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The Effects of Building Features on Indoor Air and Pollutant Movements

John C.S. Chang and Zhishi Guo

SUMMARY

Full-scale residential house tests were conducted to study the effects of building features on indoor air and pollutant movements. It was found that the activated heating and air-conditioning (HAC) system served as a conductor which enhanced indoor air movement and transported pollutants from the sources to the rest of the house. Interior doors functioned either as a barrier or as a channel for air exchange between the source room and the rest of the house. The outside window reduced pollution due to leaks. The area exhaust fan was a very effective pollutant remover when properly used.

INTRODUCTION

Common household activities, such as those using aerosol cans, can create potential indoor air pollutants. For instance, it has been shown that, depending on a building's features, pollutants released from an aerosol can could stay in a house for up to four days. (Jackson et al. 1990). When air pollutants are released from an indoor source, the distribution of these pollutants depends on the air movement 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 managing such building features as the heating and air-conditioning (HAC) system, windows, doors, and area exhaust fans.

Dr. John C. S. Chang is a project officer in the Indoor Air Branch, Air and Energy Engineering Research Laboratory, U.S. Environmental Protection Agency. He is responsible for research on residential indoor air quality and biocontaminants. He earned his doctoral degree in chemical engineering from the University of Texas at Austin.

Dr. Zhishi Guo is a Staff Scientist in the Environmental Systems Division, Acurex Corporation. His doctoral research at the University of North Carolina at Chapel Hill was in heterogeneous photochemical reactions. Dr. Guo works in indoor source and sink testing, model development, and indoor air quality simulation.

To study the effects of 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 the aerosol can application. The concentrations of CO at several locations inside the house were monitored to establish time history curves. The reason that CO, instead of sulfur hexafluoride (SF_6), was used as a tracer was that 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 research were to investigate the functions of specific building features—the HAC system, two bathroom doors, the master bathroom window, and the main bathroom exhaust fan. The impact of those building features on the indoor conditions and on the indoor air pollutant movements were also evaluated. It was intended to find out what indoor conditions may lead to serious pollution and what measures can be taken to prevent and minimize indoor air pollution from sources such as aerosol cans.

EXPERIMENTAL

The experiments were conducted in the EPA Indoor Air Quality (IAQ) Test House (**Figure 1**). The total volume inside the house was estimated to be 300m^3. The house has a natural gas heating and electric air-conditioning HAC system. HAC supply registers are located in each room including the two bathrooms. The HAC return-air vent is located in the middle of the house as shown in **Figure 1.** The main bathroom has an exhaust fan with an estimated capacity of 50m^3/h. The details of the house have been reported earlier (Tichenor et al. 1990).

