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OCCUPANT-CONTROLLED RESIDENTIAL VENTILATION

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ABSTRACT

The effects of opening windows on the ventilation rates of two detached houses and a two-story condominium were studied. The scenarios studied under various wind conditions included, when possible, opening windows on the windward side, the leeward side, both the windward and leeward sides, and on the two other sides not in the direction of the prevailing wind. Two window settings, either 3 in or wide open, were employed in each scenario. In some cases, opening windows increased ventilation by as little as 20%, while in other cases residential ventilation rates were increased by as much as 11 times the original rate. Use of a kitchen range hood nearly doubled the ventilation rate in two residences, while opening the main garage door increased garage ventilation rates from as little as 4 times to as much as 25 times the initial rate.

INTRODUCTION

Adequate ventilation of any enclosed space is essential for good indoor air quality and for thermal comfort. New energy-efficient, low-air-leakage houses located in extreme weather areas are usually mechanically ventilated, since the infiltration rates of these houses are not sufficient for moisture control or acceptable indoor air quality. However, the majority of the houses in the United States are ventilated by infiltration. While infiltration rates of many groups of houses have been measured and reported in the past (ASHRAE 1985), little quantitative information exists on the effect of opening windows, despite the fact that it is the principal means by which occupants can increase ventilation when needed.

Such information would have many uses. For example, many consumer products contain chemicals which can, under certain conditions of use, create a health hazard to users and to other occupants of a residence. Quite often these products are labeled with a warning to use with "adequate ventilation."

Because information regarding residential ventilation rates with windows open under different conditions is lacking, what constitutes adequate ventilation is not clear to the consumer and may not even be known to those responsible for the warning label, i.e., is adequate ventilation provided by a large, drafty house; a house with a window open under windless conditions; or a garage with the main door open and a fan blowing to exhaust any pollutants emitted from the product? (The U.S. Consumer Product Safety Commission warning label requirement for products containing methylene chloride is an exception to this [*Federal Register* 1986]. The label for these products specifies that the product should be used outdoors if possible, but if it must be used indoors that all windows and doors should be opened or other means used to ensure that ventilation is provided.) Quantitative data about the effects of opening windows on residential ventilation could be used in models to estimate the pollutant concentrations produced under many conditions of use and thereby provide specific information regarding the applicability of different ventilation strategies to the public.

Kvisgard et al. (1985), using constant-concentration tracer gas techniques in 25 Danish occupied dwellings, monitored winter ventilation and infiltration rates over a period of one week. Their results indicate a mean increase in ventilation rates due to occupant behavior of 2.6 times in naturally ventilated houses and of 5.7 times in mechanically ventilated houses. The infiltration rates ranged from 0.20 ach to 0.40 ach, whereas the ventilation rates (including infiltration) ranged from 0.20 ach to 1.56 ach.

A large-scale study of the behavior of house inhabitants (AIVC 1988) conducted in five European countries, which examined energy losses due to winter ventilation, concluded that ventilation, as controlled by the occupant, is related to the type of room in which it occurs, to the weather conditions, and to the design characteristics of the dwelling and its heating system.

A study by De Gids and Van Schijndel (1979) conducted in a European apartment indicated a maximum increase of 4.3 in the apartment's ventilation rate when three windward windows were opened. A maximum increase of 1.5 was observed when two leeward windows of the same apartment were opened.

The results of a survey of 332 California residences conducted through the mail by the California Department of Health Services (CDHS)*, part of which are shown in Figure 1, indicated that window-opening behavior exhibits a strong seasonal dependence. In addition, this survey found that 75.6% of the residences surveyed were single-family houses, and 75.8% of the residences had a kitchen fan.

Another survey of 661 California mobile home occupants, also conducted through the mail by the CDHS*, provided information about occupant control of ventilation. The results shown in Figure 2 suggest that opening windows depends on the type of room in which it occurs as well as on the season. The data also indicated that 23.0% of the mobile home occupants used their kitchen fan 1 to 10 minutes per week, and that 20.2% used their kitchen fan 21 to 40 minutes per week.

This paper reports on a study of the effect of opening windows on residential ventilation rates. Among the factors studied were the effects of wind speed, the amount the window was opened, the wind direction in relation to the window, and the number of windows opened. In addition, ventilation measurements were taken in the garages at each of these residences since limited information exists regarding venti-

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tion rates in garages (e.g., Hodgson and Girman 1987) despite the fact that they can be areas of high exposure to pollutants because of storage of solvents or because of hobbyists' activities.

DESCRIPTION OF THE STUDY

Three residences were studied—two detached houses (Residences 1 and 2) and one condominium (Residence 3). The scenarios employed under various wind conditions included, when possible, opening windows on the windward side, the leeward side, both the windward and leeward sides, and on the two other sides not in the direction of the prevailing wind. Two window settings, 3 in and wide open, were employed in each scenario.

