Modeled and Measured Infiltration in Ten Single-Family Homes

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Real-time ventilation and infiltration measurements were made on ten single-family homes. Seven of these had crawlspaces and were in the Pacific Northwest. Two had daylight basements and were also in the Pacific Northwest. The other is an energy efficient demonstration ‘‘smart’’ house built in Rocklin, CA, and was built on a crawlspace. All of the homes were tested under heating season conditions. The home in Rocklin was also tested under cooling conditions.

Each house was divided into multiple zones, including buffer spaces, and each test period lasted about a week. Tests were conducted to compare ventilation and infiltration during periods when the forced-air distribution system was on to those times when it was off. Special one-time tests were also done with exhaust fans operating. Detailed data was collected in each house using a real-time multi-tracer measurement system.

This paper presents the results of testing on these ten buildings. Blower door test results are compared, and the ability of various models to predict infiltration for the different foundation types are analyzed.

INTRODUCTION

In recent years increased 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 is useful in determining answers to these questions, as well as confirming existing infiltration models and illuminating ways in which these models can be improved.

In 1990 Ecotope, in collaboration with Lawrence Berkeley Laboratory (LBL), began a study to perform detailed infiltration measurements on homes in the Pacific Northwest. The primary purposes of this study were to test carefully selected homes in order to resolve weaknesses in a commonly used infiltration model developed at (LBL) (Sherman & Grimsrud 1980) and to better understand the effects of mechanical ventilation systems. Field testing was performed by LBL personnel. Four homes were initially tested (Palmiter & Bond 1991a), designated Sites 1–4. The main source of natural infiltration in these homes was from stack effect, and exhaust fans had little effect on the average daily ventilation rates. Three more homes were added to the study, which were selected to maximize information relating to wind effects on infiltration and the interaction of natural infiltration and mechanical systems (Palmiter & Bond 1994). These were designated Sites 5–7. Out of these first two studies came proposed revisions to the methods of use of the LBL infiltration model.

After this testing was completed, it was felt that the sample could be enhanced in two ways. One was to test a home in a different climate. The other was to test homes with different foundations. The first seven homes were built over crawl spaces, which tend to be well connected to outdoors. Testing homes built on foundations that have less leakage through the floor would improve our knowledge of how different construction influences infiltration. This testing also would provide a means of evaluating the validity of some of the assumptions used in standard models and the accuracy of these models for different foundation types. To address these issues, three more homes, designated Sites 8–10, were tested (Palmiter & Francisco 1996).

This paper presents a condensed summary of some of the results contained in the three detailed reports. The original reports should be consulted for details of the methodology and theoretical background. The homes tested are case studies, and are not intended to be taken as a statistical sample.

Each set of tests was short-term, lasting about a week. Timer-controlled air handler tests were performed each day to analyze the effect of the air handler on airflows within the home. Each home was separated into several zones, including accessible crawlspaces, attics, and garages. Time-series data was taken at the level of minutes. A different tracer gas was injected at a constant rate into each zone, and the concentration of each gas in each zone was measured using a multizone tracer measurement system (Sherman, Feustel & Dickerhoff 1989). The flows were then calculated using a matrix deconvolution program developed at Ecotope. We also measured temperatures and pressures throughout the homes and outdoors. Sites 1–3 were occupied during testing, while Sites 4–10 were unoccupied.

SITE CHARACTERISTICS

All of the homes except for Site 8 were in the Pacific Northwest and were tested under heating season conditions. Site

8 was in Rocklin, California, and was designed as a demonstration energy efficient ‘‘smart’’ house. This home was tested under both heating and cooling season conditions. Table 1 provides a summary of the important site characteristics for the ten homes, and Table 2 gives the environmental conditions during the test periods. Note that the average wind speed during a test period rarely got much higher than 2.0 miles per hour (mph).

Sites 1–7 were built over crawlspaces, and all of the supply ducts in these homes were located in the crawlspaces. Two of the homes were manufactured homes built to energy-efficiency standards.

Site 8 was built mostly over a crawlspace; however, the living room is dropped by a foot compared to the floor level of the rest of the first floor, and this portion of the foundation is a slab. The supply ducts were located in the house, minimizing the unintentional air flow pathways through the floor which helps to make the floor more resistant to flow than in the previous seven homes. We analyzed data from four separate test periods at Site 8, one set starting in each of August, September, October, and November 1992. These tests were designated as Test I, Test II, Test III, and Test IV, respectively.

Sites 9 and 10 were built over full daylight basements, meaning that at least one wall was completely exposed to outdoors. Site 9 had the south wall exposed to outdoors, and Site 10 had the east wall exposed to outdoors. These homes had the supply and return ducts all located inside the home. This duct placement and the construction of the basement walls and floor make these homes more resistant to air flow through the floors than at Sites 1–7. For the analysis of Site 9, the first and second floors were considered to be the living zone and the basement was considered to be a buffer space. For Site 10, which was a one-story house, the basement was included as part of the living zone. The basement at Site 9 was unheated, while the at Site 10 the basement was heated.