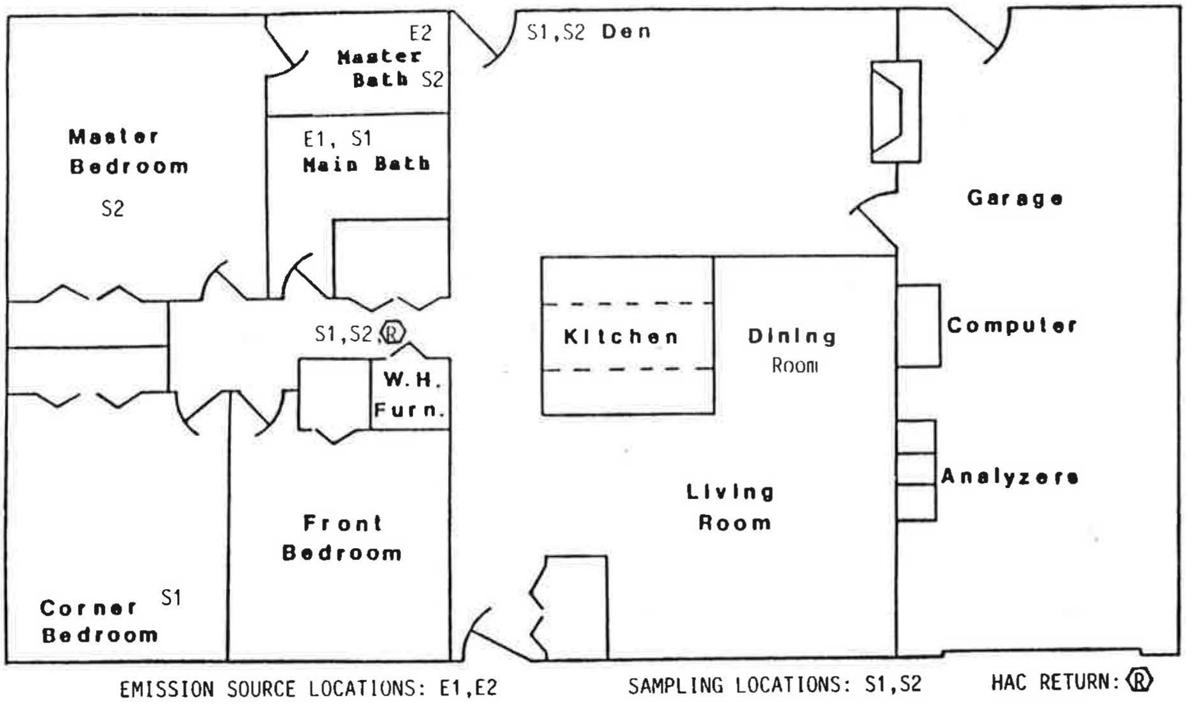

Figure 1: EPA Indoor Air Quality Test House.

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 0.64cm (0.25 in.) diameter tubing. The volume of CO released was controlled at 50 liters (STP) for each test and was measured by an on-line dry gas meter. It took approximately 20 seconds to release 50 liters of CO. For tests with main bathroom (E1) CO injection, indoor air was sampled from 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 frequency was once every 15 minutes. The CO concentrations in the indoor air samples were measured by a continuous CO monitor (Thermo Electron Model 48) which 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 effects of building features tested included:

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

Table 1. Summary of Tests #2—#9 (with CO introduced 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

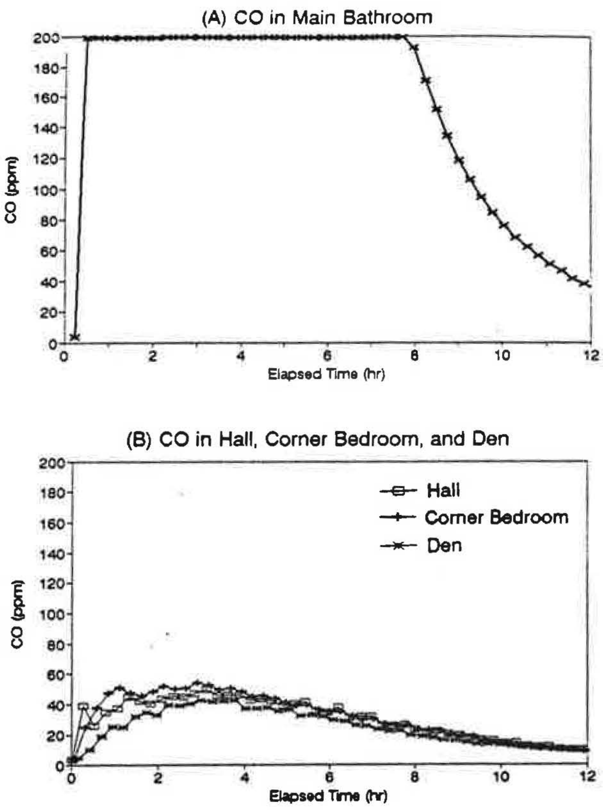

Figure 2: Test #2—CO was released from main bathroom with HAC off/main bathroom door closed/fan off.

