Impact of Mechanical Systems on Ventilation and Infiltration in Homes

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Infiltration is an important factor which affects heat loss and air quality in residential buildings. Modern, energy-efficient homes are tighter than older homes, and mechanical ventilation systems may be required to maintain adequate air quality. This paper summarizes the results of detailed tracer measurements made with a real-time multizone tracer system on seven homes in the Pacific Northwest. In each house, experiments were performed to estimate the magnitude of effects due to the air handler, bath and kitchen exhaust fans, and the mechanical ventilation system if present. Each home was measured for approximately one week. Two homes had designated timer-controlled bath fan exhaust ventilation systems; one home had a multiport central exhaust system, and one home had a balanced-flow air-to-air heat exchanger. One home had a ventilation system with a fresh-air supply fan connected to the return of the air handler.

In agreement with previous studies, the first phase of this study indicated that forced-air distribution systems have large effects on infiltration rates. The second phase of this study was designed to focus on forced-air systems and included one home with a heat pump and one with a gas furnace. The operation of the heating system had dramatic effects on the infiltration rates of the homes. With the air handler running, the infiltration rate was more than double that of the stack-driven natural infiltration in four of the six homes with forced-air systems. Closure of a single bedroom door with the air handler running also produced large increases in infiltration.

Introduction and Background

Air infiltration is a major source of heat loss in residential buildings; it is also an important factor affecting indoor air quality. The American Society of Heating, Refrigeration and Air-Conditioning Engineers Standard 62-89 specifies a minimum ventilation rate of 0.35 air-changes per hour (ACH) for residential buildings (ASHRAE 1989).

The infiltration and ventilation characteristics of new all-electric homes under typical winter conditions in the Pacific Northwest have been surveyed in a number of studies (Palmiter and Brown 1989; Palmiter et al. 1990a, 1990b, 1992a). These studies utilized the time-averaged perfluorocarbon tracer technique (PFT) in conjunction with blower door depressurization tests. The results of these studies are summarized by Palmiter et al. (1991).

Findings of these studies pertinent to the present paper are as follows:

- A baseline of electrically-heated homes not constructed under utility energy-efficiency programs have relatively low infiltration rates, about 0.38 ACH. About 50% of these homes fail to meet Standard 62.
- Newer electrically-heated homes are significantly tighter, with both blower-door-determined leakage and PFT-measured infiltration about 30% lower than the baseline. About 75% of these homes fail to meet Standard 62.
- In most of the energy-efficient homes, the ventilation systems had a small effect on infiltration, particularly in the case of the exhaust-fan systems which are common in the Northwest.
- Forced-air heating systems had large effects on infiltration, producing air-change rates 17 to 36% greater than those in homes with baseboards or wall heaters. If homes with forced-air heating systems are excluded from either the baseline or energy-efficient groups, the percentage of homes failing to meet Standard 62 is greatly increased.

Because the separate contributions of wind and stack (temperature) effects to natural infiltration and the interaction of mechanical systems with natural infiltration were poorly understood, a study was initiated in 1990 to investigate these mechanisms in real homes, with a view toward developing improved infiltration models (Palmiter and Bond 1991a, 1992). Detailed real-time multizone infiltration and pressure measurements were made by Lawrence Berkeley Laboratory in six electrically-heated homes and one gas-heated home in the Pacific Northwest. This paper reports on those aspects of the study related to mechanical systems.

Modeling

The interaction of mechanical ventilation and natural infiltration is quite complicated. The additional ventilation provided by supply and exhaust fans can be estimated using a simple fan model initially proposed by the authors during the first year of detailed infiltration measurements (Palmiter and Bond 1991a). The model was extended to predict the infiltration effects of forced-air systems in which both supply and return duct leakage exist. A comprehensive discussion of the interaction of fans with stack effect is given by Palmiter and Bond (1991b).

It is useful to separate ventilation systems into balanced flow systems (neutral pressure) and unbalanced flow systems, which are further subdivided into supply-fan (positive pressure) and exhaust-fan (negative pressure) systems. A balanced-flow system has two fans, one pumping air into the building and one pumping the same amount of air out. The pressure within the building remains unchanged, so there is no interaction between the mechanical system and natural infiltration. The inward flow through the balanced system is simply added to the natural infiltration. Unbalanced systems change the internal pressure, which alters the infiltration and exfiltration through the envelope. This fan model accounts for this interaction and predicts the infiltration resulting from balanced or unbalanced flows induced by mechanical ventilation systems.

Equations for the model are given in Table 1; Q_{nat} is the natural infiltration rate. The interaction of natural and mechanical infiltration results from changes in house pressure due to unbalanced flows. We define the maximum flow Q_{max} as the larger of the total mechanically-induced flow into or out of the envelope, including leakage into or out of the duct system. The minimum flow Q_{min} is the smaller of the two flows. If there is only a single exhaust fan, Q_{max} is the fan flow and $Q_{min} = 0$. For a balanced ventilation system or balanced duct leakage, Q_{max} and Q_{min} are equal. We define the duct leakage flows Qd_{max} and Qd_{min} as the maximum and minimum leakage into or out of the duct system only.

The unbalanced flow to the house is given by the difference between Q_{min} and Q_{max}. A change in the equations for added flow occurs when the unbalanced flow is greater than twice the natural infiltration rate. The additional term in the equations for duct leakage results because some of the air which leaks into the return exits through supply leaks.

