Infiltration and Ventilation Measurements on Three Electrically-Heated Multifamily Buildings

Paul W. Francisco and Larry Palmiter, Ecotope, Inc.

Ventilation and infiltration measurements were performed on three electrically-heated multi-family buildings. These tests were done under Pacific Northwest heating season conditions. Data was collected using a real-time multi-tracer measurement system.

We tested 5-6 individual units in each building. Tests were done to compare ventilation and infiltration during periods when ventilation fans in all units were on, periods when all ventilation fans were off, and periods when the fans in single units were on.

Average temperature differences to the outside ranged from 25-30 F. The average natural infiltration for each of the three buildings ranged from 0.14-0.22 air changes per hour (ACH), with individual units averaging from 0.075-0.31 ACH. These ventilation rates are significantly below current standards. With ventilation fans in all of the units on, the average outdoor air ventilation for the buildings increased to 0.38-0.47 ACH with individual units ranging from 0.31-0.54 ACH.

Due to stack effects units on lower floors experienced a higher percentage of outdoor air in the total unit flow. Interzone flows were found to be dominated by stack effects. Running all ventilation fans caused little change in interzone flows. Running individual ventilation fans caused an increase in flow to the unit in which the fan was operating due to depressurization of the zone.

Introduction

In recent years increasing importance has been placed on energy efficiency in residential buildings. This has resulted in tighter buildings, which raises concerns about whether the amount of ventilation is sufficient to provide acceptable indoor air quality. The measurement of air flow in residential buildings can be useful in determining answers to these questions. Single family homes have been tested extensively. These buildings can frequently be treated as having only a single zone, and numerous methods have been developed for this purpose. Fewer studies have been performed on multi-family buildings where the multiple zone interaction makes testing more difficult.

This paper presents results from the testing of three multi-family buildings in the Pacific Northwest under typical heating season conditions. An innovative multizone multi-gas tracer measurement system was used for these tests (Sherman et al. 1989). We tested 5-6 units in each building, with a different tracer gas being injected at a constant rate into each, and obtained the flows with a multizone deconvolution program described by Palmiter et al. (1993). We measured the temperatures in the center of each zone with thermocouples, and the pressures with transducers placed across walls, ceilings, and floors. Ventilation fans were cycled on and off during the test period. Fan on-times were typically two hours. Tests with all fans on were performed 2-3 times per day at the same times each day. Tests with only individual fans running were also performed. The situation when all fans are on provided the maximum infiltration, whereas the individual tests were perhaps more closely related to real cases, since it is not likely that all families will turn on their fans at the same time. A more detailed description of the results in one of the buildings is given by Palmiter et al. (1993), and the testing methodology can be found in more detail in Palmiter and Bond (1991) and Palmiter and Bond (1994).

The purpose of these tests was to determine the variation in ventilation among units based on location relative to other units, differential tightness, and fan operation. The results of these tests can also give insight into how well buildings may meet minimum ventilation standards.

Site Descriptions

We tested three multi-family buildings. Each of these was built to the Bonneville Power Administration's region-wide energy efficient specifications in 1992-93. Note that these specifications have changed since testing the first two sites to require continuous fan operation and fans rated to at least 80 cfm, partially as a result of the preliminary results of this study. Testing was done immediately after construction and before occupancy at all three sites. All three buildings had poured 1% inch gypcrete-on-plywood floors which makes them essentially gas-tight. Table 1 provides a summary of the important site characteristics, including environmental conditions.

Site A has three two-bedroom units per story, with two adjacent mirror-image apartments in front and a larger apartment in back. The front units have floor areas of 912 square feet. The back units have floor areas of 960 square feet. The upper units have cathedral ceilings in the dining and living rooms which add to their total volume. This was the only building tested that had a common stairwell.

Site B is a three-story, 21-unit building. The six units tested were separated from the rest of the building by double fire walls, which for the purposes of analysis were assumed to provide negligible airflow. The six units tested consisted of two mirror-image two-bedroom units per story. The floor areas are 831 square feet for all units. The top floor units have cathedral ceilings, adding to their total volume.