AIR FLOWS

We evaluated air flows through the ten homes in two ways. The first is on a volumetric basis. The second, which accounts for different house volumes, is in air changes per hour (ACH), which is the volumetric flow rate divided by

Table 1. *Site Characteristics*

Site	Year Builtqc	Floor Area (ft^2)	Volume (ft^3)	Number of Stories	Foundation Type	Heating system	Ventilation system	Air handler location	Supply duct location	Return duct location
1	1988	1553	12367	2	Crawl	Wall htr	Multiport	—	—	—
2	1979	2213	17589	2	Crawl	HP	None	Garage	Crawl	Attic
3	1984	1812	14226	1.5	Crawl	Furnace	None	Garage	Crawl	House
4	1988	1182	9496	1	Crawl	Furnace	Bath fan	House	Crawl	None
5	1988	3503	28510	2	Crawl	HP	AAHX	Closet	Crawl	Attic
6	1985	1695	14876	2	Crawl	Furnace	None	Garage	Crawl	Attic
7	1990	1217	9746	1	Crawl	Furnace	Bath fan	House	Crawl	None
8	1992	2651	28003	2	Crawl	Furnace	Multiport	House	House	House
9	1930s	1512	10630	2	Basement	Furnace	Kitchen fan	Basement	House	House
10[a]	1960s	2324	16951	2	Basement	Furnace	Kitchen fan	Basement	House	House
Ave.		1826	16239	1.75						

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[a] The living zone at Site 10 includes the daylight basement.

Table 2. *Average On-Site Environmental Conditions*

	TEMPERATURE (F)			WIND SPEED
Site	Indoor	Outdoor	Difference	(mph)
1	72.4	52.8	19.5	1.53
2	70.1	51.6	18.4	2.06
3	69.6	55.1	14.5	1.60
4	85.4	54.7	30.7	1.10
5	71.2	47.5	23.8	3.52
6	68.9	44.8	24.1	1.91
7	69.8	42.8	27.0	11.77
8-I	69.9	88.6	18.7	4.90
8-II	67.8	77.7	9.9	3.51
8-III	74.9	62.1	12.8	6.89
8-IV	78.4	53.7	24.7	3.58
9	80.2	49.6	30.6	2.04
10	80.2	46.8	33.4	1.74

the total house volume. For direct comparison purposes, only the flow rates normalized for house volume are presented here. With this notation, some houses that had very large volumetric flow rates may actually have the smallest normalized flow rates. For example, Site 8, which is a very large house, has the highest volumetric flow rate of air from outdoors (as opposed to air from buffer spaces) during Test IV of any of the latest three homes, but when measured in ACH both Sites 9 and 10 have higher flow rates. This should be kept in mind when interpreting the data presented here.

Natural Infiltration and the Effects of Running Air Handlers

Natural infiltration in a building, defined as air that comes into the building when no mechanical ventilation system is running, is the result of both wind-generated pressures on the exterior of the building and pressures caused by temperature gradients between indoors and outdoors. The temperature gradients cause the density of the indoor air to differ from that of the outdoor air. Under winter conditions, when the outdoor air is colder and therefore more dense than the indoor air, the result is a buoyancy effect. This is known as the stack effect, which pulls air into the building near the bottom and causes it to flow upward, exiting near the top of the building.

Except at Site 7, which was in an exceptionally windy area, natural infiltration was dominated by flow due to stack effect. Analysis of the measured data, based on times when all fans were off and wind speeds were less than 2.24 mph, provided the average flows due to stack effect shown in the first column of Table 3. These flows include air from buffer spaces. The flows due to wind in the second column were calculated by subtracting the average flows due to stack effect from the average measured total infiltration with all fans off.

The dominance of stack effect over wind effect is emphasized by comparing Tests III and IV. Test III, during which

Table 3. *Natural Infiltration Characteristics*

	Stack Effect (ACH)	Wind Effect (ACH)[a]	Total (ACH)	Percentage Stack (%)
1	0.264	0.022	0.286	92.3
2	0.383	0.062	0.445	86.1
3	0.305	0.058	0.363	84.0
4	0.139	0.005	0.144	96.5
5	0.261	0.026	0.287	90.9
6	0.373	0.004	0.377	98.9
7	0.230	0.431	0.661	34.8
8-I	0.070	0.005	0.075	93.3
8-II	0.084	0.002	0.086	97.7
8-III	0.148	0.041	0.189	78.3
8-IV	0.216	0.006	0.222	97.3
9	0.556	0.003	0.559	99.5
10	0.259	0.000	0.259	100.0
Ave.	0.253	0.051	0.304	88.4

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[a] Calculated as the difference between the total flow and the flow due to stack effect.

winds were frequently in excess of 10 mph and reached as high as over 20 mph, still had less flow than was experienced during Test IV, when the wind speeds were much lower. Table 4 shows that the flow of air through Site 8 increased from one test period to the next, corresponding to colder outdoor temperatures. This is consistent with stack-dominated flow when outdoor air is colder than indoor air. However, when the outdoor temperature is higher than indoor temperature, theory states that flow due to stack effect should increase with increasing temperature, in a manner symmetric to the heating season situation. The decrease in flow rate as the temperature difference increases during the cooling season tests indicates that some other effect is preventing air from entering the house.