The manner in which our model combines mechanical flows with natural infiltration in the case where unbalanced flows are less than twice the natural flow (the building is not fully pressurized or depressurized) is illustrated for several cases in Figure 1. The left column of pictures shows the effect of duct leakage; the right column of pictures are identical except for the addition of a 50-cfm exhaust fan. The upper left picture shows the base case of stack-driven natural infiltration of 100 cfm and exfiltration of 100 cfm.

Table 1. Equations for Fan and Duct Leakage Model

Cause	Condition	Added Flow
Ventilation fans	$Q_{max} - Q_{min} \geq 2\,Q_{nat}$	$\frac{1}{2}\,(Q_{max} + Q_{min})$
	$Q_{max} - Q_{min} < 2\,Q_{nat}$	$(Q_{max} - Q_{min})$
Duct leakage	$Q_{max} - Q_{min} \geq 2\,Q_{nat}$	$\frac{1}{2}\,(Q_{max} + Q_{min}) - \frac{Qd_{max}}{Q_{fan}}\,Qd_{min}$
	$Q_{max} - Q_{min} < 2\,Q_{nat}$	$Q_{max} - Q_{nat} - \frac{Qd_{max}}{Q_{fan}}\,Qd_{min}$

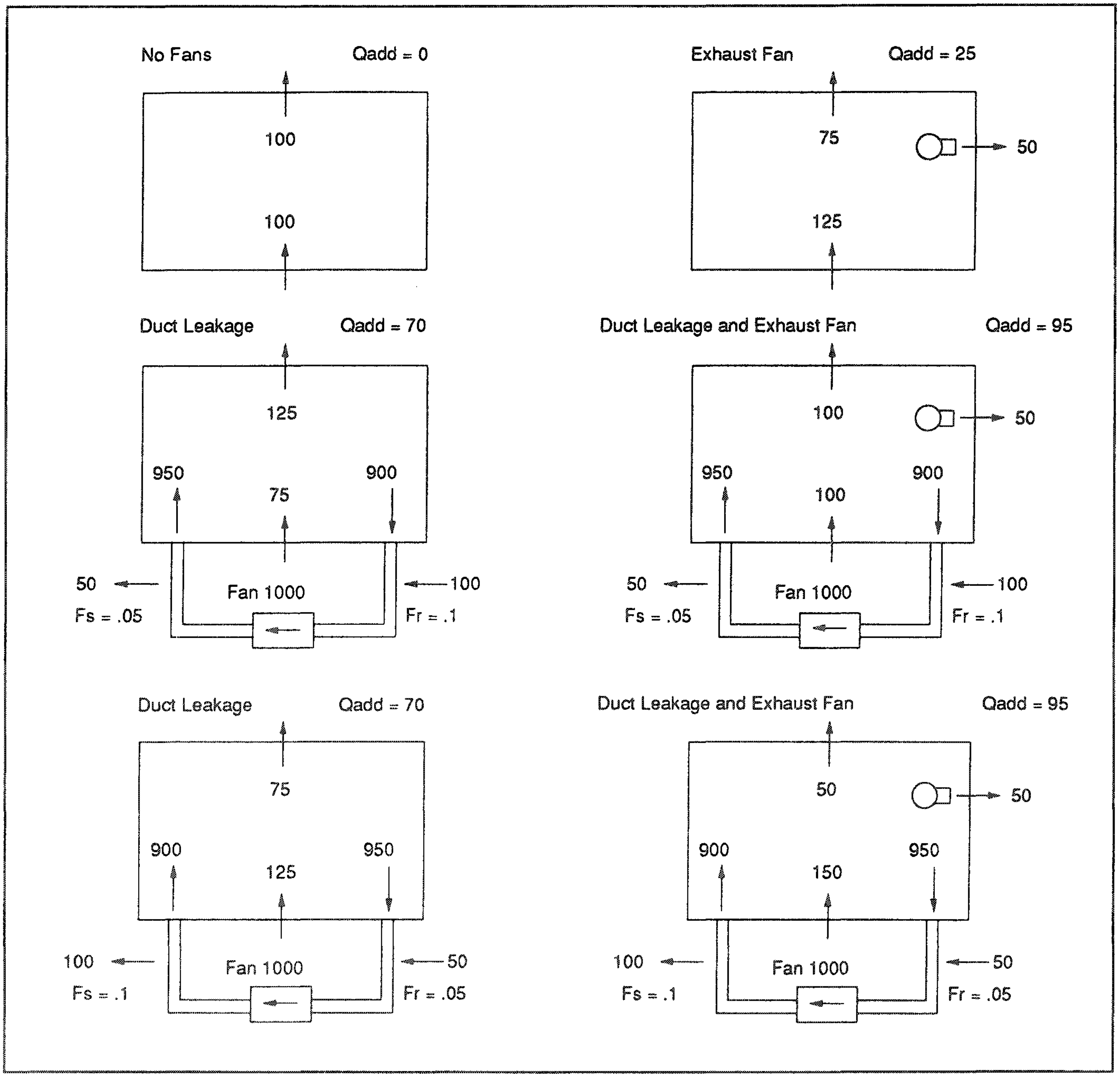

Figure 1. Examples of Combined Flows. Qadd is the added flow due to exhaust fans or duct leakage; Fs and Fr are the supply and return leak fractions. The vertical arrows in the center are infiltration and exfiltration through the envelope due to the combination of stack effect and mechanical ventilation.