Site C is a split-level apartment building. The front of the building is two-story and the back is three-story, with only one unit per level. The floor areas are all about 1000 square feet. The walls are 8 feet high in the top units and 7.62 feet high in the other three units. The top units also have fireplaces. All units have two bedrooms.

Results

For analysis purposes, we selected data for an integral number of days at each site. We chose the starting time to allow for equilibrium after the initial setup and the ending time such that additional testing would not interfere with the analysis. We used six days at Site A, eight at Site B, and six at Site C. Because the data was noisy we condensed the selected data to an average daily profile with

Table 1. Site Characteristics

		Site A	Site B	Site C
Location		Portland, OR	Portland, OR	Issaquah, WA
Year Built		1992	1992	1992
Number of Stories		2	3	2/3
Number of Units Tested		6	6	5
Average Floor Area	(ft^2)	928	831	993
Average Volume	(ft^3)	7550	6469	7719
Average Ceiling Height	(ft)	8.14	7.78	7.77
Foundation Type		Built over Garages	Slab-on-grade	Crawl Space
Entry to Units		Common Area	External Stairwell	External Stairwell
Heating Fuel		Electric	Electric	Electric
Heater System		Wall heaters	Wall Heaters	Wall Heaters
Ventilation Fans		Range Hood, Laundry, Two Bath	Range Hood, Laundry, Two Bath	Range Hood, Dryer Laundry, Two Bath
Designated Fan Rating		50 cfm	50 cfm	90 cfm
Passive Ventilation		Slot Vents	Slot Vents	Slot Vents
Test Start Date	(m/d/y)	2/9/92	2/22/92	3/13/93
Number of Days of Test		6	8	6
Average Indoor Temperature	(F)	76.3	78.9	77.3
Average Outdoor Temperature	(F)	50.4	51.6	47.4
Average Temperature Difference	(F)	25.9	27.3	29.9
Average Wind Speed	(MPH)	1.57	2.06	1.30

12-15 minute intervals. The fan test on- and off-times were trimmed to include only times when the flows were at a steady state. This typically resulted in 1% hour on-periods surrounded by two 1% hour off-periods for each cycle.

Zone and Building Flows from Outdoors

Table 2 shows the average flows from outdoors, total zone flows. and the percentage of the total flow that comes from outdoors. These are shown for each individual unit and as a unit average, and with all fans on and off.

The first column of Table 2 shows that, based on flow from outdoors with all fans off, Site B was the leakiest building with an average flow of outdoor air per unit of about 24 cubic feet per minute (cfm). Sites A and C were both significantly tighter, with Site A having an average flow of outdoor air per unit of about 17 cfm and Site C having an average of approximately 18 cfm. We normalized these flows by volume to get the air flow in air changes per hour (ACH), as shown in the second column of Table 2. By this measure Site B was still the leakiest with an average of 0.22 ACH. Sites A and C both were measured to have 0.14 ACH with all fans off.

Table 2. Average Flows from Outdoors (in cfm and ACH), Total Zone Flows (in ACH) and Percentage of Total Flow from Outdoors

