Carbon Monoxide Exposure from a Vehicle in a Garage

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ABSTRACT

A family experiencing health problems installed a carbon monoxide (CO) detector. The detector alarm was activated several times. The utility company and heating contractors verified the presence of CO but were unable to locate the source. Testing determined the source was carbon monoxide emissions from a car in the attached garage. Although the overhead garage door was open while the vehicle warmed up, high concentrations of carbon monoxide remained in the garage after the car was backed out and the door shut. Pressure differences between the garage and the house forced carbon monoxide into the house.

Carbon monoxide concentrations were measured in the tailpipe of the vehicle, in the garage, and in the house. House and garage leakage and pressure differences were measured. Operation of a garage exhaust fan effectively limits entry of carbon monoxide into the house as long as the house/garage door is closed.

INTRODUCTION

Carbon monoxide (CO) is the leading cause of poisoning deaths in the United States, killing over 3,500 persons each year. Nonfatal poisonings can cause serious damage. As many as 15% to 40% of victims of serious nonfatal CO poisonings develop neuropsychiatric symptoms (Ellenhorn and Barceloux 1988). Recognizing the serious toxic effects of CO, the Environmental Protection Agency's (EPA) primary standard for protection of community health is 9 ppm as an 8 h average concentration not to be exceeded more than once per year in any community, rural or urban. The secondary EPA standard for CO is 35 ppm, which is the maximum 1 h concentration not to be exceeded more than once per year in any community. There is no accepted United States CO standard for residential indoor air (Penney 1996).

Elevated concentrations are often found in homes. Data collected in a California study suggested that for 5% to 10% of California residents, indoor wintertime concentrations of carbon monoxide exceed the federal air standards for outdoor air. In 30% to 40% of the homes, carbon monoxide inside was measurably higher than the outdoor concentrations, thus implying the existence of indoor CO emissions (Colome et al. 1994).

Heating contractors and utility companies are responding to thousands of carbon monoxide detector alarm activations. In many cases, they do not find a source of carbon monoxide (Greiner et al. 1997). A study of 50 houses conducted to determine if the cause of multiple carbon monoxide alarm activations were "false alarms" found that in 37 cases vehicles in attached garages were potential sources of carbon monoxide in the house. In one example, garage carbon monoxide peaked at 600 ppm approximately 20 minutes after the vehicle was started and backed out of the garage. Carbon monoxide in the house rose after 2 ¾ h to a peak value of 51 ppm (Minnegasco 1997).

CASE BACKGROUND

An Iowa family bought and moved into a house in December 1993. The wife is self-employed, working from an office in the basement. For several years she experienced headaches and chest pains, most often in the winter. Doctors were unable to determine a cause for the chest pains or headaches. A passive chemical dot carbon monoxide detector next to the furnace did not noticeably change color. In November 1996, they purchased a carbon monoxide detector with audible alarm (UL 1995) and installed it in the master bedroom.

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The detector gave a low-level warning at 6 p.m. on November 18, 1996. A local heating technician was contacted, who at 7 p.m. found 25 ppm of carbon monoxide throughout the house. The furnace and water heater were inspected, but no identifiable source was determined. Carbon monoxide concentrations dropped when the house was opened and concentrations rose when the house was closed and the furnace operated. A hairline crack in the heat exchanger was suggested as the possible cause even though the technician could not find a problem with the furnace. He aired out the house, turned the heat up to 75°F (24°C) in the house (to cause the furnace to operate), and planned to check the CO concentration first thing the next morning. The family was experiencing headaches and eye irritation. He advised them to sleep elsewhere that night.

At 11:59 p.m. on November 18, 1996, the family still experienced headaches and eye irritation and their 23-month-old son was lethargic. At the emergency room that same night their measured carboxyhemoglobin levels (COHb) were 2% to 4%. Endogenous carboxyhemoglobin levels range from 0.4% to 0.7%, and smokers typically have carboxyhemoglobin levels of 5% to 9% (Ellenhorn and Barceloux 1988). They were placed on 100% oxygen for three hours. They decided to move out of the house until the carbon monoxide problem could be identified and corrected.

