temperature difference, insulation level and air change rate (all of which affect the space-heating demand), the availability of other sources of heat, and occupant activities.

A study of several hundred homes in California was conducted to investigate the relationship between the indoor levels of CO, and PAH (polycyclic aromatic hydrocarbons), and different types of combustion sources (Sheldon et al. 1993). Twenty-four hour average air samples were collected in homes selected to represent specific source categories, including tobacco smoking, fireplaces, wood-burning stoves and gas heat. Most of the analysis concentrated on the PAH levels and their relationship to the sources and various house characteristics. Only a few homes showed elevated CO levels, and most of these were associated with the existence of gas heating or fireplaces.

3.1 Unvented Combustion Appliances

The unvented combustion appliances relevant to indoor CO levels include gas-fired ovens and ranges, as well as gas, propane and kerosene-fired space heaters. A number of field and laboratory studies have been conducted to determine the emission rates of these appliances and to assess the impacts of these appliances on CO levels in residential buildings.

The CO emissions from gas-fired ovens and ranges have been measured in laboratory chambers, in which pollutant concentrations are monitored during appliance operation and a single-zone mass balance model is used to estimate the emission rate per unit of fuel consumed (Girman et al. 1982; Traynor et al. 1982a). Measurements have also been made in houses in a similar manner, though obviously with less control of ventilation rates (Goto and Tamura 1984). This study also examined the impact of infiltration and kitchen hood exhaust operation on indoor contaminant levels, including CO. A study of 157 residences in Texas examined the impacts of gas range operation (as well as the operation of unvented gas space heaters as discussed later) on indoor CO levels (Koontz and Nagda 1988). This study provides a great deal of information on the distribution and use patterns of gas ranges, as well as house characteristics, in this region of the country. Integrated CO samples were collected over 15 h, and a stepwise regression analysis was performed to determine the influence of variables related to the house, occupants and appliances. While no single variable was found to be a significant predictor of the indoor CO levels, poor appliance tuning or the use of multiple appliances appeared to be related to elevated CO levels.

The emissions of CO and other pollutants from kerosene and gas-fired unvented space heaters has been studied for many years using a variety of test methods (Billick 1985). There are reports of emission rate measurements in laboratory chambers (Girman et al. 1982; Leaderer 1982; Porter 1984; Traynor et al. 1983b and 1985) and in houses (Hedrick and Krug 1995; Ritchie and Arnold 1984; Tamura 1987; Traynor et al. 1983a). These tests have yielded CO emission rates for a variety of heater types and settings.

A study of 157 residences in Texas, referred to previously with respect to gas ranges, examined the impact of unvented gas space heaters on indoor CO and NO_2 levels (Koontz and Nagda 1988). This study provides a great deal of information on the distribution and use patterns of these heaters. As discussed previously, poor appliance tuning or the use of multiple appliances appeared to be related to elevated CO. In 12% of the homes where space heaters were the primary source of heat, the average CO concentration based on a 15-h average exceeded 10 mg/m^3 (9 ppm). In a more detailed study of the impact of gas-fired space heaters, a single unvented appliance was operated in a test house under various conditions of window and door position and heater location (Koontz et al. 1988).

Other unvented combustion appliances include gas-powered refrigerators, portable generators and charcoal grills, but no emission rate measurements were found for these appliances. When operating properly, gas-powered refrigerators are not expected to produce significant amounts of CO, but the latter two sources will produce significant quantities of CO and strong recommendations against using them indoors exist (CPSC, Liu et al. 1993).

3.2 Vented Combustion Appliances

Vented combustion appliances that can be sources of indoor CO include furnaces, water heaters, fireplaces, wood-burning stoves, gas dryers and gas well heaters. Discussions of the emission of CO from furnaces, water heaters and fireplaces have tended to focus on cracks and openings in venting systems, cracks in furnace heat exchangers, and spillage of combustion products into the building interior (Moffat 1985). While a properly operating furnace or water heater should not produce much CO, the combination of high CO production with any of these defects could result in the introduction of significant amounts of CO into the occupied space. While these issues have been discussed in the literature, there have been no measurements of CO emission rates by these various mechanisms. It is expected that these emission rates would be a function of the amount of CO produced by the combustion process, the nature of the defect, and the pressure and airflow patterns in the building.

A great deal of attention has been focused recently on the issue of flue gas spillage (Greiner and Wiggers 1995; Nagda 1995; Nagda et al. 1995). It is important to note that spillage will not be a significant source of indoor CO unless the combustion process is also producing atypical levels of CO. Significant CO production does not normally occur in properly-operating furnaces and water heaters, but can occur in wood-burning stoves and fireplaces. Research conducted in Canada in the 1980s investigated the existence of house depressurization that could lead to flue gas spillage and the existence of such spillage itself (Fugler 1989; Scanada Sheltair Consortium 1987; Wilson et al. 1986). A number of factors were identified that could increase the extent of depressurization in the area of the house containing the vented appliance based on field surveys (Scanada Sheltair Consortium 1987) and theoretical considerations (Dumont and Snodgrass 1990). These studies focused on the interaction of house tightness, weather conditions and the operation of exhaust systems (exhaust fans, clothes dryers and fireplaces) in causing depressurization. The likelihood that any given level of depressurization would lead to spillage was seen to increase when there was deterioration of the flue, exterior chimneys, improperly-sized chimney liners and a lack of appliance servicing (Scanada Sheltair Consortium 1987). These research projects included the development of test protocols to determine the extent of depressurization possible in spaces containing a combustion appliance and the determination of the magnitude of depressurization that leads to spillage conditions. This work led to the development of a spillage test standard that includes a procedure for assessing house depressurization potential and depressurization limits for various combustion appliances (CGSB 1995). The Canadian research included measurements of indoor CO levels in a small number of the over 1000 houses tested, and these levels were never more than 6 mg/m^3 (5 ppm) under spillage conditions (Nagda et al. 1995). Higher concentrations were measured under conditions of spillage induced by artificially high levels of house depressurization or chimney blockage (Fugler 1989). Even under induced spillage, none of this research has included measurements of CO emission rates.

There have been measurements of the indoor emissions of CO from wood-burning stoves (Traynor et al. 1987a; Nabinger et al. 1995). The former study was conducted in a single-family house, while the latter was conducted in a small, single-room test house. The emission rates from the two studies were similar in magnitude. In both studies, the wood-burning stoves were operated normally, without any attempt to induce spillage by house depressurization or any reason to suspect that depressurization was a strong driving force for combustion products entering the living space. A study of depressurization-induced spillage from wood-burning stoves was conducted in a 12 m^3 (420 ft^3) laboratory chamber and in two houses (Tiegs et al. 1993). In this study, the stoves were operated under various conditions of depressurization and indoor CO levels were monitored. The CO levels were dependent on the magnitude of the induced pressure and the integrity of the stove-flue system. While some of the measured CO concentrations were quite high, on the order of 115 mg/m^3 (100 ppm) in the houses, the study did not measure CO emission rates from the stoves into the interior volume.

3.3 Other Indoor Sources

Two other indoor sources of CO in residential buildings are tobacco smoke and attached or underground parking garages. Carbon monoxide emissions from sidestream tobacco have been measured in a laboratory chamber in units of mass of CO per cigarette (Girman et al. 1982). These results, and those obtained by others, are on the order of 50 mg to 100 mg of CO per cigarette (Mueller 1989). The net emission rate into a building will therefore depend on the number of cigarettes smoked per hour, but will generally be well below the levels emitted by other indoor sources. Previously-cited studies have shown that the presence of cigarette smoking increased residential CO levels by about 1 mg/m^3 (0.9 ppm).

The migration of motor vehicle exhaust from garages into residential living spaces has been identified as an issue in both single-family and high-rise residential buildings (Limb 1994). However, there have been no measurements of the rate of CO transport from garages to living spaces in either type of building. The transport mechanisms, and the factors affecting this transport, are very different in single-family and high-rise residential buildings. Garages in single-family buildings generally have only one or two cars, and there is only a single door connecting the garage and the living space. However, in some homes, the heating and air-conditioning equipment is located in the garage, and this location of the forced-air fan and ductwork can lead to significant contaminant transport into the living space (Hawthorne et al. 1986). Nazaroff et al. (1996) examined data on CO emission rates from motor vehicles in an analysis of accidental deaths due to these emissions in single-family residential buildings.

High-rise buildings with underground or otherwise enclosed garages can be significant sources of CO, with transport to the living space occurring via stack-driven airflow through elevators, stairways and other vertical shafts (Boelter and Monaco 1987). The ASHRAE HVAC Applications Handbook (1995) provides guidance on garage ventilation and suggests that CO levels in parking garages be maintained at 29 mg/m^3 (25 ppm), with peak levels not exceeding 137 mg/m^3 (120 ppm). Such garages constitute a potential CO source, particularly when garage CO levels are elevated and significant levels of airflow exist from the garage to the living space. In a study of air movement and indoor air quality in several buildings in Canada, cited earlier in this report, CO levels were measured in several multifamily buildings, ranging from four to twenty-one stories (Gulay et al. 1993). The higher CO levels in this study, between 5 mg/m^3 and 13 mg/m^3 (4 ppm and 11 ppm), appeared to be associated with underground parking garages.

3.4 Ambient Air

Carbon monoxide in the outdoor air is another source of indoor CO, though not at levels that would typically cause a CO detector to alarm. The CO detector standards contain performance tests to prevent so-called "false alarms" that might be induced by hours or days of elevated ambient CO levels, as well as by indoor levels not expected to cause acuate health effects (BSI 1996; UL 1992 and 1995). In fact, the UL standard was revised in 1995 to increase the requirements of the false alarm performance test (UL 1995).

