Measured Infiltration and Ventilation in 472 All-Electric Homes

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ABSTRACT

This paper summarizes the results of five recent infiltration studies on electrically heated, single family homes in the Pacific Northwest. In each of these studies, infiltration was measured by time-averaged perfluorocarbon tracer tests (PFT) and estimated with blower-door depressurization tests combined with the infiltration model developed at Lawrence Berkeley Laboratories (LBL). Results are given for a total of 472 homes.

We also discuss the results of a detailed study on one home in which the LBL model and PFT predictions were compared with real-time multizone tracer measurements.

The PFT-measured air-change rates ranged from 0.38 ACH for the baseline study to 0.27 ACH for newer energy-efficient homes with ventilation systems. Depending on the study, 50 to 85% of the homes failed to meet current standards for minimum ventilation rates.

Homes with forced-air heating systems had infiltration air-change rates which averaged 17 to 36% greater, depending on the study, than homes with baseboards or wall heaters.

The homes in three of the studies had various mechanical ventilation systems. The additional ventilation provided by these systems was small, except in homes with continuously operating systems.

INTRODUCTION

Air infiltration is a major source of heat loss in residential buildings; in modern well-insulated homes, it may account for as much as half of the total heat loss. It is also an important factor affecting indoor air quality. In this paper, we use the term "infiltration" to mean the total flow of outdoor air into the conditioned space, including any flow induced by exhaust fans, ventilation systems, duct leakage, and occupant effects.

Due to the recent emphasis by home buyers and builders on energy efficiency, tighter homes are being constructed. In the past, it was generally assumed that natural infiltration would provide adequate ventilation [ASHRAE 1989]; however, in modern energy-efficient homes, this is no longer the case. This concern has led to the development of minimum ventilation standards and requirements for mechanical ventilation systems.

Infiltration characteristics of electrically heated, occupied, single family homes in the Northwest have been measured in a series of research and demonstration projects. This paper summarizes the results of five of these studies: the Northwest Residential Infiltration Survey, Cycle I and Cycle II (NORIS I and NORIS II); site-built homes constructed under the Residential Construction Demonstration Project Cycle II (RCDP); manufactured homes constructed under RCDP; and a control group of manufactured homes.

Descriptions of these studies are given in Table 1. In each of these studies, infiltration was measured by time-averaged perfluorocarbon tracer tests (PFT) and estimated with blower-door depressurization tests combined with the infiltration model developed at Lawrence Berkeley Laboratories (LBL).

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NORIS I was intended to provide a base line for homes completed between January 1, 1980 and November 1, 1987. Mobile homes, homes built under utility conservation programs, and homes with air-to-air heat exchangers were excluded. Using a telephone survey based on random-digit dialing, we recruited a sample of 134 homes from the estimated target population of 124,771. We placed special emphasis on statistical and scientific defensibility. Detailed descriptions of the sample selection and data analysis are given in two reports [Palmiter & Brown, 1989a; Palmiter & Brown, 1989b].

NORIS II investigated homes built to April 1987 Super Good Cents (SGC) specifications. Mobile homes, homes with heat-recovery ventilation systems, and homes built under the RCDP program discussed below were excluded. A probability sample of 49 homes was drawn from 186 homes which were built after June 1987 and passed the utility's SGC inspection before October 1988. The results of this study are given in Palmiter et al. [1990a].

Under RCDP, 182 site-built homes were constructed in the BPA service area during 1987 and 1988, with the primary objective of demonstrating new construction techniques and product innovations. These homes were also required to meet April 1987 SGC specifications; they had various types of ventilation systems. Ventilation data are available on 129 of these homes; a detailed analysis of this study is given in Palmiter et al. [1990b].

From 1987 to 1989, eight of the 18 manufacturers in the Northwest constructed homes to SGC standards. Ventilation data were collected on 131 of these homes under the RCDP program; these homes all had exhaust-fan ventilation systems. For clarity, we will refer to these homes as manufactured homes, although they are also RCDP homes. These homes all had forced-air heating systems, and many also had makeup air systems to the air handler. Further details are given by Palmiter et al. [1990c].

Ventilation data were also collected on 29 manufactured recruited primarily from the NORIS I database for use as a control group. Like the SGC manufactured homes, all of these homes had forced-air heating systems and some had makeup air systems. However, these homes had no ventilation systems. Results of these measurements are also summarized in Palmiter et al. [1990c].

Measurements were done in the mid to late winter to obtain weather conditions similar to those during an average heating season. The NORIS I homes were tested in January through May, 1988, and the NORIS II and RCDP homes in February through May, 1989. Both groups of manufactured homes were tested in November through March, 1990. Field contractors visited each home to perform a site audit and blower door tests, and to deploy PFT sources and samplers. The protocol for the field visits is described in detail by Ecotope [1989].

Both pressure and depressure tests were done on the house with the ventilation system as found; all windows were closed, any ventilation systems were turned off, and dampers on wood devices were closed. In NORIS II and RCDP, the tests were also done after sealing openings due to the ventilation systems. The results presented here are derived from the depressure test on the house with the ventilation system as found.

Each house was divided into one to three zones for the purposes of the PFT test. The average duration of the PFT tests was 17 days.

OVERALL RESULTS

Overall results of the five studies are summarized in Table 2. The first line shows the number of homes in each study. The number of occupants per home is somewhat lower for the newer homes. The percentage of homes with forced air (FA) heating systems (central forced air and heat pumps) decreases for the newer homes (i.e., NORIS II and RCDP). The impact of FA distribution systems on infiltration is discussed later in the paper.