The picture on the middle left illustrates a situation with dominant return leakage. The flow through the air handler is 1000 cfm, with 100 cfm of return leakage and 50 cfm of supply leakage. In this case, Q_{min} is 50 cfm and Q_{max} is 100 cfm. For this case and those which follow, Qd_{min} is 50 cfm and Qd_{max} is 100 cfm. This results in an unbalanced flow of 50 cfm to the home. Because the supply flow exceeds the return flow, the home is partially pressurized, reducing the flow inward through the floor by 25 cfm and increasing the flow outward through the ceiling by 25 cfm. There are inward flows of 75 cfm through the floor and 100 cfm on the return side of the fan, but 5% of the fresh air entering the return is lost through supply leaks, resulting in only 95 cfm of added infiltration. The total flow is 170 cfm, thus yielding an added flow of 70 cfm over natural infiltration.

The lower picture shows the situation with dominant supply leakage of the same magnitudes as the return leakage case. Q_{min} and Q_{max} are 50 and 100 cfm, respectively. In this case, the home is partially depressurized, resulting in reduced flow through the ceiling and increased flow through the floor. The added flow is 70 cfm, as before. If the magnitudes are the same, excess return leakage or excess supply leakage lead to the same added infiltration.

Turning to the cases with the exhaust fan, the upper right picture shows the case with an exhaust fan with a flow of 50 cfm. Here, Q_{min} is 0 and Q_{max} is 50 cfm. The flow through the ceiling then decreases by 25 cfm, or half of the fan flow, while the flow through the floor increases by 25 cfm. The total infiltration rate is thus increased by 25 cfm.

The middle picture on the right shows the excess return leakage case combined with the exhaust fan. The 50 cfm of extra supply flow is just balanced by the 50 cfm flowing through the fan, so the home remains at neutral pressure. Q_{min} and Q_{max} are both 100 cfm. The natural infiltration remains at the base value, but an added 95 cfm comes through the return system.

The lower right picture shows the exhaust fan combined with the excess supply leakage case. In this case, rather than cancelling, the exhaust fan combines with the excess return flow of 50 cfm to produce 100 cfm of outward flow, which depressurizes the home more strongly than either system alone. In this case, Q_{min} is 50 cfm and Q_{max} is 200 cfm. The total infiltration now includes 150 cfm entering through the floor and 45 cfm entering through the ductwork; the total added infiltration is 95 cfm.

It is interesting to note that the effect of combining an exhaust fan with duct leakage is symmetric with respect to whether the duct leakage is predominantly on the return side or the supply side, so the added flow does not depend on which side the leakage occurs. However, in one case the building remains at neutral pressure, while in the other case it is strongly depressurized.

Detailed Measurements

The homes in this study were chosen for the presence of a forced-air distribution system or a mechanical ventilation system. Table 2 gives a brief description of each home. The homes varied from small one-story manufactured homes with floor areas of 1200 square feet to a large four-bedroom two-story home of 3500 square feet.

The seven homes included two with heat pumps, four with furnaces, and one with wall heaters. Of the six homes with forced-air heating systems, three had the air handler inside the heated space, and three air handlers were located in the garage. Four of the homes had designed ventilation systems.

Infiltration and interzonal flows were measured using a MultiTracer Measurement System (MTMS) developed at Lawrence Berkeley Laboratory (Sherman and Dickerhoff,

Table 2. Physical Characteristics of Seven Homes

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Year built	1988	1979	1984	1988	1988	1985	1990
Heating system	Wall htr	HP	Furn	Furn	HP	Furn	Furn
Floor area (ft^2)	1553	2213	1812	1182	3503	1695	1217
Volume (ft^3)	12367	17589	14226	9496	28510	14876	9746
Number of stories	2	2	1.5	1	2	2	1
Occupied during testing?	Yes	Yes	Yes	No	No	No	No
Ventilation system	Multiport	None	None	Bath fan	AAHX	None	Bath fan
Air handler location	--	Garage	Garage	House	Closet	Garage	House
Supply duct location	--	Crawl	Crawl	Crawl	Crawl	Crawl	Crawl
Return duct location	--	Attic	House	None	Attic	Attic	None

1989). This system employed the constant injection technique with up to five tracer gases; it measured concentrations in each zone every two to four minutes. The living areas of each home were divided into one to three tracer zones, and the attic, garage and crawl space were measured as separate zones. Twelve-minute averages of the calculated flow data were used for the graphs and summaries.

We measured pressure differences at one or two points across the floor, the ceiling, and each exterior wall. These data were recorded every 30 seconds to one minute, depending on the site. We also measured temperatures outside and in each tracer zone; two 20-foot meteorological wind towers measured wind speed and direction. These data were typically recorded once every four minutes.

We also assessed the leakage of each home using the blower door technique. In homes with forced-air distribution systems, tests were done with all registers open and all registers sealed. The difference between the two measurements was taken as the amount of leakage in the duct system.

Table 3 summarizes results from the blower door tests for each home. The first block of the table gives several measures of total envelope leakage: the effective leakage area (ELA) and the flow at 50 Pascals in both air-changes and cfm. The second block of the table gives the percentage of the total leakage which can be attributed to duct leakage.

In each house, experiments were performed to estimate the magnitude of effects due to the air handler, bath, and kitchen exhaust fans and the mechanical ventilation system if present. Air handler and ventilation fans were either controlled by timers or cycled by the occupants. Use of the air handler or any fans was logged and compared with the measured infiltration.

Natural infiltration was predicted using two models: one developed at Lawrence Berkeley Laboratory by Sherman and Grimsrud (1980), known as the LBL model, and one developed at the University of Alberta by Walker and Wilson, known as the AIM2 model (1990). Both models use weather data and blower door test results to predict infiltration caused by indoor-outdoor temperature differences (stack) and wind effects. Weather conditions measured at the site, along with the calibrated wind and stack models, were used to predict the natural infiltration characteristics of the homes. These are given in Table 4.