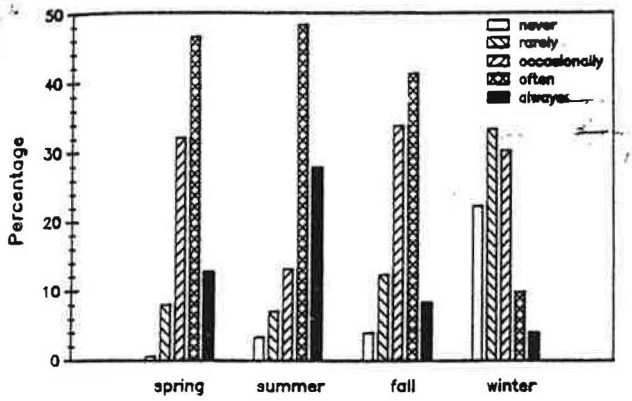

Figure 1 Occurrence of open windows and doors in a sample of 332 occupied California residences according to season

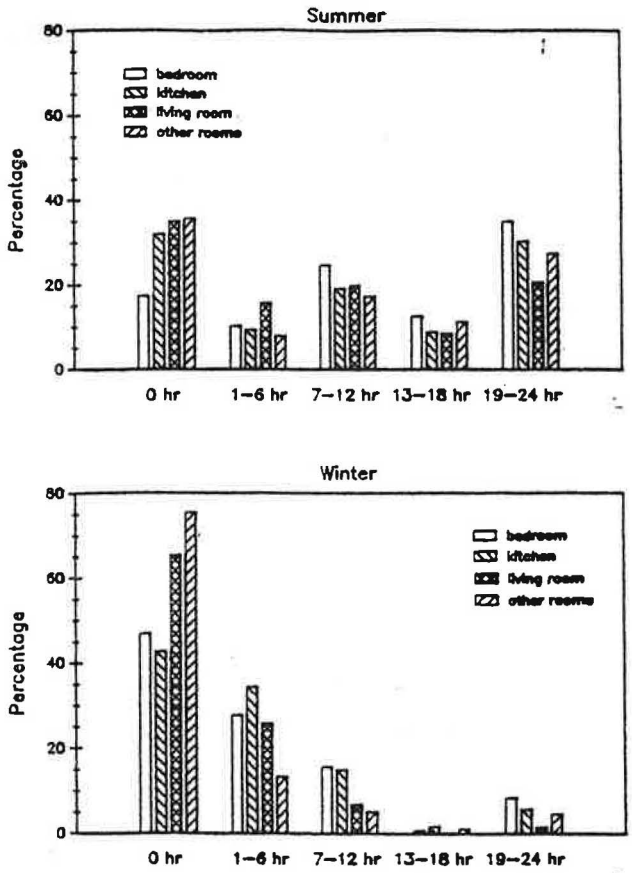

Figure 2 Duration of open windows in a sample of 661 occupied California mobile homes according to season and type of room

Natural infiltration rates were measured at Residences 1 and 3 under various wind conditions. The effects of the range hood operation on the ventilation rates were also studied. In addition, the effect of the furnace fan on air mixing at the two-story condominium (Residence 3) was examined. Finally, garage ventilation rates with the main door open and closed were measured in all three residences.

Air change rates were determined after sulfur hexafluoride (SF_6) was released upstream of the furnace fan in Residences 1 and 2. In Residence 3 several injections of SF_6 were made throughout the condominium and small portable fans were used for mixing. After allowing 30 to 40 minutes for mixing in all three residences, the fan(s) were turned off, and the SF_6 decay was monitored in several locations by using a computer-controlled, multi-location sampling technique. This technique has been described in detail elsewhere (Alevantis 1989). Range hood flows were determined by making multi-point traverses across the range hood inlets using a hot-wire anemometer.

DESCRIPTION OF THE RESIDENCES

Residence 1 (see Figure 3) is a one-story, 1321 ft², two-year-old, three-bedroom house with no outside sheltering on the southwestern side and fencing on the other three sides. This house has horizontal sliding windows and is served by a forced-air heating and cooling system. The average outdoor temperature during the study was 82°F and the average indoor temperature was 74°F.