The next morning, November 19, the technician returned and found 5 ppm CO in the empty house. The cause of the carbon monoxide was suggested again as a hairline crack in the furnace heat exchanger. It was hypothesized that frost on the screening in the furnace intake and exhaust vents might have forced carbon monoxide from the burner into the house. The screening on the vents was removed. The water heater had a considerable amount of rust on the burner. The rust was removed. The connector vent, which had a horizontal section, was revented so the vent had a positive slope upward. The family purchased a second carbon monoxide detector, with digital display, audible alarm, and memory, and installed it in the first-floor hallway outside the bedrooms. For several days neither detector sounded. The problem was believed to be corrected, and the family returned to the house.

The wife continued to have morning headaches. She noticed that levels on the digital detector in the first-floor hallway would typically climb to 11 ppm to 17 ppm during the day. The highest readings often occurred between 10:30 a.m. and noon. When readings occasionally reached 35 ppm, she would air out the house. Several times the local utility company, plumber, or heating contractor was contacted. When the house was closed up, operation of either the furnace or the water heater would cause the CO concentrations to rise, but technicians could not pinpoint which unit caused the problem or why.

On the evening of December 20, 1996, relatives of the couple stayed overnight. They complained of difficulty sleeping, eye irritation, and headache. The next morning, December 21, the relatives warmed up their car outside the open attached garage, packed, and left. Ten minutes after their departure, the CO detector in the master bedroom alarmed (full alarm). The digital detector in the first-floor hallway did not alarm, but read 79 ppm. The local utility found "a detectable level of CO that needs correcting—needs the attention of a professional heating or plumbing specialist." Although the utility policy was to not tell homeowners of the concentrations, the couple were led to believe that the digital display detector agreed closely with the utility company's instrument. Uncertain of the cause of the carbon monoxide, the couple moved out of their home again.

On Monday, December 23, 1996, another heating contractor inspected the furnace. He explained that their furnace model had a history of heat exchanger problems and suggested that their furnace had a large crack in the heat exchanger. Arrangements were made to order and replace the heat exchanger. The thermostat was set at 55°F, and the family continued to live elsewhere.

IDENTIFICATION OF POTENTIAL CO SOURCES IN THE HOUSE

Furnace

An induced-draft furnace, with 60,000 Btu/h (17.6 kW) input, was located in the basement. The design pressure to the burners was 3.5 in. (88.9 mm) water column (wc). Burner gas pressure was above specifications, at 4.7 in. (11.9 mm) wc. Actual firing rate by clocking the gas meter was 63,000 Btu/h (18.5 kW), a 5% overfiring. Combustion analysis (resolution 1 ppm with an accuracy of ±5% reading or ±10 ppm, whichever is greater) showed that the furnace produced elevated levels of carbon monoxide in the flue products, 163 ppm CO-air-free, and was overfired. Exhaust venting was through a 2¼ in. (57.2 mm) inside diameter plastic pipe through the west side wall of the house. Velocity in the pipe was 1050 ft/min (5.33 m/s), and flow was 29 ft^3/min (13.7 L/s). Combustion air was supplied through a 2 in. (50.8 mm) inside diameter plastic pipe to the outdoors and connected to the furnace case. Airflow velocity in the intake pipe was 236 ft/min (1.2 m/s), giving a flow rate of 5 ft^3/min (2.4 L/s), a small portion of the combustion air needed. The remainder of the combustion air entered the furnace case through designed combustion air openings and incidental openings.

During an inspection with a heating technician, the burners were removed and the back cover opened. Access to the entire heat exchanger was possible. Using a mirror and flashlight, both from the burner compartment and from the exterior, no cracks were observed. During extended operation of the overfired furnace, no carbon monoxide was detected around the furnace, around the heat exchanger, coming from the registers, or within the house. The furnace was not identified as the source of CO that caused the alarms or health conditions.

Water Heater

The water heater is a 40 gal (150 L) unit rated at 35,500 Btu/h (10.4 kW). Combustion analysis showed no carbon monoxide in the flue products. The vent had proper rise (it had been replaced earlier). Under extended operation, no carbon monoxide was observed in the flue products, around the burner door, around the draft diverter, or in the home. The water heater was not identified as the source of CO that caused the alarms or health conditions.

Kitchen Range

A new kitchen range oven produced 756 ppm CO-air free upon start up, which dropped to 235 ppm after 13 minutes operation. The kitchen range oven was not in operation most of the times when elevated carbon monoxide were identified. The kitchen range oven is a source of carbon monoxide in the house, but because of the open window, the time of operation, and the use of the exhaust vent, it was not identified as the source of CO that caused the alarms or health conditions.