While ambient CO is not a major source of indoor CO, a comprehensive database exists for ambient CO levels. Ambient CO levels are regularly monitored at a number of sites in the U.S. (EPA 1991) in order to assess compliance with NAAQS, and reports are issued annually on national trends in ambient CO concentrations and emissions (EPA 1995). These reports, however, do not include detailed information on temporal patterns over hours or days. The EPA criteria document for CO shows examples of seasonal and daily patterns of ambient CO levels for a number of cities (EPA 1991). These examples show that the time of year and the time of day at which elevated CO occurs is site specific based on the combined effects of meteorology, topography, wind-induced transport, atmospheric stability and mixing depth. Therefore, generalizations can not be made regarding the magnitude or variation in peak ambient CO levels, but data is available for a number of cities across the U.S. from EPA's Aerometric Information Retrieval System (AIRS) (EPA 1991).

4 Mixing

There have been a number of studies of air and contaminant mixing within and between rooms, conducted both in real buildings and in laboratory test facilities. These studies have examined the impact on mixing of the operation of forced-air fans, the position of interior doors, source location and source heating, temperature differences between zones, heat sources in the space, and ventilation rate. This section includes a subsection that covers studies of mixing within rooms (intra-room) and a subsection that covers between-room mixing (inter-room). A number of studies have examined both aspects of mixing, and these are discussed first.

In a study designed to provide a detailed characterization of contaminant migration patterns in an unoccupied research house, CO was used as surrogate contaminant (Koontz et al. 1988). In this study, CO was released from a point source in the master bedroom at a constant, known rate over 1.25 h. The source was thermally neutral and was released with no significant discharge velocity. A network of nine continous CO detectors was deployed to measure horizontal and vertical concentration gradients in the release area, in a connecting hallway and at entrances to nearby bedrooms. During the release period, CO concentrations were about 3 to 4 times higher in the release area than in the other upstairs areas. Within about 45 min to 60 min after the release ended, the concentrations upstairs approached spatial uniformity even with the forced-air fan off. Some evidence of CO migration downstairs was observed, but the downstairs concentrations were substantially lower than upstairs. Variable vertical gradients in CO concentrations were observed in the release area and along the migration pathways, suggesting a fairly complex system of forces involved in mixing and transport. The vertical gradients seen in the release area largely dissipated once the CO reached other rooms, and the peak concentrations were lower and delayed in these other rooms compared with the release room.

A follow-up study in the same house included a three-dimensional array in the breathing zone, but less detailed monitoring of within-room and building-wide exposure (GEOMET 1989). This study included CO releases of 30 min, under a wider range of conditions, in the master bedroom, kitchen, garage and outdoors. When CO was released in the master bedroom with the air-conditioning system off and the windows closed, the breathing-zone concentrations were about twice those in the rest of the room, and the concentrations elsewhere in the room were five to ten times higher than in the rest of the house. Concentrations throughout the master bedroom were quite uniform after the CO release, and the concentrations elsewhere upstairs approached those in the master bedroom within 90 min. When CO was released in the master bedroom with the air conditioning system on, the concentrations were relatively uniform throughout the room during the release, and the average concentration in the room of release was about five times higher than the rest of the house. The CO levels were nearly uniform across the entire house within one hour after the release. When CO was released in the master bedroom with the windows open, the concentrations were somewhat lower in all areas of the house compared to the windows being closed, but the relative concentration differences among different areas of the house were similar to those with the windows closed. When CO was released in the kitchen, the concentrations in the breathing zone during release were similar to those for releases in the master bedroom except the concentrations elsewhere in the zone of release were about ten times lower due to the larger volume available for dilution. Concentrations in the release zone were still about two times those in other upstairs areas. After the CO release, uniform concentrations throughout the upstairs were achieved in 15 min to 30 min with the air conditioner on and 40 min to 45 min with the air conditioner off. When CO was released in the garage with the garage doors closed, the breathing zone concentrations were similar to releases in the master bedroom and kitchen, but the concentrations in the living space were largely unaffected. The study results suggest that when releases occur in the living space, the average concentrations in the breathing zone are not greatly affected by surrounding conditions, that is, air conditioner operation or window opening. However, concentrations in the release zone after release and concentrations beyond the release zone during and after release are more substantially affected by these parameters.

Another study of mixing in a research house involved releases of CO, CO_2 and NO_2 from gas cylinders at rates similar to those emitted by unvented gas space heaters (Hedrick et al. 1993). The tests were conducted under three sets of experimental conditions: fans mixing the entire first floor; no mixing fans; and, first floor divided with a physical partition to create two zones (bedrooms and kitchen/living room) with mixing fans in each zone. In these tests, the gases were injected into the living room. Under the first set of conditions (single zone with mixing), the concentrations in the living room and kitchen were indistinguishable, with the bedroom concentrations somewhat lower. Under the second set of conditions (single zone, no mixing), there were more short term fluctuations in concentration, on the order of 10%. The concentration in the bedroom was substantially lower than under the first set of conditions. The third set of conditions (two zones with mixing) was similar to the second set, but there were less concentration fluctuations. These tests showed that the house acts as multiple chambers, with poor mixing in the individual rooms with no forced mixing.

Another study of tracer gas mixing in a four-room test house involved the release of CO_2 in one room at a time from 100-W heat sources intended to simulate human bodies (Stymne et al. 1990). With interior doors closed, there was relatively good mixing within the source room, with only a slight tendency for higher concentrations at the ceiling. A maximum difference of 10% from the room-average concentration was observed. With the interior doors open, differences in concentration at different heights were more pronounced in both the source room and the unoccupied rooms. There was no general rule on which height had the highest concentration, and no difference was observed in concentration gradients between CO_2 released from the heated body and a passive tracer. The reasons given for the uneven concentration distribution were the large airflow through open doorways and its interaction with other air movements set up by convection around heated bodies, radiators, cold walls, and inlet jets.

4.1 Intra-room

Studies of air and contaminant mixing within rooms have generally involved the release of a tracer gas and the subsequent analysis of the tracer gas concentration at various points in the room. Some of the studies have presented plots of tracer gas concentrations versus time and made qualitative statements about mixing. Others have employed quantitative measures of within-room mixing.

In a study using predominantly qualitative analysis of the results, West (1977) performed experiments in a test room using an unheated tracer source. The test room had no significant heat sources, and the source location and ventilation rate were varied between the different test cases. The results are presented in the form of plots of tracer gas concentrations over time at different points in the room. The results showed no significant effect of source location and ventilation rate on the variation in average tracer gas concentrations, though short-term concentration variations were affected by source location. Mixing was observed to improve at low ventilation rates. A more recent study investigated the impact of the characteristics of a ventilation air jet and of source location on the variations in tracer gas concentration in a room (Heiselberg 1992). Few experimental details were provided, but the experiments showed that the tracer distribution depended on the location of the source and on the ventilation rate.

Other studies of mixing in rooms have employed more quantitative measures. A number of parameters that quantify air and contaminant mixing have been developed by Sandberg (1981). These parameters are defined in terms of the ratio of the concentration at a point in the space and the concentration in the exhaust under transient conditions of concentration decay or at steady-state for a constant contaminant source. A number of other useful parameters for quantifying mixing are also presented including the age of air at a point in a space and the local residence time of a contaminant. Experimental procedures for determining these parameters are described.

In a study of mixing in a kitchen, a tracer gas was injected over a stove, and a three-zone model of the kitchen was employed to analyze the tracer mixing (Ozkaynak et al. 1982). The results revealed relatively uniform tracer gas concentrations within about 10 minutes of injection, both with the stove on and off.

A relatively recent study employed a computational fluid dynamics model to examine the mixing of tracer gas in a single zone (Shao et al. 1993). The simulations began with a uniform tracer concentration throughout the zone and predicted the concentration decay at multiple points. A number of cases were analyzed in which the inlet air velocity, air change rate and zone volume were varied. While lower air change rates were generally beneficial to mixing, no critical value of air change rate was seen below which satisfactory mixing is guaranteed. In addition, smaller building zones and higher inlet airflow velocities had positive effects on mixing. Two parameters were introduced to describe the uniformity of concentration. One was based on the difference between the volume integral of tracer concentration at a point and the mean concentration, divided by the mean concentration. Another parameter, referred to as the spread in tracer gas concentration, was defined as the difference between the maximum and minimum concentration divided by the average of the two values.

A detailed study of tracer gas mixing was conducted in a test room in which a neutrally-buoyant tracer gas source was released near a 15 W heat source to simulate sidestream smoke from a cigarette (Baughman et al. 1994). Tracer gas concentrations were measured at 41 locations in the room under three test conditions: nearly isothermal conditions in the room; a 500-W heater in the room; and incoming solar radiation through a window. The room ventilation rates were very low to avoid mixing due to the ventilation flows. A characteristic mixing time was defined as the time required for the relative standard deviation of the tracer gas concentrations at the 41 measurement points to become less than 10% of the mean. The results indicated characteristic mixing times of 80 min to 100 min for the isothermal case, 13 min to 15 min with the 500-W heater, and 7 min to 10 min for the solar case. Another study in the same one-room chamber examined the impact of mixing fans on tracer gas concentration uniformity (Drescher et al. 1995). Multiple cases were run with different numbers of mixing fans and different fan airflow rates. In these tests, there were no heat sources in the room other than the fans. The mixing time was seen to correlate with the inverse of the cube root of the mechanical power of the mixing fans, but the tests involved only one configuration of the fans relative to the tracer source and a limited range of a dimensionless fan parameter.

Another study of tracer mixing in a chamber examined the difference in the measured concentration from a well-mixed model (Furtaw et al. 1995). Multiple cases were examined with the tracer gas concentrations measured at various distances from the emission source under a variety of ventilation conditions. Concentrations near the source deviated significantly from the predictions of a well-mixed model, with the deviations a function of distance and ventilation rate. A two-zone model was developed in which one zone was a small compartment containing the source and the other zone was the rest of the room. A stochastic airflow rate between the two zones was used to provide a more realistic simulation of exposure than a well-mixed model.

A previously-cited study of NO_2 in California homes included an examination of the vertical distribution of NO_2 within rooms (Wilson et al. 1986). In this effort, weekly-average NO_2 concentrations were determined at 6 heights in a bedroom and near the kitchen. A significant increase in concentration with height was seen with the concentration 15 cm (6 in) from the ceiling about 40% above the concentration near the floor, through the vertical gradients varied among the homes.