Residence 2 (see Figures 4a and 4b) is a two-story, 1326 ft², approximately 60-year-old, two-bedroom house with trees sheltering the southwestern, northeastern, and northwestern

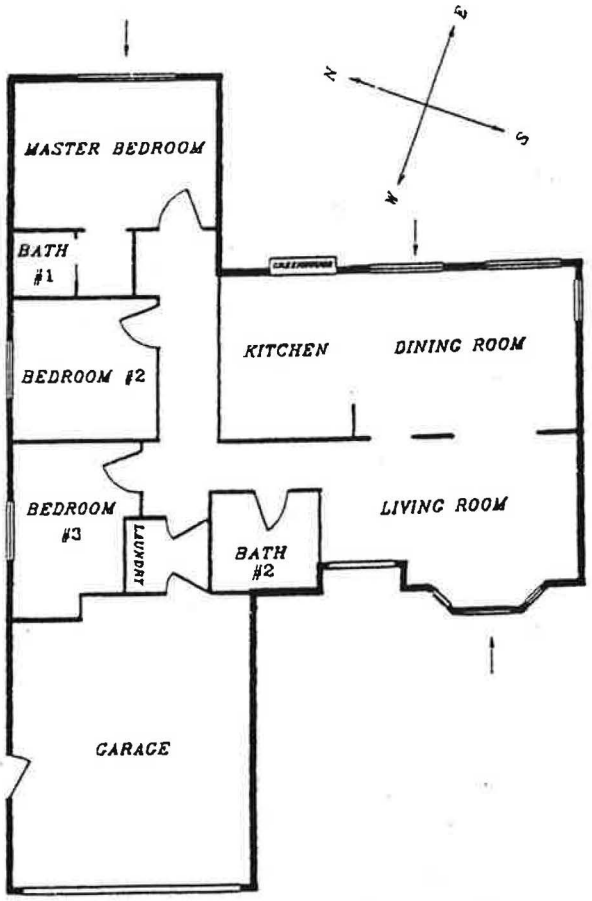

Figure 3 Floor plan of Residence 1

sides, and fencing on the northwestern and southeastern sides. The ground floor consists of a garage and a small, one-bedroom rental unit, while the main two-bedroom house occupies the entire second story. This house principally has double-hung windows and few casement windows. The main house is served by a forced-air heating system, while the rental unit is served by a gas-fired convection wall furnace. During the study the average indoor temperature was 68°F and the average outdoor temperature was 58°F.

Residence 3 (see Figures 5a and 5b) is a two-story, 872 ft², approximately seven-year-old condominium with adjacent units located on the southwestern and northeastern sides. This residence has horizontal sliding windows and a forced-air heating system serves both floors. The average indoor temperature during the study was 68°F; outdoor temperature was not continuously monitored but was estimated to be 55°F.

RESULTS AND DISCUSSION

In Residences 1 and 3, several infiltration rates were obtained under different wind conditions with all the windows closed. Infiltration rates of these two residences were then plotted against wind speed (see Figures 6 and 7) assuming a linear relation (ASHRAE 1985). The increase in a residence's ventilation rate due to opening window(s) is defined here as the ratio of the ventilation rate with the window(s) open to the infiltration rate under similar wind conditions with all the windows closed. In Residence 2, since wind conditions were largely invariant, an average infiltration rate was calculated irrespective of wind speed.

Residence 1

The effect of wind speed (4.8 to 25 mph) on infiltration with all windows closed is shown in Table 1 (Cases 1 through 4) and Figure 6. Wind speed increased the house infiltration rates monotonically from as little as 4.1 times (Case 2) to as much as 8.7 times (Case 4) when compared to the base case (Case 1).

Opening windows (Cases 5 through 8) resulted in an increase in the house's ventilation rate from as little as 4.6 times (Case 6: one windward and two leeward windows open 3 in; wind speed 11 mph) to as much as 7.7 times (Case 5: one windward window open 3 in; wind speed 4.8 mph) over the house's infiltration rate with all the windows closed under similar wind conditions. Operation of the kitchen range hood doubled the ventilation rate (Cases 9 and 10).

The garage ventilation rates are shown in Table 2. An average ventilation increase of 5.0 times (average increase of Cases 4 and 5) was observed when the garage door, located on the windward side of the house, was opened.

Residence 2

At this house, since wind speed was fairly constant, as seen in Table 3 (Cases 1 through 5), the average infiltration rate of these cases was the basis for comparison with the ventilation rates when windows were opened. The house ventilation rate was increased from as little as 1.2 times (Cases 6 and 13: one side window open 3 in; Case 18: one side window wide open; and Case 8: one leeward window open 3 in) to as much as 7.5 times (Case 17: one small casement