		Flow from Outdoors				Total Zone Flow		% from Outdoors	
		Fans Off		Fans On		Fans Off	Fans On	Fans Off	Fans On
	Floor	cfm	ACH	cfm	ACH	ACH	ACH		
Site A (fan rating: 50 cfm)									
Unit 1	1	18.2	0.14	45.9	0.36	0.14	0.36	100.0	99.4
Unit 2	1	18.3	0.15	59.5	0.49	0.15	0.49	99.4	100.0
Unit 3	1	19.2	0.16	47.1	0.39	0.16	0.40	99.6	97.6
Unit 4	2	13.8	0.10	42.5	0.31	0.13	0.34	77.3	91.3
Unit 5	2	18.0	0.14	46.0	0.37	0.20	0.44	70.0	82.8
Unit 6	2	14.7	0.12	49.1	0.39	0.15	0.45	77.3	86.5
Average		17.0	0.14	48.4	0.38	0.16	0.41	87.3	92.9
Site B (fan rating: 50 cfm)									
Unit 1	1	21.0	0.20	42.8	0.41	0.24	0.44	84.9	93.2
Unit 2	1	32.6	0.31	56.9	0.54	0.33	0.57	94.7	95.8
Unit 3	2	18.6	0.18	39.0	0.37	0.25	0.43	71.3	85.5
Unit 4	2	16.3	0.16	34.3	0.33	0.24	0.39	63.9	83.3
Unit 5	3	29.9	0.26	48.1	0.42	0.31	0.45	66.1	83.1
Unit 6	3	23.0	0.20	42.4	0.37	0.40	0.56	65.2	76.3
Average		23.6	0.22	43.9	0.41	0.30	0.47	74.4	86.2
Site C (fan rating: 90 cfm)									
Unit 1	1	17.5	0.14	63.9	0.51	0.14	0.51	99.0	99.7
Unit 2	1	18.6	0.15	65.2	0.52	0.15	0.52	98.3	99.4
Unit 3	2	9.6	0.08	50.9	0.40	0.12	0.44	63.8	91.7
Unit 4	2	17.4	0.13	65.4	0.49	0.15	0.52	85.2	95.1
Unit 5	3	24.5	0.19	58.3	0.44	0.22	0.48	83.8	91.2
Average		17.5	0.14	60.7	0.47	0.16	0.49	86.0	95.4

This trend was different when all fans are on. As shown in the third column of Table 2, Site B had the smallest average flow of outdoor air per unit when all fans were on, at about 44 cfm. Site A had about 48 cfm with the fans on, while Site C had the largest at approximately 61 cfm. When measured in ACH, however, Site A was the tightest, with only 0.38 ACH flow from outdoors with all fans on, as shown in the fourth column of Table 2. Site B had an average of 0.41 ACH and Site C had 0.47 ACH with all fans on.

Figures 1 and 2 show the average daily flows from outdoors, in cfm and ACH, respectively, for a single stack of units in each building. The fan on-periods are clearly visible in these figures. Times when flows in all of the units increase indicate periods when all fans were turned on. Similarly, when a single unit shows an increase in flow, the fan in that unit was operating individually.

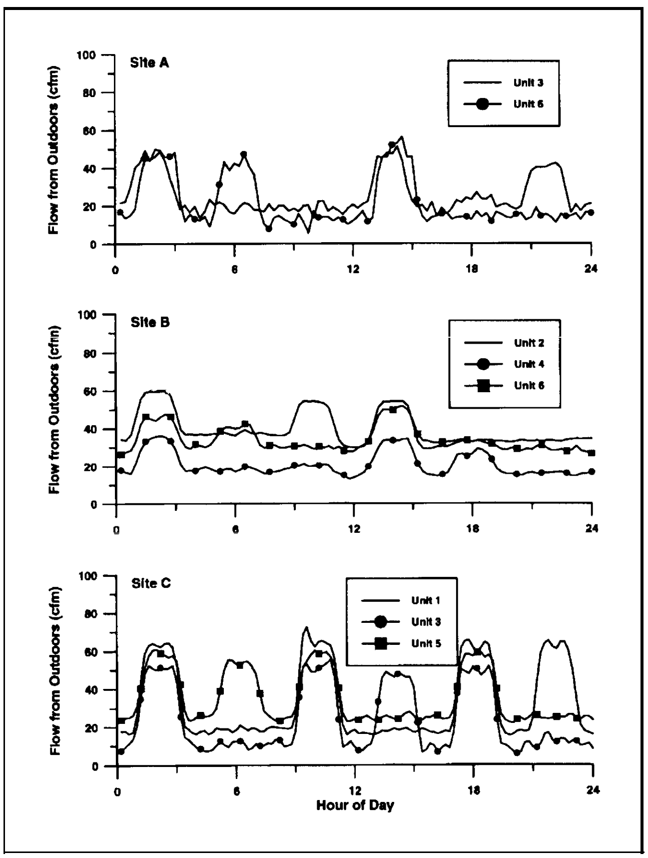

Figure 1. Flows from Outdoors into Individual Units, Shown for a Single Stack in Each Building