Basic physical characteristics of the homes are summarized in the second block. The stack height is one of the parameters of the LBL infiltration model; as used in these studies, it is the average height of a column of warm indoor air above grade. The traditional measure of the height of a home is from the lowest leak above grade to the highest ceiling. We believe that the average height is a more appropriate measure. In the NORIS I study, the average stack height was 32% lower than the average house height. Stack model predictions using the average stack height were about 15% lower than those using the house height. The homes in the three site-built sets are of comparable size; the newer homes are slightly larger.

The third block of Table 2 gives three blower-door measures of tightness. The first is the effective leakage area (ELA) at 4 Pa as defined by Sherman et al. [1982]. To approximate the physical leakage area, the ELA should be divided by 0.6. The ELA is strongly dependent on the size of the home; a better indicator of the intrinsic tightness of the home is the specific leakage area (SLA), which is 10,000 times the ELA divided by the floor area. Air changes at 50 Pa (ACH50), predicted from the blower-door leakage function, is a common measure of tightness used in many building standards.

The SLA and ACH50 are also illustrated graphically in Fig. 1. The homes with energy-efficiency measures are much tighter than those without such measures; the RCDP homes are the tightest.

We assigned each home to the nearest National Weather Service (NWS) station, from which we obtained hourly outdoor temperatures and wind speeds. All of the figures in this paper are based on NWS data for the period of the PFT test for each home unless otherwise noted; extrapolations to Typical Meteorological Year (TMY) data for the heating season of November through April are also included.

Environmental conditions, summarized during the PFT test period for each home, are given in the fourth block of the table. During the site visit, the field contractors measured the indoor temperatures in each zone. Temperature recorders were installed in one zone in 69 of the homes in NORIS I and all of the homes in NORIS II. The average recorded temperatures correlated well with the temperatures measured by the contractors. The indoor temperatures are averages of the zone temperatures, using the recorded temperatures when available.

The indoor-outdoor temperature differences compare well with the TMY heating season averages, with the notable exception of the RCDP study, where there is a 34% difference. Wind conditions compared more closely.

In the NORIS I study, the full LBL model with the shielding and terrain factors estimated by the field contractors predicted infiltration rates about 40% greater than those from the PFT test. Investigation revealed a strong correlation between the amount of overprediction and the wind-induced infiltration predicted by the LBL model.

New shielding and terrain factors for the LBL model were estimated by Dr. Sherman of LBL. The new shielding and terrain factors were each about one class lower; combined with the reduction in house height, this resulted in a decrease of 55% in the predicted infiltration due to wind. However, the full-model predictions were still greater than the PFT test, and some correlation of the overprediction with the magnitude of the wind effect remained.

Similar discrepancies were noted in NORIS II and RCDP, and shielding and terrain factors were also estimated for these homes. The new factors are used in all the calculations and tables in this paper. These factors were not re-estimated for the manufactured homes; their shielding and terrain classes are about one greater than in the other studies. As a result, the wind effect was greatly overpredicted for the manufactured homes.

We found that the stack portion of the LBL model agreed more closely with the PFT tests in homes without FA systems, both in terms of the mean value and in terms of the degree of scatter. In addition, a detailed hourly multizone infiltration test in one home (discussed below) resulted in similar conclusions. In the author's opinion, the wind-related aspects of the LBL model need to be refined before the full model can be reliably used in field studies. Until such work can be completed, we propose use of the stack portion only to predict infiltration from blower-door data and weather conditions for these relatively shielded homes.

The next two blocks of Table 2 give air change rates and infiltration air flow from the PFT test, the stack portion of the LBL model, and the full LBL model (stack and wind combined). The PFT measurement and the stack model decrease for the newer homes roughly in proportion to the reduction in leakage, although the PFT results for the RCDP homes show less reduction due to the presence of effective ventilation systems in some of the homes. The relationship between the PFT results and the LBL model is shown in Fig 2. The PFT results display a much closer relationship with the LBL stack model than with the full model. A more detailed analysis of this comparison is given in the original reports.

The last block of Table 2 gives air-change results, extrapolated to TMY weather data for the heating season. The PFT value was obtained by adjusting the measured PFT value by the ratio of the LBL stack model predictions for TMY heating season weather versus PFT period weather. The values in this block represent our best estimate of heating season air-change rates; they provide better comparisons between studies, particularly for the RCDP homes which were measured under warmer conditions. The lower blocks of Fig. 1 show the PFT measurements and LBL stack predictions. As noted previously, the newer, energy-efficient homes are tighter; this results in less natural infiltration. The PFT results for each study follow the same trend; the one exception is the RCDP homes, in which the measured infiltration increases because some of the homes have effective ventilation systems.

HEATING SYSTEM EFFECTS

There are several physical reasons to expect higher infiltration rates in homes with FA systems. First, leaks in portions of the exterior ductwork (e.g., in unheated attics and crawlspaces) add to natural infiltration by increasing the leakage area. Second, when the central heating system is operating, portions of the ducts are under much greater pressure than that across the envelope (50 to 150 Pa versus 1 to 10 Pa), thus producing greater infiltration per unit leakage area than that predicted by the LBL model. Third, the mass flow of supply air may not equal the mass flow of return air, resulting in an overall pressurization or depressurization of the envelope which induces additional ventilation. Fourth, distribution systems which do not include a return in each room with a supply create differential pressures between rooms and across the envelope when doors in the home are closed; these pressures can be about the same magnitude as natural driving forces. The first three effects do not occur in the absence of duct leakage. Modera gives a more detailed review of these effects [1989].