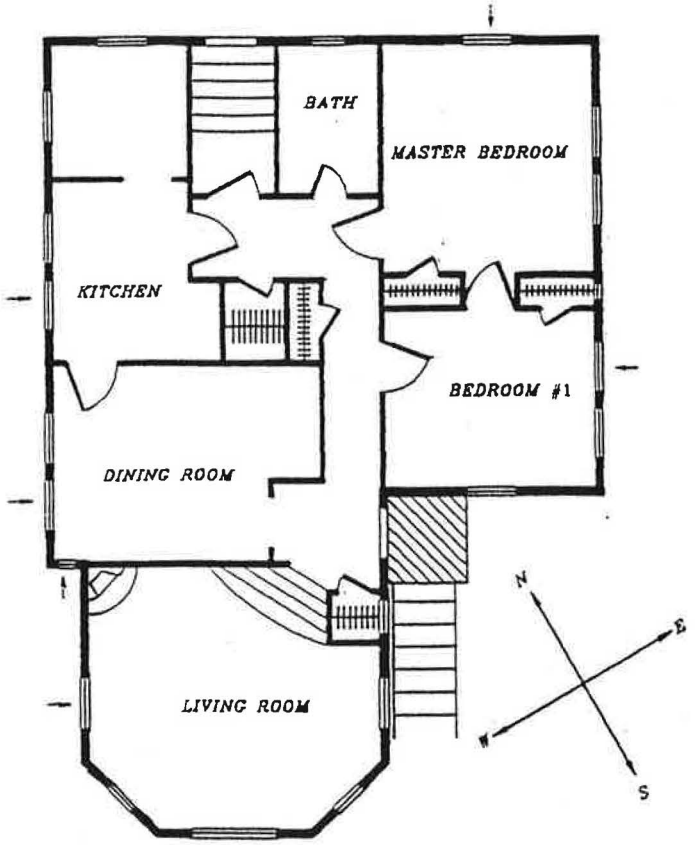

Figure 4a Second-story floor plan of Residence 2

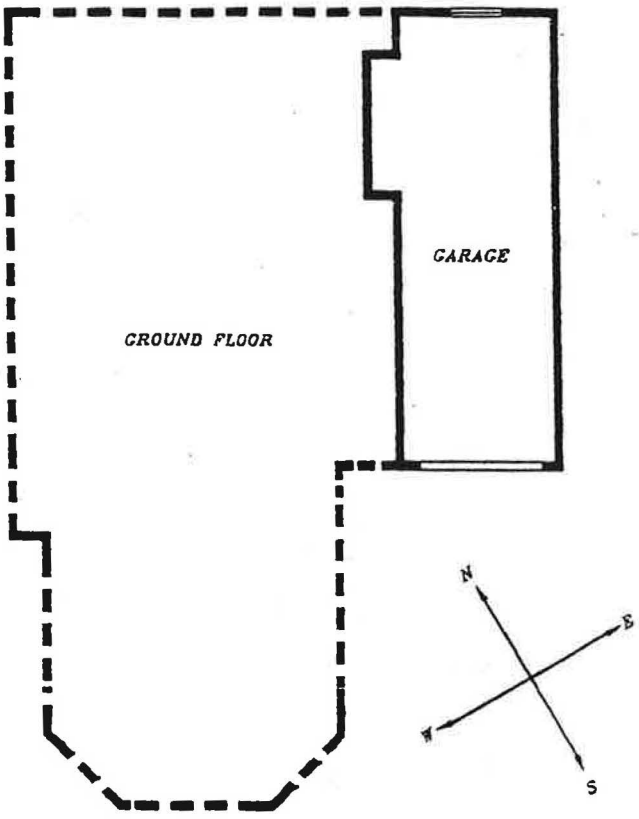

Figure 4b First-story floor plan of Residence 2

[illegible]ward window and one sliding leeward window wide [illegible]pen). Operating the kitchen range hood (Cases 20 and 21) [illegible]d not increase the ventilation rate measurably, presumably [illegible]ecause of the low flow of the fan (60 cfm or 102 m³/h).

The garage ventilation rates are shown in Table 4 with [illegible]e main garage and sliding doors open and closed (these [illegible]oors are located on the windward and leeward sides, respectively), and with a portable window fan (22 in wide by 22 in tall) on and off. An eightfold increase in the ventilation rate was observed (Case 3) when the main garage door was opened. A more than sixtyfold increase was measured (Case 2) when both the garage door and the sliding door (located across from the garage door) were opened, resulting in a drafty but not windy indoor environment. The portable fan doubled the garage ventilation rate (Case 6: main garage door open; sliding door closed) when compared to Case 3 (main and sliding garage doors closed; no fans running). However, the fan did not result in any ventilation rate increase when both garage doors were open (Case 5).

