#5598

The Effects of Building Features on Indoor Air and Pollutant Movements

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ABSTRACT

Full-scale residential house tests were conducted and it was found that the activated heating and air-conditioning (HAC) system served as a conductor that enhanced the indoor air movement and transported pollutants from their sources to the rest of the house. The interior door functioned either as a barrier or as a channel for the air exchange between the room and the rest of the house. The outside window had leaks. The area exhaust fan was a very effective pollutant remover when properly used.

It is recommended that either an outside window or exhaust fan be installed in rooms where indoor pollutants may occur. Should the indoor air pollutants be accidentally released, it is recommended that the source be isolated by closing the door of the room and turning off the HAC system. Outside windows should be open, and the area exhaust fan in the polluted room should be kept on for several hours to completely dissipate the indoor air pollutants.

INTRODUCTION

Common household activities, such as using aerosol cans, can create sources for potential indoor air pollution (Jackson et al. 1990). When air pollutants are released from an indoor source, the distribution of the air pollutants depends on air movements inside the building. On the other hand, when the source and sink strength is fixed, the severity (concentration and duration) of the indoor air pollution depends primarily on the air exchange rate between the inside and outside of the building (Sparks 1988). Both air movement and air exchange rates can be affected by such building characteristics as floor plan, insulation, and indoor conditions. For finished and occupied buildings, the indoor conditions can be controlled and adjusted by the heating and air-conditioning (HAC) system, windows, doors, and area exhaust fans.

In order to study the effects of such building features on indoor air and pollutant movements, experiments were conducted in a full-scale house. Carbon monoxide (CO) was used as a tracer to represent the gas-phase pollutants from aerosol products. A fixed amount of CO was released in a controlled manner to simulate use of an aerosol can. The concentrations of CO at several locations inside the house were monitored to establish the time history curves. CO was used as a tracer instead of sulfur hexafluoride (SF_6) because the analysis of SF_6 is costly and time-consuming; it was impractical and difficult to get good time resolution for the concentration changes.

The objectives of the experiment were to investigate the functions of four building features—the HAC system, the inside door, the outside window, and the area exhaust fan. The impacts of those building features on indoor conditions and the movement of indoor air pollutants were also evaluated. The intent was to find out what indoor conditions may lead to serious pollution and what measures can be taken to prevent or minimize indoor air pollution from sources such as aerosol cans.

EXPERIMENTS

The experiments were conducted in the Environmental Protection Agency's Indoor Air Quality (IAQ) Test House (Figure 1). Details of the house have been reported by Tichenor et al. (1990).

The CO source used was a high-pressure gas tank with CO purity of 99%. CO was injected into either the main bathroom (E1) or the master bathroom (E2) through 0.64 cm (0.25 in.) diameter tubing. The volume of CO released was controlled at 50 litres for each test and was measured by an on-line dry-gas meter. It took about 20 seconds to release 50 litres of CO. When CO was injected into the main bathroom (E1), air was sampled in the main bathroom, hallway, corner bedroom, and den (S1s in Figure 1). When CO was injected into the master bathroom (E2), air in the master bathroom, master bedroom, hallway, and den was sampled (S2s in Figure 1). The sampling probes were located at the center of each room, 1.6 m (63 in.) above the floor. For each room, the sampling was conducted once every 15 minutes. The CO concentrations in the samples were measured by a continuous CO monitor that has a range of 0-200 ppm. With the HAC system off and the gas-heated hot water tank at normal working condition, the background CO concentration in the test house was usually below 1 ppm with a typical value of 0.6 ppm. Higher CO background concentration was observed when the natural gas central heating system was on, but it was still less than 3 ppm.

The building features tested include:

- HAC system (on/off)
- bathroom door (open/closed)
- master bathroom window (open/closed)
- main bathroom exhaust fan (on/off)

Since there are four building features and each can be set at two positions, a total of 16 (2^4) tests were conducted to cover a complete test matrix. All the windows and outside doors were closed except for the master bathroom window, which was open by

