VENTILATION STRATEGIES AND MEASUREMENT TECHNIQUES

6th AIC Conference, September 16-19 1985, Netherlands

PAPER 6

EFFECT OF UNVENTED COMBUSTION APPLIANCES ON AIR EXCHANGE AMONG INDOOR SPACES

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SYNOPSIS

The effects of operating unvented appliances and opening windows on indoor pollutant levels and air exchange rates are being studied under the sponsorship of the Gas Research Institute. The study is being conducted in an instrumented, well-characterized bilevel house located near Washington, D.C. Air leakage due to window openings is characterized by pressurization measurements and the air exchange increment is characterized through tracer gas measurements. Two unvented space heaters, one radiant and the other convective, are operated singly and in combination with a gas cooking range.

When an upstairs heater is operating, there is rapid horizontal mixing of pollutants but little penetration to the downstairs area. When a downstairs heater is operating, there is rapid mixing throughout the entire indoor space. Results to date also indicate that effect of opening windows on pollutant levels and air exchange is quite variable. Simultaneous operation of two or more unvented combustion appliances results in peak concentrations that are greater than what would be expected by summing the peaks for each single-source case.

1.0 INTRODUCTION

In the United States, 40 percent of all occupied housing units in the country use natural gas as the primary fuel for cooking, according to the results of the 1980 Census of Population and Housing. The fraction of housing units using natural gas as the primary heating fuel is 53 percent; a relatively small proportion, probably about 2 percent, of housing units use unvented gas space heaters (UVGSHs) as the primary means of heating. As a general rule, UVGSHs tend to be used more often in areas of the country that have only a moderate heating demand, and more specifically in neighborhoods with housing units built predominantly before 1960.

As a product of the combustion, certain air pollutants such as carbon monoxide (CO) and nitrogen dioxide (NO_2) are emitted by unvented appliances into residential air spaces. The impact of these appliances on indoor air quality depends on the complex interplay among various types of factors such as size of the structure, number and type of unvented appliances and their patterns of use, the condition of the appliances, prevailing air infiltration rates, and ventilation practices by occupants. These ventilation practices include both mechanical ventilation, such as using a range exhaust fan, or natural ventilation, such as opening windows or doors.

During the past year, GEOMET has been performing investigations involving unvented gas appliances in an unoccupied test house under controlled conditions. This work, which has been sponsored by the Gas Research Institute, concerns the impact of unvented gas appliances on indoor air quality and the effects of different ventilation practices during appliance operation on air exchange and indoor air quality. The focus of this paper is on results concerning UVGSHs but some results related to the gas range are also provided.

2.0 RESEARCH METHODS

The setting for this research is two unoccupied, bilevel houses that were built during the fall of 1982 as part of a new subdivision approximately 35 km northwest of Washington, D.C., in Gaithersburg, Maryland. The two houses were built side-by-side with a mobile laboratory between them that contains most of the analytical devices used for measurements and an automated data recording system. Since their construction, these houses have been used for various types of research on infiltration, energy, and indoor air quality. Parameters measured in these houses include air infiltration, various air pollutants, energy consumption, indoor and outdoor temperatures and relative humidity, barometric pressure, solar radiation, and windspeed and direction. A related paper[1] presented at this conference shows a picture of these houses and lists their construction characteristics.

Both of the houses have gas ranges and one of the houses was recently equipped with two UVGSHs--a 10,000 Btu/h convective unit located in the upstairs master bedroom and a 15,000 Btu/h radiant unit located in the downstairs living area. Figure 1 shows the floor plan including the locations of unvented appliances and three sampling points (X, Y, and Z) for CO, NO_2, and tracer gas (SF_6) in one of the houses. The upstairs zone is connected to the downstairs with a stairwell; the opening at the bottom of the stairs is 90 cm x 240 cm high and is without a door. The other house has an identical floor plan but has no UVGSHs and only one sampling line located in the upstairs living room.

Experiments concerning the impacts of UVGSHs and window openings were conducted during the 1984-85 winter; during each experiment, the house without a UVGSH was operated with its normal electric, forced-air furnace for comparison purposes. Each experiment was conducted between the hours of 9 a.m. and 4 p.m., during which one of the UVGSHs was operated for 4 h, shut off for 1 h, and then reoperated for 2 additional h. The specific sequence of events for each experiment is shown in Table 1.

The intent of the experiments was not to simulate any particular pattern of occupant use but rather to view the effect of intermittent UVGSH use in a repeatable way. During some experiments, the window nearest the heater was opened either 3.2 mm (1/8 in) or 19 mm (3/4 in). These rather narrow openings were expected to be typical of those that might be used in the coldest parts of winter. During a few of the experiments, the gas range was also operated during the last 40 min of the second period of UVGSH operation (see Table 1) so that the impacts of multiple appliances could be assessed; windows were not opened during any of the experiments that included the gas range. The choice of