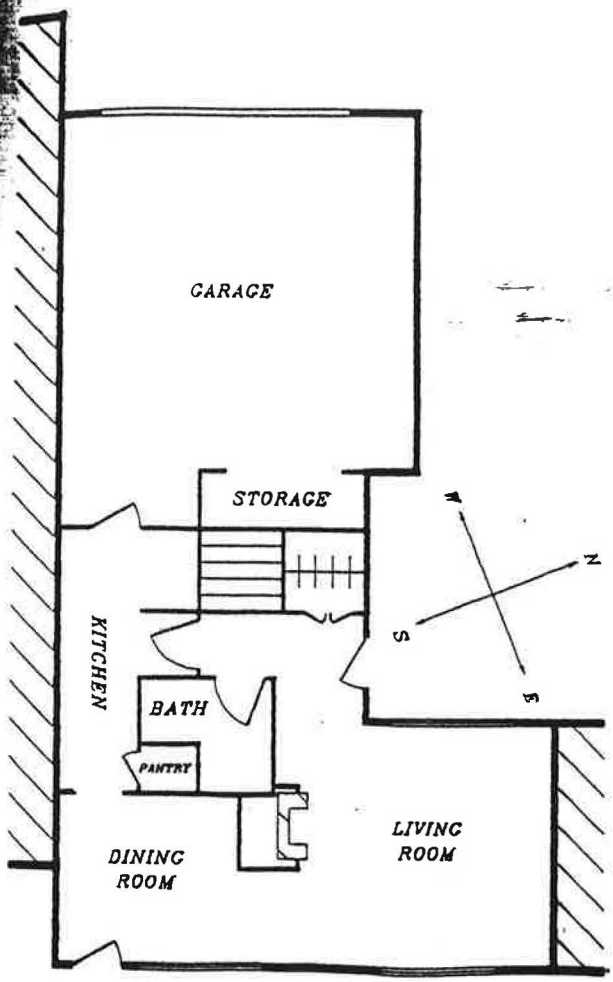

Figure 5a First-story floor plan of Residence 3

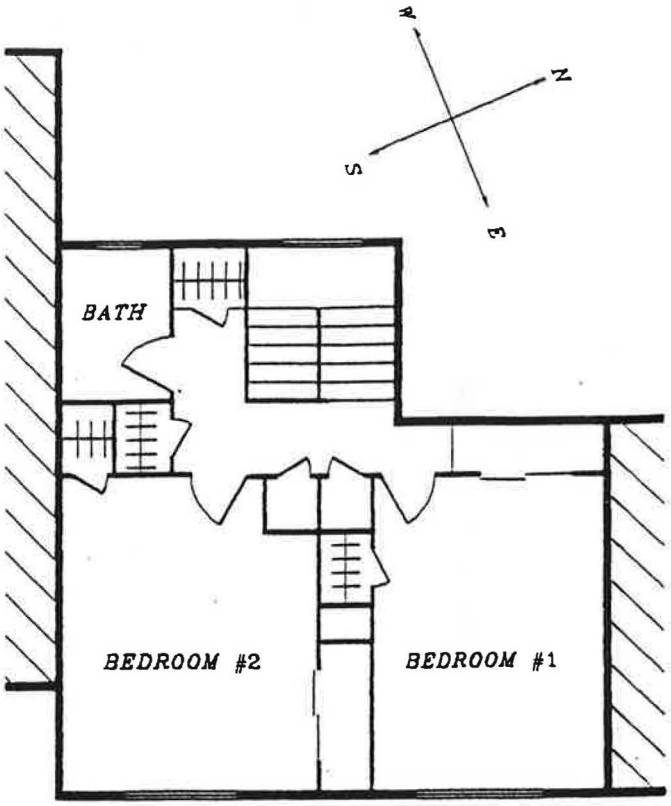

Figure 5b Second-story floor plan of Residence 3

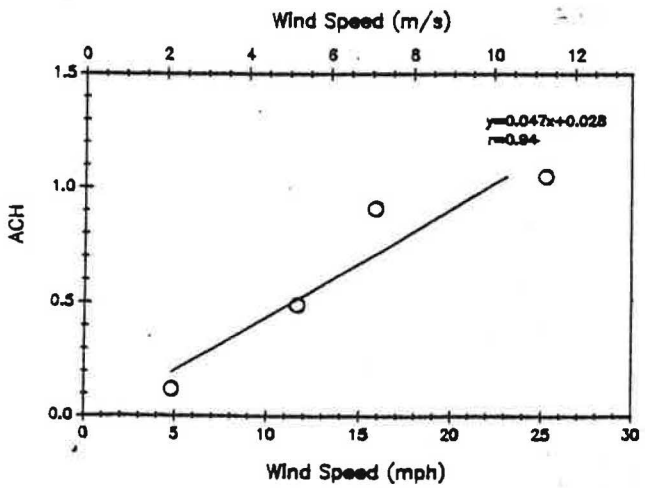

Figure 6 Effect of wind speed on natural infiltration (all windows closed) of Residence 1. Line is least-squares, linear fit.