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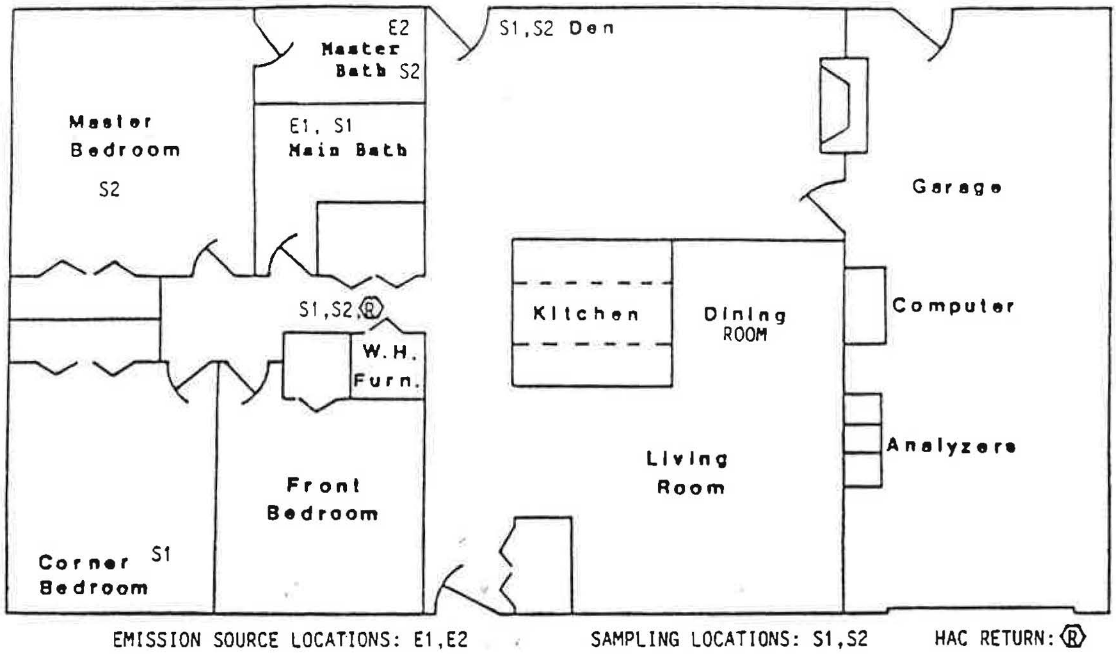

Figure 1 EPA IAQ test house

5 cm (2 in.) for two tests. All the interior doors were open except for the bathroom doors, which were closed for four tests. The indoor temperature was maintained at 20 °C.

RESULTS AND DISCUSSIONS

A summary of the testing conditions for all 16 tests is listed in Tables 1 and 2. Figures 2-12 show the time history CO concentration profiles as a function of sampling locations for selected tests.

As far as exposure risk is concerned, test #2 represents the worst case in the main bathroom. As shown in Figure 2A, the CO concentration in the main bathroom stayed above 200 ppm (the upper detection limit) for more than seven hours. This occurred because the CO was released in the main bathroom with the HAC system off, the exhaust fan off, and the main bathroom door closed. Since the main bathroom is located near the center of the house, the only way for the CO to dissipate after its release was to be transported slowly by diffusion and leaks through the interior walls and around the main bathroom door. Figure 2B shows that the CO concentrations were fairly even in the rest of the house, which reflects the slow processes of diffusing and leaking out of the main bathroom.

However, when CO was released with the HAC system on (test #3), the CO concentration of the main bathroom stayed above 200 ppm for less than one hour (Figure 3A), which is significantly shorter than the seven hours observed in test #2 with the HAC system off (Figure 2A). Figure 3B shows that, for test #3, the CO concentration in the hallway was considerably higher than that in the corner bedroom and the den until the CO concentrations evened out throughout the whole house. The reason is that the HAC system return is in the hallway (Figure 1). Apparently, when the HAC system was on, the fan created a pressure differential between the hallway and the main bathroom that significantly increased the CO diffusion and leaking

TABLE 1
Summary of Tests #2-#9
(with CO released into the main bathroom)

Test ID	#2	#3	#4	#5	#6	#7	#8	#9
HAC System	off	on	on	off	off	on	on	off
Bath Door	closed	closed	open	open	closed	closed	open	open
Bath Fan	off	off	off	off	on	on	on	on
Bath Window	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

TABLE 2
Summary of Tests #10-#17
(with CO released into the master bathroom)

Test ID	#10	#11	#12	#13	#14	#15	#16	#17
HAC System	off	on	on	off	off	on	on	off
Bath Door	closed	closed	open	open	closed	closed	open	open
Bath Fan	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Bath Window	closed	closed	closed	closed	open	open	open	open

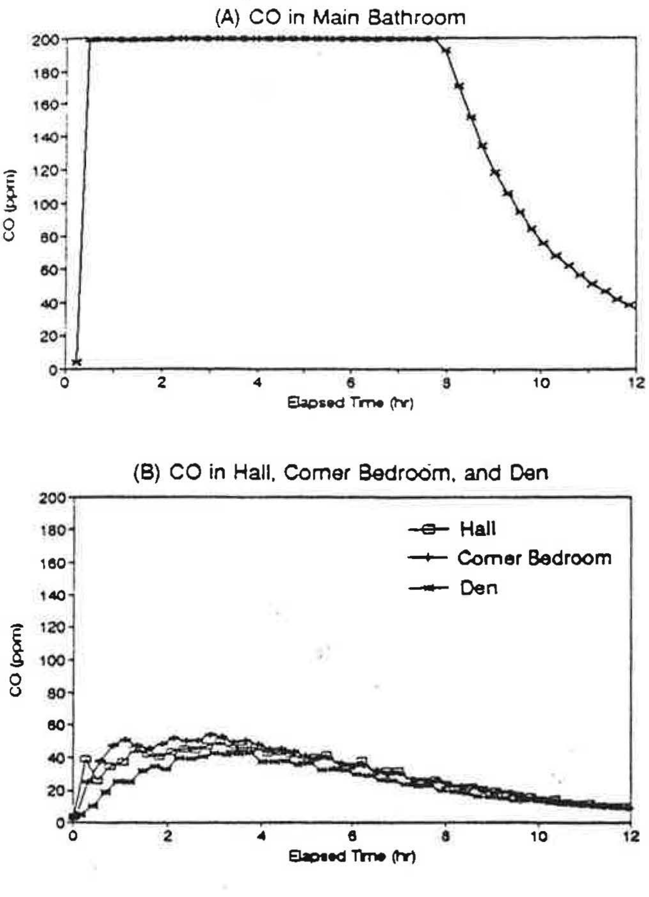

Figure 2 *Test #2—CO released into the main bathroom with the HAC off, the main bathroom door closed, and the fan off*