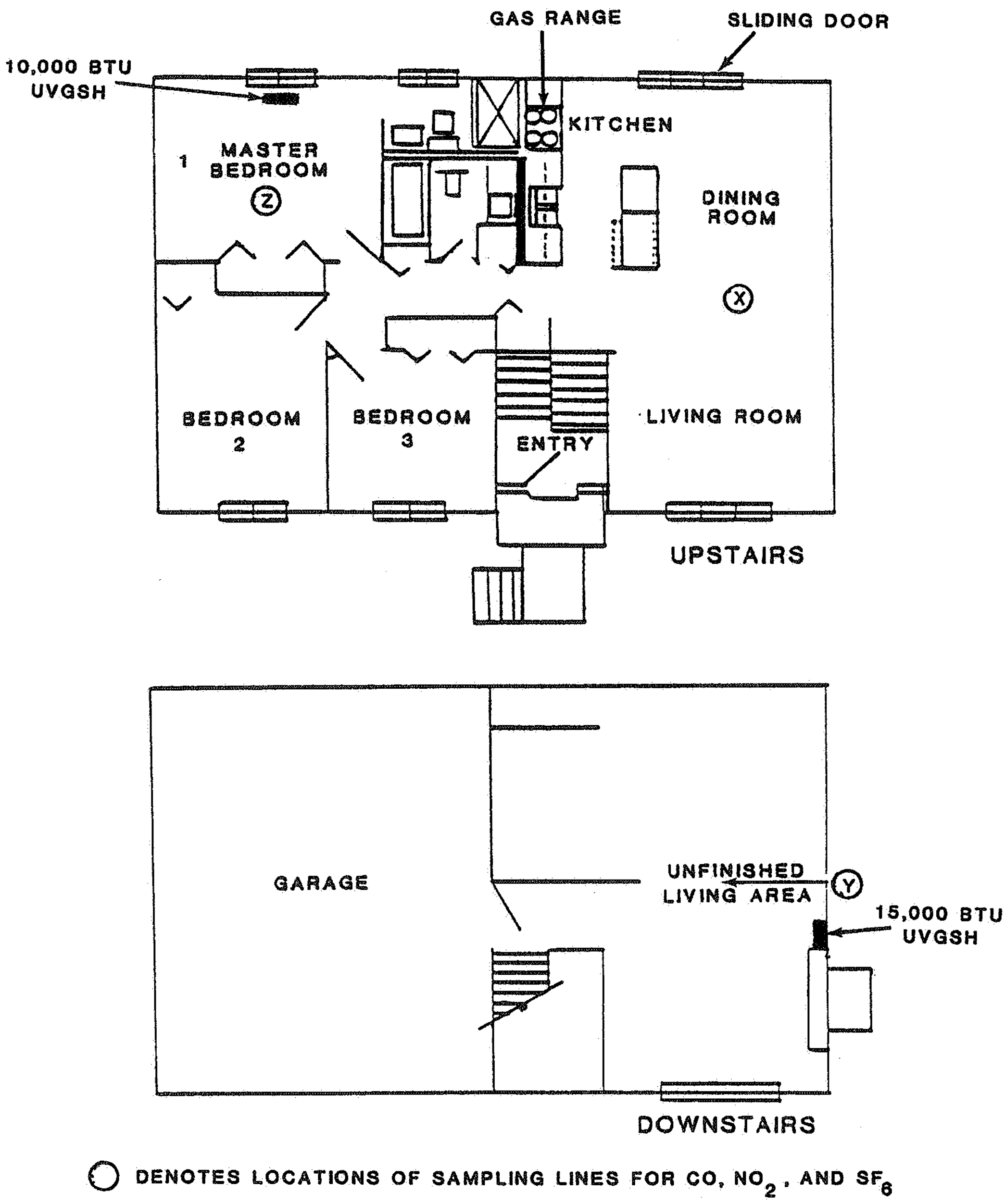


Figure 1. Floor Plans for the Test House Equipped with UVGSHs.

Table 1

SEQUENCE OF EVENTS FOR EXPERIMENTS CONCERNING UVGSHs

Time Period	Activity
8:00 to 8:30 a.m.	Inject and mix the tracer gas (SF_6) using the central air circulation system
9:00 a.m. to 1:00 p.m.*	Operate one of the UVGSHs at its maximum heat setting
1:00 to 2:00 p.m.	No source activity
2:00 to 4:00 p.m.*	Reoperate the UVGSH that was operated from 9:00 a.m. to 1 p.m.
3:20 to 4:00 p.m. (for selected experiments)	Operate the gas range with one burner fully on and the oven set at 175 °C

* For the experiments in which the gas range was not used, the window nearest the UVGSH was opened either 3.2 mm or 19 mm.

40 min for gas range operation was for compatibility with some previous experiments that concerned only the gas range.

Additionally, during the summer of 1984, experiments were conducted to examine the impacts of ventilation practices associated with the operation of a gas range on air infiltration and indoor air quality. The following ventilation practices were examined:

- Operation of a range exhaust fan
- A 15-cm (6-in) partial opening of a sliding glass door near the gas range in combination with the range exhaust fan
- Partial opening of the sliding door and additional windows to allow for cross ventilation.