Operating the air handler depressurized Sites 2–9, causing an increase in flow through the living zones. The depressurization indicated that supply-side leakage dominated the duct leakage. The increase due to running the air handler varied greatly since the level of interaction between the air handler and infiltration depended on the degree to which the flows through the supply and return sides were unbalanced. At Site 10 the distribution system was completely inside the living space and the return was on the main floor. The door between the main floor and the basement was closed during testing, isolating the basement from the return. This pressurized the basement. The main floor was depressurized, but by a smaller amount than the basement pressurization. This pressurization resulted in a decrease in the total flow through the living zone.

Table 4. *Effect of Ventilation Fans on Infiltration*

Site	Fan	Induced Infiltration (ACH)
1	Exhaust Fan	0.177
3	Bath Fan	0.057
4	Bath Fan	0.166
4	Bath Fan + Air Handler	0.397
4	Range Hood	0.192
5	Range Hood	0.215
6	Bath Fans (3)	0.250
8-II	Exhaust Fan	0.169
8-II	Exhaust Fan + Air Handler	0.184
9	Kitchen Fan	0.704
9	Bath Fan	0.165
10	Jenn-Air	0.486
10	Jenn-Air + Range Hood	0.932

Figure 1 shows the average flows from outdoors into the living zone and total living zone flows with the air handler off, and the total living zone flow with the air handler on for all ten homes. These results are averages from the measured data and are summarized for times when the air handler was on and when the air handler was off. No other fans were operating during the times summarized. The horizontal line corresponds to 0.35 ACH, the minimum living zone ventilation rate required by ASHRAE Standard 62 (ASHRAE 1989) for times when the home is occupied. The total flow rates with the air handler off shown in Fig. 1 differ from the data in Table 3 because only measured data for those times when the air handler was off were used for the bar in Fig. 1.

Effects of Running Ventilation Fans

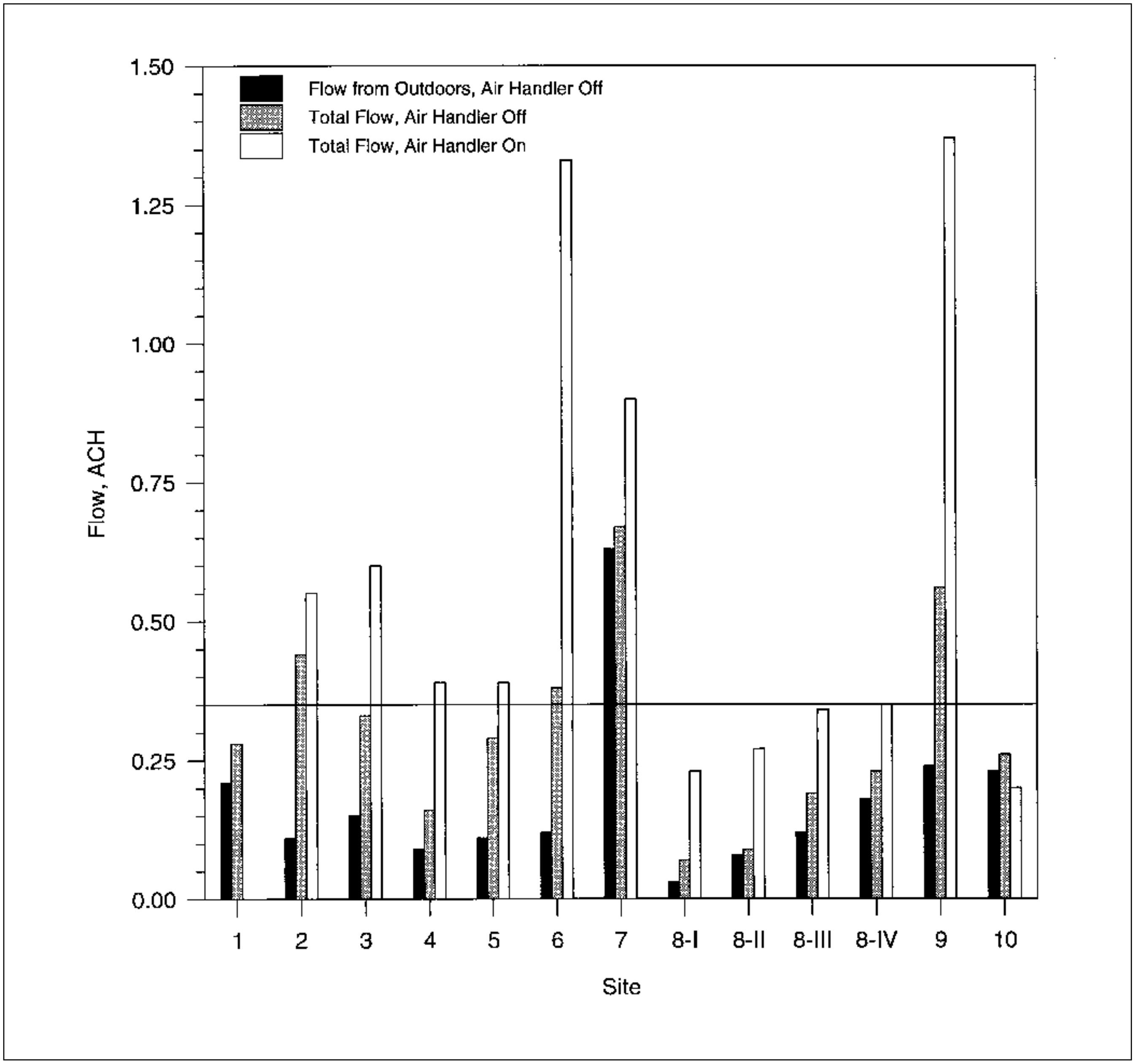
Many ventilation fans induce a large amount of additional infiltration when they operate. These fans depressurize the home and cause additional air to enter the home. Ventilation fans were tested at eight of the ten homes. The induced infiltration caused by these fans, including flow from buffer spaces, is summarized in Table 4.