The current standard for ventilation in residential buildings, as stated by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE), is that there should be at least 0.35 ACH per unit or 15 cfm per occupant, whichever is greater (ASHRAE 1989). Based on an occupancy of three people this means that, in order to meet the minimum standards, Site A must have at least 0.36 ACH, Site B must have at least 0.42 ACH, and Site C must have at least 0.35 ACH. The results show that none of the units met this standard when all fans were off. With all fans on Site A had five out of six units that met the standard, though only one unit had more than 0.40 ACH. Unfortunately, since it is difficult to assure that all fans will operate simultaneously, Site A will at times be underventilated. Site B had two units that met the standard with all fans on, one of which was exactly 0.42 ACH. Site C met the standard in all units with all fans on, with no units under 0.40 ACH. Ventilation levels with individual fans operating also met the standard in the three units for which individual fan tests were performed.

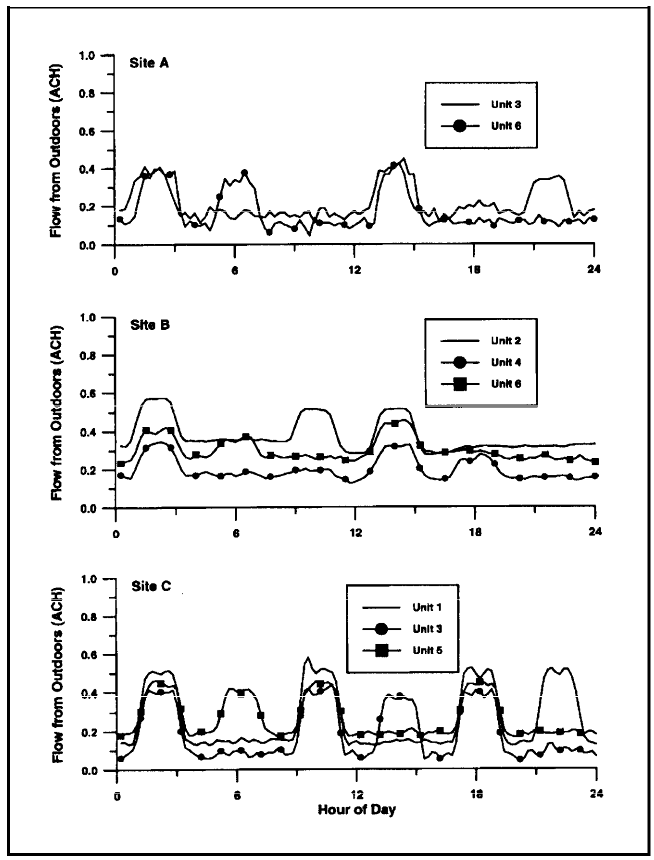

Figure 2. Air Changes per Hour from Outdoors for Individual Units, Shown for a Single Stack per Building

On an individual unit basis, we found in Sites B and C that intermediate level units had significantly less flow from outdoors. This is because intermediate level units have less surface area exposed to outdoors and are also subject to vertical flows due to stack effects from units directly beneath them. These vertical flows are the primary contributors to interzone flows. Units on bottom floors are not subject to flows due to stack effect, so the air coming into these units originates almost entirely from outdoors. Top floor units have ceilings that are completely exposed to the attic. Ceilings tend to be leaky because of penetrations for fans and lights and therefore allow additional outdoor air to enter the top floor units.