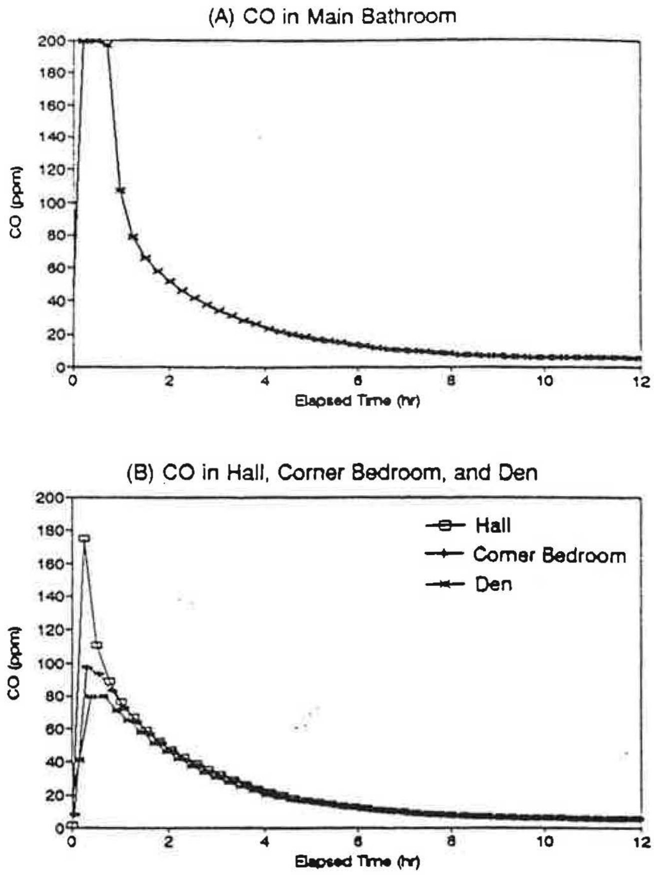

Figure 3 *Test #3—CO released into the main bathroom with the HAC on, the main bathroom door closed, and the fan off*

rates out of the main bathroom. As a result, the CO concentration of the main bathroom decreased much faster with the HAC system on (Figure 3A) than with the HAC off (Figure 2A). Since the CO had to pass the hallway before it was transported through the HAC duct to the rest of the house, the CO concentration in the hallway stayed higher than that in the rest of the house until it was equalized. Comparison of Figure 3B with Figure 2B indicates that the HAC system also affected the peak CO concentrations in the hallway, corner bedroom, and den.

During tests #4 and #8, the main bathroom door was kept open while the HAC was on. The difference between the two tests is that the exhaust fan was turned off during test #4 and was on during test #8. The CO time history curves obtained from those two tests are very similar, which indicates that the indoor air movement was not significantly affected by the functions of the exhaust fan when the main bathroom door was open and the HAC system was on. Figure 4A indicates that the main bathroom CO concentration never exceeded 200 ppm during test #4 and decreased faster than those observed in tests #2 and #3. Figure 4B shows that the CO concentrations remained fairly even throughout the house during test #4. Comparison of test #4 (Figure 4B) with test #3 (Figure 3B) shows that, with the main bathroom door open, the hallway peak CO concentration decreased, but peak CO concentrations in the corner bedroom and the den increased. This occurred because, first, the source (main bathroom) CO concentrations never exceeded 200 ppm during test #4 (Figure 4A) and, secondly, opening the main bathroom door provided a CO transportation channel with little resistance, which significantly increased the air exchange between the rooms. As a result, the main bathroom CO did not have a chance to accumulate to the high levels observed in previous tests. The hallway air was also transported rapidly by the HAC fan to the rest of the house, and good mixing was achieved throughout the house.

The HAC system was turned off during tests #5 and #9 and the main bathroom door was kept open. Although the exhaust fan was on during test #5 and off during test #9, the CO time history curves obtained from those two tests are very similar. The results confirmed that, with the main bathroom door open, the indoor air movement was not significantly affected by the functions of the exhaust fan indicated by tests #4 and #8. The effects of the HAC fan on the internal air exchange rate are illustrated by comparisons between tests #4 (Figure 4) and #5 (Figure 5). Due to the lowered internal air exchange rate caused by the inactive HAC system, the CO concentrations accumulated to higher levels during test #5 (Figures 5A and 5B) than during test #4 (Figures 4A and 4B). The effect of opening the main bathroom door on the air movement between the rooms can be illustrated by comparisons between tests #5 and #2. Apparently, the air exchange rate between the main bathroom and the hallway increased when the main bathroom door was kept open, which shortened the time that the main bathroom CO concentration stayed above the 200 ppm level (Figure 5A vs. Figure 2A). On the other hand, the increased air exchange rate caused the higher peak CO concentrations in the hallway, corner bedroom, and den (Figure 5B vs. Figure 2B).