Most of the fans tested added about 0.17 ACH to 0.22 ACH when they operated singly. Only one fan, a small bath fan at Site 3, added significantly less flow. Two of the fans added a lot more infiltration when they ran. One was a large kitchen fan at Site 9. This fan added about 0.70 ACH, more than any other fan that was tested. The other was a Jenn-Air kitchen fan at Site 10, which added about 0.49 ACH.

A few tests were also conducted with a fan and the air handler, or multiple fans, running simultaneously. At Site 4, when the bath fan was run at the same time as the air handler, the total induced infiltration was about the same as the sum of running them separately.

During Test II at Site 8, when the air handler and multiport bathroom ventilation fan were operated simultaneously, the air change rate did not increase significantly compared to when the ventilation fan operated alone. This indicates that the air handler and ventilation fan may each cause pathways that would have been used by the other to be blocked.

__Figure 1.__ Air Change Rates for Ten Homes



At Site 10, with the Jenn-Air kitchen exhaust fan range hood fan both running, the total flow through the living zone increased by 0.93 ACH.

Flow through Buffer Spaces

When possible, flows were measured in garages attics, garages, and crawlspaces. The results are shown in Table 5.

This table shows that attics and crawlspaces were very leaky, with attics averaging 6.4 ACH and crawlspaces averaging 4.8 ACH, including flow from other portions of the house. During the heating season, attics had a sizable flow from other portions of the house because of stack effect. In the cooling season tests at Site 8 there was not much flow through the attic from other portions of the house. Crawlspaces, on average, did not receive much flow from other portions of the house.

Garages, on the other hand, were not very leaky. The average flow rate was under 1.5 ACH even when flow from the rest of the house was considered. If Sites 9 and 10 are omitted, the average flow from outdoors through the garages was

Table 5. *Flows through Buffer Spaces, in ACH*

	ATTIC		GARAGE		CRAWLSPACE	
	From Outside	Total	From Outside	Total	From Outside	Total
1	—	—	0.84	1.14	4.36	4.55
2	3.12	3.78	0.88	1.59	7.15	7.23
3	5.97	7.62	0.75	1.22	2.37	2.37
4	—	—	—	—	3.32	3.32
5	7.23	9.46	—	—	0.95	1.04
6	3.79	6.17	0.64	0.89	7.58	8.32
7	—	—	—	—	6.48	6.82
8-I	5.10	5.18	0.18	0.23	5.71	5.90
8-II	5.81	5.94	0.29	0.32	6.76	6.93
8-III	6.73	7.01	0.28	0.32	10.47	10.48
8-IV	7.25	7.94	0.38	0.39	4.87	4.89
9	—	—	2.60	2.61	—	—
10	2.00	3.86	2.24	2.30	—	—
Ave.[a]	4.89	6.40	1.19	1.45	4.64	4.82

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[a] Including Test IV at Site 8, but not Tests I, II, and III.

only 0.7 ACH, and when flow from the rest of the house is included the average is just over 1 ACH.

ASHRAE Standard 62

Standard 62 requires a minimum ventilation rate of 0.35 ACH for the home or 15 cfm per occupant, whichever is greater, when the home is occupied. This air must come from outside to be considered acceptable ventilation. However, the standard does not state explicitly whether flow from buffer spaces is acceptable.

Figure 1 shows that, except for Site 7, with its exceptionally high flow due to wind, none of the ten homes met Standard 62 based on flow directly from outdoors with the air handler off. If flow from buffer zones was considered four of the ten homes met Standard 62.

When air handlers operated and flow from buffer spaces was included, Sites 1–7 and 9 did meet Standard 62. Standard 62 was not met at Site 8 except with the air handler operating during Test IV, when the measured ventilation rate was exactly 0.35 ACH. Site 10 did not meet Standard 62 even when the air handler operated. All of the homes did meet Standard 62 when any of the ventilation fans that were tested operated.