A ventilation study of R-2000 homes in Canada gave PFT test results for a small sample of control homes which also showed a marked increase in air change rates for ducted heating systems [Riley 1986].

In an infiltration survey performed on homes in the Residential Standards Demonstration Program (RSDP), both PFT and blower door tests were administered on 161 post-1978 all-electric control homes. The PFT results showed a marked difference between homes with ducted (central forced air and heat pumps) and non-ducted (baseboard, wall heaters, radiant) heating systems [Parker 1989].

There is, however, a tendency for correlation between heating system type, house type, tightness, and climate due to local construction practices. In the RSDP study, homes in cold-climate regions were much tighter than those in the warmer regions, and were almost always heated with baseboards; the homes in warmer climates had a significant fraction of forced-air systems. Therefore, a simple comparison of measured infiltration rates between homes with and without forced-air systems may considerably overestimate the infiltration effects of duct leakage in this study.

Comparisons of homes with and without FA systems are given in Table 3. The greatest differences in infiltration rates are in the RSDP and overall NORIS I studies. Both of these samples, especially RSDP, are subject to the correlation between climate, heating system type, and tightness discussed previously.

In order to eliminate the effect of correlations between heating system type, climate, and local construction practice, we embedded a special heating system study within the NORIS I sample. The homes in this substudy were located in the Puget Sound area and were tested under the same weather conditions. This special substudy shows a smaller and more representative effect.

The NORIS II study, in which all the homes are in the same county, shows a much smaller effect. We believe that a substantial proportion of the duct systems were interior to the home in this sample, but the percentages of homes in each study with exterior ductwork are not available. Overall, we conclude that FA distribution systems increase infiltration rates by 15% to 36%, depending on the amount of exterior ductwork.

The heating system comparison reinforces the findings of other studies that forced air distribution systems have a significant impact on infiltration rates ([Cummings 1989], [Cummings 1990]; see Parker [1989] for further citations). This issue should clearly receive further investigation.

Because all the manufactured homes had forced-air heating systems, comparisons with other studies using homes with FA systems only may be more appropriate. In this comparison, the SGC manufactured homes have even less ventilation relative to other studies, 15% less than RCDP site-built homes with FA and 40% less than NORIS I homes with FA. The control group of manufactured homes has 25% fewer air changes than do NORIS I homes with FA. These differences may reflect better duct sealing practices for manufactured homes.

COMPLIANCE WITH VENTILATION STANDARDS

There are a growing number of standards relating to ventilation, indoor air quality, and air leakage. We evaluated the homes in terms of ASHRAE Standard 62 [1989] for minimum ventilation.

Standard 62 requires a minimum whole-house ventilation rate of 0.35 ACH, but not less than 15 cfm per person. Criteria based on cfm per occupant are used for commercial buildings; the underlying assumption is that the occupants are the primary source of pollutants (e.g., carbon dioxide, body odor). If the primary source of pollutants is the building itself, a criteria based on air changes is more appropriate. The two guidelines give very different compliance rates when applied to homes.

Percentages of homes failing to comply with Standard 62-89 is given in Table 4. For the site-built homes, these are given separately for ducted and nonducted heating systems as well as for each sample as a whole; all of the manufactured homes had ducted heating systems. The values are based on the PFT-based air changes and cfm.

Since one can argue that any chosen value for a standard is somewhat arbitrary, percentages of homes which would fail lower ventilation requirements are also shown in Table 4. It should also be noted that most European standards require rates of 0.5 ACH or greater.

The proportion of homes failing to meet Standard 62 is cause for concern. Even if the required ventilation were only 0.25 ACH, more than 60% of the site-built energy-efficient homes without FA systems (NORIS II and RCDP) fail the requirement even though they have ventilation systems. Although all the manufactured homes had FA systems, 53% would fail the reduced requirement of 0.25 ACH. However, only 40% of RCDP homes with air-to-air heat exchangers have less than 0.25 ACH; many of these systems operated continuously.

DETAILED CASE STUDY

We conducted a detailed study on a typical occupied two-story, electrically-heated home [Palmiter and Brown, 1989a]. The home was located in Olympia, Washington, less than a quarter mile from the open waters of Puget Sound toward the east. The floor area, volume, and stack height were very similar to the average for two-story homes in the NORIS I sample; the home was slightly leakier than the average for NORIS I homes in the Puget Sound area.

The special study used a real-time MultiTracer Measurement System (MTMS) developed at LBL [Sherman and Dickerhoff, 1989]. The home was divided into three zones for the tracer measurements, and a one-week PFT test using the same three zones was conducted concurrently with the MTMS measurements. LBL technicians performed blower door tests.

Wind speed and indoor and outdoor temperatures were recorded on a real-time basis. Wind speed was measured with a low cut-in speed cup anemometer mounted on a portable 30-foot tower near the home. The wind and temperature data are summarized in the first block of Table 5. For comparison purposes, we also present concurrent data from the NWS station at the Olympia airport, which is located about five miles inland and has a 20 foot wind tower.

As shown in the table, the average wind speed at the airport is larger than that at the site by a factor of 2.5. The terrain factor in the LBL model is supposed to adjust the wind airport speeds to those at the home, but prediction of the observed site wind speed requires a terrain class beyond the range of conventional terrain class assignments.