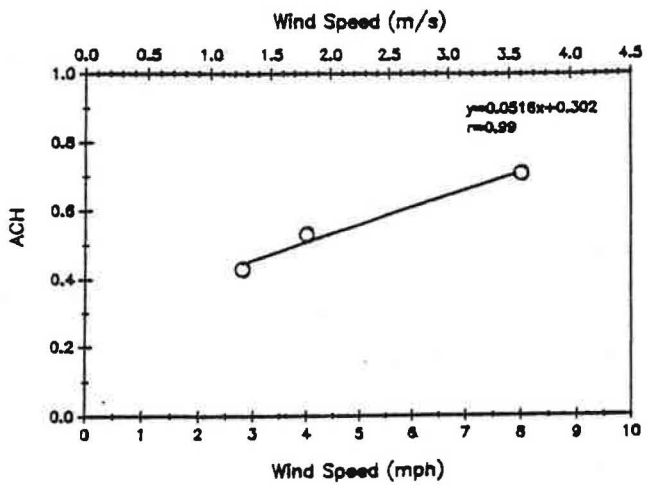

Figure 7 Effect of wind speed on natural infiltration (all windows closed) of Residence 3. Line is least-squares, linear fit.

TABLE 1

Residence 1 — Air Change Rates

Case No.	Living Room[a] (WSW)	Dining Room[b] (ENE)	Master Bdrm[c] (ENE)	Range Hood	Wind Speed (mph)	Wind Dir.	Avg. ACH	ACH / ACH_{inf}[d]
			A. Base Cases: All Fans Off, All Windows Closed					
1	closed	closed	closed	off	4.8	SW	0.12	—
2	closed	closed	closed	off	12.0	WSW	0.49	—
3	closed	closed	closed	off	16.0	WSW	0.91	—
4	closed	closed	closed	off	25.	WSW	1.0	—
			B. Effect of Open Windows (all fans off)					
5	3 in	closed	closed	off	4.8	SW	0.92	7.7
6	3 in	3 in	3 in	off	11.	SW	2.3	4.6
7	12 in[e]	closed	closed	off	11.	WSW	3.1	6.6
8	12 in[e]	12 in[e]	12 in[e]	off	11.	W	2.8[f]	—
			C. Effect of Range Hood (Hi: 128 CFM, Lo: 115 CFM) (all windows closed, all other fans off)					
9	closed	closed	closed	hi	12.	WSW	1.0	1.9
10	closed	closed	closed	lo	12.	WSW	1.0	2.0

[a]window height is 57 in
[b]window height is 77 in
[c]window height is 38 in
[d]ACH_{inf} is the infiltration rate under the same wind conditions with the furnace fan off, and all windows closed (see Figure 6)
[e]wide open
[f]air mixing was poor

TABLE 2

Residence — Garage Ventilation Rates

Case No.	Garage Door (WSW)	Wind Speed (mph)	Wind Direction	Average ACH	ACH / ACH_{inf}[a]
1	closed	12.	W	9.9	—
2	closed	13.	WSW	15.	—
3	closed	13.	WSW	14.	—
4	open	12.	W	79.	6.0
5	open	14.	W	53.	4.1

[a]ACH_{inf} is the average garage infiltration rate of Cases 1 through 3 with the door closed

Residence 3 (Figure 5)

In Residence 3, the two-story condominium, infiltration rates (Tables 5 and 6: Cases 1 through 5) were obtained under two air-mixing conditions: with the furnace fan off and on. The local air change rates for Case 5 (when the furnace fan was on) indicate good mixing. In contrast, mixing was poor when the furnace fan was not running and the wind speed was more than 4.0 mph (Cases 3 and 4). The occupant of this condominium was dissatisfied with the performance of the furnace because the upstairs rooms were always too hot in the winter and the downstairs rooms were uncomfortably cold. The furnace fan operates only when heat is called for. Wind speed and wind direction increased the infiltration rates from no change at all to as much as 1.6 times (Cases 1 through 4). The effect of wind on infiltration is shown in Figure 7.

Opening windows caused the ventilation to increase from as little as 4.1 times (Case 11: one windward window wide open; wind speed 4.6 mph) to as much as 11 times (Case 8: four leeward and one windward windows wide open; wind speed 4.0 mph). An increase of 4.2 (Case 9: wind speed 3.8 mph) was observed when four leeward windows were opened. Use of the range hood nearly doubled the ventilation rate (Case 12).

The effects of operating a portable fan and of opening the garage door (located on the windward side) on the garage infiltration and ventilation rates are shown in Table 7. An average increase of 21 (Cases 4 and 5) in the garage ventilation rate occurred when the garage door was opened. The portable fan (when the garage door was closed—Case 3) increased the garage ventilation rate by 40%.