Fireplace

A wood-burning fireplace is located in the living room and is used by the family. When using the fireplace, a window is always opened to ensure a good draft. There was no evidence of sooting in the house. Wood-burning fireplaces are potential sources of carbon monoxide, both from spillage during operation and from downdrafting as the fire dies down. Spillage and downdrafting are serious concerns in the house. The fireplace was not used during most of the carbon monoxide incidents and, although a potential hazard, the fireplace was not identified as the source of CO that caused the alarms or health conditions.

Clothes Dryer

The clothes dryer is electric. Operation of the clothes dryer does not produce carbon monoxide, but the blower does decrease the pressure in the house relative to the outdoors.

INVESTIGATIVE PROCEDURES

The unoccupied house was evaluated by pressure testing both the house and garage, visually verifying the flow with theatrical smoke, and conducting a controlled experiment measuring CO concentrations. Combining these results led to a conclusion about the potential of a carbon monoxide exposure produced by a vehicle started in the attached garage.

The standard procedure for pressure testing was followed (ASTM 1987; CGSB 1986). The house pressure testing was conducted by placing the blower door in the front door in the east wall shown in the first floor plan in Figure 1. This testing was conducting using natural conditions (no other devices operating), under various conditions using the furnace blower, and using exhaust fans in bathrooms. Analysis of the measured values was performed by supplied software (version 1992).

The garage pressure testing was conducted by placing the blower door in the exterior west door to the garage shown in

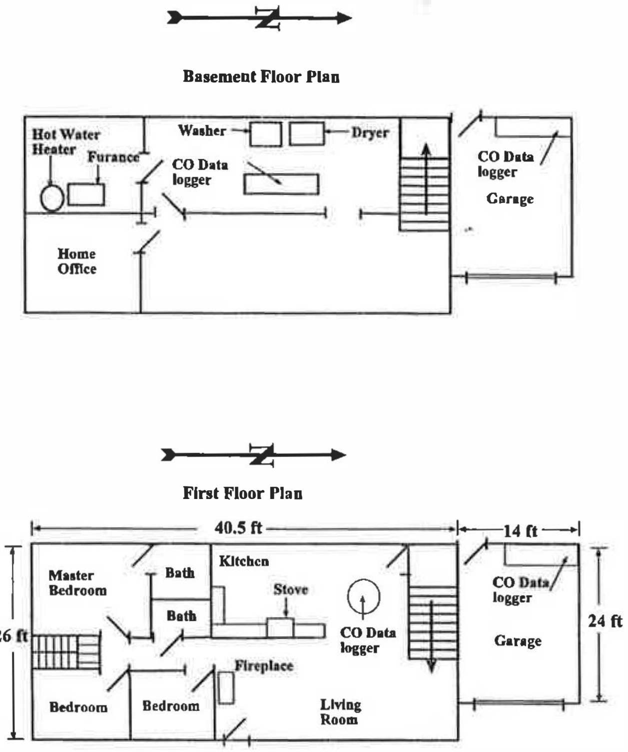

Figure 1 Floor plans of house and garage.

the first floor plan in Figure 1. This testing was conducted using natural conditions (no other devices operating).

Pressure differences were measured using a digital pressure and flow gauge (micromanometer), electronic micromanometer, and U-tube manometer. Calibration of both micromanometers was checked against the U-tube manometer and against each other at 4.0 in. wc (1000 Pa). They were within stated accuracy of ±2% of readings. Resolution of the flow gauge is 4.0×10^{-3} in. wc (1 Pa), and resolution of the electronic gauge is 1 digit at 0.1×10^{-3} in. wc (0.02 Pa). Airflows from the garage exhaust fan were measured using a micromanometer and flow hood. Airflows in the furnace intake and exhaust vents and the water heater vent were determined with a pitot tube and micromanometer with a direct readout of feet per minute with a resolution of 1 ft/min (0.3 m/s) and accuracy of ±3% of reading.

Visual verification of the interconnection between house and garage was made using theatrical smoke under natural pressure conditions (i.e., exhaust fans were operated). The garage was filled with theatrical smoke. The smoke was made by using chemical smoke and standard theatrical smoke from a smoke generator. The house was monitored for signs of theatrical smoke and elapsed time was recorded for describable events.