Table 3. Blower Door Test Results from Seven Homes

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Effective leakage area (in^2)	86.8	159.9	163.4	44.3	189.7	158.6	59.6
Flow at 50 Pa (ACH)	7.24	10.10	12.79	5.01	7.16	10.55	7.03
Flow at 50 Pa (cfm)	1492	2962	3033	792	3400	2616	1141
Duct Leakage as Percent of Total							
Flow at 50(%)	--	8.9	18.9	4.8	4.8	32.8	19.3
ELA (%)	--	7.8	21.8	4.8	6.7	39.3	21.5

Table 4. Natural Infiltration Characteristics of Seven Homes

	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Stack Effect (ACH)	0.264	0.383	0.305	0.139	0.261	0.373	0.230
Wind Effect (ACH)	0.022	0.062	0.058	0.005	0.026	0.004	0.431
Natural Infil (ACH)	0.286	0.445	0.363	0.144	0.287	0.377	0.661

Field Results

Of the seven homes tested, one experienced very low indoor-outdoor temperature differences and had very high duct leakage, one was located on an extremely windy site, and in one the results were complicated by occupant effects (frequent window openings). The remaining four homes are more representative of the typical magnitudes of the effect of mechanical systems relative to natural infiltration rates under typical winter conditions. The measured infiltration and predicted living-zone infiltration rates at these sites are illustrated in Figures 2 through 5. Each figure consists of two panels. In each panel, the light line is the measured infiltration rate.

The bold line in the upper panel is the natural infiltration rate predicted with the AIM2 infiltration model, which has been adjusted with a multiplier to track the lower envelope of the measured infiltration. At Site 1, the predictions were adjusted upward by 10%; at Site 4, they were decreased by 15%. At Sites 5 and 6, the predicted wind-effect infiltration was reduced by 30% and 40%, respectively, before combination with the stack-effect infiltration.

The bold line in the lower panel in each figure shows the infiltration prediction including the effects of mechanical systems. At each site, flow hood measurements of mechanical ventilation fan flows were used in combination with the adjusted infiltration rates in the fan model. The infiltration effects of duct leakage in the forced-air distribution system were estimated directly from the measured whole-house infiltration rate at Sites 5 and 6, and therefore do not constitute a validation of the duct leakage model. At Site 4, the predicted impact of duct leakage is a validation of the model, because multizone tracer measurements of the flow from the house to the crawlspace were used to determine Q_{max}.

Some of the details of the infiltration at each of the four sites are discussed below.

Site 1 had no forced-air heating system; its ventilation system was a multiport exhaust system with a measured flow rate of about 75 cfm. During the tracer test, we operated the exhaust system on a timer, twice each day for a period of four hours. In addition, there were six other exhaust fans, which the occupants used extensively. We used times recorded in occupant logs and fan flows measured with flow hoods to produce a total fan flow for use in the model.

Even with the extensive fan use, the overall infiltration rate is still dominated by the stack effect, which accounts for 66% of the total infiltration. The multiport exhaust