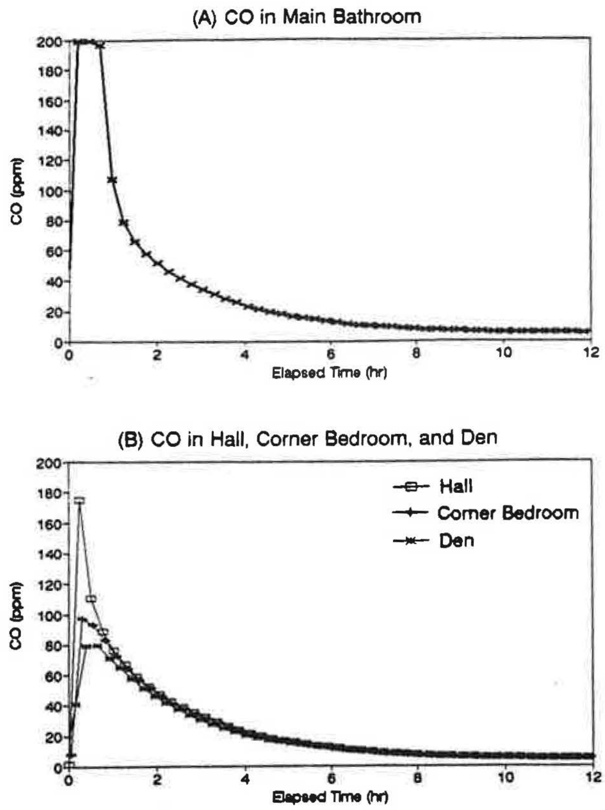

Figure 3: Test #3—CO was released from main bathroom with HAC on/main bathroom door closed/fan off.

Since there were four building features and each could 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 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 DISSCUSSIONS

A summary of the testing conditions of the 16 tests conducted 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 main bathroom CO concentration stayed above 200 ppm (the upper detection limit) for more than 7 hours. This was because the CO was released in the main bathroom with the

Table 2. Summary of Tests #10—17 (with CO introduced into the master bathroom).

Test Id	#10	#11	#12	#13	#14	#15	#16	#17
HAC System	off	on	on	off	off	on	on	off
BathDoor	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

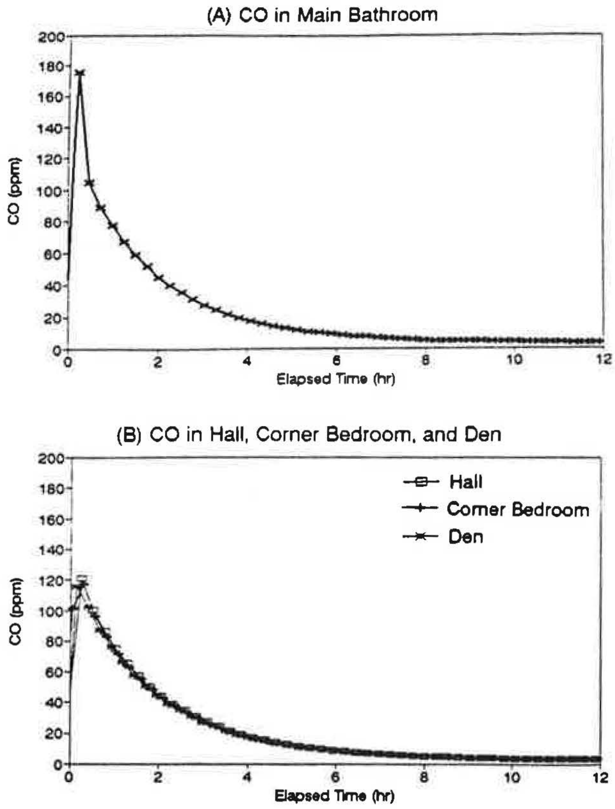

Figure 4: Test #4—CO was released from main bathroom with HAC on/main bathroom door open/fan off.