Weather conditions for the duration of the test were collected. The weather data are given in Table 1.

To determine if carbon monoxide from a vehicle was the source of the carbon monoxide in the house, a test sequence

TABLE 1
Weather Conditions for CO Testing

Date	Temperature		Wind	Wind
	High °F (°C)	Low °F (°C)	Average Speed mph (m/s)	Direction (degrees)
12/29/96	14 (−10)	2 (−17)	6.7 (3.2)	330
12/30/96	30 (−1)	4 (−16)	8.4 (4.0)	100

was conducted from late Sunday night, December 28, 1996, to 10 a.m., Monday, December 30. The vehicle used was the family's 1991 Ford Taurus, V-6, 183 in.^{3} (3.0 L) car with 127,000 miles (204,000 km). The vehicle was cooled for six hours in the cold garage (outside temperature 2°F [−17°C]) before testing began. The vehicle was started in the garage using a typical start-up routine of starting and warming the vehicle for two minutes in an open garage. The routine began with a person who would enter the garage from the house, open the overhead vehicle garage door using the electric garage door opener, start the vehicle, leave the vehicle running to warm up, and return to the house through the connecting house to garage door. The person would then return to the garage through the connecting house to garage door, simulate placing the child in the car seat located in the back seat, return to the driver's seat, back the car out of the garage, close the garage door using the remote control, and drive away. The sequence requires approximately two minutes to return to the house, pick up the child, position the child in the car seat, and return to the driver's seat. Backing out of the garage required approximately ten seconds, and closing the garage door required approximately ten seconds. During testing, the routine was duplicated using a two-minute time lapse from start to backout. The door-opening sequence was duplicated, including opening and closing the connecting door between the house and the garage. The door then remained shut during the following ten hours.

Carbon monoxide concentrations were taken in the tailpipe of the vehicle. A modular gas analyzer was used to measure tailpipe CO concentrations. The analyzer measures the CO concentration with a resolution of 100 ppm. The instrument was within 4% of a certified calibration gas concentration of 80,000 ppm.

The house remained closed. Carbon monoxide concentrations were recorded in the closed garage, in the kitchen, and in the basement. The CO concentrations in the garage were recorded with a gas unit with temperature compensation. The gas unit measures the CO concentration with a resolution of 1 ppm of ±3% of reading or 4 ppm, whichever is greater. The unit collected CO concentrations every minute for the first 47 minutes of the test. The unit was located on a work surface at the back of garage as shown in the first floor plan of Figure 1. Two grab samples were taken with a probe under the weather stripping on the house to garage door. The CO concentration was measured with a resolution of 1 ppm and accuracy of ±5% of reading or 10 ppm, whichever is greater. The samples were taken at 2:25 a.m. and 10:00 a.m.

The CO concentrations were measured in the house in the kitchen and basement. CO data loggers were placed on the kitchen table, as shown in the first floor plan of Figure 1, and on an exercise bench in the basement exercise room, as shown in the basement floor plan of Figure 1. The data loggers used are not temperature compensated, so they were calibrated at 70°F (21°C) and used inside the house, which was kept at 70°F (21°C). These units measure the CO concentrations with a resolution of 1 ppm and accuracy of ±3%.

All units were calibrated using calibration gas within 30 days prior to the investigation. Calibration was checked 3 days after the investigation. All instruments read to within ±4% of calibration gas values. Before entering the house for the testing, instruments were zeroed in outside air. The house is located in a rural Iowa town with no nearby industrial activity. No outside ambient carbon monoxide was detected.

FINDING AND RESULTS OF INVESTIGATION

Blower Door Testing

A blower door was used to measure air leakage. Accuracy is within ±3%. The house CFM50 (standard cubic feet per minute at 0.20 in. wc [50 Pa] test pressure) was 871 cfm (411 L/s), equivalent leakage area was 47.67 in.^{2} (30.8×10^{-3} m^2), and estimated natural infiltration was 48 cfm, (22.7 L/s) or 0.17 air changes per hour (ACH). The garage CFM50 was 801 cfm (378 L/s), equivalent leakage area was 41.46 in.^{2} (26.7×10^{-3} m^2), and estimated natural infiltration was 0.88 ACH.