For each experiment, the gas range was operated for a 40-min period. Some of the ventilation practices were concurrent with gas range operation whereas others began 20 min after the range was turned on; this latter mode of operation was chosen to represent the fact that some occupants might use ventilation only to reduce heat, odor, or smoke generated by the range and cooking. Another ventilation practice, continuous use of an air-to-air heat exchanger, was examined under a previous project[2] for the Electric Power Research Institute;

results concerning use of the heat exchanger during the period of range operation are also included in this paper.

3.0 RESULTS AND DISCUSSION

Results are presented in the next four subsections. First, the effects on pollutant and air-movement behavior when each UVGSH was operated without ventilation are examined. Second, the impact of opening a window nearest the UVGSH during its operation is discussed. Third, the effects of alternative types of natural and mechanical ventilation practices during gas range operation are shown. Fourth, the results of operating both a UVGSH and the gas range, with no ventilation, are provided.

3.1 UVGSH Operation with No Ventilation

Figure 2 shows CO concentrations during and after two periods of UVGSH operation. When the upstairs heater was operating (upper part of the figure), there was rapid mixing throughout the upstairs space but there was little impact downstairs; moreover, the peak CO concentration at the end of each period of UVGSH operation was slightly higher in the living room than in the bedroom where the heater is located. When the downstairs heater was operating (lower part of the figure), there was rapid mixing in both upstairs and downstairs or throughout the entire indoor space; the living room zone again had slightly higher peak concentrations than any of the other measurement zones and the bedroom had the lowest peak. It is also noteworthy that each time the downstairs heater was shut off the CO concentrations declined most rapidly downstairs. This greater rate of decrease is due to a higher rate of air infiltration downstairs; this higher rate, particularly during periods of cool weather, has been consistently demonstrated by tracer gas decay studies over the past several years[2] and has been verified recently by constant-concentration tracer gas measurements.[1]

NO_2 concentrations were also highest in the living room zone, regardless of the heater that was operating (Figure 3); it should be noted that the living room is directly above the room where the downstairs heater is located, as indicated by the floor plan (Figure 1). When the upstairs heater was operating, there was no evidence of NO_2 penetration to the lower level, as for CO. It also should be noted that the NO_2 concentration declined more rapidly than the CO concentration and that the rate of decrease appeared to be similar in all zones, in contrast to CO; this result is due to the fact that NO_2 is a highly reactive pollutant and its rapid rate of chemical decay overwhelms any dilution effects of air infiltration.[2]