4.2 Inter-room

A number of studies have examined air and contaminant mixing within buildings, with some of the studies focusing on mixing between floors and others looking at room-to-room mixing. In most cases a tracer gas was used to simulate a contaminant source, but in others an actual contaminant source was studied. An early study of a two-story house employed a tracer gas to examine mixing between the building floors (Freeman et al. 1982). Tests were conducted with the kitchen exhaust and the non-forced air heating system on and off. The heating system was designed to provide different temperatures in the sleeping and living rooms, and this temperature difference helped to mix the air in the building. The test results without heating showed greater differences in tracer gas concentration between floors than those with heating and showed that mixing within a floor was more efficient than between floors with the heating off. The results with heating had almost equal integrated tracer exposures outside the source room. A more recent tracer gas study in a two-story research house showed that airflow rates from the basement level to the upstairs were almost always greater than the airflows in the opposite direction when interior temperatures were above outdoors (GEOMET 1988). Other measurements in the same house involved the operation of unvented space heaters on the different floors of the house (Nagda et al. 1985a). When a heater was operating upstairs, there was rapid horizontal mixing of pollutants on that floor but little penetration to the downstairs area. When a heater was operating downstairs, there was rapid mixing throughout the entire indoor space. Therefore, the measurements with the heaters confirmed the tracer gas test results that showed a dominance of upward airflow in the building under heating conditions.

Another tracer gas study of airflow between floors involved a single-story test house with a basement (Sieber et al. 1993). In these tests, a different tracer gas was injected on each level, and a differential mass balance analysis was employed to analyze the tracer gas decay. Three test cases were examined: furnace fan off and no mixing fans; furnace fan off and two mixing fans on each floor; and, furnace and mixing fans on. In addition to calculating the airflow rates between the two levels, the tracer gas concentrations were examined qualitatively in terms of the mixing between the two floors. The operation of the furnace fan was seen to mix the two levels in about 45 min. With the furnace fan off, it took about 3.5 h to achieve the same concentrations on the two levels.

A number of other studies of inter-room mixing focused on mixing between rooms rather than between floors. In a qualitative study of mixing, CO was used as a tracer gas in a one-story test house (Chang and Guo 1991). The study examined the effects of forced-air fan operation, positions of the bathroom door and bedroom window, and bathroom exhaust fan operation for isothermal CO releases in the bathroom and the master bedroom. The paper presents plots of CO concentration versus time in the source room, hall, corner bedroom and den, and these concentration profiles are discussed qualitatively. Operation of the heating and air-conditioning system fan enhanced indoor air movement and transported the tracer gas from its source to the rest of the house. The interior doors functioned as either a barrier or channel for air movement, depending on the operating status of the bathroom exhaust fan. Another tracer gas study examined the mixing of methane released in a kitchen to simulate the operation of a gas stove (Haghighat et al. 1990). Test variables included mixing fans, range hood and forced-air fan operation, and interior door position. Plots of tracer concentration versus time are presented for multiple locations. Open-door conditions resulted in fairly uniform concentrations (except right at the source), even with the furnace fan and range hood off. The closed-door tests exhibited nonuniformities in concentration, even with the forced-air fan on. Another series of qualitative tracer gas decay measurements were carried out in a test house in which a uniform tracer gas concentration was established and the subsequent tracer gas concentration decay was monitored in each zone (Maldonado and Woods 1983a and 1983b). The different decay rates in each zone and the integrals of the tracer gas concentration decays in each zone were compared. However, there was little discussion of the results, as these papers were focused on presenting the procedure as a means of evaluating ventilation air distribution in a multizone building.

A significant amount of work has been done studying airflow rates through large openings connecting two rooms, some of which was done to support the design of passive solar buildings (Barakat 1987; Brown and Solvason 1962; Mahajan and Hill 1987). This research examined airflow through doorways connecting two rooms at different air temperatures and determined the relationship between these airflow rates and the dimensions of the doorway and the temperature difference between the two rooms. Riffat (1989a) measured airflow rates through a doorway connecting the upper and lower floors of a house using a tracer gas and compared the results to existing models of buoyancy-driven airflow through doorways. The measured dependence of the airflow on temperature difference and doorway dimensions was in agreement with previous work. Cheong et al. (1995) also studied buoyancy-driven air and particle flow in a two-zone chamber.

Research has also been performed in multifamily buildings to investigate the transport of air and contaminants. This transport is generally more complex in multifamily buildings, as compared to single-family residences, due to the larger number of zones, the existence of vertical shafts connecting floors, and the generally greater vertical height of these buildings. In part because of this greater complexity, there has been less study of airflow and contaminant movement in multifamily buildings than in single-family buildings. Some of the earliest measurements in multifamily buildings employed a passive, constant-injection tracer method commonly referred to as the PFT technique. This technique is described in more detail in section 6 on tracer gas techniques. A study of ventilation and indoor air quality in three apartments in a two-story, four-unit building included ventilation rate measurements in the individual units (Parker 1986). Ventilation rates were determined over 6-h to 8-h periods over three days of monitoring, and the mean air change rates in each unit were all less than 1 h^{-1}. However, the measured air change rates did not distinguish between airflow from outdoors and airflow from other apartment units. Higher ventilation rates were seen in the second floor units, and these were attributed to greater wind exposure. Another study of a six-unit, three-story building employed a multiple-tracer technique to measure interzone airflow rates (Palmiter et al. 1995). Eight days of monitoring were conducted to examine the impacts of temperature, wind and mechanical ventilation system operation. Significant airflow between apartments was seen, with temperature-driven airflows from lower to upper apartments dominating.

Other studies have examined contaminant distribution in buildings with actual contaminant sources in operation, rather than simulating sources using a tracer gas. One such study involved a number of different combustion appliances in a single-story research house with a basement (Leslie et al. 1989). The results showed that mixing of pollutants throughout the house (including the basement) occurred when the furnace operated continuously. During periods of furnace cycling, basement concentrations were between the outdoor and first-floor concentrations indicating incomplete mixing of sources on the first floor. When the furnace was off for extended periods, the basement concentrations tracked the outdoors indicating little airflow from the first floor to the basement. Concentrations in the bedroom, with the furnace fan off and a source in the kitchen, were somewhat lower than the living-room concentrations, indicating partial mixing on the first floor. Unvented heater operation on the first floor affected the first-floor levels but not those in the basement. Additional experiments were conducted in which a tracer gas was injected into one zone at a time under various conditions of furnace operation and door position. With the furnace off and doors closed, no detectable airflow was seen from the first floor to the basement. Almost no airflow existed from the bedroom to the living room area when the doors were closed, but some airflow was seen from the living room to the bedroom.

Another study involving real contaminant sources investigated inter-room transport of pollutants from unvented kerosene heaters (Traynor et al. 1987b). In this study kerosene space heaters were operated in the master bedroom and in the living room of an unoccupied house under several simulated use conditions. Tests were conducted in the master bedroom with the bedroom door and the bedroom window open and closed. In addition to indoor concentrations, inter-room pollutant transport rates are reported based on the use of carbon dioxide as a tracer and a two-zone mass balance between the bedroom and the rest of the house. Inter-room airflow rates were less than 10 m^3/h (6 cfm) with the bedroom door closed, but they ranged from 16 m^3/h to 53 m^3/h (9 cfm to 31 cfm) with the bedroom door open 2.5 cm (1 in) and from 190 m^3/h to 3400 m^3/h (110 cfm to 2000 cfm) with the door fully open.

5 Surveys of Residential Ventilation Rates and House Sizes

In addition to CO emission rates, two other parameters that are key in determining indoor CO levels are building ventilation rates and the volumes of buildings and rooms. Based on the expectation that these parameters may be considered in future phases of this effort, this literature review examined studies in which ventilation rates and building tightness values were measured in large numbers of residential buildings. These residential ventilation surveys have considered predominantly single-family residential buildings; ventilation and airtightness measurements have been made in only small numbers of multifamily buildings as discussed previously. In addition, the data available on the interior volumes of residential buildings are also discussed.

Building ventilation rates are determined by the interaction of outdoor weather conditions (temperature, wind speed and wind direction), the interior air temperature distribution, the extent and distribution of leaks in the building envelope, the configuration of the building and its various rooms, the airtightness of interior partitions, and the operation of equipment in the building such as exhaust fans and forced-air heating and cooling systems. The interaction of these factors in determining outdoor air ventilation rates in residential buildings is discussed in ASHRAE (1993).

Residential ventilation surveys have focused on two quantities, ventilation rates and building airtightness. Ventilation rates are the actual rates at which outdoor air enters a building under normal conditions of weather and building equipment operation. These rates are a strong function of both factors, and therefore measured ventilation rates reflect only the conditions that exist at the time of the measurement. Most of the surveys discussed in this section used the constant-injection tracer gas technique, which provides estimated ventilation rates over a long period of time, several months for example (Dietz et al. 1986). This technique is sometimes referred to as the PFT technique, where PFT is shorthand for the perfluorocarbon tracer gas used in the procedure. However, the results obtained with this technique tend to have a negative measurement bias that can be as large as 20% to 30% for a seasonal average measurement (Sherman 1989). Other surveys have involved measurements of building envelope airtightness using pressurization testing (ASTM 1987). In these tests, a fan is temporarily mounted in the door or window of a house and is used to impose a series of indoor-outdoor pressure differentials across the building envelope. The airflow rate required to maintain a specific reference pressure, or an effective leakage area based on the airflow rate at a reference pressure, serves as a measure of the building airtightness. These airflow rates and leakage areas are generally normalized by the building volume, floor area or envelope surface area, and can be used to predict ventilation rates at various weather conditions using single-zone or multi-zone models. These models are discussed in section 7 of this report.

