Northwest Residential Infiltration Survey

Analysis and Results

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EXECUTIVE SUMMARY

The primary goal of the Northwest Residential Infiltration Survey (NORIS) was to provide an estimate of the average heating-season infiltration rate of new electric-heat single-family homes in the Bonneville Power Administration (BPA) service area. Special emphasis was placed on the scientific and statistical defensibility of the infiltration estimates. In particular, the sample of homes was to be statistically representative for the purpose of estimating the population mean values of the measured infiltration parameters.

Secondary goals of the survey included comparison of two different techniques for estimating infiltration, and, to the extent possible, assessing the influence of physical characteristics of the home and occupant behavior on infiltration rates.

Two infiltration estimation techniques were employed. The first used blower-door leakage tests combined with the infiltration model developed at Lawrence Berkeley Laboratories. The second used the time-averaged perfluorocarbon tracer (PFT) method.

The analysis and results in this report are based on field tests conducted in a random sample of 134 homes. We present here a concise summary of the principal findings and conclusions from the NORIS project.

The final estimates for the average heating-season infiltration air change rates are 0.40 ACH for the PFT technique and 0.45 ACH for the LBL model.

There is tremendous variation in tightness as well as in measured air change rates. The NORIS sample of homes range from extremely tight to very leaky. Most of the homes fall into a grey area where natural ventilation may be inadequate and mechanical ventilation may be superfluous.

Most of the variation in infiltration air change rates is due to differing levels of tightness per unit size as measured by specific or normalized leakage area.

Homes with forced-air heating systems have infiltration air change rates which are 35 to 45% greater than homes with baseboards or wall heaters.

Depending on the criteria used, from 20 to 50% of the NORIS homes fail to meet current ventilation standards. For homes without forced-air heat, from 36 to 64% fail.

On the other hand, 17% of the homes fail to meet current standards of leakage performance. For homes with forced-air heat, this percentage increases to 24%.

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 also include improved and less subjective methods of estimating the required inputs. It is of fundamental importance to have a simple, reliable and reasonably accurate residential infiltration model.

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-related 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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1 INTRODUCTION

Air infiltration is a major source of heat loss in residential buildings; in modern well-insulated homes, air infiltration may account for as much as half of the total heat loss. It is also an important factor affecting indoor air quality. This report summarizes the final results of a major study of air infiltration rates in new, electrically heated homes located in the Pacific Northwest.

This report is one of two which summarize the project. The companion volume, "NORIS: Sample Selection and Bias Assessment" [Palmiter and Brown 1989] presents the results of the initial telephone survey, the selection of the sample, and a statistical assessment of potential selection bias in the sample. These results are briefly outlined in Section 2, Overview Summary.

We have tried to organize the report for easy review. Most results are stated in nontechnical language, and the use of mathematics is minimized. A concise overview of the entire project combined with a summary of the major findings and conclusions is given in Section 2. Some basic information on infiltration is given in Section 3, while the other sections expand in more detail on various aspects of the analysis.

The primary results are based on a probability sample of 134 homes located throughout the Pacific Northwest. A detailed case study of one home, in which continuous multizone tracer measurements were compared with the perfluorocarbon tracer method (PFT) and the Sherman-Grimsrud infiltration model, is described in Section 4.

The weather data used for the analysis are described in Section 5. It was necessary to modify some of the input parameters for the infiltration model. These modifications are discussed in Sections 6 and 7. Section 8 presents the major infiltration model results, and Section 9 gives a simple sensitivity analysis of the model. Section 10 discusses the key concept of ventilation efficiency. Section 11 compares the PFT and infiltration model results.

A specially designed subsurvey was imbedded in the overall NORIS study to examine the impact of forced-air distribution systems on infiltration rates while controlling as much as possible the influence of other factors. The results of this study are discussed in Section 12 and compared with several other studies.