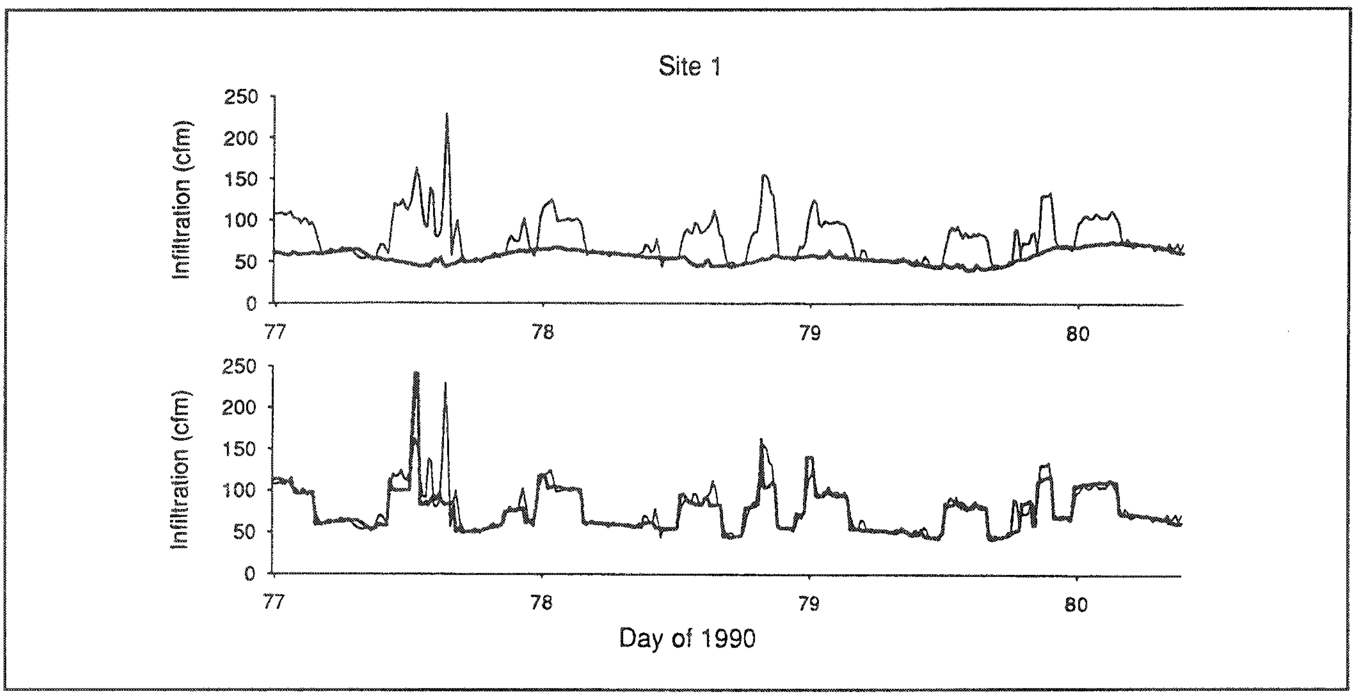

Figure 2. Measured and Modeled Infiltration at Site 1. The bold line in the upper graph is the adjusted natural infiltration prediction; in the lower graph it is the adjusted infiltration combined with the fan model.

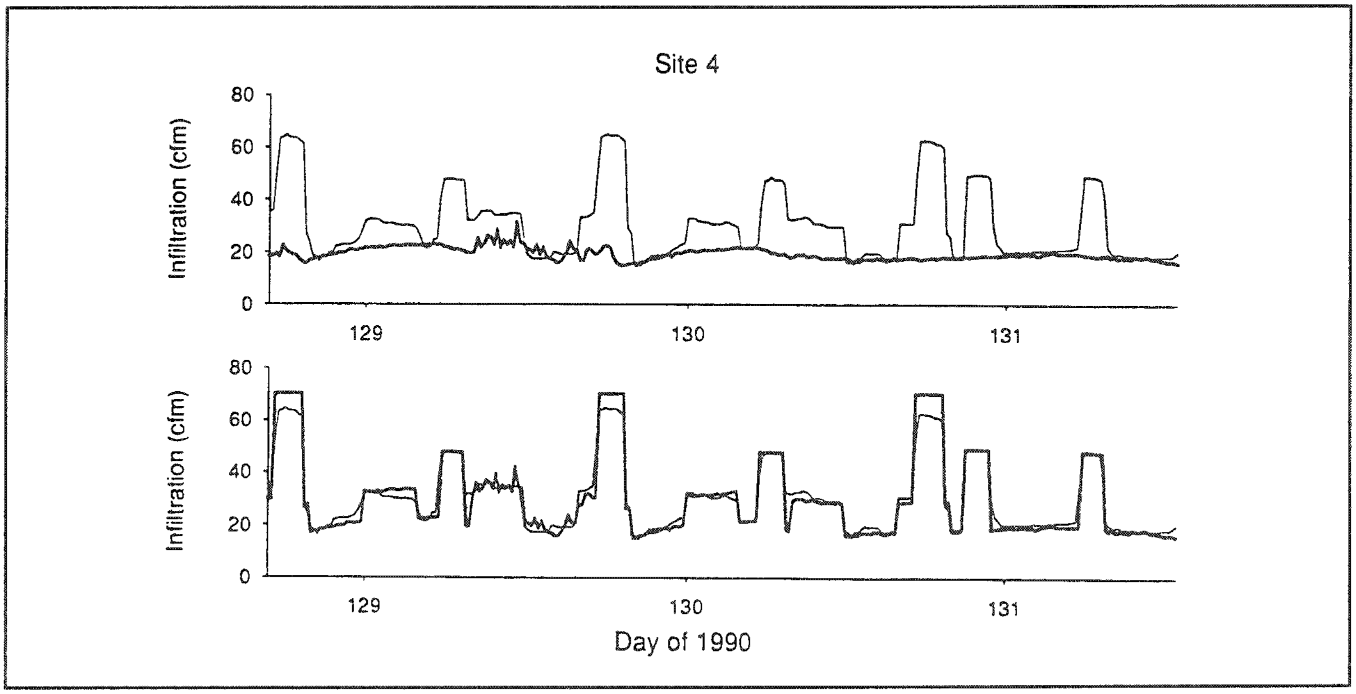

Figure 3. Measured and Modeled Infiltration at Site 4. The bold line in the upper graph is the adjusted natural infiltration prediction; in the lower graph it is the adjusted infiltration combined with the fan model.