Percentage of Flow from Outdoors

Table 6 shows the percentage of the total flow through each home that comes directly from outdoors with the air handler off and on. Neglecting Site 1 (because it did not have an air handler) and Site 7 (because of the high winds), the remaining five of the first seven homes averaged about 39% flow from outdoors with the air handler off. When the air handler operated, these five homes averaged about a 15 percentage point change in flow from outdoors as a fraction of the total flow. Two of the homes had a higher percentage when the air handler ran, two had a lower percentage when the air handler ran, and the other showed little change. Com-

Table 6. *Percentage of Flow from Outdoors*

	Air Handler Off	Air Handler On	Change
1	75	—	—
2	24	7	−17
3	45	30	−15
4	57	88	31
5	39	38	−1
6	31	44	13
7	94	97	3
8-I	45	50	5
8-II	94	69	−25
8-III	61	61	0
8-IV	76	72	−4
9	43	21	−22
10	88	91	3
Ave.	59	56	

pared to these five homes, Site 9 had the most similar percentage of flow from outdoors of the last three homes. With the air handler off 43% of the flow came from outdoors; this decreased by 22 percentage points when the air handler was on.

At Site 8 this percentage varied widely with the air handler off across the four tests, from a minimum of 45% in Test I to a maximum of 94% in Test II. Except for Test II the percentage did not change substantially when the air handler came on, increasing by 5% in Test I, remaining the same in Test III, and decreasing by 4% in Test IV. The percentage in Test II with the air handler on was more comparable to the other test periods than when the air handler was off. The high percentage for Test II with the air handler off was likely due to the fact that at these times the wind direction was not typical of the test period as a whole, and caused external wall pressures that allowed less air to go from the attic and the crawlspace to the living zone. When the air handler was on the wind directions were more typical of the whole test period as well as the other test periods, resulting in the more similar percentage.

Site 10 got almost all of its flow from outdoors regardless of whether the air handler was off or on. This was because all of the flow entering the home below the neutral level came directly into the living zone from outdoors. Even though the flow through Site 10 decreased when the air handler was on, the percentage of flow coming from outdoors increased slightly because there was also less flow coming in from the garage and attic.

Dimensionless Neutral Levels

The height at which the pressure difference between indoors and outdoors is zero, normalized by the total height of the building, is called the dimensionless neutral level β_0. Because the pressure difference is zero at this height there is no flow to or from outdoors even if leaks are present. Under conditions of stack effect only the neutral level must be between the floor and the highest ceiling ($0 \leq \beta_0 \leq 1$), and is determined by the distribution of holes, cracks, and other leaks in the building.

Both of the infiltration models discussed later in the paper use the concept of the dimensionless leakage distribution parameters R and X (Sherman & Grimsrud 1980). R is the fraction of the total leakage that is in the floor and ceiling combined ($0 \leq R \leq 1$). X is the fraction of the total leakage that is in the ceiling minus the fraction of the total leakage that is in the floor ($-R \leq X \leq R$). In the traditional model of a single-zone home as a box with uniformly porous walls and surrounded by outdoors, if there is an equal amount of leakage in the floor and in the ceiling ($X = 0$) the stack pressure will be equally divided between the top and the bottom, and the neutral level will be at the mid-height of the building ($\beta_0 = 0.5$). If there are more leaks in the ceiling than in the floor ($X > 0$), the neutral level will be closer to the ceiling ($\beta_0 > 0.5$). If there are more leaks in the floor than in the ceiling ($X < 0$) then the neutral level will be closer to the floor ($\beta_0 < 0.5$). X and R are very difficult to measure, however, and it is common to assume default values of $X = 0$ and $R = 0.5$.

Neutral levels in these homes were determined by measuring the pressure across the walls both close to the ceiling and close to the floor, and interpolating during times when the air handler was off and when wind speeds were low. Table 7 provides a comparison of the neutral levels for the ten homes.

Sites 1–4 and 9 had neutral levels close to 0.5. This suggests that the default values for X and R were reasonable for these homes. Sites 5 and 6 had neutral levels closer to 0.6, meaning

Table 7. *Median Stack Neutral Levels for Seven Homes (Data are for Periods with Wind Speeds Less than 2.2 mph, Air Handlers and Ventilation Fans Off)*

Site	Neutral height (ft)[a]	Full Height (ft)[b]	Neutral level[c]
1	7.75	16.25	0.48
2	8.45	16.25	0.52
3	8.48	16.25	0.52
4	4.60	9.33	0.49
5	11.33	17.70	0.64
6	9.94	16.30	0.61
7	3.76	9.40	0.40
8-IV	13.33	19.00	0.70
9	7.17	15.75	0.46[d]
10	11.59	16.21	0.71

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[a] Height of zero pressure point above living zone floor.

[b] Height from floor to ceiling of living zone.

[c] Neutral height as a fraction of full height.