We ran the LBL model hourly using wind speed, and indoor and outdoor temperatures, both for site data and NWS data. The MTMS and PFT volumetric flows are adjusted using the same conventions used for the PFT results in the NORIS sample. It is remarkable that the average MTMS, PFT and site-weather LBL model estimates all agree within 0.5%. The close agreement of the LBL model with the MTMS results is, as we will show, entirely coincidental and therefore somewhat misleading.

The third block of Table 5 gives LBL model infiltration rates. The LBL model using NWS weather overpredicts the infiltration by 45%. The stack effects for the two sets of weather data differ by less than 2%; the wind effects differ by more than a factor of two.

The MTMS and site-weather LBL model results on an hourly basis are shown graphically in Fig. 3. We use the stack prediction as a reference for the other flows. The upper panel shows the MTMS flows compared with the predicted stack flows, the second panel shows the full LBL model predictions compared with the stack effect, and the bottom panel shows the wind predictions compared with the stack effect.

In the upper panel, the stack effect follows the lower envelope of MTMS values very closely with the exception of the first three hours. Although the wind speed was much greater during the first four days, the closeness of this tracking of the lower boundary is about the same during the first four days as it is for the last three days.

The MTMS flows have a number of large peaks; in seven days there are seven wide peaks in infiltration, which generally start just before midnight and drop around 7 AM, and a smaller one late on the afternoon of day 16.

Days 17 and 18 have low wind speeds and low wind effect; the middle panel shows that the increase in infiltration due to wind is negligible, since the full model prediction is essentially the same as stack effect only. The large peaks in the MTMS flows on these days must be due to occupant effects. On the other hand, there are many periods during the first four days when wind effect is large, but the pattern of increase above the stack effect does not match that of the MTMS and the magnitude of the increases is much too large.

These observations lead to the hypothesis that most of the elevation of the MTMS flows above the stack effect are due to occupancy effects. This hypothesis is further supported by the occupant activity record which states that a window in the master bedroom was open each night for eight hours. Opening a three foot high bedroom window about three inches would account for the additional flow.

The time-averaged LBL model agrees with the time-averaged MTMS measurements because the overprediction resulting from overly large wind effect happens, by coincidence, to be of the same magnitude as the increase due to occupancy effect. Sophisticated analysis shows that the wind speed must be reduced by an additional factor of between two and three before the correlation between discrepancy and wind effect disappears. If the site wind speed were reduced by 60%, the full LBL model would predict 139 cfm, compared with 135 cfm for stack effect only and 160 cfm for the MTMS. Thus, wind increases the infiltration by about 3% over stack only, and occupancy effects produce an additional increase of 15%.

The detailed infiltration data lead to the following conclusions for this home under these weather conditions. For data restricted to hours in which occupancy effects are minimal (typically 8 am - 11 pm), the LBL model overpredicts by 45% when used with NWS data, and by about 15% when used with weather data measured at the site. Almost all of the overprediction error is due to wind effect. There is no evidence of bias in the whole-house PFT results compared with the MTMS, although the closeness of the results is surely not typical. Individual zone PFT infiltration rates are in error by as much as 35%.

Four additional sets of data, with much greater detail and 15-minute resolution, were taken with the MTMS in the spring of 1990 [Palmiter and Bond 1990]. These data provide additional support for the conclusion that the time-averaging bias of the PFT tests under winter conditions is small and that infiltration in Northwest homes is dominated by the stack effect.

VENTILATION SYSTEM EFFECTS

The NORIS II, RCDP, and SGC manufactured homes had designed ventilation systems. The RCDP homes had the widest range of ventilation systems, and these are described in Table 6. The systems in the NORIS II homes were of the exhaust-fan type for homes without FA systems, and primarily of the makeup type (nHRV4) for homes with FA systems. The SGC manufactured homes all had exhaust-fan (nHRV1 or nHRV3) systems controlled by 24-hour timers.

Under these weather conditions, an exhaust fan of 50 cfm produces only about 25 cfm of additional infiltration, because about half of the flow out of the fan makes up for the fan-caused reduction in outward flow due to wind and temperature. A more detailed discussion of this effect is given in the RCDP report [Palmiter et al., 1990].

We were unable to detect any effect of the NORIS II ventilation systems on infiltration rates. The effects of the ventilation systems in the SGC manufactured homes are also small. The most likely cause is very low ventilation system run-times, although these were not measured in NORIS II. In the manufactured homes, ventilation system run-times, inferred from the timer settings, have a mean of 2.3 h/day and a median of 2.0 h/day, similar to the run-times of exhaust-fan systems in RCDP.

Ventilation system results for RCDP homes are given in Table 7. The RCDP homes included neutral-pressure (two fans) air-to-air heat exchanger systems and commercial exhaust-air heat pump systems in addition to the exhaust fan types. Run-times in hours per day were measured for most of these homes. We give both the PFT results and the LBL stack model results. If we use the stack model as a baseline prediction of natural ventilation, the difference between the PFT and stack results can be taken as a rough estimate of the added ventilation due to the ventilation systems. Since the PFT test also includes wind effects, the added ventilation so determined should be interpreted as an upper limit.

The greatest increase in ventilation is for homes with neutral-pressure AAHX systems. These systems also had the largest median run-times by far; one reason for this is that many of the AAHX systems were installed to run continuously at low speed. The EAHP systems were the second best performers in terms of both added ventilation and run-time. Homes with these two types of systems were also among the tightest in terms of specific leakage area.