Tests #6 and #7 were designed to evaluate the effects of the main bathroom exhaust fan and its interactions with the HAC system. During test #6, the HAC system was turned off, the main bathroom door was closed, and the main bathroom ex-

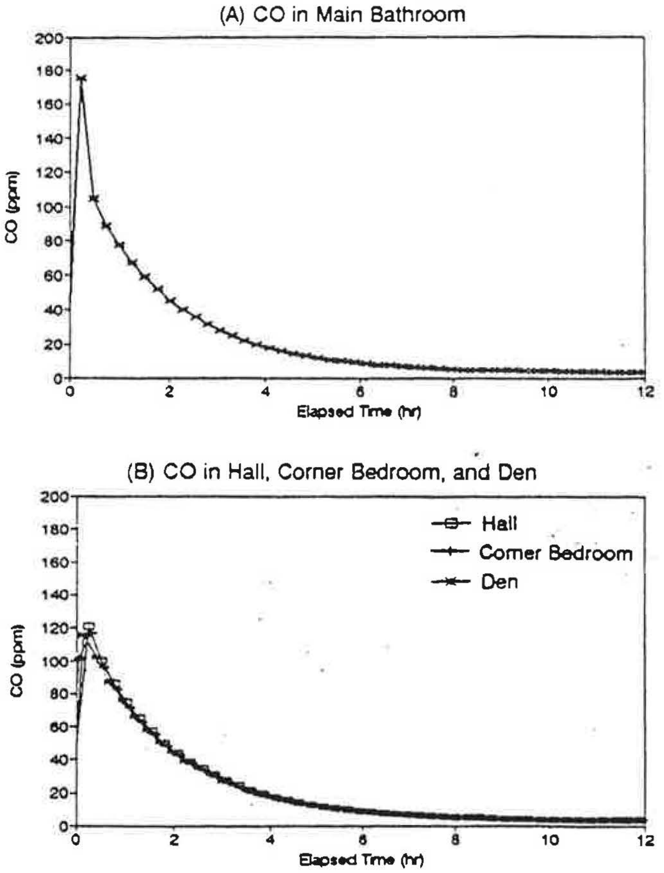

Figure 4 Test #4—CO released into the main bathroom with the HAC on, the main bathroom door open, and the fan off

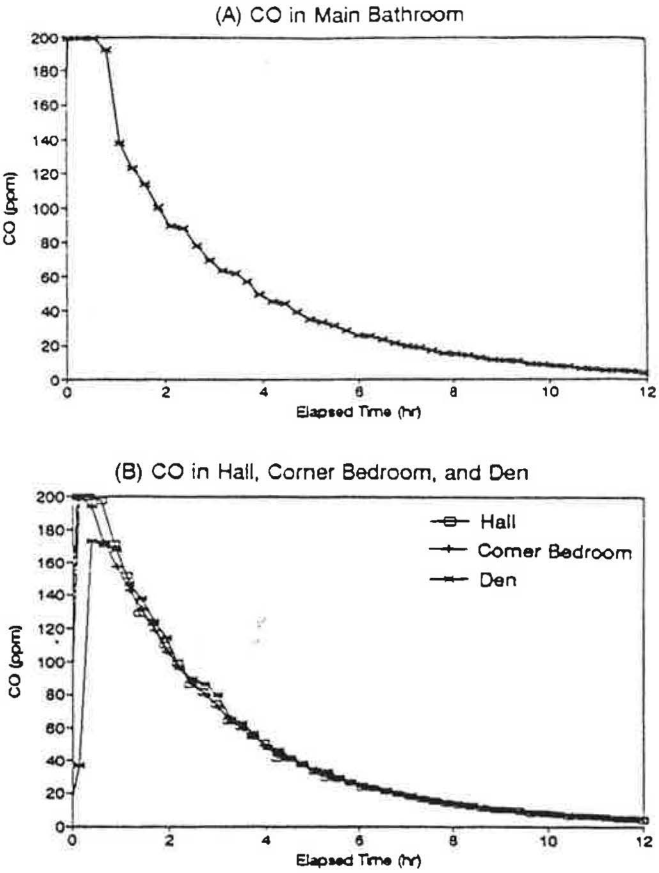

Figure 5 Test #5—CO released into the main bathroom with the HAC off, the main bathroom door open, and the fan off

haust fan was on. The objective was to isolate the CO in the main bathroom and use the mechanical draft (the exhaust fan) to withdraw the polluted air. Comparison between the CO time history curves of test #6 (Figure 6A) with that of test #3 (Figure 3A) shows that the exhaust fan worked even better than the HAC system fan in terms of decreasing the peak CO accumulation of the main bathroom when the door was closed. Furthermore, the CO concentrations in the rest of the house (Figure 6B) stayed low (below 7 ppm) throughout the test period, which was the best of the 16 tests. In other words, the CO contamination was largely confined in the main bathroom during test #6 and the CO exposure risk in the rest of the house was greatly reduced.