Total Zone Flows

The fifth and sixth columns of Table 2 show the average total zone flows measured in ACH. Total zone flows are the combination of flow from outdoors and flows from other units. Flows from other units are not considered to add to ventilation because they can carry pollution products such as smoke, and as a result do not necessarily improve the air quality in the unit. Site B had the highest per unit average of total zone flow with fans off, measured to be about 32 cfm. Sites A and C both had significantly less total zone flow with the fans off, each having an average total flow per unit of about 20 cfm. When measured in ACH Site B again had the highest total flow per unit with fans off, with an average of 0.30 ACH. Sites A and C both were calculated to have 0.16 ACH with all fans off.

When all fans were on Site B had the lowest average total flow per unit, at about 51 cfm. Site A had about 52 cfm with the fans on, while Site C had the highest at approximately 64 cfm. When measured in ACH, however, Site A was the tightest, with only 0.41 ACH flow from outdoors with all fans on. Site B had an average of 0.47 ACH and Site C had 0.49 ACH with all fans on. As with flow from outdoors, intermediate level units had less total flow than top or bottom floor units.

Percentage of Total Flow from Outdoors

The final two columns of Table 2 show the percentage of the total flow through the zones that comes from outdoors. The next to last column shows that in all three buildings the units on the bottom floor typically had nearly all of their flow come from outdoors when all fans were off. By comparison, higher units had as little as 64% of their total flow come from outdoors. It is not clear whether top floor units have a higher percentage of their flow come from outdoors than do intermediate units. Site C suggests that this may be the case, but this conclusion is harder to draw from Site B.

Bottom units still had nearly all of their flow come from outdoors when all fans were on, as seen in the final column of Table 2. The percentage of flow from outdoors in other units increased dramatically, though these percentages were still lower than those of bottom units. Intermediate units had about the same percentage as top units when all fans were on.

Figure 3 shows the daily profile of the percentage of flow that comes from outdoors for a single stack of units in each building. This figure clearly shows that the bottom floor units had a significantly higher percentage of their flow come from outdoors compared to other units. It also shows the effects of individual fan tests on these percentages in several units. In Site A, the percentage decreased for Unit 3 at about 9:00 p.m. when its fan ran individually and depressurized the unit, which pulled in air from the adjacent unit, perhaps via the common area, but pulled in a proportionally lower amount of air from outdoors. The only period when there is a significant horizontal flow between these two units was when operation of a single fan depressurized one of the units. This type of percentage decrease was not found in either of the other two sites. For example, in Site B, Unit 4 experienced an increase in its percentage when the Unit 2 fan was turned on. In Site C, Unit 3 experienced a dramatic increase in outdoor air when either its own fan or the fan in Unit 1 operated individually. A percentage increase can be seen for all of the higher units when all fans operated.

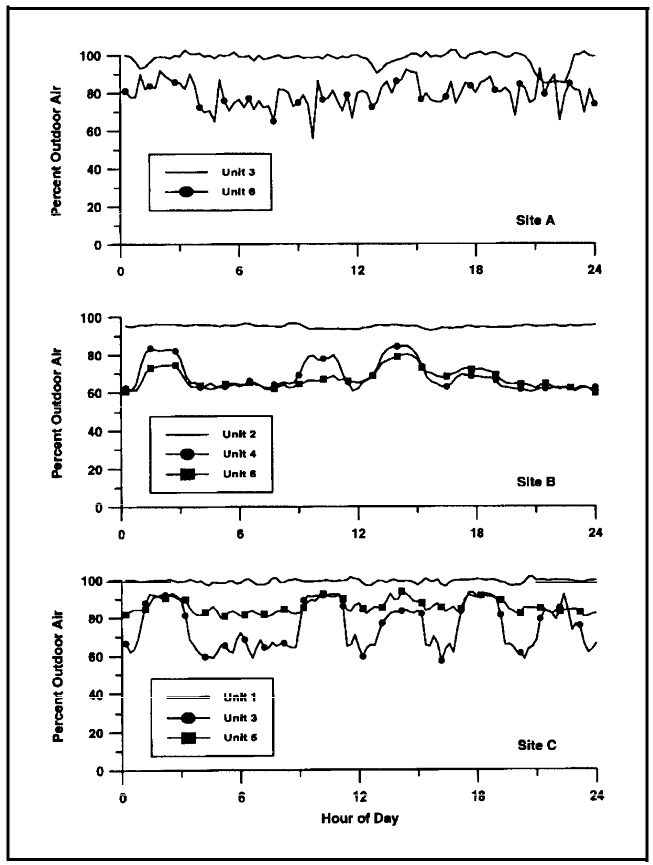

Figure 3. Percentage of Total Flow from Outdoors, Shown for a Single Stack from Each Building