The nHRV4 systems show an apparent increase of about 26 cfm, but a comparison of FA homes with and without the nHRV4 systems shows almost exactly the same mean added ventilation. We conclude that the added ventilation is due almost solely to the FA system itself and not to the presence of the nHRV4 vent system. The low levels of added ventilation for the nHRV1 (bath fan) systems are a baseline due to ordinary operation of bath fans (plus wind effects).

The additional ventilation provided by the ventilation systems tends to track the measured run-time. With the exception of the AAHX and EAHP systems, most homes had dehumidistat controls. These were typically set either to "Off" or above 50% relative humidity. Settings above 50% do not generally activate the ventilation systems.

SUMMARY OF FINDINGS

These studies were large and complex projects spanning a time period of more than three years; complete summaries and descriptions can be found in the associated reports. We present here a concise summary of the principal findings and conclusions from the five studies.

There is tremendous variation in tightness as well as in measured air change rates, even within a single study. The standard deviations of the infiltration parameters vary from 27% to 56% of the means. Most of the variation in measured air-change rates is due to differing levels of tightness, as measured by air changes at 50 Pa or specific leakage area.

The NORIS II homes were tighter than the NORIS I homes, and the RCDP homes were tighter still. The average specific leakage areas were 4.8, 3.7, and 2.8 in NORIS I, NORIS II, and RCDP respectively. The SGC manufactured homes, with an average SLA of 3.3, were tighter than the control group of manufactured homes, which averaged 4.6. The PFT-measured air-change rates were 0.38, 0.27, and 0.28 ACH in NORIS I, NORIS II, and RCDP respectively. For manufactured homes, the SGC and control groups measured 0.27 and 0.33 ACH respectively.

Infiltration rates in the various studies tend to track the tightness. From NORIS I to NORIS II, the PFT-based air change rate decreased by 29%, and the SLA decreased 23%. For the RCDP study, SLA decreased 42% and the infiltration decreased 26% from NORIS I; we surmise that the decrease would have been even greater without the operation of the ventilation systems. The SGC manufactured homes were 28% tighter than the control homes, comparable with the 20% drop in infiltration.

ASHRAE Standard 62-1989 requires a minimum ventilation rate of 0.35 air changes in residential buildings. Using PFT air-change rates, which include the effects of mechanical ventilation systems and occupant effects, 50% of NORIS I homes, 78% of NORIS II homes, 71% of RCDP homes, and 85% of SGC manufactured homes fail this standard. For homes without forced air, the percentage of failure increases to 64% in NORIS I, 85% in NORIS II, and 78% in RCDP. Overall, these studies suggest that modern all-electric homes, particularly those without forced air, have evolved to levels of tightness which require mechanical ventilation in order to meet minimum standards.

The heating system comparison reinforces the findings of other studies that forced air distribution systems have a significant impact on infiltration rates. This is clearly an issue which should receive further investigation.

There is no evidence of increased ventilation due to the ventilation systems in the NORIS II homes. The most likely explanation is that the systems operate only a small fraction of the time. Dehumidistat settings, poor system design, and field installation errors are contributing factors. In the RCDP study, two of the ventilation system types (neutral-pressure air-to-air heat exchangers and exhaust air heat pumps) provided significant additional ventilation. These two system types were also the only ones which ran a significant portion of the time. SGC manufactured homes all had exhaust-fan ventilation systems and showed very little additional ventilation.

From an engineering viewpoint, the optimum home is airtight and has a mechanical ventilation system. Although the RCDP and NORIS II homes are tighter than those in NORIS I, some are not tight enough, and natural forces still have an effect. To make an exhaust-type system function predictably, the house must be tight enough that the pressure induced by the fan at the desired ventilation rate is much greater than typical naturally produced pressures. In the same way, ventilation produced by a balanced neutral-pressure system is most predictable when the house is so airtight that the natural infiltration is close to zero. As long as there is a significant component of natural infiltration, there will be problems with control and predictability, resulting in either energy waste or inadequate ventilation.

Although current ventilation standards are given in air-changes per hour, ventilation systems are rated in cubic feet per minute. Comparisons between subsets of homes give very different results in ACH or cfm; this suggests the need to develop reliable methods for sizing ventilation systems. Without knowledge of the tightness of a home, however, one cannot determine an appropriate size for a ventilation system.

We found evidence of systematic problems with the wind-related aspects of the LBL infiltration model. We believe that further refinement and testing of the LBL model is necessary. This work should include improved and less subjective methods of estimating the required inputs.

These findings emphasize the need for further research into the causes of variation in infiltration rates and the need to devise reliable methods of achieving desired levels of tightness and ventilation. This work is all the more urgent as regions and utilities are currently implementing various infiltration and ventilation construction standards.

Without a clear understanding of these problems and the subsequent development of training programs for builders and inspectors (emphasizing diagnostic use of blower doors to ascertain tightness and *tested* methods of ventilation system design), these new standards will remain empty specifications with unpredictable consequences.

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Table 1. Description of five studies.