Both the HAC system and the main bathroom fan were on for test #7. The two fans were competing with each other in moving air out of the main bathroom. As a result, the CO concentration peak of the main bathroom (Figure 7A) was narrower than that of test #6 (Figure 6A). But the air moved out by the HAC system was also transported to the rest of the house through the HAC duct, which caused the moderate CO concentrations shown in Figure 7B.

CO was released in the master bathroom (Figure 1) for the next eight tests (tests #10 to #17). The differences between the master and the main bathrooms are that the former has an outside window but not an exhaust fan, the latter does not have any windows but has an exhaust fan, and their locations relative to the HAC system return are quite different (Figure 1).

Test #10 was conducted with the HAC system off, the master bathroom door closed, and the outside window closed. Figure 8A shows that the CO concentration in the master bathroom increased rapidly and stayed above 200 ppm for more than five hours, which reflects the restricted air movements under the test conditions. Comparing Figures 8A and 2A shows that the CO peak is narrower for test #10 than for test #2, probably because the test #10 CO release was in the master bathroom, which has an outside window. Although the window was closed, the air and CO in the bathroom still leaked to the outdoors through the cracks around the window. As a result, less CO accumulation was observed in the master bathroom (Figure 8A) than in the main bathroom (Figure 2A). Figure 8B shows the CO concentration profiles in the rest of the house for test #10. The CO concentration in the master bedroom was considerably higher than that in the hallway and the den until the CO concentrations in those three rooms equilibrated. Since the CO had to pass through the master bedroom first when it was transported to the rest of the house (Figure 1), it is reasonable for the master bedroom's CO concentration to rise and accumulate to levels above those in the rest of the house, especially when the air movement was relatively slow because the HAC system was turned off during test #10.

The HAC system was turned on for tests #11 and #15. The difference between those two tests is that the master bathroom's outside window was closed during test #11 and open during test #15. The CO time history curves obtained from the two tests are very similar, which indicates that the indoor air movement was not significantly affected by the positions of the master bathroom's outside window during those two tests. However, when compared with test #10 (Figure 8A), test #11 (Figure 9A) shows that the CO peak in the master bathroom was narrower, which indicates a faster air movement out of the bathroom as a result of the active HAC system. The fast air movement is also

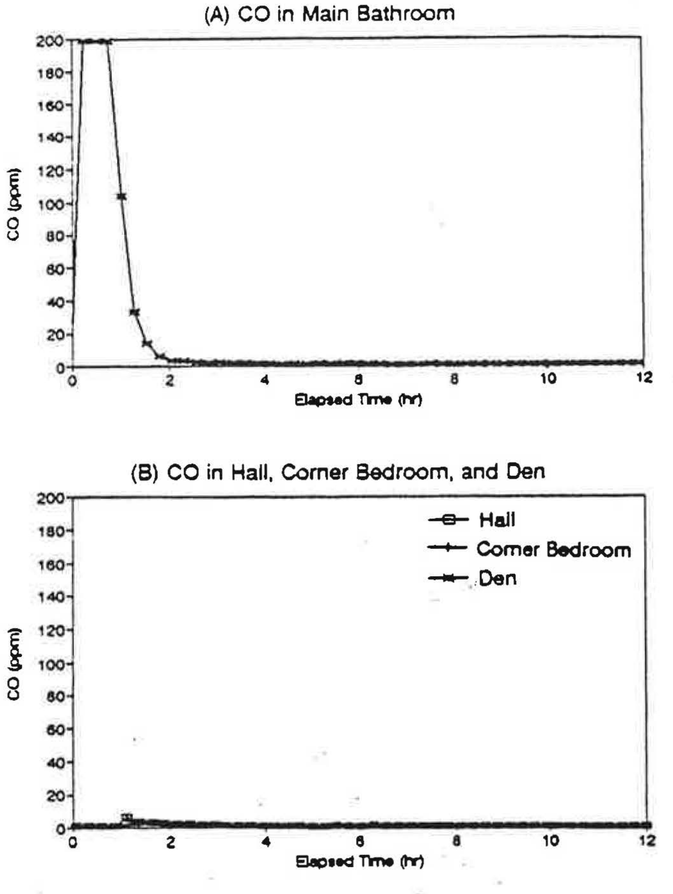

Figure 6 Test #6—CO released into the main bathroom with the HAC off, the main bathroom door closed, and the fan on