While there has not been a comprehensive survey of ventilation rates in U.S. houses based on random sampling, there are three important datasets based on measurements using the PFT technique. The first dataset consists of the results of five studies in the Pacific Northwest (Palmiter et al. 1991), the first three being conducted in site-built homes and the other two in manufactured housing. The first study, referred to as NORIS I (Palmiter and Brown 1989), was a randomly-selected group of 134 homes built to current practice between 1980 and 1987. The second and third groups of homes, the NORIS II group of 49 homes and the RDCP group of 182 homes, were built under energy-efficiency programs and are representative of tighter homes in that region constructed in the late 1980s. Of the two groups of manufactured homes, one was built to energy efficiency standards and the other was a control group built using current practice. In addition to the PFT measurements of building ventilation rates, with an average duration of 17 days, pressurization measurements of building airtightness were also conducted in these surveys.

Another dataset of ventilation rates is based on two studies conducted in single-family homes in California (Wilson et al. 1996). The first study included PFT measurements over three one-week periods in more than 500 homes in Southern California. The homes were randomly selected from six climate regions within the Los Angeles Basin. The three measurement periods occurred during March, July and January. The second study involved a probability sample of 300 homes in northern California, the Los Angeles area and San Diego county, and the measurements were made over a two-day period during the winter. The measured ventilation rates are analyzed by region and by cooking and heating appliance type.

PFT measurements of ventilation rates were conducted in the U.S. starting in 1982 in more than 4000 residences based on the protocol developed at Brookhaven National Laboratory (BNL) (Dietz et al. 1986). While the homes in which these measurements were made do not constitute a random sample, there have been several attempts to perform statistical analyses of these data. All of these analyses have eliminated some of the measurements due to data quality problems. Pandian et al. (1993) performed an analysis of 1839 ventilation rates, examining these rates by three regions of the country, number of floors and season. Another analysis of the BNL dataset examined data from 2844 residences based on a four-region breakdown by heating degree days (Murray and Burmaster 1995). Koontz and Rector (1995) performed another analysis of these ventilation rates, in this case from 2972 houses. Summary statistics are presented for four regions of the country and for some of the states within each region. The data is also analyzed by season. The analysis involved some compensation for geographic imbalance by seeking additional measurements and using weighting factors.

In addition to the surveys of building ventilation rates, there have also been surveys of building envelope airtightness based on pressurization testing. For example, the surveys in the Pacific Northwest discussed previously also involved pressurization testing (Palmiter et al. 1991). There have also been analyses of larger databases, including one of airtightness measurements in 515 houses in the U.S. and Canada (Sherman et al. 1986) based on data from a number of studies reported on in the literature. While this dataset is not a random sample, the data is disaggregated by age and envelope construction features related to airtightness. A much larger dataset of U.S. homes was analyzed by region, age, and construction type and quality (Sherman and Dickeroff 1994). This dataset consists of over 12 000 measurements. The measurement values of airtightness were found to be related to construction quality, local practices and age, but not to climate. Hamlin (1991) reports on the results of two surveys of Canadian homes conducted in 1989 involving 200 houses each and one from the early 1980s. The results of these surveys provides data on tighter homes.

There is also some information available on house and room volumes in residential buildings. Some of these data has been collected as part of the ventilation measurements described previously in the Pacific Northwest (Palmiter et al. 1991) and in California (Wilson et al. 1996). The volumes for the California dataset are analyzed by location in the state and by the type of cooking and heating appliance. Another source of data on house size and other characteristics is the survey of residential buildings conducted by the U.S. Department of Energy (DOE 1992). The results of this survey include data on floor area, building age, heating and cooling climate, region of the country, heating fuel and equipment, water heating and cooking fuel, and building type, that is, single-family detached and attached and various sizes of multifamily.

6 Tracer Gas Techniques for Measuring Airflow Rates in Buildings

A variety of tracer gas techniques exist that can be used to measure airflow rates in buildings under natural conditions of weather and building system operation (Lagus and Persily 1985; Roulet and Vandaele 1991). In these techniques, one or more tracer gases are released into a building in a controlled manner, and the tracer gas concentration response within the building is analyzed to determine the airflow rates of interest. Tracer gas techniques are included in this literature review for two reasons. First, tracer gas techniques require a uniform tracer gas concentration within a building or a portion of a building, and the experience in assessing the uniformity of tracer gas concentrations in buildings may provide some insight into the distribution of CO in buildings. Also, tracer gas techniques can be used to measure airflow rates between the zones of a building, and therefore can be useful in understanding the transport of airborne contaminants in buildings.

Tracer gas techniques can be divided into those that measure the air change rate of a whole building and those that measure interzone airflow rates in buildings that act as multizone systems. Single-zone tracer gas techniques have been used for decades (Carne 1946; Dick 1949; Marley 1935; Warner 1940) and are the subject of a standardized test method (ASTM 1995). In fact, CO has been used as a tracer gas in some of these studies (Goldschmidt et al. 1980; Goldschmidt and Wilhelm 1979; Oppl and Vasak 1960; Prado et al. 1976), although it was released intentionally and mixed during the test and therefore these results are not particularly relevant to CO distribution under normal circumstances. There are three single-zone tracer gas techniques that can be used to determine the rate at which outdoor air enters a building: decay, constant concentration and constant injection (Sherman 1990). These techniques differ in how the tracer gas is injected into the test space and how the tracer gas concentrations are analyzed to determine the air change rate. For a single-zone technique to be applicable to a given building or space, the tracer gas concentration in the building must be uniform throughout the measurement period. This uniformity can be achieved in buildings that may not appear to act as single zones through the use of appropriate tracer gas injection and mixing procedures. In some buildings, a uniform tracer gas concentration can not be maintained, in which case a multizone tracer gas technique must be used to determine the airflow rates in the building.

Single-zone tracer gas techniques are based on the critical assumption that the tracer gas concentration is uniform within the space being studied (Hunt 1980; Sherman 1990). The ASTM single-zone tracer gas test method requires that the tracer gas concentration throughout the space differ by less than 10% from the average concentration of the space. If a uniform concentration is not achieved, then there can be significant errors in the test results. When using single-zone techniques, one must verify the uniformity of the tracer gas concentration by sampling the concentration at multiple points in the building. Mixing can be enhanced by operating the air distribution fan in buildings with forced-air heating and cooling, or by operating supplemental mixing fans. Both approaches have been successfully used in the field (Bassett 1981), and the operation of forced-air fans have been shown to create a uniform tracer gas concentration in as little as 5 min in a single-family residential building (Grimsrud et al. 1980). However, operating the forced-air fan can change the air change rate of a building due to duct leakage and the creation of pressure differences across the building envelope. Also, as noted earlier in the section on intra-room mixing, nonuniformities in tracer gas concentration have been seen even during forced-air fan operation (Haghighat et al. 1990). In some buildings, convective mixing due to inter-room temperature differences may be adequate to achieve a uniform tracer gas concentration without the use of fans.

6.1 Tracer Gas Techniques for Measuring Interzone Airflow Rates

A number of tracer gas techniques exist that can be used to measure airflow rates between the zones of a building and between these zones and the outdoors. These techniques differ primarily in the formulation of the multizone tracer gas mass balance equations that are employed, as well as in the injection strategy used to distribute the tracer gas within the building (Heidt et al. 1991; Persily and Axley 1990). The most commonly-used techniques are as follows: multizone decay, integral pulse, constant concentration, semi-continuous constant injection, and long-term average constant injection.

The multizone decay method is based on a differential formulation of the tracer gas mass balance equation (Enai et al. 1990a; Enai et al. 1990b; I'Anson et al. 1982; O'Neill and Crawford 1991; Prior et al. 1985; Sieber et al. 1993; Sinden 1978; Waters and Simons 1987). Multizone decay is probably the most commonly-used technique, despite the fact that it has the problem of significant errors associated with determining time derivatives of tracer gas concentrations. This technique can be used with multiple tracer gases or a single gas. The single gas approach takes more time, during which the airflow rates could change, leading potentially to errors in the estimated airflow rates. The so-called integral pulse method is based on an integral formulation of the tracer gas mass balance, which avoids the time-derivative errors associated with the decay method (Afonso et al. 1986; Ohira et al. 1993; Persily and Axley 1990). The integral approach can also be used with multiple or single tracers, but the issue of airflow rate variation over time exists as in the decay method. In the constant concentration method, the tracer gas injection rate to each zone is controlled such that the tracer gas concentrations in all zones are maintained at a target concentration (Bohac and Harrje 1987; Freeman et al. 1982). This method requires equipment to continually control the tracer gas injection rate and determines only the outdoor airflow rates into the buildings zones and not the interzone airflow rates.

In the semi-continuous constant injection method, a unique tracer gas is injected at a constant rate into each zone in a controlled manner to maintain a target concentration in that zone. An integral formulation of the multizone mass balance equation is then analyzed over a specified time period to determine the interzone airflow rates (Sherman and Dickerhoff 1989). In the long-term average constant injection method, multiple tracers are released at a constant rate into the different building zones and long-term average (generally over days or weeks) tracer gas concentrations are determined in each zone. Passive tracer emitters and passive samplers are often employed in this technique (Dietz et al. 1986). Interzone airflow rates are determined based on a mass balance analysis assuming that the tracer gas concentration is at steady-state during the averaging period.

Qualitative multizone techniques have also been described in which one establishes a uniform tracer gas concentration in a multizone building and then monitors the subsequent tracer gas decay in each zone (Maldonado and Woods 1983a). The different decay rates in each zone, or the integral of the tracer gas concentration in each zone, can then be compared as an indication of the relative effectiveness of outdoor air ventilation in the various zones. However, these decay rates are not actual outdoor air ventilation rates, nor can this approach be used to yield interzone airflow rates.

6.2 Tracer Gas Measurements of Interzone Airflow Rates

The multizone tracer gas techniques described in the previous section have been used in residential buildings to determine interzone airflow rates. These measurements can be described as efforts to demonstrate the techniques and to investigate the issues related to their application in the field. At this point, the use of these techniques has been restricted to research efforts, and therefore, the results obtained are limited to a small number of specific circumstances and structures.