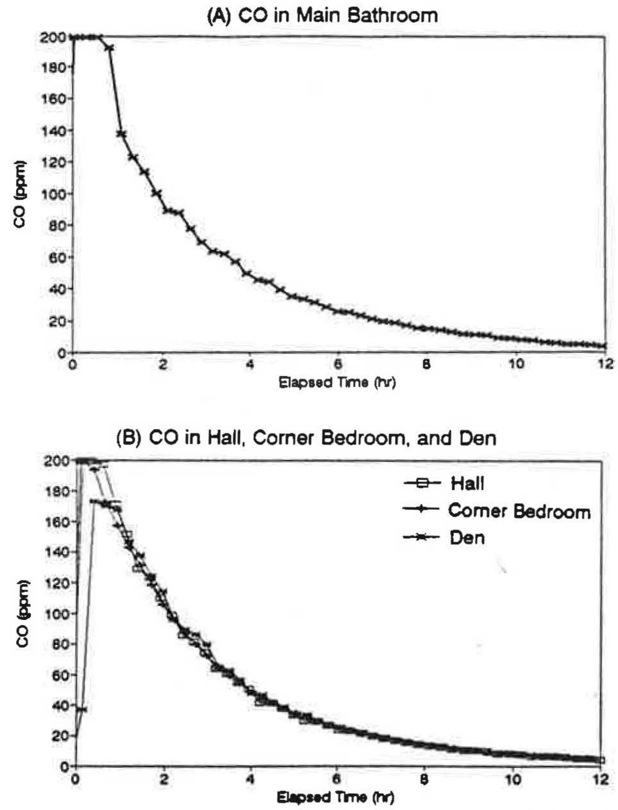

Figure 5: Test #5—CO was released from main bathroom with HAC off/main bathroom door open/fan off.

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 interior walls and around the main bathroom door. **Figure 2B** shows that CO concentrations were pretty even in the rest of the house, which reflects the slow process of diffusing and leaking out of the main bathroom.

However, when CO was released with the HAC system on (Test #3), the main bathroom CO concentration stayed above 200 ppm for less than 1 hour **(Figure 3A)** which is significantly shorter than the 7 hours observed in Test #2 with the HAC system off **(Figure 2A)**. **Figure 3B** shows that, for Test #3, the initial CO concentration in the hallway was considerably higher than that in the corner bedroom or the den, although CO concentrations later evened out throughout the whole house. The reason for the high initial hallway concentration is that the HAC system return is in the hallway **(Figure 1)**. Apparently, when the HAC system is on, the fan creates a pressure differential between the hallway and the main bathroom. This significantly increased the CO diffusion and leaking rates out of the main bathroom. As a result, the main bathroom CO concentration decreased much faster with the HAC system on than with it off. Since the CO had to pass through the hallway before it was transported via the return duct to the rest of the house, it was reasonable for the hallway CO concentration to stay higher than that of the rest of the house until the areas equalized. Comparison of **Figure 3B** with **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 two tests differed in that the exhaust fan was turned off during Test #4 and on during Test #8. The CO time history curves obtained from these two tests are very similar. This indicates that 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 on. **Figure 4A** indicates that the main bathroom CO concentration never exceeded 200 ppm during Test #4 and it decreased faster than in Tests #2 and #3. **Figure 4B** shows that the CO concentrations remained pretty 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