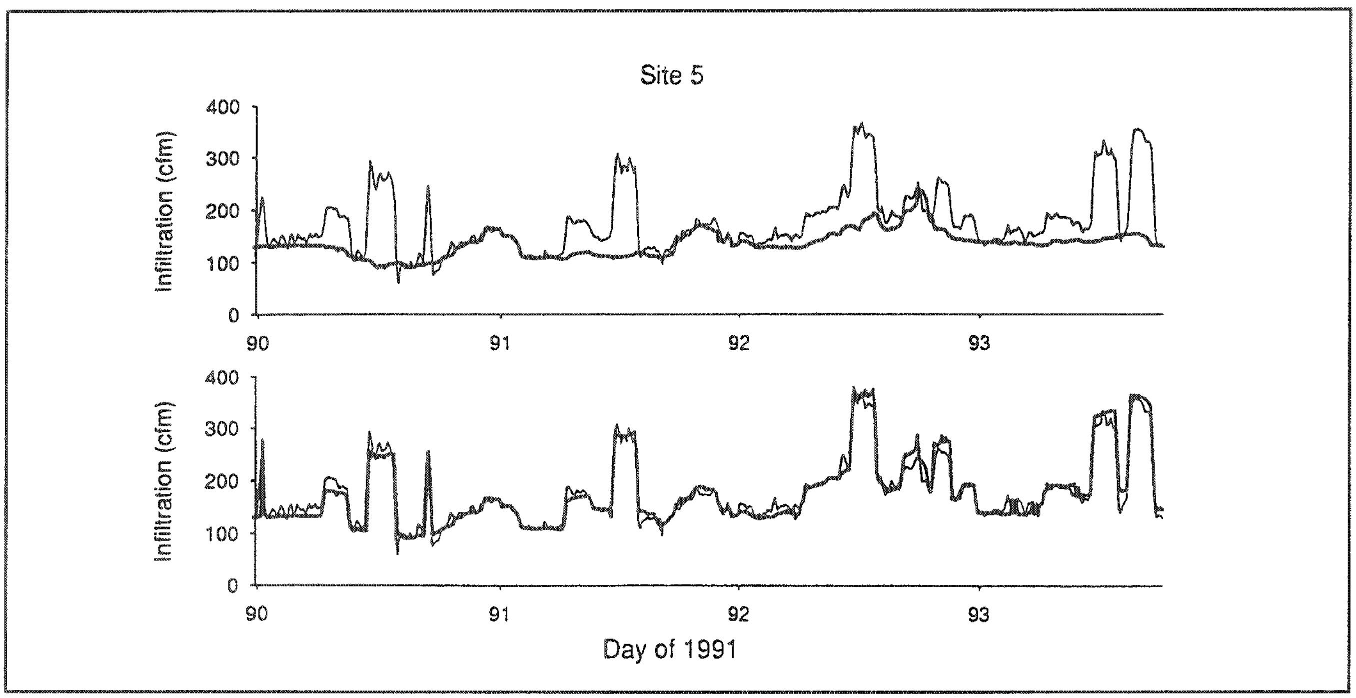

Figure 4. Measured and Modeled Infiltration at Site 5. The bold line in the upper graph is the adjusted natural infiltration prediction; in the lower graph it is the adjusted infiltration combined with the fan model.

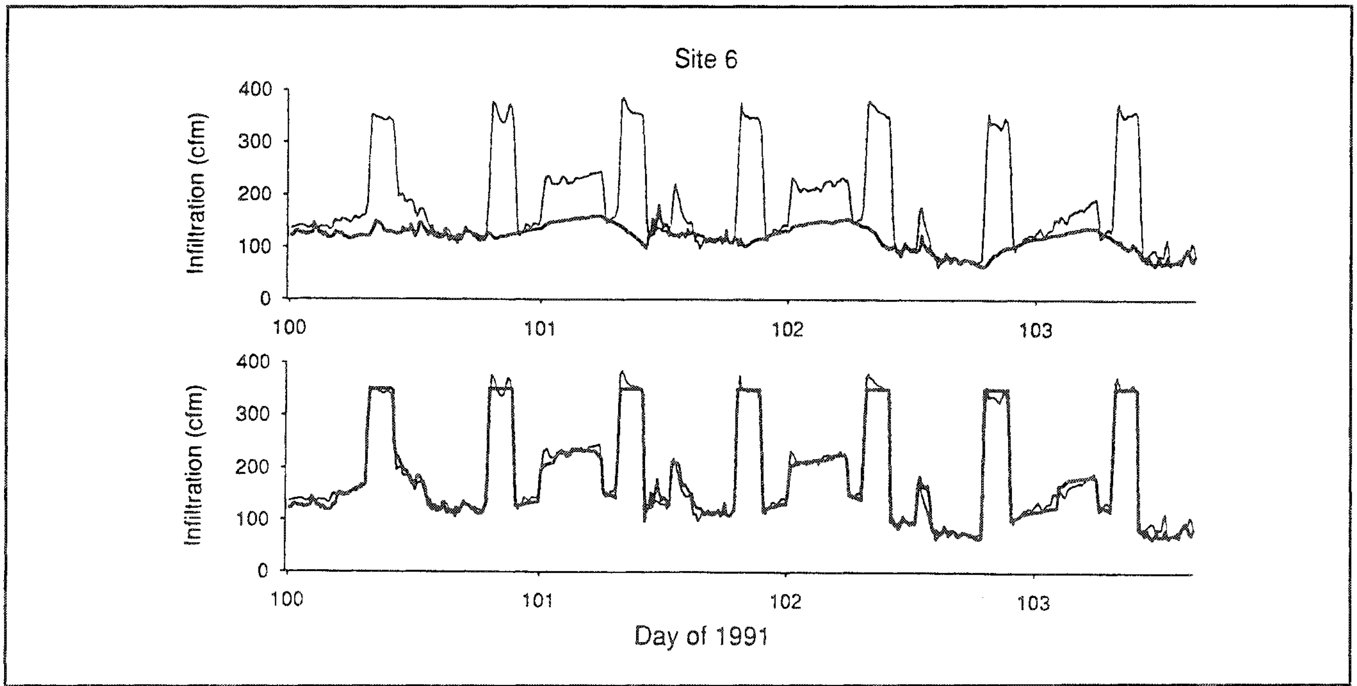

Figure 5. Measured and Modeled Infiltration at Site 6. The bold line in the upper graph is the adjusted natural infiltration prediction; in the lower graph it is the adjusted infiltration combined with the fan model.

provides 15% of the total infiltration, and other fans account for 12%. If the multiport exhaust ran continuously, the ventilation rate in this home under these conditions would average 95 cfm or 0.46 ACH.

The two spikes in the measured data on day 77 are due to door openings, which show clearly in the temperature and pressure data. We attribute the other discrepancies to errors in the occupant log and uncertainties about flows through some of the fans. Considering these uncertainties and the simplifications required for development of the model, the agreement is quite satisfactory.