CONCLUSIONS

The following conclusions can be drawn from Figure 8 (which summarizes the window-opening data), Table 8 (which summarizes the garage door-opening data), Table 9 (which summarizes the kitchen hood data for the three residences studied), and Figure 6 (which shows the effect of wind on the infiltration rates of Residence 1):

1. In the three residences studied, wind conditions (both speed and direction) were observed to cause wide variation in a residence's natural infiltration rate with all the windows closed. The maximum natural infiltration rate could be as much as 8.7 times the minimum rate at a residence under the conditions experienced during the study.
2. Wind conditions can also cause wide variation in the ventilation rate when windows are open. Opening windows on both the windward and leeward sides of a residence at wind speeds below 5 mph can cause the ventilation rate to increase from as little as 4.5 times to as much as 11 times the residence's natural infiltration rate at the same wind conditions with all the windows closed. At wind speeds between 5 mph and 11 mph, an increase in a res-

TABLE 3

Residence 2 — Air Change Rates

Case No.	Living Room[a] (NW)	Dining Room[b]	Master Bdrm[c] (NE)	Bedroom 1[d] (SE)	Kitchen[e] (NW)	Range Hood	Wind Spd. (mph)	Wind Dir.	Avg. ACH	ACH / ACH_{inf}[f]
				A. Base Cases: All Fans Off, All Windows Closed						
1	closed	closed	closed	closed	closed	off	1.9	SSE	0.31	—
2	closed	closed	closed	closed	closed	off	2.3	ESE	0.44	—
3	closed	closed	closed	closed	closed	off	2.2	SW	0.40	—
4	closed	closed	closed	closed	closed	off	2.2	SW	0.30	—
5	closed	closed	closed	closed	closed	off	2.2	SW	0.38	—
				B. Effect of Open Windows (all fans off)						
6	3 in	closed	closed	closed	closed	off	2.4	WSW	0.43	1.2
7	3 in	closed	3 in	closed	closed	off	2.4	WSW	0.75	2.0
8	closed	closed	3 in	closed	closed	off	2.8	SW	0.43	1.2
9	23 in[g]	closed	closed	closed	closed	off	2.2	WSW	0.53	1.4
10	23 in[g]	closed	23 in[g]	closed	closed	off	2.2	WSW	1.87	5.0
11	closed	closed	23 in[g]	closed	closed	off	3.5	SW	0.91	2.4
12	closed	closed	23 in[g]	closed	closed	off	2.3	WSW	0.68	1.8
13	closed	NW 3 in	closed	closed	closed	off	2.5	SSW	0.43	1.2
14	closed	NW 3 in	closed	3 in	closed	off	2.5	SSW	0.67	1.8
15	closed	NW 15 in[g]	closed	22 in[g]	closed	off	1.9	SW	1.79	4.8
16	closed	SW 8in[g]	closed	closed	closed	off	2.2	SW	0.74	2.0
17	closed	SW 8 in[g]	23 in[g]	closed	closed	off	3.3	WSW	2.8	7.5
18	closed	closed	closed	closed	29 in[g]	off	3.7	S	0.46	1.2
19	closed	closed	closed	22 in[g]	29 in[g]	off	3.7	SW	1.3	3.5
				C. Effect of Range Hood (60 CFM) (all windows closed, all other fans off)						
20	closed	closed	closed	closed	closed	on	3.0	SW	0.41	1.1
21	closed	closed	closed	closed	closed	on	3.8	SE	0.46	1.2

[a]window height is 33 in
[b]height of NW window is 58 in; height of SW window is 56 in
[c]window height is 41 in
[d]window height is 29 in
[e]window height is 16 in
[f]ACH_{inf} is the average house infiltration rate of Cases 3 through 5 with all windows closed and all fans off.
[g]wide open

TABLE 4

Residence 2 — Garage Ventilation Rates

Case No.	Garage Door (SW)	Sliding Door (NE)	Portable Fan	Wind Speed (mph)	Wind Direction	Average ACH	ACH / ACH_{inf}[a]
1	closed	closed	off	1.8	WSW	0.66	—
2	open	open	off	2.6	S	40.	6.1
3	open	closed	off	2.1	E	5.3	8.0
4	closed	closed	on	2.0	SE	0.81	1.2
5	open	open	on	2.6	ENE	37.	56.
6	open	closed	on	2.0	SE	11.	17.

[a]ACH_{inf} is the garage infiltration rate with all doors closed (Case 1)

idence's ventilation rate of up to 4.6 times over a residence's natural infiltration rate (under the same wind conditions and with all windows closed) can be expected when windows in both the windward and leeward sides are opened. Apparently, this occurs because infiltration increases at a faster rate with increasing wind speed than does ventilation due to opening windows under the same wind conditions.

3. Opening windows that are not in the direction of the prevailing wind is not as effective in increasing house ventilation as is opening windows on the windward and leeward sides. However, a modest ventilation increase of at least 20% can be expected.
4. Fully opening several leeward windows can result in approximately the same ventilation rate increase as does fully opening one windward window, or opening all windward and leeward windows 3 in.
5. Opening a window even 3 in on each of the windward and leeward sides of a house can be expected to increase the ventilation rate by at least 80%.
6. Operation of a modern range hood can double the house ventilation rate (when all the windows are closed).
7. Opening the main garage door can cause the garage ventilation rate to increase by at least 4 times over the garage's natural infiltration rate with the door closed.