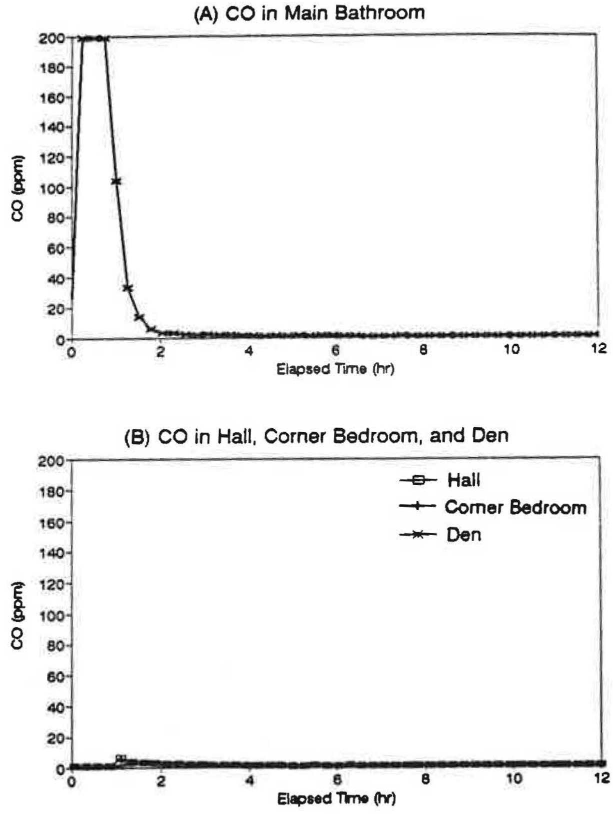

Figure 6: Test #6—CO was released from main bathroom with HAC off/main bathroom door closed/fan on.

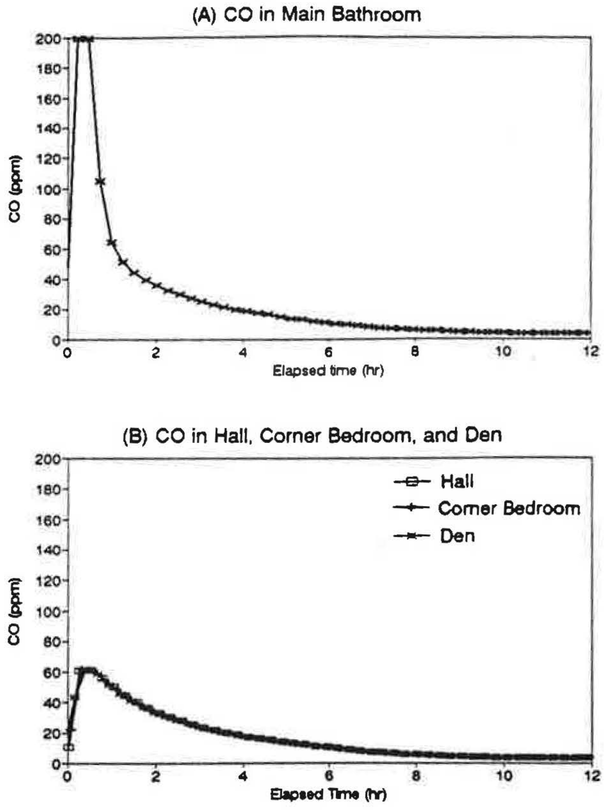

Figure 7: Test #7—CO was released from main bathroom with HAC on/main bathroom door closed/fan on.

the corner bedroom and the den increased. This was because

- first, the source (main bathroom) CO concentrations never exceeded 200 ppm during Test #4 (Figure 4A), and
- second, opening the main bathroom door provided a CO transportation channel with little resistance, significantly increasing 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 with the main bathroom door kept open. Although the exhaust fan was on during #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 function 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 (Figures 4) and #5 (Figures 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 than during Test #4. The effects 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 period the bathroom CO concentration stayed above the 200 ppm level (Figure 5A vs. 2A). On the other hand, the increased air exchange rate caused higher CO concentrations in the hallway, corner bedroom, and den (Figure 5B vs. 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 exhaust fan was on. The objective was to isolate the CO in the main bathroom and use a mechanical draft (the exhaust fan) to withdraw the polluted air. Comparison between the CO time history curves of Test #6 (Figure