Site 4, a manufactured home, had a central air handler in the home with supply ducts in the crawlspace and a single return grille located just above the air handler, so there was no return duct system. The make-up air system to the air handler was sealed for the period discussed here.

At this site, we operated the air handler fan with a timer, four hours on and four hours off. The bath fan, which was the designated ventilation system for the home, was operated by a timer twice a day for periods of two hours: once in the early morning when the air handler was off, and once in the afternoon when the air handler was running. The range hood was also operated manually once at the end of Day 130.

Because all the supply ducts ran through the crawlspace, we used the flow from the house to the crawl during periods when the air handler was on to estimate the supply leakage at about 22 cfm. We measured the flow through the bath fan at about 48 cfm.

In the infiltration graphs, the low wide pulses are caused by the operation of the air handler, and the higher narrow pulses show the effects of the bath fan. Although the bath fan, range hood, and air handler are predicted well on an individual basis, the infiltration when the air handler and bath fan operate simultaneously is overpredicted by the fan model. This suggests that the pressures created by the fan flow and supply leakage cause an interaction effect and that the total outward flow is lower than the sum of the two flows acting separately.

In this home, the flow through the bath fan ventilation system is more than twice the natural infiltration, so the total flow through the home is the bath fan flow when this fan operates. If this ventilation system were operated continuously, the 48 cfm would result in an air-change rate of only 0.30, lower than the minimum ventilation rate of 0.35 specified by ASHRAE.

In these homes, there is typically only a single return per floor; practice in the 1940s dictated returns in all rooms with supplies. As a result, rooms with supplies only, typically bedrooms, can be strongly pressurized when the air handler is running and the door is closed. Pressures across the master bedroom door in these homes ranged from one to eight Pascals.

A separate test on Site 4 (not shown in the graph) was performed with the master bedroom door closed. The pressure across the door was 6 Pa, resulting in a 4.5 Pa pressurization of the bedroom relative to ambient and a depressurization of 1.5 Pa of the rest of the home. The measured infiltration was more than doubled with the door closed. It should be noted that this effect occurs even when the ductwork is airtight.

Site 5 was a large home located on a bluff near the open waters of Puget Sound. Because of its location, it experienced a fair amount of wind. The low peaks in the natural infiltration graph (the upper plot in Figure 4) in the evenings of Days 90, 91 and 92 are due to periods of elevated wind speed.

This home had an electric heat pump and an air-to-air heat exchanger (AAHX); we operated the air handler fan from 6:30 to 9:00 each morning. We also allowed the heat pump to provide heat when required, resulting in its cycling most of the time. The added infiltration during times when the heat pump is cycling is calculated by multiplying the fractional on-time by the added infiltration predicted by the duct model.

The large pulses occurring just after noon each day are the air-to-air heat exchanger, which was timer-controlled to run for two hours each afternoon. The heat exchanger was also operated for two brief periods on Day 90. The second large pulse during the afternoon of Day 93 was caused by the simultaneous operation of the air-to-air heat exchanger and the heat pump.

Three subsidiary peaks are visible after the heat exchanger cycle on Day 92. The first and third peaks are due to our manual operation of the heat pump. The second pulse is caused by operation of the range hood for about 1-1/2 hours.

It is of interest to note that the heat pump had an electronic air cleaner and the occupants typically ran both the heat pump and air-to-air heat exchanger fans continuously, although they usually turned the heat pump fan off at night. In this home, natural infiltration alone produces 136 cfm, or 0.29 ACH. With the continuous operation of the heat exchanger, the house would receive 296 cfm or 0.62 ACH of ventilation.

Site 6 was a six-year-old home with a gas furnace. This home was pressurized by 6 Pa when the fan was operating due to the large return leaks in the duct system. One of the return ducts had been mounted in an incorrect joist space (the space adjacent to the one with the return grille), while the other duct had a large hole which was open to the attic.

The air handler fan was operated on a schedule twice a day, between 7:30 and 10:00 a.m. and 7:00 and 9:30 p.m. On the first day, we noted that the furnace cycled almost continuously to supply the heating load, so the schedule was altered to force the heat off for 1-1/2 hours before and after the fan cycles. This allowed us to get clean measurements of the impact of the air handler fan and to estimate the natural infiltration rate.

The tall pulses are the experimental operation of the air handler fan and the remainder of the elevation above natural infiltration is due to cycling of the furnace. Because the home is completely pressurized, the total flow through the home when the fan runs is the unbalanced flow through the air handler, or 350 cfm. During periods of cycling, the infiltration is modeled as the unbalanced flow multiplied by the fractional fan on-time plus the natural infiltration times the fractional off-time.

Continuous operation of the air handler fan in this home would produce a constant flow of 350 cfm, or 1.41 ACH, of ventilation.

Forced-Air Distribution Systems

As illustrated in Figures 2 through 5, forced air distribution systems can have a large effect on living-zone infiltration rates. These effects occur both when the air handler fan is running and when it is off. The blower door test results in Table 3 show that, for these homes, leakage in the ducts ranges from 5% to 33% of the total leakage of the home, to a first approximation. This means that the natural infiltration rate is correspondingly increased during the times when the fan is not running.

The infiltration effects when the air handler is running are difficult to predict because of varying pressures and differing leakage areas throughout the duct system. For example, a small hole under high pressure may leak as much as a larger hole under less pressure. In addition, many of the actual leaks in a duct system may be to or from the house rather than the crawl space or the attic. These infiltration effects are best measured using tracer gas methods.