Interconnection Between House and Garage

The house and attached garage share a common foundation wall, an above-grade wall, and an attic. The garage is finished, with plaster wallboard over the interior walls and ceiling. The wall between the house and garage is drywalled on both sides with an electrical outlet on the garage side and on the house side in the living room. The interior door connecting the house and the garage is weather-stripped, as is the exterior garage access door to the backyard and the sectional overhead vehicle door. The overhead vehicle door did have visible gaps between the door and the frame. An access door to the attic was located in the garage.

The interconnection between house and garage was estimated using a blower door and the Blasnik (1990) "add a hole" method. The equivalent leakage area, house to garage, is estimated to be 19.74 in.^{2} (12.7×10^{-3} m^2). The leakage of the house, including the house to garage wall is 47.67 in.^{2} (30.8×10^{-3} m^2). The proportion of the leakage entering the house through the garage is 41% of the 47.67 in.^{2} (30.8×10^{-3} m^2). Based on the hole sizes, it is likely that a large proportion of the air entering the house comes from the garage.

Visual Verification

Theatrical smoke was immediately observed entering the house at the bottom of the door between the house and the garage, around and through the electrical outlet in the living room, and from the foundation beam pocket in the basement. Within five minutes, smoke was observed coming from under the ceiling drywall in the basement. Within ten minutes, smoke was observed coming from the drywall around the center beam in the utility room at the end of the house opposite the garage. A noticeable haze from the theatrical smoke was observed in the entire house within 60 minutes. When the east-facing overhead garage door was opened, the theatrical smoke in the garage did not immediately blow out of the garage, but "hung" in the garage. The wind was blowing at approximately 5 mph (2.4 m/s) from the west. With both the overhead door opened and the outside entry door in the opposite (west) wall opened, the smoke quickly was blown out of the garage through the overhead garage door opening.

Worst-Case House Pressures

Worst-case testing was performed. House pressures were measured under various conditions using a digital micromanometer. The pressure difference between the basement utility room and outdoors, without any fans or furnace blower operating, was -2.0×10^{-3} in. wc (−0.5 Pa). The pressure difference between the basement utility room and outdoors increased when the furnace blower was operated. Starting at the furthest room, pressures differences between the room and the space connecting the room with the utility/furnace room in the basement were checked; doors to rooms with pressures higher than the utility room were closed, while doors to rooms with pressures lower than the utility room were opened. The following doors were opened (more return than supply): southeast bedroom to hall, southwest master bedroom to hall, east bedroom to hall, kitchen to basement, and basement family room to basement laundry. The following doors were closed (more supply than return): hall bath to hall, master bath to master bedroom, master bath to kitchen, and basement study to basement family room. The furnace supply air register in the utility/furnace room, normally open, was closed.

Exhaust fans in both bathrooms were operated. The clothes dryer was operated, as was the kitchen range hood fan. This was the worst case. Maximum pressure difference between the basement utility room and outdoors was -19.2×10^{-3} in. wc (−4.8 Pa). Airflow in the 3 in. (76.2 mm) diameter water heater vent reversed. Although flow was downward, combustion gases from the water heater changed flow direction and established draft within 60 seconds after burner ignition.

Opening the supply air register reduced the pressure difference between the basement and outdoors from -19.2×10^{-3} in. wc to -12.8×10^{-3} in. wc (−4.8 Pa to −3.2 Pa). With the supply open, airflow in the 3 in. (76 mm) water heater vent was out of the house, and draft was immediately established after burner ignition.

Under natural conditions (i.e., no exhaust fans or furnace blower operation), the pressure difference between the garage and outdoors was -0.4×10^{-3} in. wc (−0.1 Pa). The pressure difference between the house and the garage was -1.6×10^{-3} in. wc (−0.4 Pa). Under worst-case conditions, the pressure difference between the garage and outdoors increased to -0.8×10^{-3} in. wc (−0.2 Pa) and the pressure difference between the house and the garage increased to -18.4×10^{-3} in. wc (−4.6 Pa). Measured pressures fluctuated considerably from stated values, typically $\pm12.0\times10^{-3}$ in. wc (±3 Pa). To reduce fluctuations, ten readings taken once per second were averaged. The digital micromanometer has a ten-second averaging function. Electronic micromanometer readings were manually averaged. To verify that the small pressure differences measured caused airflow, smoke testing was conducted. Under all conditions tested, airflow, verified by chemical smoke pencil testing around the house to garage door frame, was from the garage into the house. When exhaust fans or the furnace blower were operated, the pressure difference between the house and the garage increased. Airflow, as demonstrated by use of a smoke pencil around the house to garage door and electrical outlets located in the common wall, visibly increased.