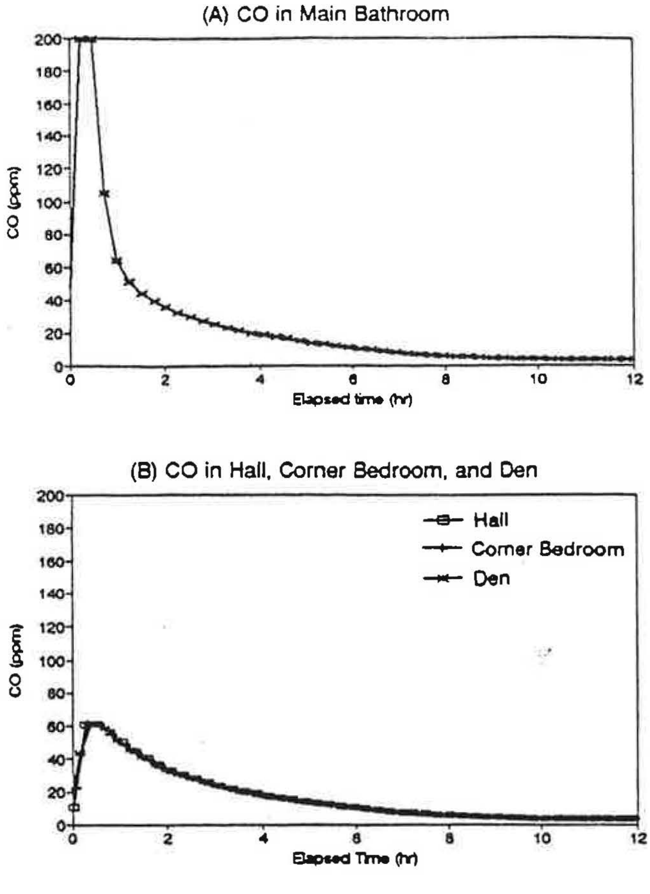

Figure 7 Test #7—CO released into the main bathroom with the HAC on, the main bathroom door closed, and the fan on

reflected by the high and narrow CO concentration peaks shown in Figure 9B. The impact of location of the bathrooms relative to the HAC system return can be illustrated by comparing tests #3 (Figure 3A) and #11 (Figure 9A) The proximity of the main bathroom to the HAC system return makes the HAC system more effective in enhancing the air and CO movement out of the room and causes the CO concentration peak to be narrower in Figure 3A than in Figure 9A.

The effects of the master bathroom's door on air movement were confirmed by tests #12 and #13, which have similar CO time history curves. Previous results in test #4 (Figure 4) indicate that opening the main bathroom door provides a transportation channel with little resistance, which tends to narrow the main bathroom (source) CO concentration peaks. This channeling effect was confirmed by comparing test #12 (Figure 10) with test #11 (Figure 9).

Test #14 was conducted with the HAC system off, the master bathroom door closed, and the outside window open. The experimental design and test objectives were very similar to those of test #6. The major difference is that test #14 used a natural draft (an open window) and test #6 used a mechanical draft (an exhaust fan) to withdraw the isolated polluted air. Figures 11A and 6A show similar bathroom CO accumulation patterns for the two tests, but, for the rest of the house, Figure 11B shows higher and larger CO concentration peaks than those of Figure 6B. It is apparent that the exhaust fan withdrew the CO-laden air from the main bathroom much faster than the natural draft did through the open window.

Tests #16 and #17 were conducted with both the master bathroom's door and the master bathroom's outside window open. Similar CO time history curves were obtained from those two tests with the HAC system on during test #16 and off during test #17. On the other hand, comparisons show that, although test #16 (Figure 12A) exhibited master bathroom CO accumulation patterns similar to those of test #7 (Figure 7A), the CO concentrations in Figure 12B, were generally higher than those in Figure 7B. These comparisons confirm that the mechanical draft by the exhaust fan was more effective than the natural draft through the open window in withdrawing the polluted air from inside the house to the outside.

CONCLUSIONS AND RECOMMENDATIONS

The IAQ Test House data indicate that the four building features tested can significantly affect the indoor air movement, the level and duration of indoor air pollution, and the exposure risk of the occupants. The air movement inside the test house was significantly enhanced when the HAC system was on. The HAC system duct acted as a conductor that transported air and pollutants from the source to the rest of the house. On the other hand, the interior door functioned as a barrier to the diffusion and leakage of air when it was closed. When it was open, it acted as a channel with little resistance to air movement. The outside window leaked inside air to the outside even when it was closed. The exhaust fan effectively depleted pollutants when the polluted air was properly isolated by closing the door of the room and turning off the HAC system.

For building design, it is recommended that an exhaust fan be installed not only in all bathrooms but also in rooms where potential air pollutants may occur, such as kitchens, storage rooms, and workshops. If no exhaust fan is to be in-