Interzone Flows

Flows between units were dominated by stack effects, which are the result of pressure gradients caused by indoor-outdoor air density differences. These pressure differences cause air from a lower unit to go up and into the unit directly above. Little interzone flow was found from higher units to lower units or between units at the same level. Bypass flows, where air flows directly between two non-adjacent units, were also much smaller than stack flows.

We measured pressures across the floors with pressure transducers. With all fans off Site A had pressures of 1.6-1.8 Pa, Site B had pressures of 1.4-2.1 Pa, and Site C had pressures of 1.9-2.4 Pa between units. The neutral levels were all close to the ceiling. We found little change when all fans operated since the depressurization due to the fans was approximately equal in all units. When individual fans operated the unit in which the fan was running was depressurized, resulting in increased flows from other units and from outdoors. In Site A this change ranged from 0.7-0.9 Pa, in Site B the change was 0.6- 1.4 Pa, and in Site C it was 1.0-1.5 Pa.

The magnitude of the flows due to stack effects varied from site to site. In Site A they were about 2-4 cfm. Site B had the largest, ranging from about 6-12 cfm. Site C was comparable to Site A, with flows due to stack effects in the range of 3-5 cfm. Note that the stack effects result in two types of flows. If the floors were airtight, all of the outdoor air would enter close to the floor and exit near the ceiling. If the floors were completely porous, the outdoor air would enter at the bottom of the building and exit at the top of the building. Since the floors restrict the flow of air, but still have some leaks, there is flow out of each unit near the ceiling and into units directly above. This behavior is supported by our pressure measurements.

Within individual buildings the bypass flows were smaller than direct flows due to stack effects. In Sites A and C very little bypass flow was found. In Site B bypass flows were measured to be about 3.5 cfm. The pathway for bypass flows is usually into the floor-ceiling cavity and across into cavities in walls, especially common walls that have plumbing and electrical equipment in them, and re-emerging in the non-adjacent units. Bypass flows were typically between bottom floor units to top floor units.

Figure 4 shows average daily vertical interzone flows for a single stack of units in each building, including upward bypass flows. This figure illustrates the effects on vertical flows due to operating fans individually. For example, the Site B plot shows the effects of turning the fan in Unit 4 on individually, as the flow from Unit 4 upward to Unit 6 decreased and the flow from Unit 2 upward to Unit 4 increased.

Horizontal interzone flows tended to be very small, usually less than 0.6 cfm, which is at the noise level of these measurements. The only exception was the flow between the lower units of Site B, which measured about 3.4 cfm when all fans were off. This flow changed only slightly when the fan in Unit 2 was run individually, but increased to about 4 cfm when all fans were on. The reason for this large flow was not determined.