2 OVERVIEW SUMMARY

The primary goal of the Northwest Residential Infiltration Survey (NORIS) was to provide an estimate of the average heating-season infiltration rate of new electric-heat single-family homes in the Bonneville Power Administration (BPA) service area. Special emphasis was placed on the scientific and statistical defensibility of the infiltration estimates. In particular, the sample of homes was to be statistically representative for the purpose of estimating the population mean values of the measured infiltration parameters. Secondary goals of the survey included comparison of two different techniques for estimating infiltration, and, to the extent possible, assessing the influence of physical characteristics of the home and occupant behavior on infiltration rates.

Two infiltration estimation techniques were employed. The first used blower-door leakage tests combined with the infiltration model developed at Lawrence Berkeley Laboratories (LBL) and hence referred to as the LBL model [Sherman and Grimsrud 1980]. The second used the time-averaged perfluorocarbon tracer (PFT) method [Dietz et al. 1986].

The target population for the survey was all single-family electric-heat homes completed after Jan. 1, 1980. Multifamily units, mobile homes, homes with air-to-air heat exchangers, and homes participating in BPA incentive programs were excluded. The homes were restricted to the BPA service area of Washington, Oregon, Idaho, and western Montana.

2.1 Telephone Survey Design

Although it is relatively easy for a utility to draw a truly random sample from customer billing records, it is more difficult to draw a sample for a regional power marketing agency with over 100 utility customers. After consideration of several alternatives, we decided to draw the sample by use of a telephone survey based on random-digit dialing. This had the advantage of being statistically bomb-proof and providing additional information on such questions as what fraction of new homes have electric heat.

By including questions in the telephone survey about items which may be correlated with infiltration rates (wood use, number of stories, heating system type, draftiness), it is possible to assess selection bias of those agreeing to field tests on their homes. Responses to these questions from the final sample were compared to those from the eligible homes. For instance, comparison of the answers for draftiness for those agreeing to participate with those not agreeing can indicate whether those with tighter or leakier homes were tending to volunteer.

The initial sampling frame was all possible valid telephone numbers in the target region. A pilot survey showed that, due to budget and time restraints, this technique would not generate the required 160 homes. Since 90% of the estimated regional growth occurred in a subset of 43 counties, a random sample was chosen from these high-growth counties. The resulting sample would then represent these counties and thus 90% of the new homes in the region.

The telephone survey instrument was designed as a filter: the interview was terminated by the interviewer when the response to a question indicated the home was not eligible. In retrospect, it would have been preferable to collect more information (i.e., heating system type for mobile homes). The information would have enhanced the value of the survey at low additional cost.

Access agreements were sent to 292 eligible homes in which homeowners had expressed some interest in participating in the survey. A total of 140 access agreements were received, 20 fewer than the targeted 160 homes.

2.2 Field Tests

Five subcontractors chosen to perform the field tests participated in several multiday training sessions covering all aspects of the field protocol. A detailed set of protocols were developed for the field tests including an occupant questionnaire, an audit of the home for heating systems, wood-burning devices, exhaust fans, room temperatures and PFT zones, a blower-door test protocol, floor plan and elevation sketches, exterior photographs, a PFT deployment protocol, and an occupant daily activity log (hours of fan use, windows open, wood stove use, etc.). The field protocol and forms are described in detail in [Parker et al. 1988]. We mention only a few pertinent items here.

The blower door tests were done using eight points equally spaced on a logarithmic scale between 15 Pa and 60 Pa house pressure. Both pressure and depressure tests were done. In 48 of the 70 homes with ducted heating systems, a second depressure test was done with the heating system registers sealed. Fireplace and wood stove dampers were closed, heating system dampers were left as found, and the exhaust fans were generally left unsealed.