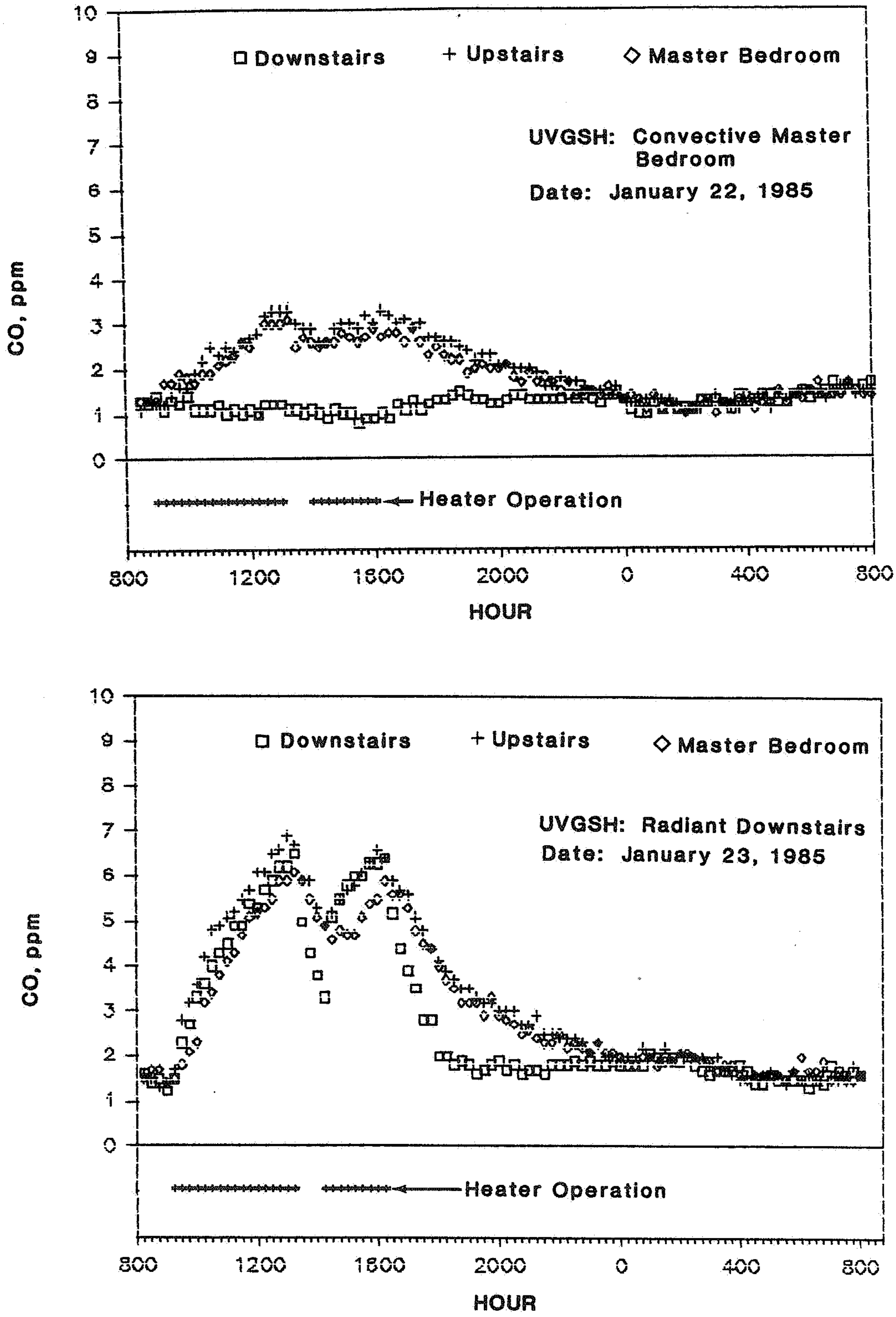
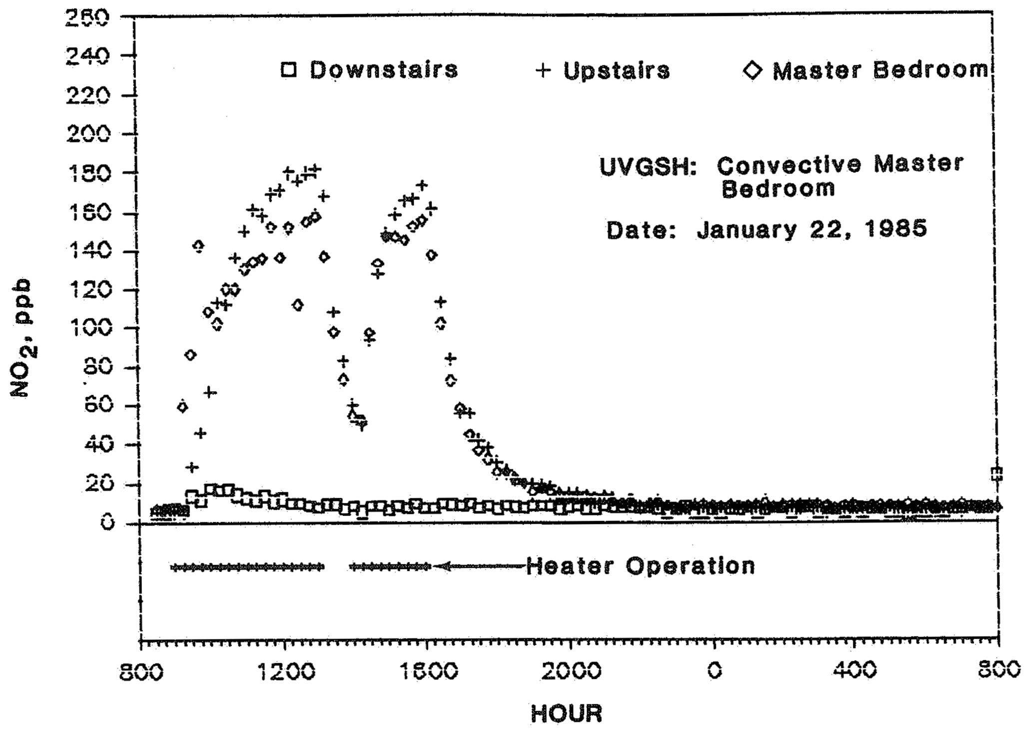


Figure 2. Carbon Monoxide Concentrations Resulting from Unvented Convective and Radiant Heaters.