[d] If the basement were included as part of the living zone the neutral level would be 0.63.

that there were more holes in the ceiling than in the floor. This was consistent with visual inspections of the homes. The neutral level at Site 7 was measured to be about 0.4, meaning that the ceiling was tighter than the floor.

Due to various factors, it was not possible to determine a clear neutral level for Tests I, II, and III at Site 8, so the value for Site 8 is from the Test IV data. Sites 8 and 10 had neutral levels of about 0.7, which suggests that there were more leaks near the ceiling than near the floor, and that the default value of $X = 0$ was not accurate. This seemed reasonable at both sites. Site 8 was built to be very tight, with all of the ducts inside the house, so a higher percentage of the flow may have been via the exhaust fan penetrations and damper leakage in the ceiling and through other ceiling installations such as lights. This home also had two fireplaces, and there were large leakage areas around where the flue pipes entered the attic. At Site 10, since the daylight basement is included as part of the living zone, the lower floor of the living zone is a concrete slab. This is highly resistant to flow, so one would expect the ceiling to have more leaks than the floor.

BLOWER DOOR TESTS

One of the most reliable indicators of the levels of infiltration is the building envelope leakage. Blower door tests provide a means of measuring the envelope leakage at high pressure differences between indoors and outdoors, and by assuming a power law relationship between flow and pressure these results can be extrapolated to give an estimate of the leakage at operating conditions as well as an estimate of the effective leakage area (ELA) of the building.

We performed blower door tests at 50 Pa depressurization at each of the ten homes. Table 8 summarizes the results for the flow, both in terms of cubic feet per minute (cfm) (Q50) and ACH (ACH50), the ELA using a reference pressure of 4 Pa, and the flow coefficient and flow exponent.

The ten homes had an average of 8.7 ACH50. This is consistent with previous studies of single-family homes in the Pacific Northwest. The NORIS I study of 134 site-built homes constructed from 1980–1987 showed an average of 9.3 ACH50 (Palmiter & Brown 1989); the NORIS II study found an average of 7.2 ACH50 for 49 site-built homes designed to meet the Super Good Cents energy efficiency specifications (Palmiter, Brown & Bond 1990a).

The tightest site-built home, Site 8, had an ACH50 of 5.7. The two manufactured homes, Sites 4 and 7, averaged 6.0 ACH50. These are comparable to the RCDP Cycle II study, which found a 5.6 ACH50 average for 129 site-built homes built to Super Good Cents specifications and a 6.1 ACH50 average for 131 manufactured homes (Palmiter, Brown & Bond 1990b).

Table 8. *Blower Door Test Results*

Site	Flow at 50 Pa (cfm)	Flow at 50 Pa (ACH)	ELA (in^2)	Flow Coefficient (cfm/Pa^n)	Exponent n
1	1492	7.2	86.8	127.4	0.629
2	2962	10.1	159.9	238.1	0.660
3	3033	12.8	163.4	187.5	0.696
4	792	5.0	44.3	64.1	0.643
5	3400	7.2	189.7	273.7	0.644
6	2616	10.6	158.6	239.6	0.611
7	1141	7.0	59.6	83.0	0.670
8	2676	5.7	113.9	142.3	0.750
9	2298	13.0	148.2	232.1	0.586
10	2500	8.8	124.3	168.8	0.689

At Site 9, a blower door test was also performed with the basement included as part of the living zone. The average flow at 50 Pa was 3276 cfm, or 12.6 ACH50. The ELA at 4 Pa was 178 in^2.

Modeling

The natural infiltration results were compared to two predictive models, known as the LBL model and the AIM-2 model, and the effects of funning mechanical systems were compared to a fan model developed at Ecotope.

LBL and AIM-2 Models

These two models predict the stack and wind components of infiltration separately. The LBL model was developed by Sherman and Grimsrud at Lawrence Berkeley Laboratory (1980). This model uses the ELA at 4 Pa and then assumes that the leakage paths have a flow exponent of 0.5 to extrapolate to the actual pressure range. To obtain a prediction for the combined stack and wind infiltration, the two components are combined in quadrature.

The AIM-2 model, developed at the University of Alberta by Walker and Wilson (1990), predicts the same infiltration at 4 Pa as the LBL model. However, the AIM-2 model uses the actual power law exponent and regression coefficient obtained from the blower door tests to predict the infiltration in the pressure range of interest. The combination of the two components to predict the total infiltration includes a term that accounts for the interaction of stack and wind on the internal pressures. This interaction term has the effect of reducing the predicted infiltration. There are also separate wind models for buildings with crawlspaces and buildings that are either slab-on-grade or built over basements.