At least two zones were used for the PFT tracer tests. If there were multiple floors, each floor was a separate zone, although some floors might contain two zones. Sources were placed in all rooms in a designated zone. One sampler was deployed per five hundred square feet of floor area in each zone. The physical restrictions on locating sources and samplers were an extension of those in [Dietz 1986]. The PFT sampler contents were analyzed by gas chromatography and the resulting concentrations were analyzed using a multizone steady-state tracer program developed by Dietz et al. [1986]. The PFT tests had a duration of two to three weeks.

During the field audit the blower door contractor measured the inside temperature in each room of the home. These were then averaged to provide an estimated inside temperature for each zone. An hourly temperature recorder was placed in homes which used wood heat, in the zone with the heating device, resulting in 68 homes with measured inside temperature in one zone. The temperatures reported in this report are whole house averages, using recorder zone temperature data where available. Recorded temperatures were also used as the source temperature for the PFT sources in the zones which included the room with the recorder.

We acquired hourly wind speed and temperature data from 12 National Weather Service (NWS) stations throughout the service area. We assigned homes to these stations by the counties in which the homes were located.

In order to test the effect of ducted systems, we embedded an experiment within NORIS. An equal number of randomly chosen ducted and non-ducted homes were randomly allocated to two contractors and three time periods. Thus both field contractor and weather differences were blocked out. Homes for this experiment were all located in a single area, in order to minimize differences due to local construction practices. The Seattle area was chosen for this subset, since there were many sample homes available.

2.3 Telephone Survey Results

The telephone survey was done during the month of October 1987. Using state and federal statistical data combined with some of the telephone survey results, we estimated a total of 198,474 single-family non-mobile units completed between Jan. 1, 1980 and Nov. 1, 1987 in the BPA service area and a total of 124,771 with electric heat.

The disposition of the survey is shown in Fig. 2.1. About 22% of the randomly-dialed numbers reached residences. This compares well with an accepted estimate of 20% on a national basis. Of those consenting to a brief interview, 24% were multifamily units. Of the single-family units, only 15% were completed after Jan. 1, 1980. Of these, 18% were mobile homes. Of the new single-family non-mobile units, 60% had electric heat.