	NORIS I	NORIS II	RCDP	Mfd Control	Mfd SGC
Number of homes	134	49	129	29	131
Type of Study	Baseline	Program	Program	Baseline	Program
Year Built	1980-1987	1987-1988	1987-1988	1980-1989	1987-1989
Location	WA/OR/ MT/ID	Seattle Area	WA/OR/ MT/ID	WA/OR/ MT/ID	WA/OR/ MT/ID
Site-Built/Manufactured	Site	Site	Site	Mfd	Mfd
Energy-Efficient Measures	No	Yes	Yes	No	Yes
Ventilation System	No	Yes	Yes	No	Yes

Table 2. Summary of results from five studies.

		Site-Built			Manufactured	
	Units	NORIS I	NORIS II	RCDP	Control	SGC
Number of homes		134	49	129	29	131
Number of occupants		3.35	3.04	2.94	3.03	3.06
Homes with forced air	%	52.2	30.6	40.3	100	100
Stack height	ft	11.71	12.15	10.89	8.02	8.14
Floor area	ft^2	1844	1977	1897	1402	1472
Volume	ft^3	15500	16450	15933	11280	11884
Effective leakage area	in^2	125	104	70	92	68
Specific leakage area		4.78	3.74	2.79	4.56	3.27
Air changes at 50 Pa	1/h	9.28	7.18	5.55	8.75	6.10
Inside temperature	F	67.2	66.3	67.4	68.0	68.7
Temperature diff	F	23.9	21.3	21.0	27.1	28.4
TMY temperature diff	F	26.6	23.6	28.2	27.4	28.5
Airport wind speed	mph	8.89	9.88	8.83	8.64	8.61
Air changes (PFT)	1/h	.384	.267	.276	.334	.267
Air changes (LBL Stack) [1]	1/h	.341	.262	.176	.305	.224
Air changes (LBL Full) [1]	1/h	.427	.354	.264	.500	.377
Air flow (PFT)	cfm	99.8	73.5	69.9	62.9	52.7
Air flow (LBL Stack)	cfm	88.6	71.4	43.9	57.3	44.1
Air flow (LBL Full)	cfm	10.6	97.7	66.4	95.6	73.8
TMY air chgs (PFT)	1/h	.401	.285	.325	.336	.268
TMY air chgs (LBL Stack)	1/h	.357	.277	.206	.309	.225
TMY air chgs (LBL Full)	1/h	.446	.371	.279	.518	.380

Note: The standard deviation of all of the infiltration parameters ranges from 30% to 50% of the mean.

* The LBL leakage ratios were assigned default values of R=0.5 and X=0 for all homes. This value of X implies a neutral level of 0.5.

Table 4. Percentage of homes not meeting minimum ventilation rates.

	NORIS I			NORIS II			RCDP II			Mfd	
	FA	NoFA	Total	FA	NoFA	Total	FA	NoFA	Total	SGC	Ctrl
≤ 0.35 ACH *	37	64	50	60	85	78	62	78	71	85	72
≤ 0.30 ACH	21	56	38	60	71	67	48	75	64	73	55
≤ 0.25 ACH	11	41	25	47	65	59	38	61	52	53	31
≤ 15 cfm/occ	6	36	20	13	29	24	12	32	24	33	28
≤ 20 cfm/occ	21	52	36	27	38	35	29	47	40	60	55

* ASHRAE Standard 62

Table 5. Summary of test home hourly weather data and infiltration results. (N=168)

		Site data		NWS data	
Variable	**Units**	**Mean**	**Std. Dev.**	**Mean**	**Std. Dev.**
Temperature	F	40.98	4.79	39.99	5.96
Wind speed	mph	3.73	2.48	9.40	5.96
Multitracer method	cfm	160.2	30.0		
PFT method *	cfm	159.8			
LBL Model, full	cfm	160.6	23.5	232.5	73.1
LBL Model, stack	cfm	134.6	12.3	137.0	14.6
LBL Model, wind	cfm	74.9	49.9	169.9	107.7

* The PFT measurement is a single time-averaged value; the other data are averaged over 168 hours.

Table 6. Ventilation system types in RCDP homes.

System	Intake	Exhaust	Number	% of Total
AAHXc	Air-to-air heat exchanger integrated with heating system		5	3.9
AAHX	Neutral pressure air-to-air heat exchanger		20	15.5
EAHP	Thru-wall vents or makeup air to forced air heating system	Exhaust air heat pump	8	6.2
nHRV1	Thru-wall vents or central ducted intake	Designated bathroom, kitchen or laundry fan	39	30.2
nHRV2	Thru-wall vents or central ducted intake	Central ducted exhaust	13	10.1
nHRV3	Thru-wall vents or central ducted intake	Separate whole house exhaust fan	6	4.7
nHRV4	Makeup air to forced air heating system	Designated fan, whole house fan, or central exhaust	38	29.5

Table 7. Infiltration characteristics of RCDP homes by system type.