The multizone decay technique has been applied in two single-family residential buildings (Prior et al. 1985; Sieber et al. 1993). In the first case, airflow rates were measured between a passively-heated conservatory and the main living space of a house. In the second study, airflows were measured between the basement and main levels of the house with and without mixing fans and furnace fans operating. The constant concentration method was applied to a two-story house to determine the rate at which outdoor air entered each room (Freeman et al. 1982). Results were presented for situations with and without the heating and the exhaust ventilation systems operating. The results showed greater differences in the ventilation rates of the two floors without heating than with heating. Without heating, the mixing within a floor was more efficient than between floors. The semi-continuous constant injection method was applied in two houses (Sherman and Dickerhoff 1989). The first was an unoccupied, four-zone house, in which the interzone airflow rates were measured over 1.5 days and reported every 30 min. The second house was occupied and set up as a three-zone system. The long-term constant injection approach was applied in four houses, in part to gain some insight into the role of attics, crawl spaces and basements in residential air movement (Dietz et al. 1986). This approach was also used to investigate airflow rates in a four-zone apartment building (Dietz et al. 1984). The qualitative decay approach was applied to a research house, in which the tracer gas decay rate was monitored at 12 indoor locations (Maldonado and Woods 1983a).

There have been a number of studies in which the results of several different multizone tracer gas techniques were compared in the same building. Riffat (1989b) performed measurements in a two-story house, comparing the results of several formulations of the multizone decay method and the integral mass balance approach. Measured airflow rates for the upstairs and downstairs zones were compared for the various methods, and a wide range of values were observed. The single-gas constant concentration, long-term constant injection and semi-continuous constant injection methods were compared in two identical test houses (Fortmann et al. 1990). In these tests, the houses were analyzed as two-zone systems, with the two zones being the upstairs and downstairs. The long-term constant injection measurements also considered airflow rates to and from the attic and garage. The measurement results were consistent for some of the airflows, while large differences existed for others. The paper also compared the methods in terms of application, equipment requirements and complexity. Another comparison of the constant concentration, long-term constant injection and semi-continuous constant injection methods took place in an apartment building (Harrje et al. 1990). As in the study cited previously, the consistency of the airflow rates determined with the different measurement techniques was variable.

The complexity of multifamily buildings, particularly those that are naturally ventilated, tall or both, makes the application of tracer gas techniques difficult. Tracer gas injection can be difficult, as can achieving and maintaining a uniform tracer gas concentration during a measurement (Shaw and Magee 1990). Other options for evaluating airflow in multifamily buildings include pressurization testing of the air leakage characteristics of exterior walls and partitions between apartments for use as inputs into multizone airflow models. Such measurements were made in a study of a 13-story apartment building (Diamond and Feustel 1995) and in another study of several multi-story buildings in Canada (Gulay et al. 1993). The latter study also used qualitative tracer gas techniques in which a tracer gas was released at a specific point in a building, and the concentration response was monitored throughout the building in order to obtain a qualitative indication of the interior airflow patterns. The results of these assessments indicate that multifamily buildings with leaky exterior walls have internal air movement dominated by stack and wind effects, and that in tight buildings air movement is more influenced by stack and internal activities than wind. These internal building activities include elevator motion, door openings and occupant movement.

7 Modeling

There are several types of models that can predict building airflows and indoor contaminant levels. They include computational fluid dynamic (CFD) models that predict airflow patterns and contaminant concentrations for a detailed grid of points within a space. Other models idealize a building as a single zone, and include airflow models that predict building infiltration rates based on building airtightness measurements and weather parameters and contaminant mass balance models that predict indoor pollutant levels. There are also multizone airflow models that represent a building as a group of interconnected zones or compartments and perform a simultaneous mass balance on all the zones to calculate interzone airflow rates. Multizone contaminant dispersal or indoor air quality models can predict contaminant concentrations in multizone buildings based on these multizone airflow rates and contaminant source characteristics; some multizone contaminant models incorporated multizone airflow models. This section describes these various models and some examples of their application that are relevant to the issue of CO dispersion in residential buildings.

7.1 CFD Models

Computational fluid dynamic models (CFD) can be used to predict the detailed airflow and contaminant concentration patterns in a space (Liddament 1991; Murakami et al. 1992). These models are based on a two or three-dimensional grid of points, usually on the order of thousands or tens of thousands of points in a room. These models can be used to determine the distribution of a contaminant in a room, taking into full account the temperature and discharge velocity associated with the source and any features of the room that might affect contaminant distribution, such as mechanical ventilation, obstructions to airflow and heat sources. The equations for conservation of mass, momentum, energy and contaminant species are then solved using a number of different techniques. A critical difference among the various CFD models is the manner in which they address turbulence. Several approaches to turbulence modeling have been used with the empirical k-ε model being the most common. An alternative approach called large eddy simulation (LES) has been found to better predict experimental results, but requires more computational resources (Murakami et al. 1996). An LES approach has recently been developed at NIST that enables LES simulations to be performed on commonly-available workstations (McGrattan et al. 1994; Baum et al. 1994). A recent International Energy Agency annex evaluated CFD models and included a number of comparisons of model predictions with measurements (Moser 1992).

Most applications of CFD modeling have been in office spaces, clean rooms and atria; there has been only limited application in residential spaces that are relevant to this effort. In one such study, CFD modeling was used to examine the effectiveness of a range hood exhaust fan (Gotoh et al. 1992). This study was supplemented with full-scale testing using a tracer gas and 1/4-scale model testing. The impact of make-up air ventilation on capture efficiency was examined and found to have the potential for interfering with the buoyant airflow into the range hood. In a study motivated by questions about the positioning of natural gas leak detectors, Cafaro et al. (1992) used CFD modeling to examine the distribution of gas in a ventilated room. In this study, the arrangement of inlet and exhaust vent location and ventilation rate were examined for a non-buoyant source.

7.2 Single-zone Modeling and Application

Models that idealize a building as a single well-mixed zone exist to predict building ventilation rates and indoor contaminant concentrations. As discussed in ASHRAE (1993), there are a number of single-zone airflow models that employ empirical relationships between weather conditions and infiltration rates. Some of these empirical models also employ a factor that characterizes the leakiness of the building envelope, which in some cases is related to the results of a fan pressurization test. There are also single-zone calculation methods based on physical models of a building as a single zone, for example the so-called LBL model (Sherman and Grimsrud 1980). This model can be used to predict whole-house infiltration rates based on the results of a fan pressurization test, weather conditions, and parameters that describe the terrain and shielding of a house. The LBL model can also incorporate the impact of mechanical ventilation rates, such as from kitchen and bathroom exhaust fans. This model has been shown to have predictive errors of about 7% for weekly-average infiltration rates and 20% for short-term (on the order of hours) infiltration rates when the model input values are well known for a building (Sherman and Modera 1986). When the inputs are less well known, the errors have been seen to average about 40% for a group of homes and to be as large as 100% for an individual home (Persily 1986; Persily and Linteris 1983). Single-zone infiltration rates can also be predicted using the multizone models described in the next section.

Single-zone models also exist that can be used to predict indoor contaminant concentrations. These are mass balance models that relate the time rate of change of the indoor contaminant concentration to the rate at which a contaminant enters the space from an indoor source or from outdoors and the rate at which it leaves due to ventilation, air cleaning devices or other loss mechanisms such as deposition on indoor surfaces (Traynor 1989; Traynor et al. 1989). A key assumption in the use of these models is that the indoor contaminant concentration is uniform throughout the space being studied. The use of these models generally requires values for a number of input parameters including ventilation rates, contaminant emission rates, penetration factors for outdoor contaminant entry, and indoor decay rates.

Single-zone mass balance models have been used to determine emission rates of CO and other combustion products from combustion appliances in laboratory chambers and in houses based on measurements of indoor contaminant concentrations (Hedrick and Krug 1995; Nabinger et al. 1995; Tamura 1987; Traynor et al. 1982a; Traynor et al. 1987a). These models have also been used to compare predicted and measured contaminant concentrations (Borazzo et al. 1987; Davidson et al. 1984) and to analyze the factors that impact indoor contaminant levels such as building ventilation rates (Lambert and Colome 1984; Traynor et al. 1982b; Wilson et al. 1995).

7.3 Multizone Airflow and Contaminant Dispersal Modeling

While single-zone airflow and contaminant mass balance models can be used to predict ventilation rates and contaminant concentrations in some buildings with adequate precision, other buildings can not be modeled as single zones. Also, in some situations, information on the concentration variations within a building is desired, for example when considering the impacts of a local CO source on CO levels within a building. In these cases, multizone models must be used in which the building is idealized as a series of interconnected zones, each of which is assumed to be at a uniform concentration. Several multizone airflow models are available that can be used to predict interzone airflow rates based on descriptions of the airflow connections between the building zones, leakage information on the airflow paths between zones and the outdoors, any mechanical ventilation airflow rates that exist, outdoor weather conditions, and exterior surface wind pressure coefficients (Allard and Herrlin 1989; Etheridge and Alexander 1980; Feustel and Raynor-Hoosen 1990; Herrlin 1985; Walton 1984 and 1989). General discussions of these models exist that compare the features of available multizone airflow models (Feustel and Dieris 1991; Liddament and Allen 1983).

Multizone contaminant dispersal or indoor air quality models predict indoor contaminant concentrations in multizone building systems (Axley 1989; Sparks et al. 1993; Walton 1994). The available models differ in the contaminant dispersal mechanisms that they model and the ways in which they represent these mechanisms mathematically. Some of the models require the user to input interzone airflow rates as a function of time (Sparks et al. 1993), while others incorporate a multizone airflow model and predict these airflow rates based on the inputs described previously

(Walton 1994).

There have been studies in which multizone indoor air quality models have been applied to situations to analyze indoor CO concentrations (Axley 1989; Emmerich and Persily 1996). In the latter study, eight single-family residential buildings were represented within the multizone airflow and contaminant dispersal model CONTAM, and the impacts of a number of indoor sources of CO were investigated. These sources included a gas stove, an unvented gas space heater and infiltration of CO from outdoors. The model was used to predict indoor CO concentrations in all of the building zones over 24 h, but the model has the capability of simulating periods up to one year.