The fan-on infiltration effects of duct leakage for these sites are summarized in Table 5. The first line shows the flow through the air handler fan. The second section characterizes the percentage leakage with the air handler running; total leakage ranges from 3% to 64% of the flow through the air handler. It is clear that the leakage at Site 6 is disastrously large.

It is important to distinguish supply leaks from return leaks, because of the differing temperatures. Under heating conditions, a return leak simply introduces additional infiltration into the home, while a supply leak not only creates additional infiltration but results in the loss of air which has already been heated. The equations to account for the additional thermal effects of supply leakage are given in Palmiter and Bond (1991a) and will not be discussed here.

If we assume that, under design conditions, the temperature difference across the furnace is approximately the same as that from the house to outdoors, the calculated efficiency loss in percent while the furnace is running is given in the last line of Table 5. For these homes, this loss ranges from 3% to 47%, with a median of 9%.

Because, for the most part, the air handler fans were run as scheduled experiments in these homes, the amount of added infiltration as realized in the measured data is not necessarily representative of actual operating conditions. In addition, some of the homes were measured under conditions with a greater temperature difference than the others.

In typical winter weather, we estimate that the furnace or heat pump will operate on a 33% duty cycle for 18 hours each day. During the other six hours, the system will be off. This results in an overall runtime of six hours per day.

In order to calculate the overall infiltration impact of the ductwork, we have adjusted the natural infiltration in each of the homes to correspond to a temperature difference of 25°F and assumed a runtime of six hours per day for the heating system.

The results of these calculations are given in Table 6. The first line shows the natural infiltration assuming measured wind and a temperature difference of 25°F. The second block summarizes the added infiltration with the fan on, the fan off, and the total. The last block gives the total infiltration and the infiltration added by the heating system as a percentage of the total. These percentages range from 13% to 60%.

In general, the findings concerning added infiltration due to duct leakage, both with the fan off and with the fan on, are consistent with other findings in the literature (Cummings and Tooley 1989; Cummings et. al. 1990; Modera 1989; Modera et. al. 1991; Parker 1989).

Conclusions

The principal findings can be summarized as follows for ventilation and forced-air distribution systems.

Ventilation Systems

- If supply and exhaust flows are balanced, there is no interaction with natural infiltration. The added infiltration is simply the inward flow through the ventilation system.

Table 5. Tracer-Based Estimates of Duct Leakage

	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Air handler flow (cfm)	1100	727	700	1500	955	680
Duct Leakage with Air Handler Running (Percent of Fan Flow)						
Supply leak (%)	2.8	11.5	3.2	2.9	19.4	7.0
Return leak (%)	2.8	7.8	0	3.9	45.0	4.5
Total leak (%)	5.6	19.3	3.2	6.8	64.4	11.6
Estimated Impact on Furnace Efficiency at Design Conditions						
Efficiency loss (%)	5.5	20.2	4.8	3.3	47.4	12.4

Table 6. Overall Infiltration Impact of Ductwork (Air handler running 6 hours/day)

	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7
Base natural infiltration (cfm, sealed)	127.4	82.2	20.4	127.4	78.9	86.1
Q Added, fan on (cfm)	11.0	20.0	3.2	14.1	67.3	14.4
Q added, fan off (cfm)	9.4	14.4	.8	4.8	28.9	15.4
Total added (cfm)	20.4	34.4	4.0	18.9	96.2	29.8
Total infiltration (cfm)	147.8	116.6	24.4	146.3	175.2	115.9
Added as % of total	13.8%	29.5%	16.3%	12.9%	59.9%	25.7%

- If supply and exhaust flows are not balanced, the ventilation system pressurizes or depressurizes the home. Under these conditions, the induced flows interact in a complex fashion with natural infiltration. We have proposed a simplified model of this interaction which agrees reasonably well with the measured data in these homes.

- For typical natural infiltration rates seen in energy-efficient all-electric homes, and a typically sized exhaust fan system (50 cfm), it is necessary to operate the system continuously in order to meet Standard 62. Intermittent operation of one to two hours in the morning and evening will produce almost no measurable increase in ventilation.

Forced-Air Distribution Systems

- Forced air distribution systems and associated duct leakage can have large effects on pressures and whole-house infiltration rates. Assuming a standard runtime of 6 hours/day, the median infiltration due to duct leakage was 21% of the total. Infiltration rates are increased both when the fan is off and when it is on.

- In these homes, the median increase in natural infiltration due to duct leakage was 14%, which compares with other recent studies indicating a 16 to 20% increase (Palmiter and Brown 1989; Palmiter et. al. 1991).

- The increased infiltration when the fan is on tends to be much larger than the increase in natural infiltration, because the pressures produced by the air handler are much greater than natural pressures.

- The measured data also show a large impact on infiltration due to closing one or more doors to bedrooms with supplies but no returns. Typical pressures measured across the bedroom doors were 4 Pascals.

- The extension of the fan model to unbalanced flows due to duct leakage agrees reasonably well with the measured data.

- Although a return leak and a supply leak of the same magnitude have the same effect on infiltration, supply leaks have much greater impacts on furnace efficiency than do return leaks.

Acknowledgements

This work was sponsored in part by the Residential Ventilation Consortium and administered by John Kesselring of the Electric Power Research Institute. Darryl Dickerhoff of LBL performed the bulk of the field measurement work, and Max Sherman of LBL made many valuable suggestions and provided constant guidance with respect to the theoretical modeling. The cooperation and assistance of many other individuals, including the homeowners, made this project possible.

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