REFERENCES

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TABLE 5

Residence 3 — Air Change Rates

Case No.	Dining Room[a] (ESE)	Living Room[a] (ESE)	Stair-way[b] (WNW)	Master Bedrm[c] (ESE)	Bedroom 1[c] (ESE)	Range Hood	Furn. fan	Wind Spd. (mph)	Wind Dir.	Avg. ACH	ACH / ACH_{inf}[d]
				A. Base Cases: All Fans Off, All Windows Closed							
1	closed	closed	closed	closed	closed	off	off	2.8	SW	0.43	—
2	closed	closed	closed	closed	closed	off	off	4.0	WNW	0.53	—
3	closed	closed	closed	closed	closed	off	off	4.4	S	0.40	—
4	closed	closed	closed	closed	closed	off	off	8.0	NNW	0.71	—
				B. Air Mixing Effect of Furnace Fan (all windows closed)							
5	closed	closed	closed	closed	closed	off	on	4.0	NNW	0.47	—
				C. Effect of Open Windows (all fans off)							
6	3 in	3 in	3 in	3 in	3 in	off	off	2.9	NW	2.0	4.5
7	3 in	3 in	closed	3 in	3 in	off	off	6.2	SSE	1.7	—[e]
8	33 in[f]	33 in[f]	21 in[f]	33 in[f]	33 in[f]	off	off	4.0	NW	5.5	11.
9	33 in[f]	33 in[f]	closed	33 in[f]	33 in[f]	off	off	3.8	NNW	2.1	4.2
10	33 in[f]	33 in[f]	closed	33 in[f]	33 in[f]	off	off	7.0	S	4.9	—[e]
11	closed	closed	21 in[f]	closed	closed	off	off	4.6	W	2.2	4.1
				D. Effect of Range Hood (178 CFM) (all windows closed, all other fans off)							
12	closed	closed	closed	closed	closed	high	off	3.7	NW	0.95	1.9

[a]window height is 47 in
[b]window height is 35 in
[c]window height is 39 in
[d]ACH_{inf} is the house infiltration rate under the same wind conditions with all windows closed and all fans off (see Figure 7)
[e]insufficient points for estimating infiltration under existing wind conditions
[f]wide open

TABLE 6

Residence 3 — Local Air Change Rates

Case No.	Injection Location	Dining Room	Living Room	Stair-way	Master Bedrm	Bedroom 1	Average ACH
			A. Base Cases: All Fans Off, All Windows Closed				
1	space	0.43	0.44	0.45	0.44	0.39	0.43
2	space	0.52	0.53	0.55	0.55	0.50	0.53
3	space	0.46	0.44	0.42	0.41	0.28	0.40
4	space	0.85	0.79	0.74	0.59	0.60	0.71
			B. Air-Mixing Effect of Furnace Fan (all windows closed)				
5	space	0.46	0.47	0.47	0.49	0.47	0.47

TABLE 7

Residence 3 — Garage Ventilation Rates

Case No.	Garage Door (WNW)	Portable Fans	Wind Speed (mph)	Wind Direction	Average ACH	ACH / ACH_{inf}[a]
1	closed	off	3.0	WNW	0.90	—
2	closed	off	5.5	N	1.4	—
3	closed	on	5.7	N	1.9	1.4
4	open	off	3.7	NW	22.	25.
5	open	off	3.2	NNW	15.	17.

[a]ACH_{inf} is the average garage infiltration rate of Cases 1 and 2 with door closed and fan off

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TABLE 8

Summary of Garage Door Opening Data

No.	Garage door's location relative to wind	Wind Speed (mph)	ACH increase
1.	Windward	12.	6.0
2.	Windward	14.	4.1
3.	Side[a]	2.1	8.0
4.	Windward	3.7	25.
5.	Windward	3.2	17.

[a]Not in the prevailing wind's direction

TABLE 9

Summary of Kitchen Hood Data

No.	Airflow (cfm)	ACH increase
1.	128	1.9
2.	115	2.0
3.	60	1.1
4.	178	1.9

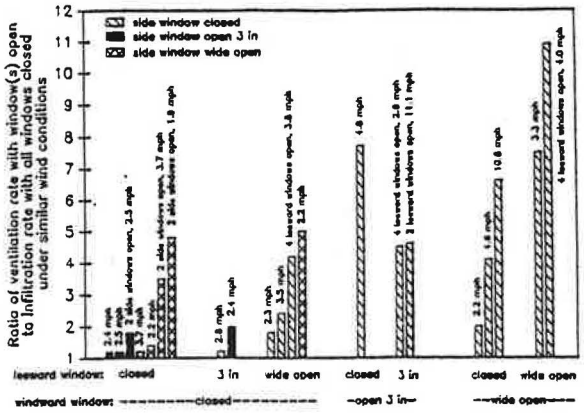

Figure 8 Summary of the ventilation data of the three residences studied

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