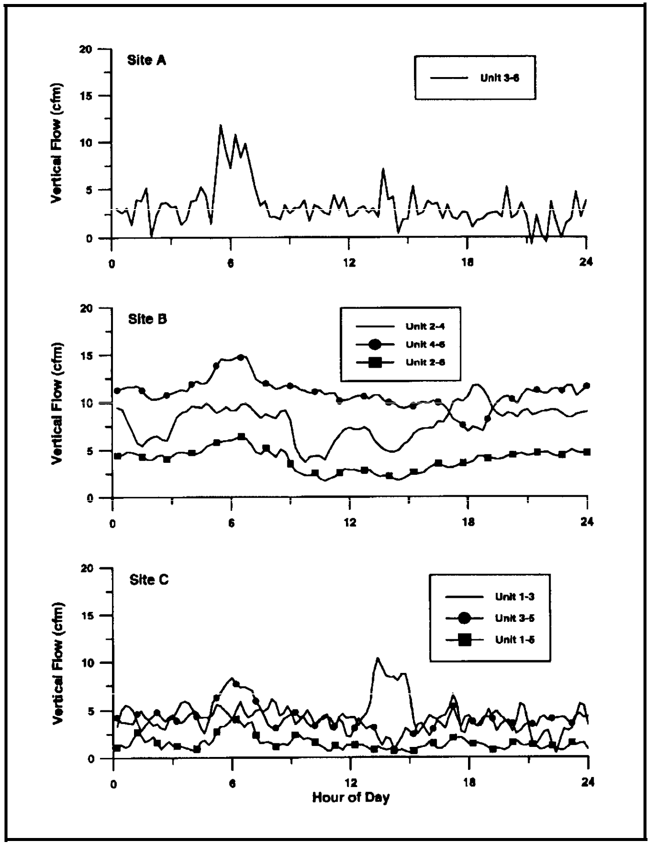

Figure 4. Vertical Flows for a Single Stack from Each Building, Including Bypass Flows for Sites B and C

Slot Vents

Slot vents above window sashes are required by the utility energy-efficiency program to increase the ventilation rates in residential buildings. The purpose of these vents is to help alleviate the depressurization caused by operation of the ventilation fans and to provide additional outdoor air to the whole unit. Questions have been raised as to the effectiveness of these slot vents. We have analyzed the effect of slot vents on air flow rates in Site A. Each unit has a total of 60 rectangular slots, each with an area of 3/16 square inches. The vents were open at the beginning of the test period and then closed partway through the testing. For the purposes of comparison we averaged the flows for the periods of slots open and closed separately. This was done for times when all fans were off so that the effects would be on natural ventilation only. To minimize the impact of wind we restricted the data used in this analysis to those times when the wind speed was less than 2.24 MPH.

Table 3 provides a summary of the effects of the slot vents on natural infiltration. All units in Site A had an increase in airflow when the slots were open and all fans were off. The average increase for all units was about 2.6 cfm, which was about 16%. Individual units ranged from about 1.6 to 3.4 cfm. The percentage increases in individual units ranged from about 11% to 26%. The average additional air due to slots was about the same when all fans were on, though individual units ranged from 0.8 to 13.6 cfm. The average percentage increase in flow due to slots when the fans were on was about 6%, with individual units ranging from 1% to 14%. There was no obvious correlation between unit location and the amount of flow increase due to slots.

Table 3. Effect of Slots on Infiltration in Site A with Fan Off and Wind Speed <2.24 MPH, in cfm

	Closed	Open	Change	% Change
Unit 1	17.1	19.7	2.6	15.2
Unit 2	17.2	20.5	3.2	18.6
Unit 3	18.9	21.0	2.1	11.1
Unit 4	13.0	14.6	1.6	12.3
Unit 5	16.5	19.2	2.7	16.4
Unit 6	13.1	16.6	3.4	26.0
Average	16.0	18.6	2.6	16.3

Other Tests

We ran blower door tests at all three sites to measure the flow at 50 Pa and the Effective Leakage Area (ELA) (Sherman and Grimsrud 1980). The results are shown in Table 4, given as the per unit average for each building with slots open and closed. At Site C ELA calculations were only made with the slots open.

The blower door test results show that at 50 Pa with the slots open Site A was the leakiest building, with a per unit average of 861 cfm. Site B was the next leakiest, with an average of 767 cfm. Site C had an average of 712 cfm. With slots closed Site A still had the largest average flow at 50 Pa, at 809 cfm. By comparison, Site B had 755 cfm and Site C had 663 cfm.