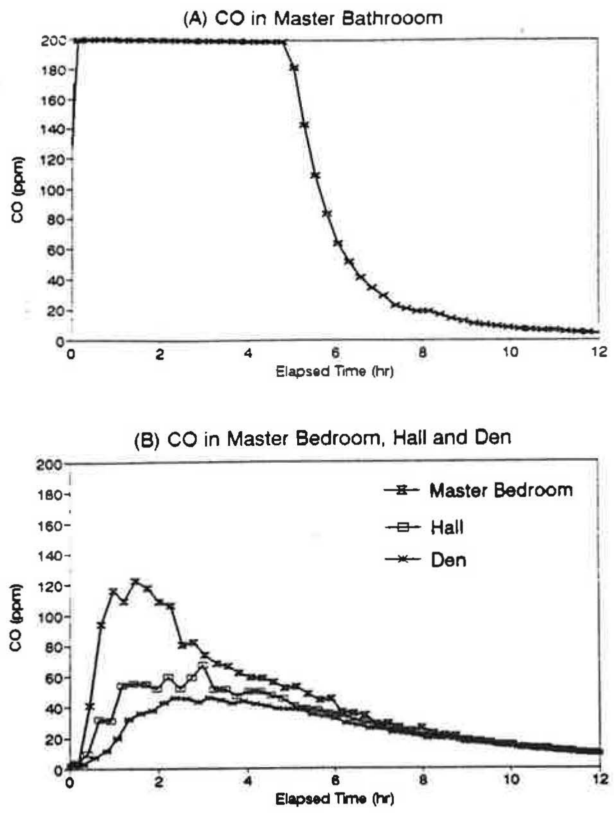

Figure 8: Test #10—CO was released from master bathroom with HAC off/master bathroom door closed/window closed.

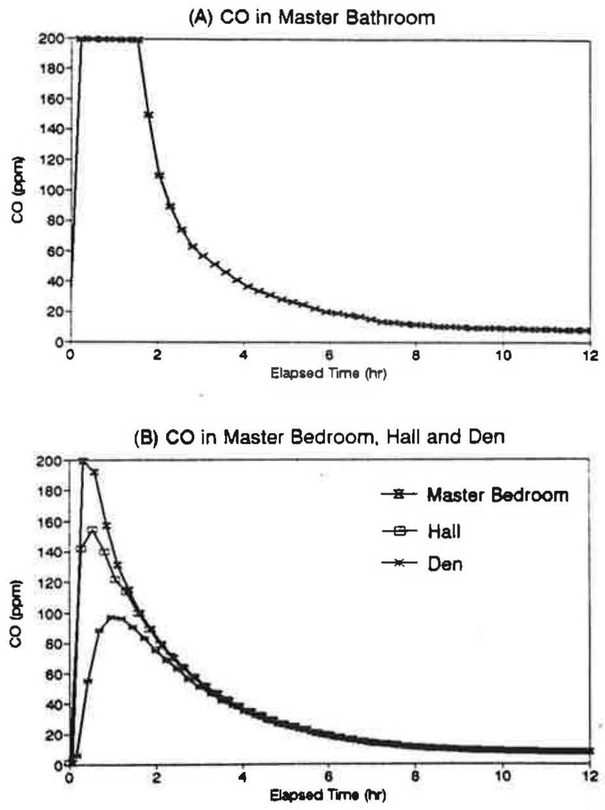

Figure 9: Test #11—CO was released from master bathroom with HAC on/master bathroom door closed/window closed.

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 main bathroom CO accumulation when the main bathroom door was closed. Furthermore, the CO concentrations in the rest of the house **(Figure 6B)** was the lowest (below 7 ppm) of the test period. In other words, CO contamination was largely confined to 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 to move air out of the main bathroom. As a result, the main bathroom CO concentration peak **(Figure 7A)** was less 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 return HAC duct which caused the moderate CO concentrations shown in **Figure 7B**.