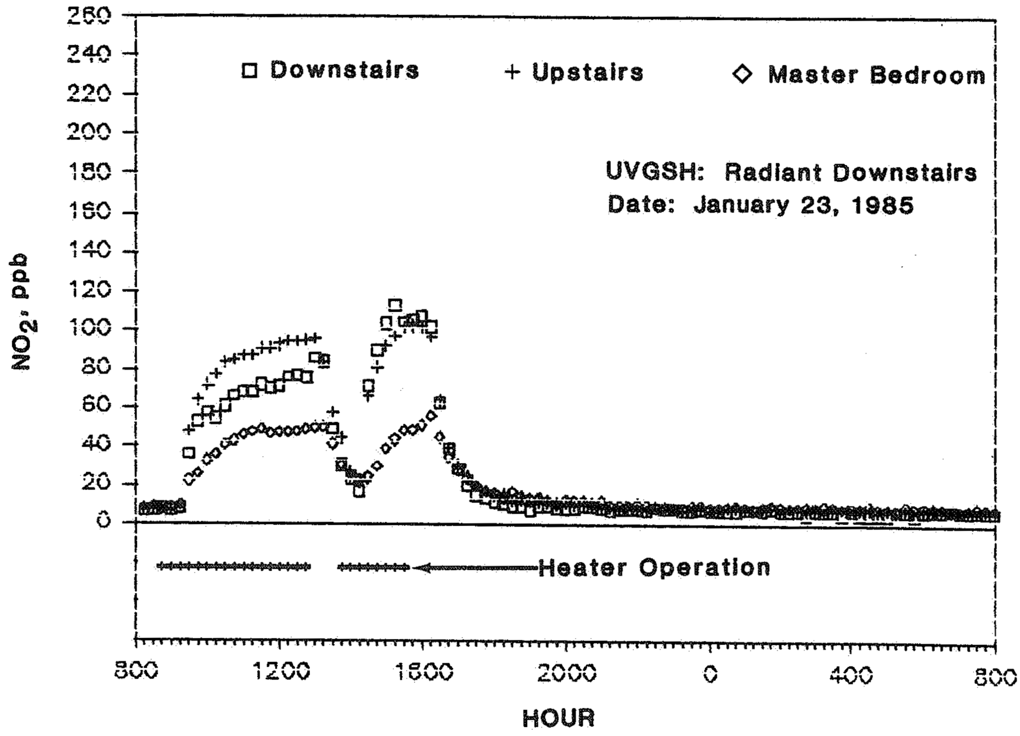


Figure 3. Nitrogen Dioxide Concentrations Resulting from Unvented Convective and Radiant Heaters.

3.2 UVGSH Operation with Opened Windows

Blower door measurements were taken to assess the potential impacts of narrow window openings on air infiltration rates. Pressurization and depressurization results at 50 Pascals are shown in Table 2. The narrow openings had a larger impact for the bedroom window than for the downstairs window. For a window opening of 3.2 mm, house tightness decreased by about 10 percent for the bedroom window and by less than 5 percent for the downstairs window. With an opening of 19 mm, the decrease in tightness was about 20 percent for the bedroom window and 15 percent for the downstairs window.

The effect of opening the master bedroom window during operation of the upstairs heater is shown in the upper portion of Table 3. With the 3.2-mm opening, there was no impact on peak CO or NO_2 concentrations. With the 19-mm opening, the CO peak was reduced by about 20 percent and the NO_2 peak by about 10 percent; however, in the case of CO, both the starting and outdoor concentrations were somewhat less than for the base case, such that the peak reduction was more on the order of 10 percent. The average air infiltration rates for these three cases were quite similar, but one of the major driving forces (ΔT or windspeed) was milder on the days when windows were opened. After an adjustment was made for weather conditions on the basis of a regression model developed from previous studies,[2] it was determined that the 3.2-mm opening increased the air infiltration rate for that day by about 0.05 ACH (11 percent) and that the 19-mm opening resulted in an increase of 0.15 ACH (33 percent). Thus, the increased air exchange seems to have brought about less than a proportionate reduction in peak concentrations.

The effect of opening the downstairs window during operation of the downstairs heater is shown in the lower portion of Table 3. Again the 3.2-mm opening had little impact whereas the 19-mm opening reduced the peaks by 10 percent. After adjusting for weather conditions the 3.2-mm opening increased air infiltration by only 0.02 ACH (5 percent) whereas the 19-mm opening caused an increase of 0.15 ACH (35 percent). It should be noted that the 3.2-mm opening had an apparent adverse effect on indoor air quality on day 713; however, this particular experiment took place on an unseasonably mild day, such that temperature and wind effects on infiltration were negligible. In addition, outdoor pollutant concentrations were somewhat higher on this day than in the other cases. A mass balance equation for indoor air quality, which accounts for the effects of indoor sources, air infiltration, and outdoor concentrations, was applied to CO concentrations for the two cases when the window was opened 3.2 mm. As shown in Figure 4, measured and modeled concentrations agreed very closely in each case; this finding means that the higher CO concentrations on day 713 can be confidently attributed to prevailing outdoor CO and temperature conditions rather than the fact that the window was opened.

Table 2

EFFECT OF SCALED WINDOW OPENINGS (3.2 and 19 mm) ON BLOWER DOOR RESULTS (ACH at 50 Pascals)

	Depressurized Conditions			Pressured Conditions			Average of Two Conditions		
	Window Closed	Window Opened	Percent Increase	Window Closed	Window Opened	Percent Increase	Window Closed	Window Opened	Percent Increase
<u>Opening of 3.2 mm</u>:									
Downstairs window	5.58	5.71	2.3	6.50	6.53	0.5	6.04	6.12	1.3
Bedroom window	5.43	6.04	11.2	6.44	6.97	8.2	5.94	6.51	9.6
<u>Opening of 19 mm</u>:									
Downstairs window	5.58	6.30	12.9	6.50	7.47	14.9	6.04	6.89	14.1
Bedroom window	5.43	6.78	24.9	6.44	7.56	17.4	5.94	7.17	20.7