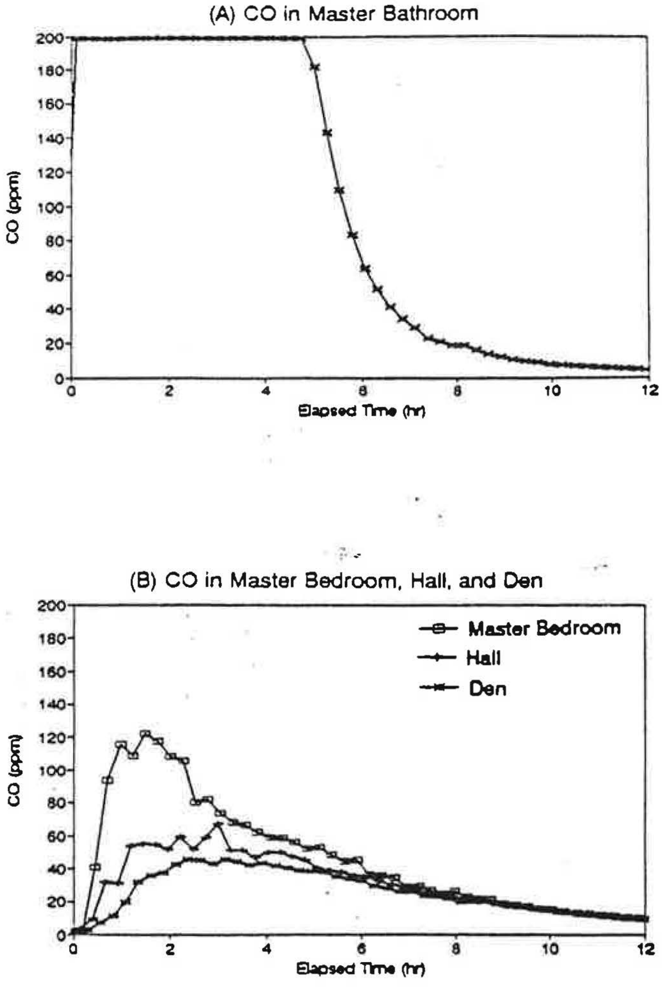

Figure 8 *Test #10—CO released into the master bathroom with the HAC off and the master bathroom door and window closed*

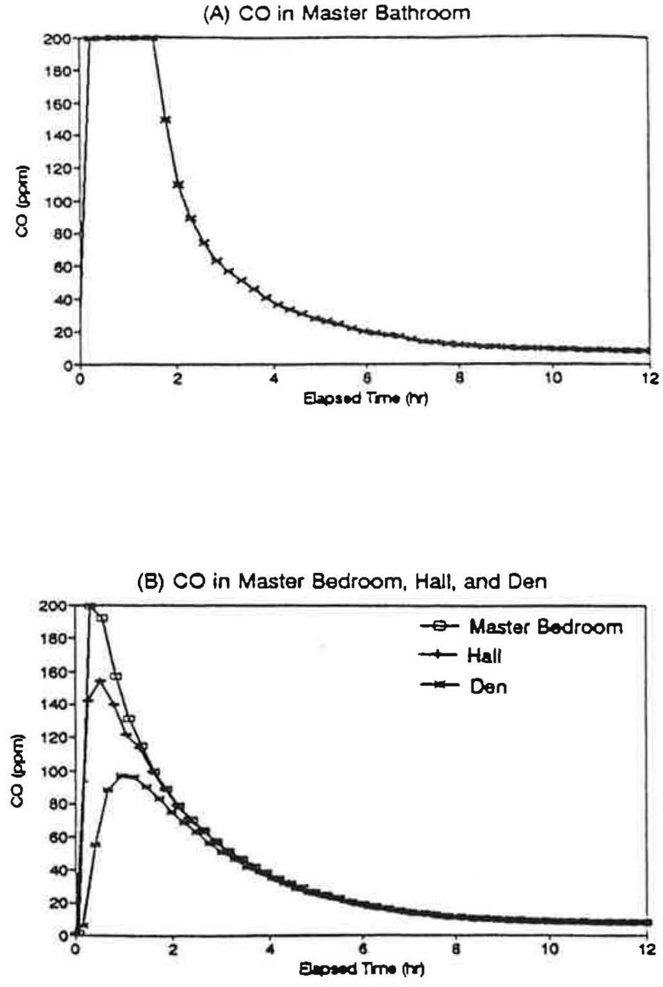

Figure 9 *Test #11—CO released into the master bathroom with the HAC on and the master bathroom door and window closed*

stalled in such rooms, outside doors and/or windows are recommended.

For people who use aerosol cans indoors, it is recommended that they turn off the central HAC system before engaging in the activity to minimize the exposure risk of vulnerable occupants in the rest of the house. The HAC should not be turned on again until the air pollutant has dissipated. It is also recommended that the exhaust fan (if there is one) be turned on and that outside windows and doors be opened to reduce the exposure levels.

If air pollutants are accidentally released, it is recommended that the exhaust fan be turned on, the central HAC system be turned off, and outside windows and doors be opened. The door leading into the house should be closed to isolate the pollutants. Again, the HAC system should not be turned on until all the pollutants are dissipated.

The experiments used CO as a tracer. Since CO is a gas at room temperature, the test house experiments actually simulated the conditions under which pollutants evaporate immediately after they are released from aerosol cans. CO has a very low affinity to most indoor surfaces; therefore, no sink effects were evaluated by the current experiments.