Multizone airflow and indoor air quality models have also been used to study air and contaminant transport in multifamily buildings. An airflow modeling study of 17 buildings in Berlin examined the impact of floor plan and interior and exterior wall leakage on ventilation rates of individual apartments (Feustel and Lenz 1984). The results showed the impact of the stack effect, with the highest infiltration rates occurring in the ground-floor apartments. A more recent modeling study examined both airflow and radon transport in a fictitious 12-story apartment building (Fang and Persily 1995; Persily 1993). The impact of the stack effect and the importance of vertical shafts, in this case elevators and stairways, were seen in the simulation results. During heating conditions, outdoor air tended to enter the building on lower floors, flow up the building through the vertical shafts, and leave on the upper floors. Radon entering the building in the basement flowed into the shafts, bypassing the lower floors, and was subsequently deposited on the upper floors of the building. Another simulation study of an apartment building involved the 13-story building mentioned in the previous section (Diamond and Feustel 1995). Based on measured air leakage characteristics, airflow rates were predicted in this building for a range of weather conditions. Again, airflow patterns were heavily impacted by the vertical flows associated with the stack effect.

8 Summary of Literature Review

The purpose of this literature review has been to identify and organize information relevant to the dispersion of CO in residential buildings within the context of the installation of CO detectors. This literature review has covered a number of issues including CO concentration measurements in single-family and multifamily residential buildings, sources of indoor CO, mixing within and between rooms, tracer gas techniques for assessing building airflow, and models of air movement and contaminant dispersal in buildings. Issues of detector performance, including sensitivity and accuracy of CO sensors, appropriate alarm levels and interference from other airborne substances, were not within the scope of this literature review and will not be considered in future phases of this effort. Also, the project is concerned only with indoor CO generated by non-fire sources.

Based on the consideration of CO exposure in residential buildings, a number of factors have been identified as affecting indoor CO concentrations: source and source-use characteristics, building features, ventilation rates, air mixing between and within rooms, the existence and effectiveness of contaminant removal systems, and outdoor concentrations. A number of indoor sources of CO have been discussed, but properly-operating combustion appliances are the only sources for which measured emission rates are available. Source strengths are not available for other potentially-important CO sources, such as airflow from attached garages and malfunctioning combustion appliances.

The organization of the information obtained in the literature review has reflected a distinction between what is known that is relevant to the issue of CO dispersion in residential buildings and the tools that are available to obtain more information. Within the first category of what is known, there have been a number of studies involving measurements of CO concentrations in residential buildings, with most of these performed in single-family residences. These studies have included CO exposure studies in which personal exposure monitors were used to determine CO concentrations associated with various activities and microenvironments. There have also been a number of indoor air quality surveys of large numbers of residential buildings in which multiple indoor pollutants were sampled, including CO. Most of these measurements of indoor concentrations have employed only a single CO sampling location in each building, but there have been a limited number of studies involving multi-point sampling. These studies have shown that CO concentrations in residential buildings are generally low compared to ambient and occupational standards, which are based on averages over one or more hours. However, under some circumstances and in a relatively small number of buildings, these average values and short-term peak values can be higher than the values in these standards and approach the levels of exposure at which CO detectors are designed to alarm.

The studies in which CO was monitored at multiple points in residential buildings have tended to focus on combustion sources. While the concentrations are generally higher in the room containing the source, the degree of concentration uniformity between rooms depends strongly on the operation of forced-air distribution system fans and local exhaust fans, the location of the source, and the position of interior doors. The measurement studies have shown a range in the CO concentration difference between the source zone and the rest of the house, from only a few mg/m^3 (or ppm) to a factor of two or more higher in the source zone. In some cases, the differences appear to be related to forced-air fan operation, but in other cases they do not. Concentration differences that do exist have been seen in some studies to dissipate about 1 h after the source is turned off, with differences between floors tending to last longer than differences on a floor.

The transport of air and contaminants is usually different in multifamily buildings as compared to single-family residences due to the larger number of zones, the existence of vertical shafts connecting floors, and the generally greater vertical height of these buildings. In part because of this greater complexity, there has been significantly less study of airflow and contaminant movement in multifamily buildings. The measurements that have been conducted indicate that higher outdoor air ventilation rates in the lower stories of a multi-story building is a typical pattern in the heating season. With indoor temperatures above outdoors, the stack effect leads to outdoor air entry on lower floors, vertical transport of air up through the building, and then airflow to the outdoors on the upper floors. This vertical airflow pattern has been confirmed in studies using multizone airflow and contaminant dispersal modeling.

There have been a number of studies of air and contaminant mixing within and between rooms, conducted both in real buildings and in laboratory test facilities. These studies have examined the impact on mixing of the operation of forced-air fans, the position of interior doors, source location and source buoyancy, temperature differences between zones, heat sources, and ventilation rate. In many of these studies, a tracer gas was used to simulate a contaminant source, but in others an actual contaminant source was studied. Some of the studies focused on mixing between the floors of a building under different conditions. Others have examined mixing between rooms. Mixing tends to be more complete within an individual floor than between floors, but there are many relevant variables, including the operation of forced-air fans, temperature differences between rooms, and source characteristics.

In addition to CO-specific factors such as emission rates, two other key parameters in determining indoor CO levels are building ventilation rates and the volumes of buildings and rooms. Based on the expectation that the impact of these parameters will be considered in future phases of this effort, this literature review examined studies in which ventilation rates and building airtightness values were measured in large numbers of residential buildings. These residential ventilation surveys have considered mostly single-family residential buildings, with ventilation and airtightness measurements made in only a small number of multifamily buildings. In addition, the data available on the interior volumes of residential buildings was also assessed.

A variety of tracer gas techniques exist to measure airflow rates in buildings under natural conditions of weather and building system operation, and these techniques have been useful for studying air and contaminant mixing in buildings. In these techniques, one or more tracer gases are released into a building in a controlled manner, and the tracer gas concentration response within the building is analyzed to determine the airflow rates of interest. Tracer gas techniques were included in this literature review for two reasons. First, tracer gas techniques require a uniform tracer gas concentration within a building or a portion of a building, and the experience in assessing the uniformity of tracer gas concentrations in buildings can provide some insight into the distribution of CO in buildings. Also, tracer gas techniques exist which can be used to measure airflow rates between the zones of a building, and these techniques can be useful in understanding the transport of airborne contaminants in buildings.

There are also several different types of models that can be used to predict building airflows and indoor contaminant levels and may be useful in future phases of this project. They include computational fluid dynamic (CFD) models that predict airflow patterns and contaminant concentrations for a detailed grid of points within a space. Another group of models idealizes a building as a single zone and includes models that predict building infiltration rates based on building airtightness measurements and weather parameters and contaminant mass balance models that predict indoor pollutant levels. There are also multizone airflow models that represent a building as a group of interconnected zones or compartments and perform a simultaneous mass balance on all the zones to calculate interzone airflow rates. Multizone contaminant dispersal or indoor air quality models can predict contaminant concentrations in multizone buildings based on these multizone airflow rates and contaminant source characteristics.

The literature review has identified a great deal of information that is relevant to air and contaminant mixing in residential buildings. However, very little of this information is focused directly on the dispersal of CO released by typical residential sources.

9 Technical Analysis

Following the literature review, the information collected was studied to determine what is known about the factors that impact CO dispersion in single-family residential buildings. This analysis was focused on single-family buildings because future phases of the project will not be addressing multi-family buildings. In addition to determining what is known about the factors affecting CO mixing, the analysis was also intended to determine what additional information is needed to understand these factors and their impacts. The technical analysis was focused on two questions, central to the overall project:

- How does the CO concentration vary within a room for a given source type and room configuration?
- How does the CO concentration vary within a building for a given source type and house configuration?

In the context of these questions and the technical analysis, the terms source type, room configuration and house configuration are used to discuss the factors that affect CO dispersion. *Source type* refers to the features of the CO source that can impact CO dispersion. They include heat generation associated with the source, mass flow from the source, and the density of the source emissions. *Room configuration* refers to those features of a room that affect mixing of air and contaminants in the room. These features include the room geometry, heat sources in the room, and airflows from ventilation systems, windows and doorways. *House configuration* refers to those features of the house that affect mixing of air and contaminants between rooms. These include the layout of the house, leakage characteristics of the building envelope, temperature differences between rooms, temperature differences between indoors and outdoors, position of interior doors, and ventilation system type, layout and operation.

The approach taken in the technical analysis was to identify the factors that define the source types and the room and house configurations, and then to examine these factors in terms of the availability of information to characterize them in single-family residential buildings. The next step was to address the questions of what we know about how source and room factors affect mixing in a room, and how source and house factors affect room-to-room mixing. Throughout the discussion, issues are identified where information is incomplete. These are summarized in the next section on research needs.

9.1 Description of Key Factors

In order to answer the two questions on mixing presented at the beginning of this section, specific combinations of source type and room configuration, and source type and house configuration, are considered. While sources, rooms and houses can be described by a wide range of attributes, the discussion presented here is focused on those attributes that are expected to impact CO dispersion. As discussed earlier, the features of a CO source that can impact mixing are heat generation, mass flow and density of emissions. The first factor refers to whether or not the source is associated with heat generation, and if so the value of the heat generation rate. Many CO sources are associated with combustion processes that also generate heat, which in turn cause buoyancy-driven airflow in a room. The second key factor of a CO source is the mass flow associated with the CO generation. The mass flow is characterized by the mass flow rate of the gases containing the CO and the velocity of the emissions, including the direction at which the emissions are discharged. The last source factor is the density of the gas released by the source, which is a function of its temperature and composition. Composition affects density based on the densities of the gases that comprise the emissions. Within this context, questions have been raised regarding the impact of the CO concentration of the source emissions on mixing. The density of even pure CO is so close to that of air that the CO concentration will not have a significant impact on the density of the emitted gas relative to air. The temperature of the gas is the most important factor, and to a lesser degree the presence of other compounds with densities that are different from air (for example, water vapor, CO_2 and NO_2).