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

Test #10 was conducted with the HAC system off and the master bathroom door and outside window closed. **Figure 8A** shows that the CO concentration in the master bathroom increased rapidly and stayed above 200 ppm for more than 5 hours. This reflected the restricted air movements under test conditions. Comparing **Figures 8A** and **2A** shows that the CO peak is narrower for Test #10 than for Test #2. This is probably because the Test #10 CO release was in the master bathroom which has an outside window. Although the window was closed, there were still leaks through 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 master bedroom is the room where the CO had to pass through first as it was transported to the rest of the house, it is reasonable for the master bedroom's CO concentration to rise and accumulate to levels above those in the rest of

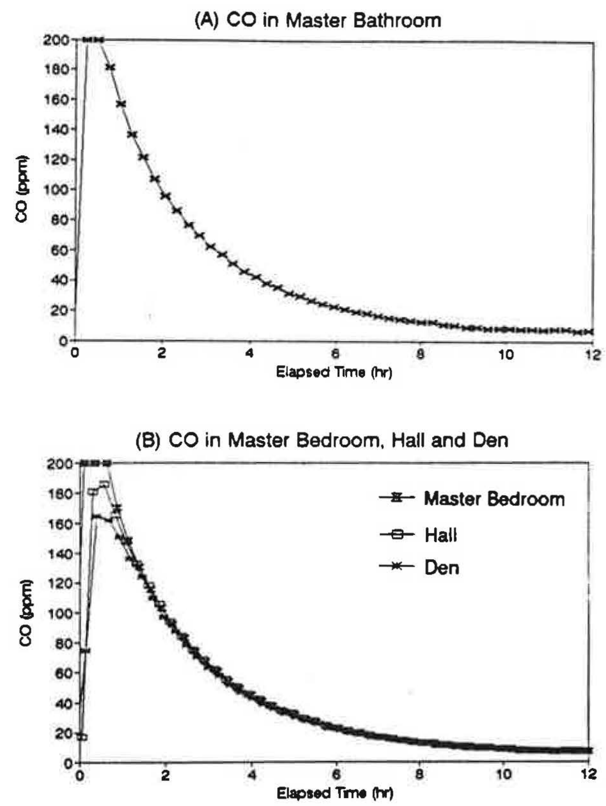

Figure 10: Test #12—CO was released from master bathroom with HAC on/master bathroom door closed/window open.

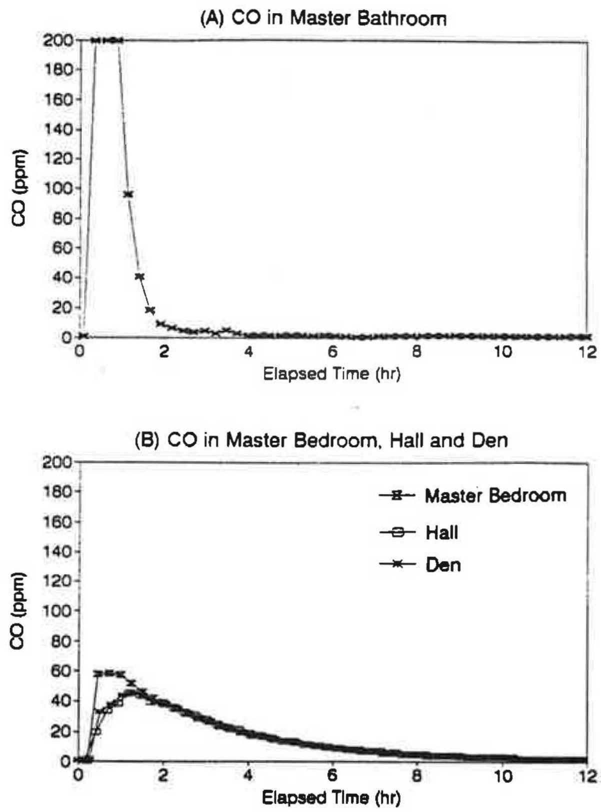

Figure 11: Test #14—CO was released from master bathroom with HAC off/master bathroom door closed/window open.

the house, especially when the air movements were relatively slow due to an inactive HAC system.

The HAC system was turned on for Tests #11 and #15. The differences between those two tests were that the master bathroom 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 master bathroom outside window positions during those two tests. However, when compared with Test #10 (**Figure 8A**), Test #11 (**Figure 9A**) shows that the master bathroom CO peak was narrower which indicated a faster air movement out of the bathroom as a result of the active HAC system. The fast air movement is also reflected by the high and narrow CO concentration peaks shown in Figure 9B.