CO Concentrations from the Vehicle Exhaust

Vehicles produce higher carbon monoxide concentrations on a cold start due to cold engine surface, a rich fuel/air mixture, and a cold catalytic converter (ASHRAE 1995). Figure 2 shows the CO tailpipe concentrations. The concentrations reached 87,200 ppm one minute after starting and dropped to 76,900 ppm after two minutes. The tail pipe concentration when the garage door closed was 60,000 ppm. After the vehicle was driven at 20 mph to 30 mph for 15 minutes, tailpipe CO concentrations decreased to 300 ppm.

CO Concentrations in the Garage

Carbon monoxide concentrations increased rapidly in the garage, even though the overhead garage door was opened (Figure 3). The CO concentrations in the garage increased to 450 ppm after one minute of operation of a cold engine started in the garage. Another minute of operation raised the concentration to 500 ppm. The vehicle was removed from the garage after two minutes and the garage door shut. Carbon monoxide concentrations remained at 500 ppm for six minutes, then began falling to 420 ppm after 47 minutes. Concentrations in the garage remained elevated for several hours after the vehicle was removed from the garage, with 411 ppm after 2 hours, 25 minutes, and 30 ppm after 10 hours. Using a probe from outdoors, no carbon monoxide was detected around the overhead door cracks.

Carbon Monoxide Concentrations in the House

Carbon monoxide concentrations in the basement rose to a peak value of 20 ppm after 40 minutes. Figure 4 shows that