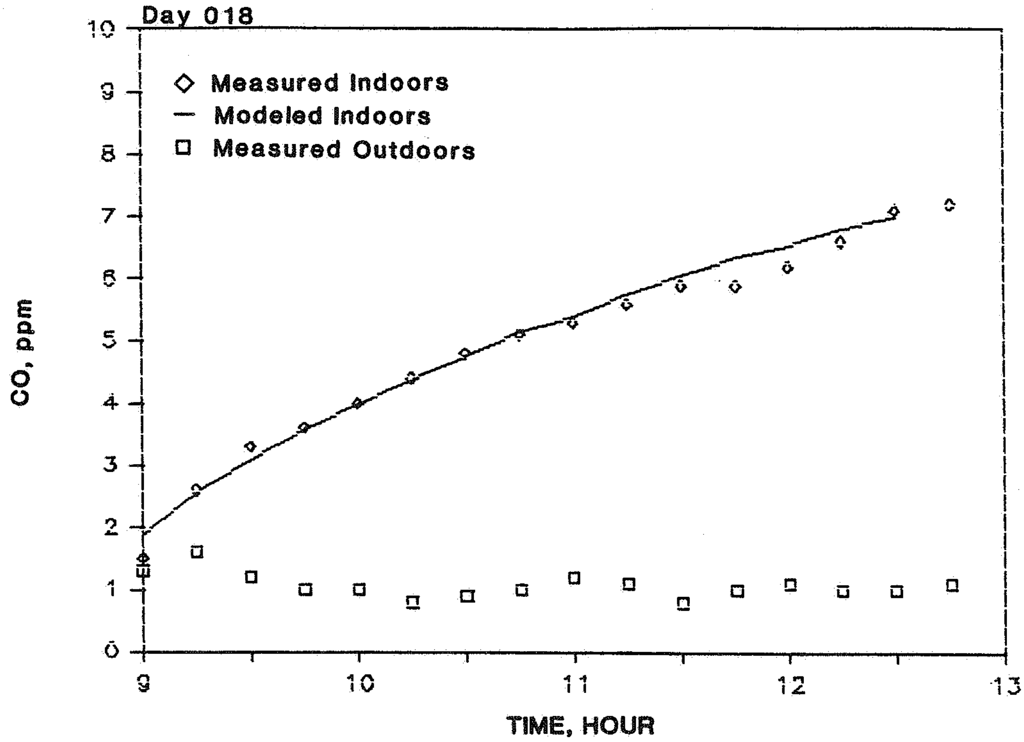
Table 3

EFFECT OF WINDOW OPENINGS DURING UVGSH OPERATION ON CO AND NO_2 CONCENTRATIONS AND AIR INFILTRATION RATES

	Upstairs Heater (Convective)		
	No Opening (Day 22; 1/22/85)	3.2-mm Opening (Day 11; 1/11/85)	19-mm Opening (Day 58; 2/27/85)
CO (ppm)			
Initial*	1.2	1.6	1.0
Peak*	3.3	3.6	2.6
Outdoors	0.8	1.0	0.6
NO_2 (ppb)			
Initial*	5	4	5
Peak*	181	183	161
Outdoors	11	14	9
Infiltration Rate (ACH)†	0.46	0.42	0.43
Average ΔT (°C, in - out)	17.9	15.9	5.2
Average Windspeed (mph)	10.6	4.1	10.9

	Downstairs Heater (Radiant)			
	No Opening	3.2-mm Openings		19-mm Opening
	(Day 23; 1/23/85)	(Day 18; 1/18/85)	(Day 713; 12/13/84)	(Day 59; 2/28/85)
CO (ppm)				
Initial*	1.4	1.5	2.1	1.7
Peak*	6.9	7.2	10.0	5.6
Outdoor	1.0	1.0	1.6	0.2
NO_2 (ppb)				
Initial*	7	5	4	5
Peak*	96	83	109	86
Outdoors	13	13	28	10
Infiltration Rate (ACH)†	0.43	0.38	0.13	0.46
Average ΔT (°C, in - out)	15.6	12.3	0.7	8.8
Average Windspeed (mph)	5.5	2.7	2.5	2.8

* Based on measurements taken in the upstairs living room zone.
† Average air infiltration rate for the entire house during the period of UVGSH operation (0900 to 1300 in each case).