The LBL model predicted higher infiltration than did the AIM-2 model at all ten homes. For the wind portion of the LBL model, terrain and shielding factors provided by LBL personnel were used. Table 9 shows the LBL and AIM-2

Table 9. *LBL and AIM-2 Model Predictions, in cfm*

		LBL MODEL			AIM-2 MODEL	
Site	stack	wind	full	stack	wind	full
1	51	18	56	39	9	40
2	106	52	124	82	30	90
3	78	41	95	60	23	68
4	31	8	33	25	4	25
5	149	105	191	124	74	149
6	132	45	144	117	30	121
7	37	110	118	28	106	108
8-III						
X = 0, R = 0.5	73	107	135	47	98	115
X = R = 0.371	64	116	136	40	104	116
8-IV						
X = 0, R = 0.5	100	57	119	76	39	90
X = R = 0.371	88	62	111	65	41	83
Site 9						
X = 0, R = 0.5	174	34	179	152	42	159
X = -0.08 = -R	145	41	153	121	48	133
Site 10						
X = 0, R = 0.5	107	20	110	86	23	90
X = R = 0.368	93	22	97	75	20	78

model predictions for flows due to stack only, due to wind only, and the combined effect at each of the ten homes. At the first seven homes these models were run with the standard assumed leakage distribution of $X = 0$ and $R = 0.5$. For the final three homes, these models were run with the standard assumption as well as with a second leakage distribution designed to minimize the prediction of flow due to stack effect for a prescribed neutral level. This distribution was determined by using the calculated dimensionless neutral level and analytically calculating the value where $X = \pm R$. When running the AIM-2 model the appropriate wind model was chosen for each home. Since the models do not account for mechanical ventilation, comparisons were made for only those times when the air handler and all ventilation fans are off.

During the two cooling season tests at Site 8 the predictions did not show any clear relationship to the measured data. Why this should be is not entirely clear. In a cooling season situation air enters the home toward the top and leaves toward the bottom, which is the reverse of the heating season situation. Since cold air stays near the bottom of the home, especially with a tight floor, it may be that a layer of cold air sits at the bottom of the home, causing the actual height over which the stack effect operates to be decreased. There would then be less height below the neutral level through which air would actually flow. However, there is not sufficient information to determine if this is the cause of the poor modeling predictions, and more testing needs to be done in this area to determine if this is the case. For the two Site 8 heating season tests, as well as for the remaining nine homes, both models did track the measured data when flows due to stack effect and wind were combined. However, both models were off by a fairly consistent percentage relative to measured data.

The LBL model was found to greatly overpredict the impact of wind on natural infiltration, especially for strong winds. This can be seen by looking at periods of high winds, such as Test III at Site 8. Analysis of the measured data indicated that wind contributed an average of about 19 cfm to the natural infiltration, which is about 30% of the infiltration level due to stack effect only. With the standard assumption of $X = 0$ and $R = 0.5$ the LBL model predicted that wind increased the natural infiltration during this time by 62 cfm, about 85% of the flow due to stack effect only. With $X = \pm R$ the LBL model predicted an increase of 72 cfm, which is about 12% more than the flow due to stack effect.

The ratios of the stack only and combined stack and wind predictions to measured data are shown in Table 10. Ratios of flows due to stack only were not evaluated for the first seven homes, and during Test III at Site 8 it was not possible to get a good estimate of this ratio because for most of the test the wind speeds were high enough to make a good stack-only prediction unobtainable. The ratios of the flows that were due to stack effect only were determined by screening the measured data for those times when wind speeds were low and therefore had little impact on the measured data.

These results show that each model did closely predict the measured combined flows in some cases. In the first seven homes the models averaged about 16% error relative to the measured results. However, in the last three homes, the model predictions were typically not so close to the measured data. The LBL model had an average error of about 46% for the standard assumption of $X = 0$, $R = 0.5$, and an average error of about 26% when $X = \pm R$. The AIM-2 model had an average error of about 27% with $X = 0$, $R = 0.5$ and an average error of about 16% when $X = \pm R$.

Fan Modeling

The change in infiltration through a zone due to running a ventilation fan can be predicted using a model developed at Ecotope (Palmiter & Bond 1991b; Palmiter & Bond 1992). This model is now a part of the ASHRAE Handbook of Fundamentals (ASHRAE 1993). For a single fan, this model states that if the fan flow is less than twice the natural infiltration rate then the added flow through the zone with the fan on is half of the fan flow. If the fan flow is twice the natural infiltration rate or greater, then the added flow through the zone when the fan operates is the difference between the fan flow and the natural infiltration rate.

Table 11 compares the measured and predicted flows, in cfm, when the specified ventilation fan operated. The first column shows the measured fan flow. The second column shows the measured change in infiltration due to operating the fan, based on the tracer gas testing. This is compared to the predicted change in infiltration using the fan model, shown in the third column. The ratio of the prediction to the actual measured flow for each unit is shown in the final column.

All of the listed fans from the first seven homes delivered less than twice the natural infiltration rate, so the predicted changes in infiltration through the homes were half of the fan flow. All of the listed fans from the last three homes delivered more than twice the natural infiltration rate, so the predicted changes in infiltration through the homes were the difference between the fan flow and natural infiltration. At Site 8 the predicted change was almost twice the measured change. The predictions were much better at Sites 9 and 10. At Site 9 the kitchen fan produced a change of about 24% more than the model predicted. Running the Jenn-Air kitchen fan at Site 10 produced about 13% less flow through the living zone than was predicted by the model. The mean absolute percentage error for the nine tests was about 16%.