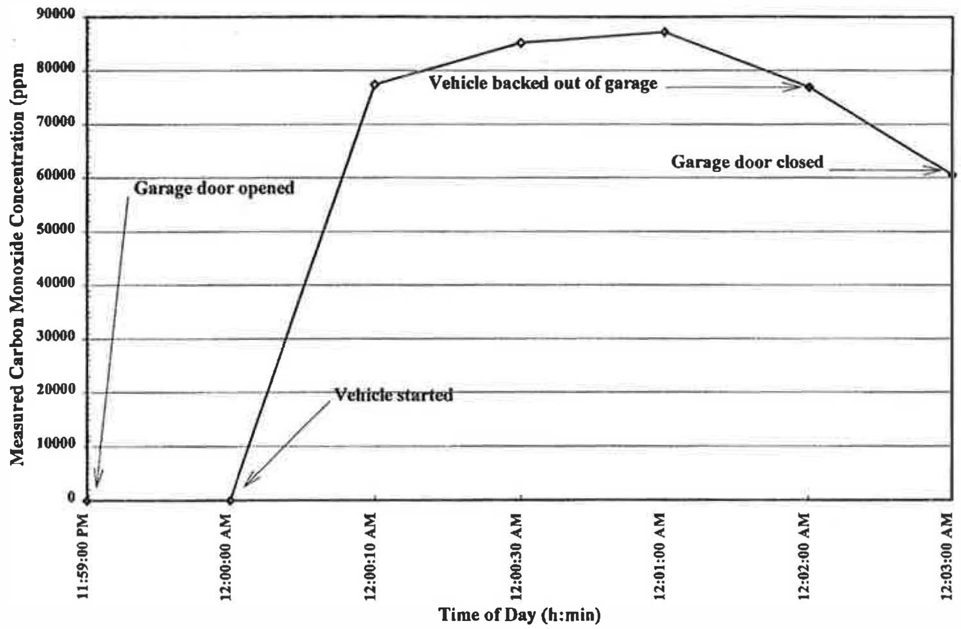

Figure 2 *Measurement of CO concentrations in vehicle tailpipe.*

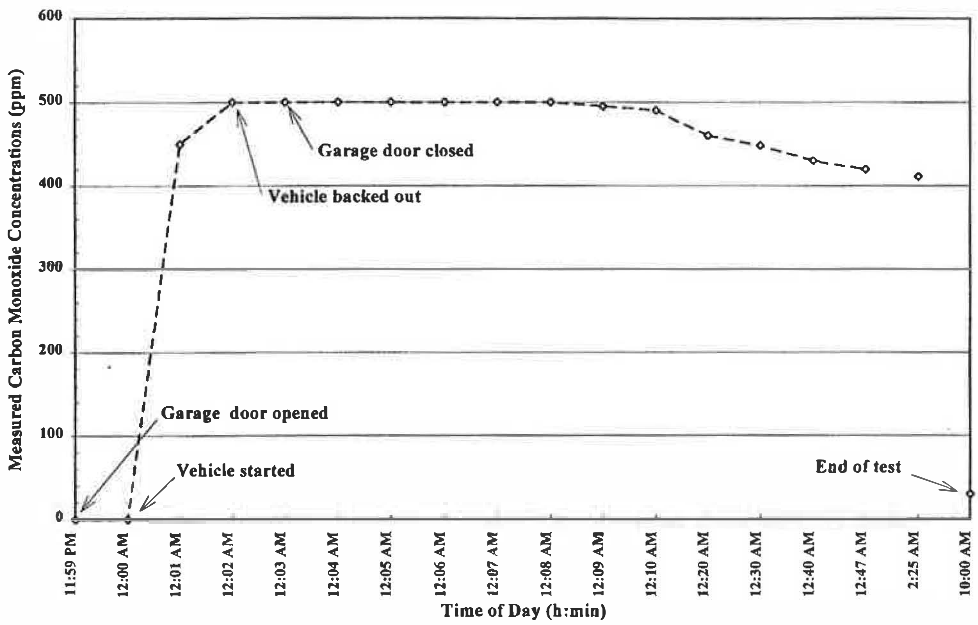

Figure 3 *Measured CO concentrations in the garage.*

concentrations in the kitchen rose more slowly, reaching 14 ppm after 40 minutes. The peak CO concentration for the kitchen was 20 ppm after 117 minutes. Furnace and blower operated as controlled by a thermostat set at 70°F (21°C).

Two hours after first starting the car, concentrations in the kitchen and basement were equal. Concentrations then decreased more quickly in the basement room. At 11 a.m. (11 hours after the car was first started), several doors and windows in the garage and house were opened. Within ten minutes, CO concentrations decreased to an undetectable level.

Measures to Avoid Future CO Exposure

To avoid future exposures from the garage, an exhaust fan in the garage was designed and installed. The system was sized to slowly remove low-level CO concentrations from the garage and to depressurize the garage relative to the house. Depressurization causes air to flow from the house to the garage, thus preventing garage contaminants from entering the house. An 8 in. (203 mm) diameter, centrifugal in-line duct fan rated at 492 cfm (232 L/s) at 0.125 in. wc (31.3 Pa) static pressure was used. A variable-speed fan controller was installed. Fan speed was increased until the pressure difference between