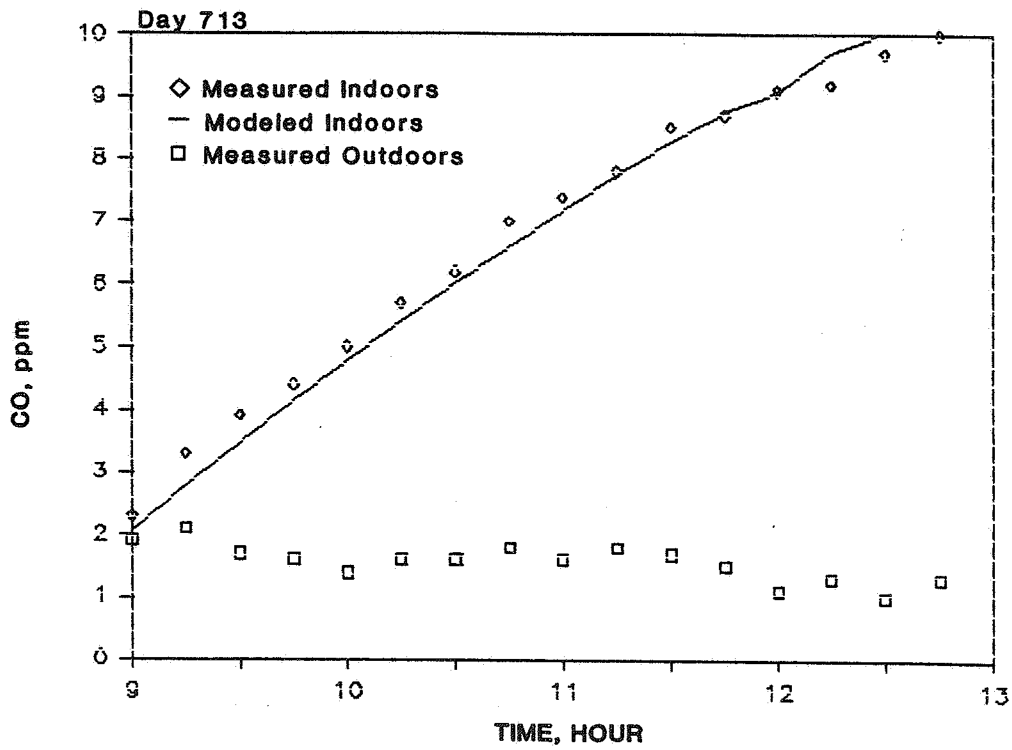


Figure 4. Measured and Modeled Indoor CO Concentrations with the Downstairs UVGSH Operating and a Window Opened 3.2 mm--Results from Two Different Days.

3.3 Ventilation Practices During Range Operation

The impacts of different natural and mechanical ventilation practices during the operation of a gas range are summarized in Table 4. In this case, the increment in air exchange due to each practice could be determined directly by comparing air infiltration rates during the 40-min period of range operation with rates before and after this period. A number of striking results are apparent:

- Operation of the heat exchanger had little impact on peak concentrations.
- The range exhaust fan reduced peak pollutant concentrations by nearly 50 percent when operating concurrently with the range but had little impact when its use was delayed by 20 min; results were similar whether the exhaust fan was operating in isolation or in combination with opening a sliding door near the kitchen.
- Opening the sliding door and one window in a remote part of the house had little impact on the CO peak and increased the NO_2 peak, even though air exchange was increased by more than 0.5 ACH.
- Opening the sliding door and all upstairs windows reduced the CO peak by about 30 percent but had no impact on the NO_2 peak, in spite of an air exchange increment of more than 1.0 ACH.

The effects of these practices on 8-h average CO concentrations were also examined; these are reported elsewhere.[3] The range exhaust fan had the greatest impact because it removes high-concentration air that is in the immediate vicinity of the emission source. One of the exhaust vents for the heat exchanger is located in the kitchen but the pollutant concentrations are already diluted by mixing with other indoor air by the time they reach this vent. Natural ventilation practices had variable effects because they result in unpredictable air movement patterns even though they increase air exchange. This is particularly true under summer conditions when stack forces are relatively mild.

3.4 Operation of Multiple Unvented Appliances

The results of operating the gas range during the last 40 min of bedroom heater operation are shown in Figure 5. There were marked increases in CO and NO_2 peaks, particularly in the living room zone. For example, when the gas range is the only source, our previous research[2] has shown that the usual CO peak in the living room is about 8 to 9 ppm. Similarly, when the bedroom heater is the only source, the CO peak in the bedroom or living room is about 3 to 4 ppm (Figure 2). For the

Table 4

IMPACT OF VENTILATION PRACTICES DURING GAS RANGE OPERATION ON AIR EXCHANGE RATES AND PEAK POLLUTANT CONCENTRATIONS

Type of Ventilation	Minutes Used with Gas Range*	Air Exchange Increment (ACH)	Peak CO Concentration (ppm)	Peak NO_2 Concentration (ppb)
None	--	0†	6.3	69
Air-to-air Heat Exchanger	All 40	0.33	5.9	62
Range Fan	Last 20	0.14	5.6	65
Range Fan	All 40	0.29	3.5	39
Range Fan and Sliding Door	Last 20	0.23	6.1	68
Range Fan and Sliding Door	All 40	0.56	3.1	36
Sliding Door and Window in Bedroom 2	All 40	0.63	5.9	96
Sliding Door and Windows in Living Room and All Bedrooms	All 40	1.24	4.4	65

* The gas range was operated for a period of 40 min in each case with one burner fully on and the oven set at 175 °C.

† Air infiltration rates during the period of testing were usually between 0.1 and 0.2 ACH in the absence of ventilation practices.