Table 10. *Ratios of Modeled to Measured Flows*

Site	LBL MODEL stack only[a]	LBL MODEL stack and wind	AIM-2 MODEL stack only[b]	AIM-2 MODEL stack and wind
1	—	0.94	—	0.68
2	—	0.95	—	0.69
3	—	1.11	—	0.79
4	—	1.30	—	1.00
5	—	1.40	—	1.09
6	—	1.23	—	1.03
7	—	1.10	—	1.01
Average Error[c]	—	15.9%	—	15.9%
8-III				
X = 0, R = 0.5	—	1.44	0.54	1.06
X = R = 0.371	—	1.43	0.47	1.04
8-IV				
X = 0, R = 0.5	1.00	1.09	0.76	0.81
X = R = 0.371	0.88	1.01	0.65	0.73
9				
X = 0, R = 0.5	1.79	1.82	1.65	1.63
X-0.08, R = 0.08	1.48	1.55	1.31	1.30
10				
X = 0, R = 0.5	1.46	1.49	1.18	1.21
X = R = 0.368	1.27	1.31	1.02	1.04
Average Error[c]				
X = 0, R = 0.5	37.3%	46.0%	38.2%	27.2%
X = ±R	29.0%	25.5%	30.2%	16.2%

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[a] Ratios not calculated for Sites 1-7. Prediction did not track measured flow due to stack effect for Site 8-III.

[b] Ratios not calculated for Sites 1-7.

[c] Mean absolute percentage error.

CONCLUSIONS

A number of important conclusions came out of these studies. The conclusions mentioned here are a summary of those presented in the three full reports.

During the heating season tests, the average site natural infiltration rate was about 0.30 ACH. Natural infiltration was dominated by stack effect in all of the homes except for Site 7, even though several of the sites were chosen for high winds. By one method of accounting, stack effect contributed a median of 92.3% of the total natural infiltration at the ten homes. Wind speeds were low at most sites, with a median of about 2.0 miles per hour.

Mechanical systems, including ventilation fans and forced-air distribution systems, typically had a significant effect on the infiltration rate of the homes. Several ventilation fans,

Table 11. *Assessment of Ecotope Fan Model*

		CHANGE IN INFILTRATION		
Site / Fan	Measured Fan Flow (cfm)	Meas. (cfm)	Pred. (cfm)	Ratio
1 - Exhaust	75	37	38	0.987
3 - Bath	27	14	14	1.000
4 - Bath	50	26	25	1.032
4 - Range hood	67	31	34	0.916
5 - Range hood	205	85	102	0.829
6 - Bath (3)	94	61	47	1.298
8-II - Exhaust	191	79	150	0.527
9 - Kitchen	198	125	101	1.238
10 - Jenn-Air	227	137	158	0.867

with flow rates ranging from about 50 cfm to over 200 cfm, were tested during these experiments to validate a fan model developed at Ecotope and now a part of the ASHRAE Handbook of Fundamentals. Predictions from this model had a median absolute percentage error of 13.3%.

Running the air handler in Sites 2–9 caused these homes all to be depressurized. This depressurization was due to differential duct leakage, indicating that supply leakage was greater than return leakage. Tests were run at Site 10, where the ducts were all interior to the living zone, and at Site 4 to determine the effect of closing internal doors in homes with few returns. These tests showed that differential pressure effects due to isolating portions of the home from the returns could more than double the induced infiltration due to running the air handler.

During the heating season tests, the ten homes had a median of 57% of their natural infiltration come directly from outdoors. If flow from buffer zones is included as part of the ventilation rate for homes, as was assumed in all work previous to these studies, half of the homes met Standard 62 based on natural infiltration alone. Sites 8 and 10, which had living zones that were the least connected to outdoors through the floor, were the only homes that had forced-air systems which did not increase the ventilation rate sufficiently to meet Standard 62.

Measured neutral levels during the heating season tests were generally consistent with observed site characteristics. Homes with either very tight floors or very leaky ceilings had dimensionless neutral levels significantly higher than 0.5, while most other homes had neutral levels at about 0.5. In homes where the neutral level departed from 0.5, the default values for the leakage distribution parameters X and R are not valid.

During the heating season tests, the LBL and AIM-2 natural infiltration models generally track the measured results. The median absolute percentage error was 23% for the LBL model and 19% for the AIM-2 model using the measured site weather data and the default values for the leakage distribution parameters. Predictions for the two homes with daylight basements were poorer than for the rest of the sample. The LBL model predicted higher infiltration rates for all of the homes than did the AIM-2 model. The LBL model also greatly overpredicted the flow due to wind, especially at high wind speeds. A correction to the LBL model reduced the wind prediction by about 40%, but even with this correction the effect due to wind was still overpredicted. With X and R set to provide a minimum flow at Sites 8–10, the median absolute percentage error was 31% for the LBL model and 27% for the AIM-2 model.

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