The impact of the bathroom locations relative to the HAC system return can be illustrated by comparing Tests #3 (**Figures 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 that bathroom and caused the CO concentration peak to be narrower in **Figure 3A** than in **Figure 9A**.

The effects of the master bathroom door on air movements were confirmed by Tests #12 and #13 which have similar CO time history curves. Test #4 (**Figure 4**) had previously indicated that opening the main bathroom door provided a transportation channel with little resistance; this tended to narrow the main bathroom (source) CO concentration peaks. This channeling effect was confirmed by comparing Test #12 (**Figures 10**) with Test #11 (**Figures 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 differences were that the current test used natural draft (an open window) and Test #6 used mechanical draft (an exhaust fan) to withdraw the isolated polluted air. **Figure 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 forced draft of the exhaust fan was more effective than the natural draft through the window opening in reducing CO concentrations.

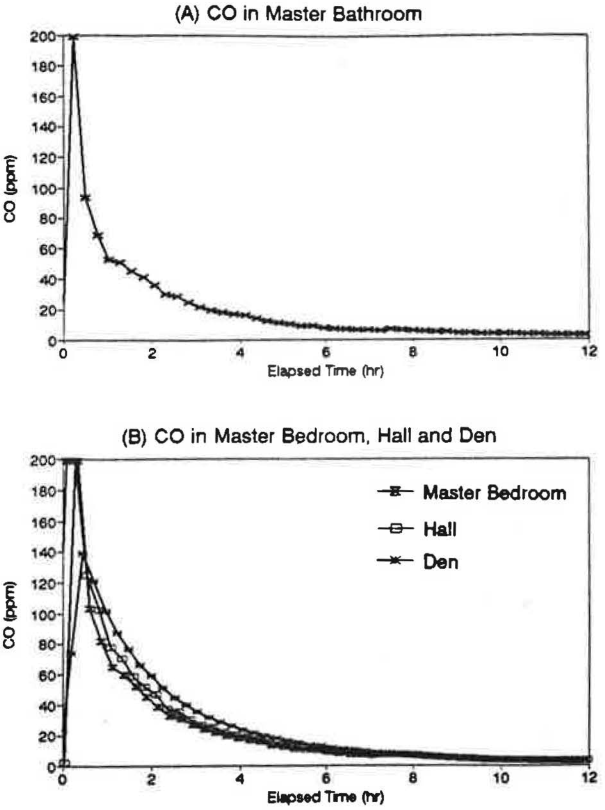

Figure 12: Test #16—CO was released from master bathroom with HAC on/master bathroom door open/window open.

Tests #16 and #17 were conducted with both the master bathroom door and the master bathroom 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 similar master bathroom CO accumulation patterns to those of Test #7 (**Figure 7A**), yet 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 window opening in withdrawing the polluted air from inside the house to the outdoors.

CONCLUSIONS AND RECOMMENDATIONS

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

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 can be installed in such rooms, outside doors and/or windows are recommended.

For people who use aerosol cans indoors, it is recommended that the central HAC system be turned off before activities are engaged in, 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 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 which leads 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.

Realistically, the implementation of the above procedures should not be very difficult if the occupants have some basic understanding of the function of the building features and use common sense. Separate air handling systems are desirable for rooms where indoor air pollution sources may be prevalent, but the cost of the additional ventilation system may make it unrealistic. However, it is recommended to have powerful and large capacity exhaust fans to accelerate the dissipation of the indoor air pollutants.

Note that these experiments used CO as a tracer. Since CO is a gas at room temperature, the test house experiments actually simulate conditions under which the pollutants evaporate immediately after they are released from aerosol cans. Also note that CO has a very low affinity to most indoor surfaces. Therefore, no sink effects are evaluated by the current experiments.

ACKNOWLEDGEMENT

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