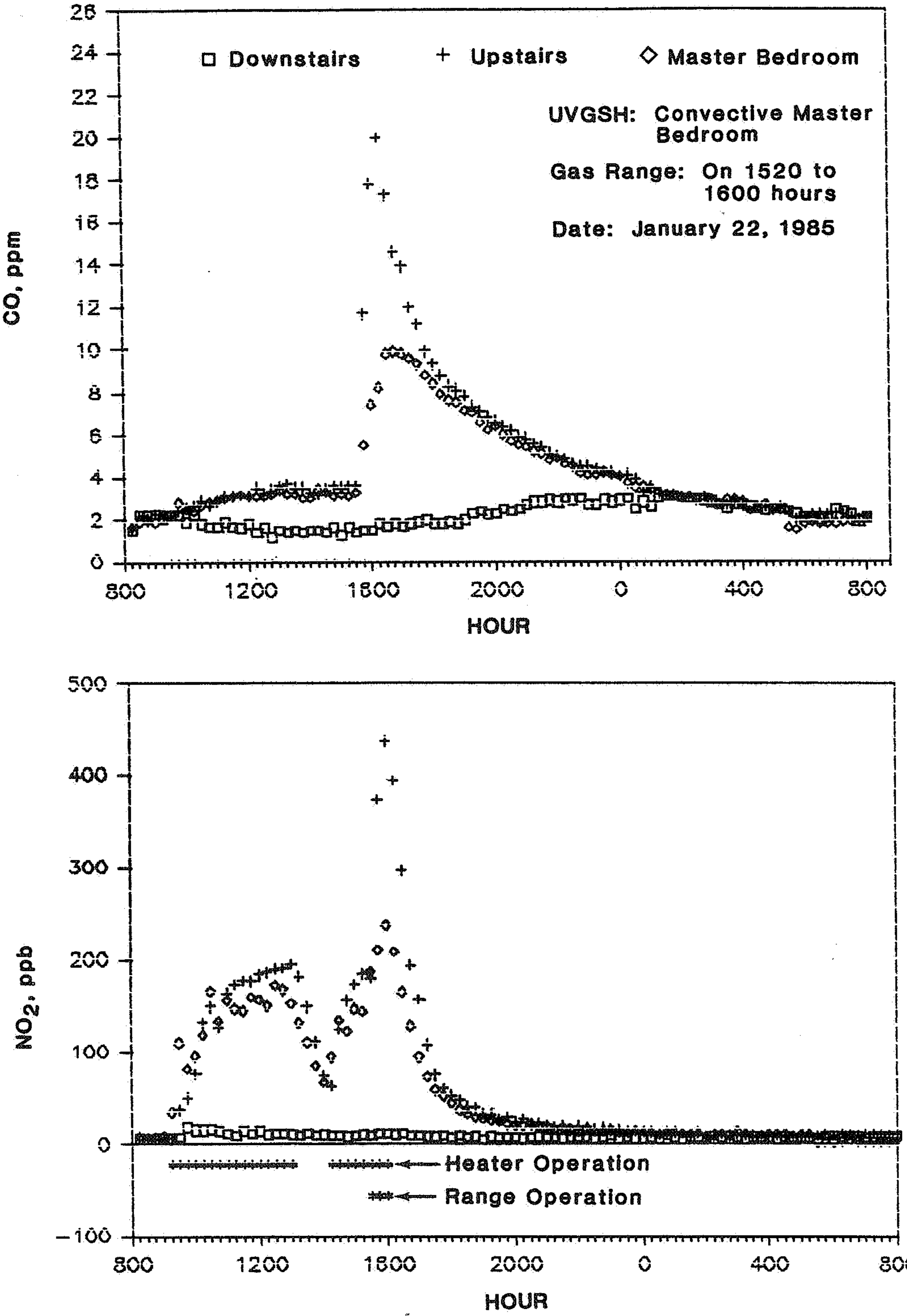


Figure 5. Effect of UVGSH and Gas Range Operation on CO and NO_2 Concentrations--Convective UVGSH in Master Bedroom.

case shown in Figure 5, the CO peaks in either zone are more than twice their values for the single-source case. A plausible explanation is that the convective forces that normally promote rapid horizontal mixing were restricted when the two heat sources were present. This would result in CO emissions from the range being confined mainly to the kitchen/dining room/living room area and CO emissions from the heater being confined mainly to the bedrooms and bathrooms, thus increasing peak concentrations. These high peaks last as long as 1 h after the heater and range are shut off, at which time the concentrations tend to equalize.

4.0 CONCLUDING REMARKS

This paper presents preliminary findings from research conducted in test houses. The findings include the following:

- Consistent with source emissions data[4] a radiant heater produces higher levels of CO than a convective heater. Similarly, as expected, NO_2 levels were lower for the radiant than the convective heater.

- Because of the buoyancy of combustion gases, concentrations of CO and NO_2 were higher than outdoors for only the upstairs area when the heater located upstairs was operating; the concentrations downstairs were similar to the outdoors under this situation. When the downstairs heater was operating the concentration on both floors were fairly well mixed, but those upstairs were somewhat higher than those downstairs.

- When windows were opened, there was a somewhat greater impact on air exchange due to differences in indoor/outdoor temperatures than the size of opening per se. Thus, the impact of opening windows to reduce levels of combustion contaminants was highly variable, particularly when the gas range was operating.

- For the gas cooking range, operating the range-hood exhaust fan during the entire cooking episode was most effective in reducing CO and NO_2 concentrations.

- Operating two unvented appliances created peak concentrations that were more than twice those of either of the single-source cases. It is presumed that this phenomenon was due to reduced air exchange between spaces.

The above should be considered tentative conclusions. More research needs to be conducted, especially on the last observation regarding multiple unvented appliances. This research would benefit from using multiple tracer studies as an integral part of the measurement approach.

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