	Units	AAHXc	AAHX	EAHP	nHRV1	nHRV2	nHRV3	nHRV4
Number of homes		5	20	8	38	13	6	39
Specific leakage area		1.71	2.09	1.77	2.68	2.12	2.82	3.82
Air changes at 50 Pa	1/h	3.3	4.3	3.3	5.4	4.1	5.4	7.6
Air changes (PFT)	1/h	.219	.372	.267	.229	.176	.220	.324
Air changes (Stack)	1/h	.114	.130	.123	.174	.131	.189	.234
Air changes (PFT-Stack)	1/h	.105	.242	.144	.055	.044	.031	.090
Air flow (PFT)	cfm	76.0	78.7	94.0	57.1	42.4	61.1	82.7
Air flow (Stack)	cfm	41.0	29.1	46.3	42.5	28.5	48.5	57.2
Air flow (PFT-Stack)	cfm	35.0	49.6	47.7	14.6	13.9	12.6	25.6
Mean run time	h/day	1.45	15.78	13.04	2.52	7.26	1.48	1.67
Median run time	h/day	.82	18.20	8.41	1.19	1.27	.32	.25

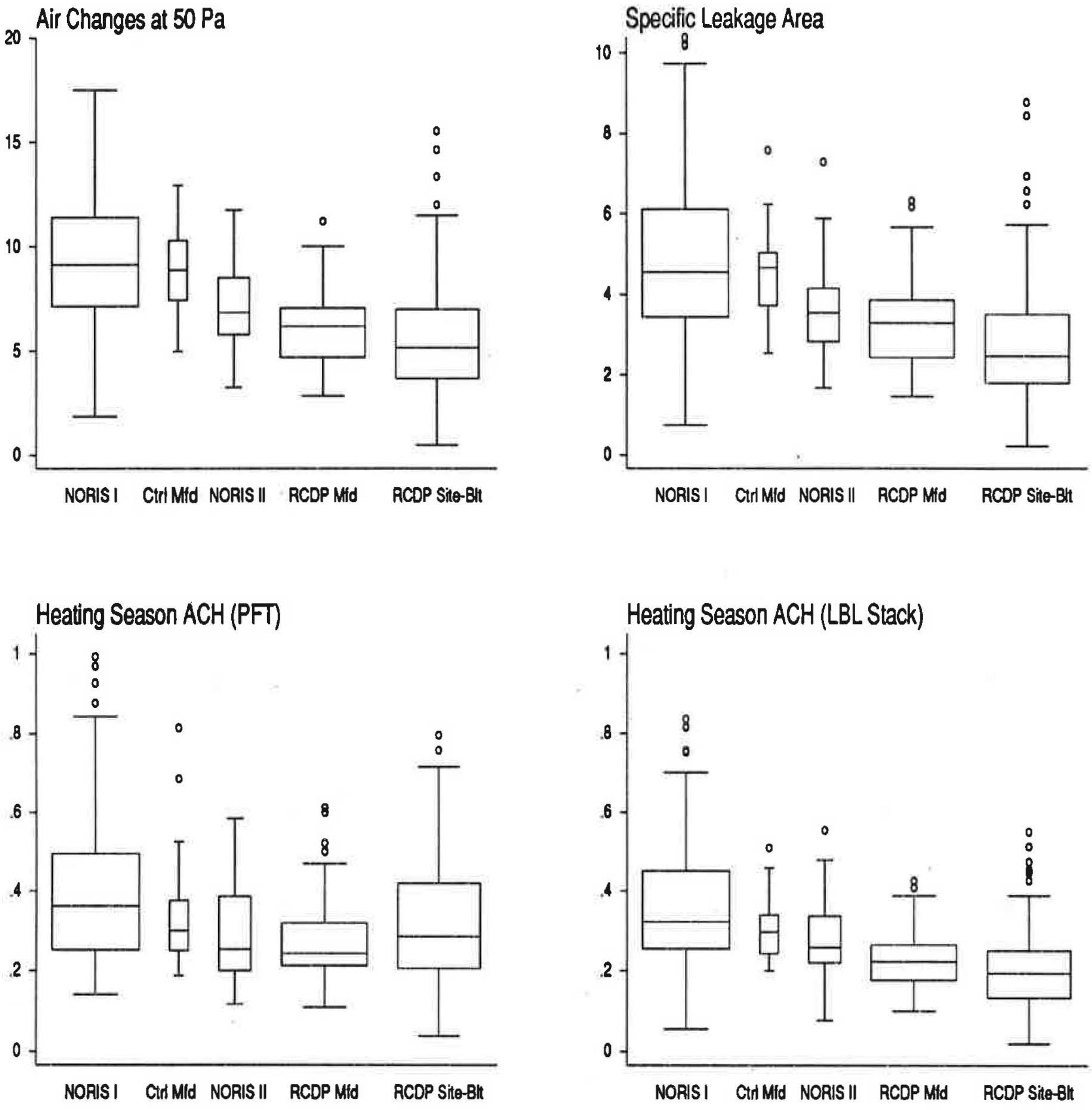

Figure 1. Box plots of tightness and infiltration for each study. The line through the middle of each box is the median (the value below which half of the sample falls). The upper and lower bounds of each box are the quartiles. The width of each box is proportional to the square root of the number of data points.