Room configuration refers to the features of a room that affect mixing of air and contaminants within the room. The geometry of the room is certainly relevant to mixing, and includes the room shape and physical dimensions, in particular the ceiling height. Another potentially important aspect of room geometry is the existence of obstructions to airflow such as furniture and partitions. Another key room feature is the existence of heat sources in the room, in addition to any heat generated by the CO source itself. Such sources could include appliances, solar radiation through windows, and warm wall surfaces. Similarly, the existence of cold surfaces such as windows and walls can be important in determining airflow patterns in a room. Ventilation system airflows also impact room air mixing, with the relevant factors including the existence of a ventilation system, the airflow rates involved, the discharge velocity, and the location of the vents. Other mixing devices, such as desktop and ceiling fans, are also relevant to within room mixing.

The house configuration includes those features of a house that affect the mixing of air and contaminants between rooms. The physical layout of the house in terms of the number of rooms, their arrangement, the pathways available for inter-room airflow, the number of stories and the existence of attached garages, basements, attics and crawl spaces are important. The airtightness of the building envelope and the distribution of the envelope leakage are important in that they impact the ventilation of the building and the pressures within the building. The air temperatures of the different rooms are key determinants of inter-room airflow patterns. In addition, the temperature difference between inside and out affects the pressure distribution and airflow pattern within a building. The position of interior doors determines the paths available for inter-room airflows. In addition, the existence of other inter-room airflow paths such as wall cavities may be important. Another issue is the existence of open windows, with their distribution impacting the existence and impact of wind-driven airflow through the building. Finally, the ventilation system type, layout and operation can be critical to mixing between rooms. One of the most important issues is the existence of a forced-air distribution system. If there is a forced-air system, other issues include the system airflow rates, operating schedule, existence and location of duct leakage, and the arrangement of system returns. Some forced-air systems have a return located in each room, while others employ a central return on each floor.

9.2 Analysis of Source, Room and House Factors

A large number of factors have been described that cover the features of sources, rooms and houses that are relevant to mixing. If additional phases of this project are pursued, they will need to consider individual source-room and source-house cases through the specification of values for the source, room and house factors. In this section, these factors are discussed in terms of which are sufficiently well-understood to determine reasonable values and which require additional study. The impact of these factors on CO dispersion is discussed in the next section.

As discussed earlier in this section, the source factors include heat generation, mass flow and density. The discussion of these source factors is presented in terms of four groups of sources. These are unvented appliances that are intended for indoor use (e.g. space heaters), unvented appliances that are not intended for indoor use (e.g. charcoal grills), vented appliances in which CO is introduced to the living space due to a venting system failure such as flue gas spillage, and outdoor sources including airflow from attached garages. For unvented appliances, the heat generation rate can be determined based on the fuel consumption rate. Fuel consumption rates are fairly straightforward to characterize for typical indoor appliances such as space heaters and stoves, but can be less so for appliances not typically used indoors such as charcoal grills. When the CO generation is associated with vented appliances that are not venting properly, the heat generation rate is difficult to characterize. It is primarily associated with the heat given off by the combustion device and the venting system components, based on their surface temperatures. However, there can also be heat generation associated with the spillage of combustion products, and the heat generation rate associated with improper venting is difficult to characterize. If the venting problem also involves the downflow of outdoor air through the venting system, there will be a heat generation (or loss) associated with this outdoor air. Other CO sources, in particular airflow from attached garages and ambient air, are not associated with heat generation, although the temperature of air that transports the CO into the living space may be important.

The second key source feature is the mass flow rate associated with the CO source and the discharge velocity, including direction, of that flow. The mass flow rate of unvented appliances can be estimated from the fuel consumption rate, and the direction can be based on the configuration of the appliance. The discharge velocity of unvented appliances is not as easily characterized, and presumably depends on the nature of the appliance being considered. For vented appliances where the source is improper venting, the mass flow rate and velocity is even harder to determine and has not received much attention in the literature. If there is 100% spillage, one can estimate the mass flow rate of the combustion products based on the fuel consumption rate, but one also needs to know the rate at which air flows from the outdoors into the living space through the venting system. This airflow rate can be calculated based on the pressure in the room containing the appliance, using a network airflow model, and the airflow resistance of the venting system. When the CO source is airflow from an attached garage, the mass flow rate is based on the CO concentration in the garage and the airflow rate from the garage into the house. While there have been limited measurements of CO concentrations in garages, there have been no reported measurements of airflow rates between garages and the living space in single-family residential buildings.

The last source-type feature is the density of the gas released by the source, which depends on the temperature and composition of the emissions. The composition of emissions from unvented appliances is generally well-characterized, except in situations where the appliance is not functioning properly. However, this latter situation is of most interest here, since this is when CO generation is most likely to be significant. The temperature of emissions from unvented appliances will be a function of the fuel consumption rate and the appliance design. Similarly, the density of emissions from vented appliances is fairly well-characterized in cases where the emissions contain only combustion products under proper operation, undiluted by backdrafting outdoor air. However, the CO generation is likely to be low under these conditions, and the composition of combustion products under conditions of high CO generation is less well-understood. The density of air entering a house from an attached garage, or from the outdoors, is a function of the air temperature in the garage.

The factors that define room configuration include the room layout, the heat sources in the room, and the ventilation system airflows. The aspects of room layout that appear to be most relevant to mixing include floor area and ceiling height. There is not much information on the statistical distribution of floor areas and ceiling heights, but it is not difficult to arrive at reasonable values for these parameters since they generally do not vary too significantly. An exception might be utility rooms that contain furnaces, boilers and water heaters or laundry rooms that contain gas dryers. The floor areas of these rooms are likely to be more variable, and may be relevant to CO mixing in these rooms.

Another room factor that affects mixing is the existence of heat sources, other than any heat generated by the CO source itself. Heat generation rates are available for a number of appliances. Warming due to solar radiation can be calculated based on room geometry, fenestration system characteristics, season, and time of day. The temperatures of exterior walls, warm and cold, can be calculated based on insulation levels, indoor and outdoor temperatures, and incident solar radiation. Airflows associated with ventilation systems definitely impact room air mixing, with these impacts characterized by the airflow rate, discharge velocity, and vent location. These factors are know for typical ventilation system designs, but there are a large number of different possibilities. The impact of other mixing devices, such as desktop and ceiling fans, can be characterized by the airflows they induce, their position in the room and the direction of the airflow.

The house configuration is defined by the layout of the house, the airtightness of the building envelope, the air temperatures in the various rooms, the indoor-outdoor air temperature difference, the position of interior doors and windows, and the ventilation system type, layout and operation. There is a wide range of variation in the layout of the houses and little statistical data on the relevant variables, that is the number of rooms, their arrangement, the number of stories, and the existence of attached garages, basements, attics and crawl spaces. Some of the variation is based on the region of the country and the age of the house. Information on building floor area, which can be related to volume, is available from the DOE residential building survey (DOE 1992) as a function of region and year of construction.

Information on the airtightness of single-family residential buildings is available, though not in the form of a statistically-representative database by region and house age (Sherman and Dickeroff 1994). Less information exists on the distribution of these leaks over the envelope, although some data on the leakage of individual envelope components is available (ASHRAE

1993). This data has been used to specify the detailed leakage characteristics of a building in a reasonable manner (Emmerich and Persily 1996). However, while the distribution of envelope leakage impacts the distribution of airflows and pressures within a building, it would not be expected to be very relevant to CO mixing except in extreme cases where the leakage is concentrated over a limited area of the building envelope.

Air temperatures within the different rooms of a house typically cover a fairly narrow range, but temperature differences of even a few degrees are sufficient to induce significant airflows between rooms. When a room contains a combustion-related CO source, such as a space heater, the temperature is likely to be higher than in adjoining rooms. While the air temperatures in individual rooms are a complex function of heat sources and thermal properties of the building, reasonable values can probably be estimated for typical situations. Indoor-outdoor temperature differences can be determined fairly reliably based on weather data.

The positions of interior doors can have a major impact on between-room mixing, particularly for doors to rooms containing sources. For even a relatively simple house, the number of different combinations of door positions can be quite large, and there have been little study of door opening patterns in buildings. However, reasonable scenarios of door openings can be arrived at for a given house. Similarly, window opening patterns determine the existence and impact of wind-driven airflow through the building. There has not been much study of window opening patterns, though reasonable scenarios can be determined based on the location of windows and weather conditions.

Finally, the impacts of ventilation system type, layout and operation on mixing between rooms are based on a large number of variables. These include system airflow rates, operating schedule, existence and location of duct leakage, and the arrangement of system returns. The existence and operation of local exhaust fans, such as in kitchens and bathrooms, is another factor to consider. However, the most important issues appear to be whether there is a forced-air distribution system and whether it is operating.

9.3 Analysis of Mixing Impacts

This section summarizes what is known about how source and room factors affect mixing in a room, and how source and house factors affect mixing in the house, based on the information obtained in the literature review. Rather than discuss the impact of each individual factor on mixing, this section focuses on those situations or combinations of factors for which the impact on mixing appears to be significant. In this discussion, the impacts on mixing that are not particularly well understood are also identified as input to the discussion of research needs in the next section of the report.