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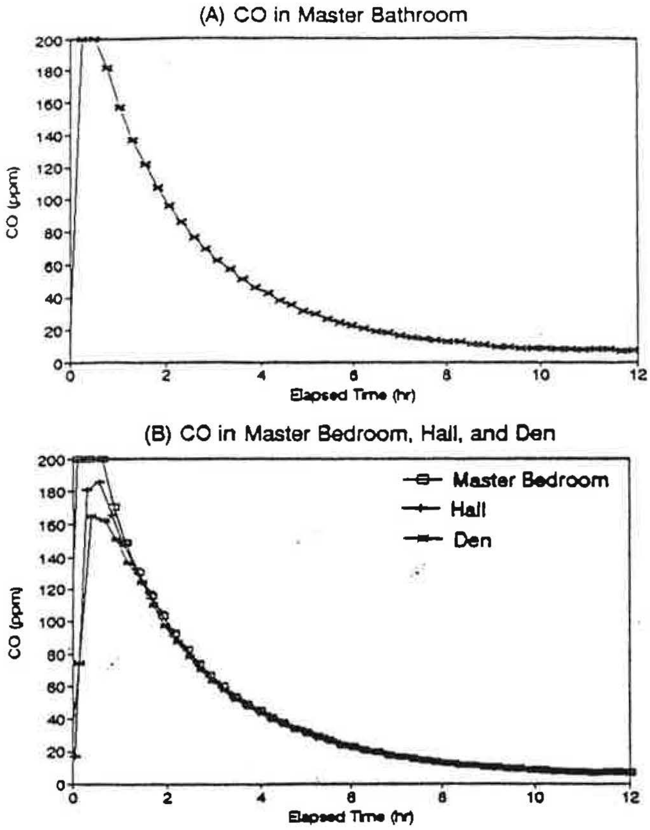

Figure 10 *Test #12—CO released into the master bathroom with the HAC on, the master bathroom door closed, and the window open .*

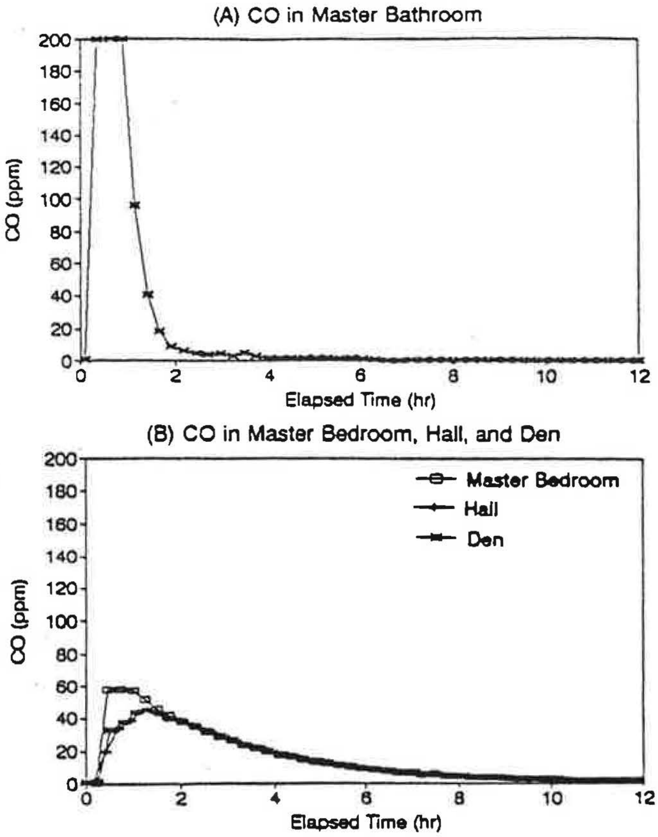

Figure 11 *Test #14—CO released into the master bathroom with the HAC off, the master bathroom door closed, and the window open*

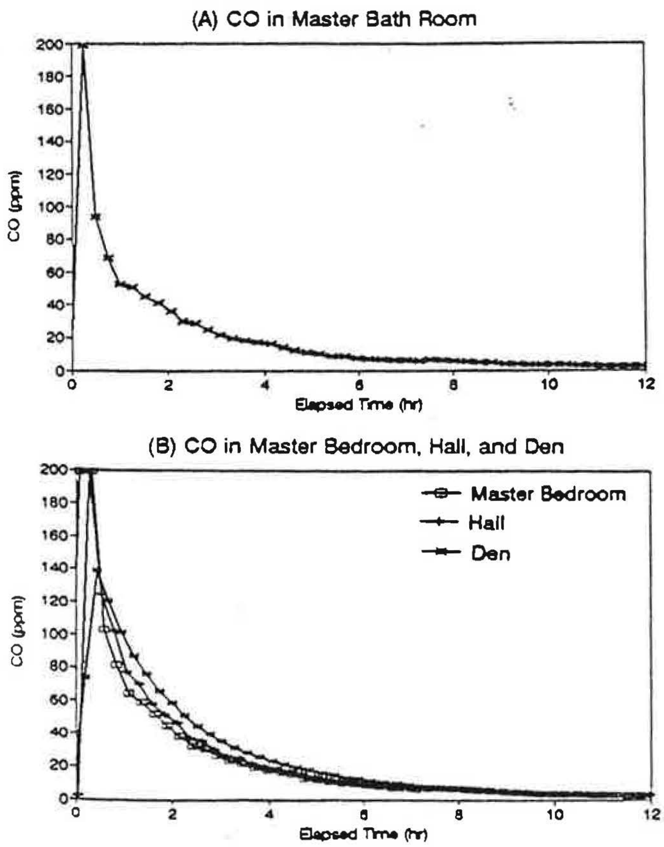

Figure 12 *Test #16—CO released into the master bathroom with the HAC on and the master bathroom door and window open*