We also made flowhood measurements to determine how the fans performed relative to their flow output ratings. We found that fans typically did not meet their advertised specifications. Measured fan flows are shown in the first column of Table 5. In Site A, measured fan flow averaged 93% of the rated flow of 50 cfm, though fans in the top story units actually exceeded the rating by about 2 cfm. The fans in Site B delivered only about 71% of their rated flow of 50 cfm, and Site C performed at about 77% of their 90 cfm rating. A change in utility specifications now requires larger fans such as those found in Site C.

Table 4. Results of Blower Door Tests, Average per Building

	Site A	Site B	Site C
Slots Open			
Q50 (cfm)	861	767	712
ELA (in^2)	45.9	38.8	44.3
Exponent	0.668	0.673	0.602
Slots Closed			
Q50 (cfm)	809	755	663
ELA (in^2)	42.9	36.1	--
Exponent	0.688	0.692	--

Zone fan flows can be used to predict the total flow through the zone using the model developed by Palmiter and Bond (1991). The comparison between measured total zone flow and the flow predicted by the model are shown in the last two columns of Table 5, The average measured flow per unit through Site A was about 12% higher than the prediction. Site B average measured flows were only 3% higher than predicted flows, while Site C average measured flows were about 9% smaller than the prediction.

Conclusions

Several important conclusions can be drawn from this study of tracer gas tests on three multi-family buildings in the Pacific Northwest. Caution should be taken when applying these results. While we believe that these buildings are representative of newer Pacific Northwest buildings of this type, they may not be representative of all multi-family buildings in the Northwest taken as a whole.

Under heating conditions all three of the buildings were seriously underventilated when natural infiltration was the only source of external air. Ventilation levels did significantly increase when all fans were turned on, but even when all fans were running the levels of ventilation for many units were below minimum ASH RAE standards. This results partially from fans not delivering their rated output due to excessive hydraulic resistance in the duct systems. Running individual fans is not as effective in improving the ventilation level of the building as a whole, and in fact increases the potential for pollutants to travel between units.

Table 5. Comparison of Measured and Predicted Infiltration Effects of Fans, in cfm

	Fan Flow Measured	Total Flow Through Zone Measured	Total Flow Through Zone Predicted
Site A (fan rating: 50 cfm)			
Unit 1	37.9	46.2	37.9
Unit 2	42.5	59.6	42.5
Unit 3	44.4	48.3	44.4
Unit 4	51.9	46.6	51.9
Unit 5	51.9	55.5	51.9
Unit 6	51.9	56.7	51.9
Average	46.7	52.1	46.7
Site B (fan rating: 50 cfm)			
Unit 1	37.0	45.9	43.3
Unit 2	40.7	59.4	54.7
Unit 3	29.5	45.6	40.8
Unit 4	23.9	41.1	37.5
Unit 5	41.6	51.0	55.6
Unit 6	38.8	63.0	65.3
Average	35.3	51.0	49.6
Site C (fan rating: 90 cfm)			
Unit 1	65.8	64.1	65.8
Unit 2	71.4	65.6	71.4
Unit 3	66.8	55.5	66.8
Unit 4	79.8	68.7	79.8
Unit 5	63.0	63.9	63.0
Average	69.4	63.6	69.4

Since it is unlikely that all residents will operate their fans simultaneously, fans should be installed and operated continuously and without resident-controlled switches. The fans should also be manufactured better to meet their ratings, and the fans to be installed should be silent and of sufficient size to assure acceptable ventilation. Note that, partially due to preliminary results of this study, the current utility specifications require continuous fan operation and fans rated to 80 cfm.

Another conclusion from this study is that stack effects accounted for the majority of interzone flows. These flows did not increase significantly when all fans were turned on; however, when a single fan was turned on flows into that unit from other units did show a marked increase. Flows due to stack effect may carry pollution from lower units to higher units, reducing the percentage of outdoor air and therefore diminishing the air quality in the higher units. This effect is most severe in intermediate units since they receive less flow from outdoors than other units.

Slot vents in Site A did increase the amount of air coming into the units from outdoors. However, the amount of additional air was only about 16% of the natural infiltration rate. With fans operating the additional air due to slots was only about 6% of the total infiltration rate.

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