The first factor discussed under CO sources, heat generation, definitely impacts room airflow patterns based on the decrease in air density as the heat source warms the nearby air. These impacts also apply to other heat sources in the room, that is, those not associated with CO generation. The effects of thermal plumes from heat sources on room airflow have been studied, showing a tendency to create circulation cells in a room and in some cases to establish a warm, stable layer of air at the upper levels in a room. However, the impacts of these airflow patterns on contaminant mixing have received less attention. Two studies of contaminant mixing due to heat sources were cited in the section of literature review on mixing (Baughman et al. 1994; Stymne et al. 1990). The first study examined the time required to reach uniform tracer gas concentrations with a 500 W heater in the room and with solar radiation entering through a window. The latter study focused on concentration differences within the room, noting only a slight tendency for higher concentrations at the ceiling with a 100 W heat source. From these two studies, it appears that heat sources can cause significant mixing in a room, but the tendency to produce stratification versus the tendency to mix merits additional study. Such study needs to consider the relative position of the heat and CO sources. Also many CO sources and other indoor heat sources produce higher heat generation rates than those examined in these studies, and there is a need to understand the impacts of these higher rates on mixing.

Mass flows associated with a CO source, as well as mass flows from ventilation systems, can also induce significant mixing in a room. Drescher et al. (1995) examined the impacts of mixing fans on tracer gas concentration uniformity in a chamber. The mixing time was correlated with the inverse cube root of the mechanical power of the mixing fans. These tests were conducted for one configuration of the fans relative to the tracer source and for a limited range of a dimensionless fan parameter. A study by Heiselberg (1992) showed that the distribution of tracer in a room depended on the position of ventilation opening relative to the source. Additional study is needed to examine the impacts of ventilation-induced mixing of CO for residential ventilation system flow rates in combination with expected positions of residential CO sources. This work would also need to consider the interactions with mixing induced by heat sources.

The impact of the density of the emissions from a CO source can lead to buoyancy-driven airflow patterns in a room, similar to those induced by a heat source. Since these emissions will almost always be warmer than the room air, that is at a lower density, they will tend to rise and may lead to stratification in the room with higher CO concentrations near the ceiling. However, the existence of other mixing mechanisms, caused by ventilation airflows or other heat sources, may interact, and even counteract, such stratification. As noted in the earlier discussion of the impacts of heat sources on mixing, there has not been much work on the subject of contaminant mixing due to buoyancy-driven airflows.

With regards to room configuration factors that impact contaminant mixing, the layout of the room probably impacts mixing most through the room size and ceiling height. These factors are most likely to be important as they impact the stratification of warm air at a high CO concentration. The issue is probably most relevant to utility and laundry rooms that might contain CO sources, as these rooms can vary substantially in size. Ceiling height may be less of an issue, since the variation is generally not as large as the variation in floor area. Study of the impact of room size is needed to determine how this factor impacts mixing and stratification.

Considering mixing within a house, the layout of the house in terms of number of stories and the source location has been shown to impact the mixing of CO. Additional factors, predominantly the position of interior doors, have also been examined within this context. Field measurements have shown that CO concentrations are fairly uniform throughout the floor on which the source is located (Hedrick et al. 1993; Nagda et al. 1985a). These and other measurements (Koontz et al. 1988; Leslie et al. 1989) have also shown that CO is transported in a predominantly vertical direction under heating conditions when the furnace fan was off. Therefore, when the source is upstairs, little CO is seen on the lower floors, but when the source is downstairs the CO is transported upstairs. However, such studies have not been performed with the indoor air temperature below outdoors, when one would expect a downward airflow pattern.

The operation of a forced-air furnace fan has been shown to have a major impact on mixing between rooms. When the furnace fan is operating, CO concentrations become fairly uniform within a house in a matter of minutes (GEOMET 1989; Leslie et al. 1989). As might be expected, the position of interior doors has a major impact on mixing within a house, limiting the transport of CO across the boundary created by the closed door (Chang and Guo 1991; Traynor et al. 1987b). The impact of door position on room-to-room mixing depends strongly on source location. When a CO source is located in a room with a closed door, the concentration gradients between rooms will be increased. Closed doors have been shown to interfere with the high levels of mixing induced by forced-air fan operation (Haghighat et al. 1990). The combined impact of door position and forced-air fan operation is presumably linked to the existence of return vents in the individual rooms. While the impacts of forced-air fan operation, door opening and source location have all been shown to be important, they have not been examined systematically.

In addition, mixing in houses without forced-air systems, or without these systems operating, has not been examined in much detail with regards to the impacts of door opening, source location and the driving force of temperature differences between rooms. While air temperatures within the different rooms of a house typically cover a fairly narrow range, the temperature differences are sufficient to induce significant airflows between rooms. When a room contains a combustion-related CO source, such as a space heater, the temperature is likely to be higher than in adjoining rooms and have a more significant impact on room-to-room mixing.

10. Research and Information Needs

This section presents some of the research and information needs identified in the technical analysis. The need for additional information is divided into two categories, the first focusing on the source, room and house factors. As mentioned in the previous section, some of these factors are not sufficiently well understood to specify values for modeling or experimental studies of CO mixing in rooms or houses. Obtaining some of this information may require experimental work, while information on other factors may already be available. However, significant effort may be required to collect and evaluate existing data. The second category of research needs is in the area of CO mixing itself, both within and between rooms.

10.1 Source, Room and House Factors

In the discussion of source, room and house factors, a number of areas were identified where additional information is needed to specify values for the factors in modeling or experimental studies. This section identifies those factors for which current information is incomplete, or lacking entirely. The intent of this section is not to imply that all of this information must be obtained before proceeding with any research into CO mixing, but to point out that these gaps exist. Beginning with the source factors, the heat generation rate of a combustion appliance is predominantly a function of the fuel consumption rate. While fuel consumption rates are fairly straightforward to characterize for typical indoor appliances such as space heaters and stoves, they may be less so for appliances not typically used indoors such as charcoal grills. Therefore, to study the impact of heat generation for atypical indoor combustion sources, the fuel consumption and heat generation rates are needed for these sources. This data can probably be obtained, or at least estimated, based on information available from the manufacturers of these appliances.

In terms of mass flow rates from CO sources, the study of mixing induced by these flows requires information on the discharge velocity from unvented appliances. Presumably the discharge velocity will depend on the design of the appliance, but there does not appear to be much specific information available. Similarly, for vented appliances where the source is improper venting, the mass flow rate and velocity is probably more difficult to determine and has not received much attention. The speed and direction of the discharge in a situation of improper venting will depend on the nature of the venting problem and the venting system design. Another area within the category of mass flow rates associated with sources is airflow rates between garages and living areas. Attached garages are considered a potentially important CO source, but the analysis of their impact requires quantitative data on these airflow rates, as well as more information on CO levels in garages.

In order to characterize the density of the emissions from CO sources, information is needed on the chemical composition of the emissions, especially in situations where the appliance is not functioning properly. Many appliances do not produce much CO when operating properly, but the situations of interest here involve improper operation where CO generation rates can be significant. In addition, some combustion sources, particularly those not intended for indoor use, typically produce significant levels of CO. To analyze such sources, information is needed on the composition of their emissions, including CO generation rates.

With regards to studying the impact of room configuration on mixing, the most important aspects of room layout are probably room size and ceiling height. While typical rooms sizes and ceiling heights are not difficult to establish, there does not appear to be much information on the statistical distribution of these two quantities. Such information is particularly relevant for utility rooms that contain furnaces, boilers and water heaters, laundry rooms that contain gas clothes dryers, and work areas that might contain portable generators or unvented space heaters.

In order to evaluate house configuration effects, envelope airtightness needs to be specified. While information on the airtightness of single-family residential buildings is available, it does not constitute a statistically representative database for the U.S.. Such a database is needed in order to assure that simulations of CO levels in houses are generalizable. Even less information exists on the distribution of leakage over the envelope, and this data would also be needed to increase the reliability of these simulations.

Both simulation and experimental studies in houses will require the specification of the positions of interior doors and windows. While reasonable opening patterns can be identified based on expected occupant activities, there have been few studies of door and window opening patterns in buildings.

10.2 Mixing

In addition to the need for more information on the source, room and house factors, there are a number of issues related directly to CO mixing in rooms and houses that need additional study. The research done to date and identified in the literature review has been incomplete in its consideration of the source, room and house factors that appear to impact intra-room and inter-room mixing. While this research has been helpful in identifying some of the important factors, it has not been comprehensive and does not enable the prediction of how CO disperses in single-family residential buildings. This section presents research needs related to room and house mixing based on the results of the technical analysis.

Based on the studies examined in the literature review, it appears that heat sources can cause significant mixing in a room, as well as a tendency to create stratification with higher CO levels in the ceiling. The impact of heat sources on contaminant mixing, especially when the contaminant is associated with the heat source, needs to be studied in detail. This work needs to address the apparently competing tendencies to mix the contaminant and to induce stratification. Also many CO sources, and other indoor heat sources, produce higher heat generation rates than those that have been examined in much of the work cited in the literature, and there is a need to understand the impacts of these higher rates on mixing.

Research is also needed to examine the impacts of ventilation-induced mixing of CO in rooms for residential ventilation system flows. Assessing the impact of ventilation flows on CO mixing in rooms needs to consider the positions of typical sources of airflow in residential rooms relative to expected positions of residential CO sources. This work also needs to consider the interactions with mixing induced by heat sources, as well as the impacts of room size and ceiling height

Research is needed to examine mixing between rooms in a house, as the work done to date has been incomplete in its consideration of the various source and house factors that are expected to impact such mixing. While the impacts of forced-air fan operation, door opening and source location have all been shown to be important, they have not been examined systematically. In particular, mixing in houses without forced-air systems, or without these systems operating, has not been examined in much detail with regards to the impacts of door opening, source location and the driving force of temperature differences between rooms. The studies of CO dispersion conducted by GEOMET (Koontz et al. 1988, GEOMET 1989) have been the most comprehensive to date, however this study was designed to study personal exposure to a point source such as a consumer product. In this study, the CO source was thermally neutral and released with no significant discharge velocity, which is not the case for most residential CO sources. Another factor to consider is that the studies of CO transport in houses, particularly those that have shown a tendency for upward flow of CO within the building, have been performed with higher temperatures indoors than outdoors. Such studies have not been performed under cooling conditions, when one would expect a downward airflow pattern within the house. Measurement or simulation efforts are needed under cooling conditions to investigate the counteracting effects of a buoyant CO source and a downward interior airflow pattern.

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