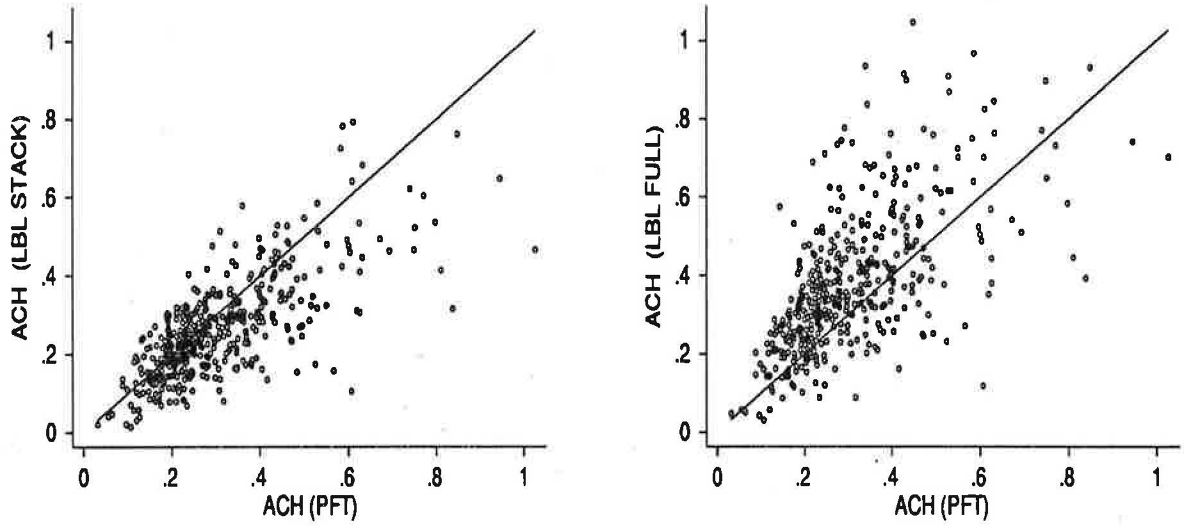

Figure 2. LBL predictions versus PFT measurements in four infiltration studies.
The line indicates equality. Homes with air-to-air heat exchangers or exhaust-air heat pumps are not included.

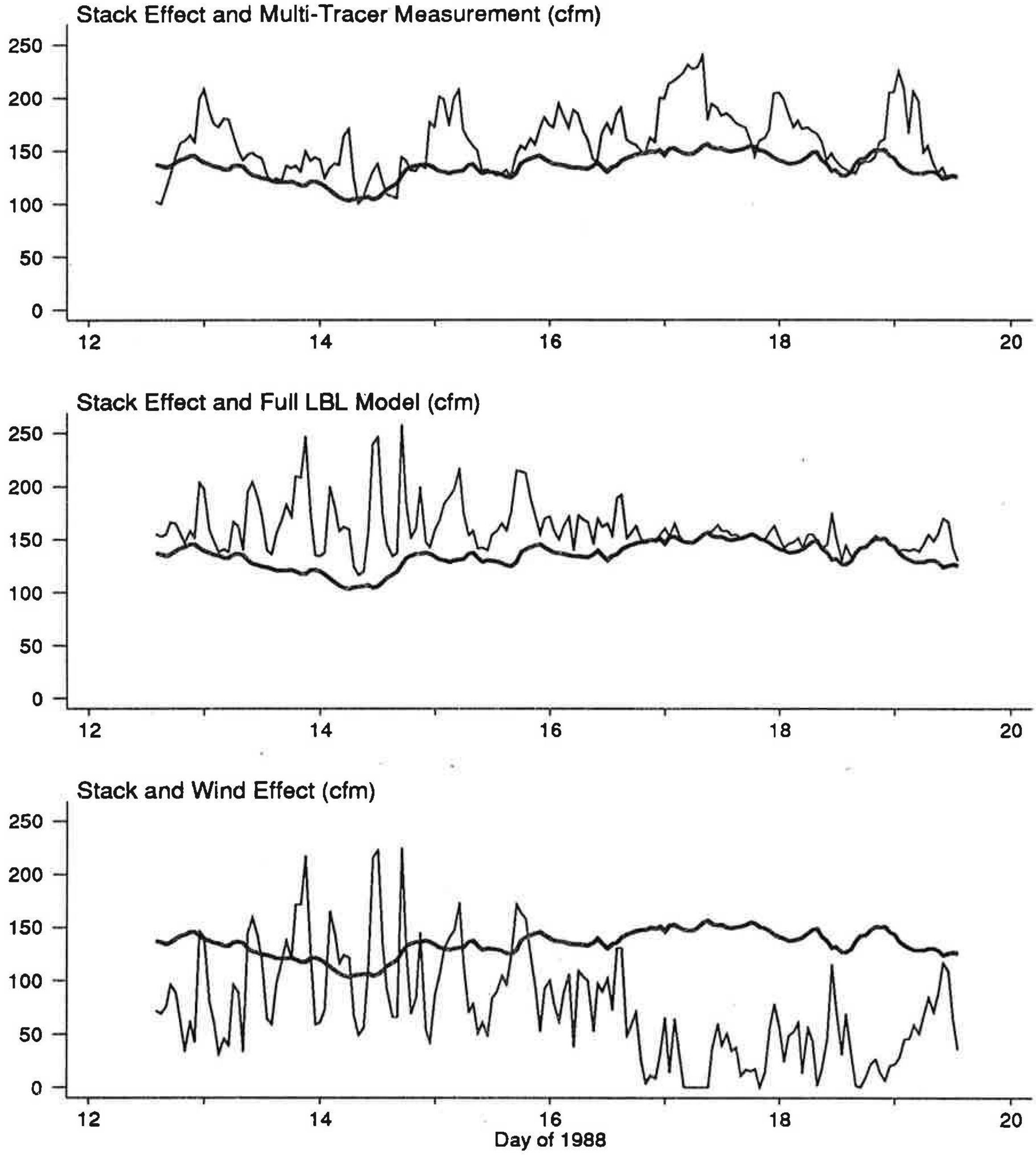

Figure 3. Comparison of LBL model and multitracer measurements.
Each panel shows the LBL-model stack effect marked with a heavy line. Other measurements are marked by a light line: the top panel shows MTMS results, the middle panel the full LBL model results, and the lower panel the LBL-model wind effect.