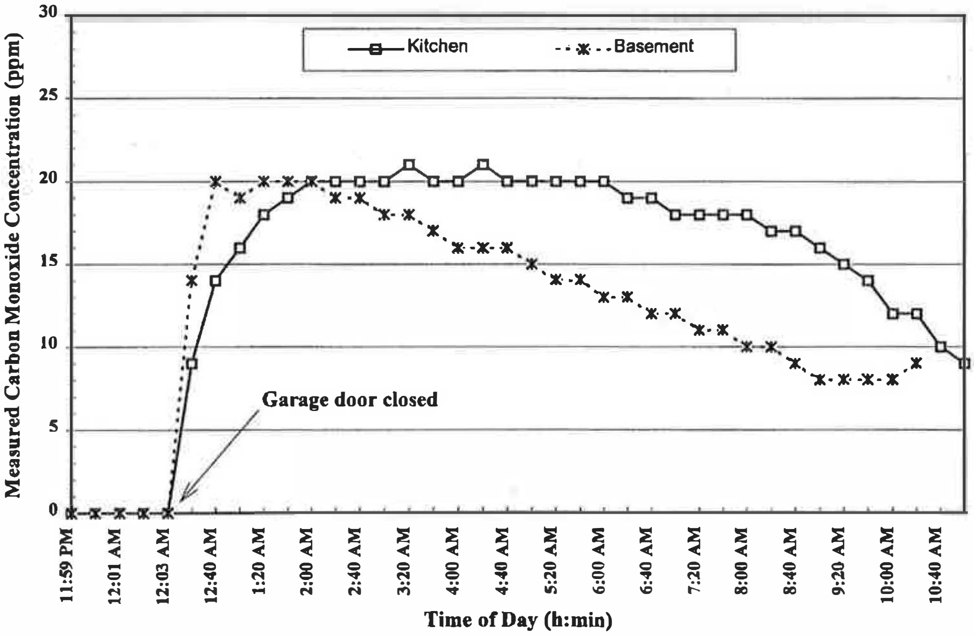

Figure 4 *Measured CO concentrations in the kitchen and basement.*

the garage and house was 16.0×10^{-3} in. wc (4.0 Pa) relative to the house. Flow through the fan was measured at 278 cfm (131 L/s). Operation of the fan effectively reverses flow direction from the garage to the house, as verified using theatrical smoke, pressure measurements, and a tracer gas test. Carbon monoxide, produced by briefly operating a lawn mower in the garage, was used as the tracer gas. Carbon monoxide concentrations in the garage increased to above 600 ppm. After two hours, no carbon monoxide was detected in the house. The garage was then thoroughly aired out by opening outside doors.

To avoid entry of other garage contaminants, the garage fan operates continuously. The exhaust fan was designed to reduce entry of CO into the house but was not adequate to allow operation of a combustion engine in the garage except for the short time needed to immediately back out from the garage.

Operating the garage fan increased the pressure difference between the house and outdoors from -2.0×10^{-3} in. wc to -19.6×10^{-3} in. wc (–0.5 Pa to –4.9 Pa) and reversed airflow direction in the water heater vent when the burner was not operating. The pressure and reversal raised concerns about future reliability of the vent (CMHC 1988). When the burner was ignited, the water heater did establish draft, but to reduce the possibility of intermittent vent failure two additional measures were taken. First, a 6 in. (152 mm) combustion air/make-up air opening was added to the south side of the house. This reduced the pressure difference between the basement utility room and outdoors to 1.6×10^{-3} in. wc (0.4 Pa) (furnace blower operating and supply air register in the room open). Second, a powered induced-draft fan blower, with safety shut-off, was added to the water heater.

CONCLUSIONS

The primary source of carbon monoxide in the house was CO emitted from a vehicle started in the attached garage. The vehicle, when first started, emitted high concentrations of carbon monoxide (87,200 ppm). Some of the carbon monoxide emitted, even with the overhead door opened, remained and was pulled into the garage and trapped when the overhead door was closed.

The measured pressure in the garage was lower than the outside pressure, preventing the release of CO to the outside. Pressure in the house was lower than pressure in the garage, establishing flow from outdoors into the garage and from the garage into the house. The balance between pressures and airflows caused CO concentrations in the garage and house to remain elevated for several hours after the CO was emitted. Visual confirmation was achieved by theatrical smoke.

There were several reasons CO from operating a vehicle in or near the garage was a likely source. Understanding the events surrounding the CO exposure is key to identifying CO sources. The four identifiers in this case follow:

1. The digital CO detector often registered the highest readings between 10:30 a.m. and noon.
2. Readings did not correlate with operation of the furnace, water heater, kitchen stove, or fireplace.
3. CO readings occurred after the operation of a vehicle in or outside the garage.
4. The family routinely allowed the car to briefly warm up in the garage (with the overhead garage door open).

The exhaust fan installed in the garage is effective at preventing CO entry into the house from the garage. After six months of operation, the only known occurrence of carbon monoxide in the house occurred when a car was left idling in the garage with the overhead garage door open and the house to garage door open. The digital CO detector showed a reading of 11 ppm, which was quickly reduced to zero by opening the front and back door of the house. The family indicates fewer headaches, and headache occurrences do not appear to be associated with starting the car in the garage.

This study concludes that

- CO detectors warned the family of the presence of toxic carbon monoxide concentrations,
- correct diagnosis of CO exposures is more complex than investigating the furnace and hot water heater for spillage of CO,
- small differentials in pressures within a house, garage, and outside can promote CO transfer from carbon monoxide emitted during vehicle starts in an attached garage, and
- heating contractors, plumbers, and utility technicians did not consider CO transfer from the garage.

ACKNOWLEDGMENTS

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