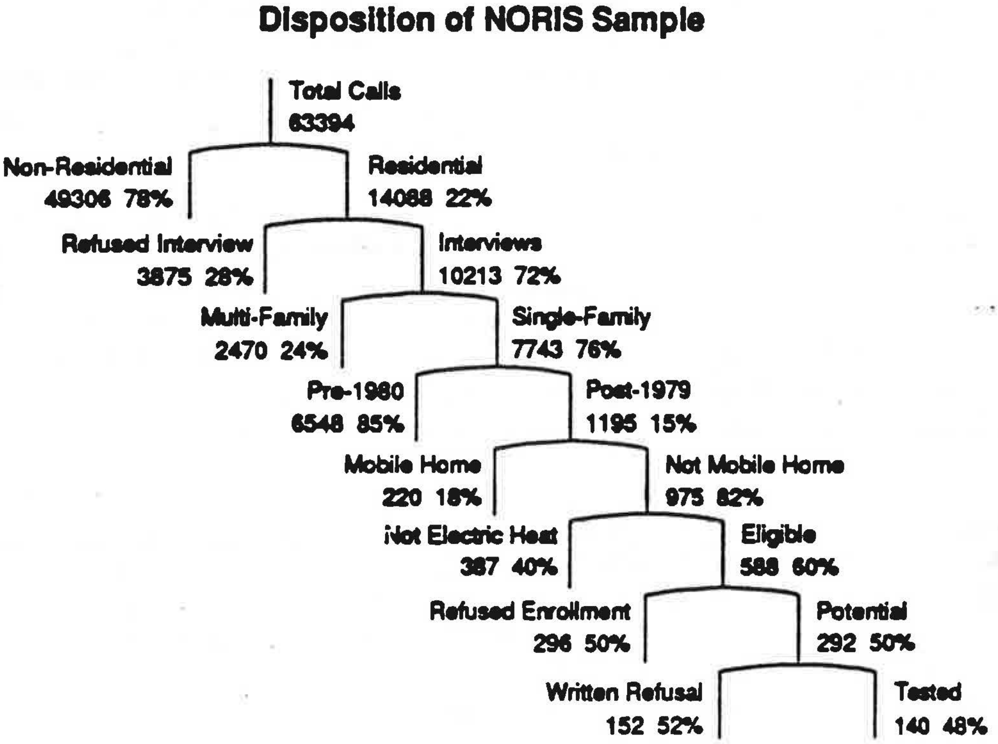

Figure 2.1. Disposition of telephone survey sample

Out of a total of 10,213 households for which we had completed interviews, 588 were eligible for the field tests. Of those eligible, 296 declined during the telephone survey to participate in the field survey, and another 152 did not return access agreements, leaving a total of 140 homes. Thus, the overall response rate of the eligible homes was less than 25%. From a statistical sampling viewpoint a level of response this low generates concern about selection bias. We made a number of statistical tests for bias based on the telephone survey questions and the field test results. None of the tests revealed any significant bias.

2.4 Field Test Results

The field tests were done in January through April of 1988, with the bulk of tests in February and March. The outdoor temperatures and wind speeds were similar to long-term heating-season values. Of the 140 homes in which blower door tests and PFT tests were done, the PFT results were lost in analysis for three homes. An additional three homes had large discrepancies in the PFT and blower door results. We restrict our discussion to the remaining 134 homes.

Initial hourly runs of the LBL model predicted an average 0.67 ACH, almost 60% greater than the PFT value. Max Sherman of LBL and the authors examined a random selection of contractor booklets and visited a smaller random selection of NORIS homes in the Seattle area. We concluded there were serious problems with the contractors' estimates of house height, terrain class, and shielding class.

The building height had been calculated using the rule-of-thumb "from the lowest leak to the highest leak." We recalculated the heights as the average stack height of the home (height of column of warm interior air) using contractors' plans, elevations and photographs. The new heights were 32% less on average, resulting in about a 12% reduction in LBL model predictions.

The terrain and shielding classes are poorly described, highly subjective, and lack empirical justification for low-rise building applications. This is an aspect of the LBL model which requires considerable further work. New terrain and shielding classes for each home were estimated by LBL using photographs of the homes. Combined with the height adjustments, these changes reduced the LBL model predictions by 36%.

The final estimates for the regional average infiltration rates are given in Table 2.1. Results are given for two methods: one based on PFT tests and one based on the LBL model. The first set labeled 1988 is for the period of the PFT test in each home. The second set is for typical long-term weather data. The PFT-based values for the long-term data were derived by multiplying the 1988 PFT results by the ratio of the LBL-model TMY to LBL-model 1988 values.

For each of the four results, the table gives the sample mean for 134 homes followed by the 95% confidence interval for the population mean. The interpretation of the confidence interval is that in many repeated samples of 134 homes, confidence intervals constructed in this fashion will contain the true population mean in 95% of the samples.

The confidence intervals are a measure of the random error only; they do not account for any systematic error in the estimates. The difference of 0.04 ACH or 10% between the two techniques is far too large to have occurred due to random error and thus indicates the presence of a systematic difference. It is reasonable to believe that each of the techniques, as applied in this study, may have a systematic error of 5 to 10% (or more).

Table 2.1. Regional average heating season infiltration rates (ACH)

Method	Weather Data	Sample Mean	95% Confidence Interval for Population Mean
PFT	1988 NWS	.384	.35 - .42
LBL Model	1988 NWS	.427	.40 - .46
PFT	TMY	.401	.37 - .43
LBL Model	TMY	.446	.41 - .48

Given the likely presence of systematic error and the fact that we have no way of knowing for sure which of the techniques was the most nearly correct, the state of our knowledge about the true population value is less exact than indicated by the width of the confidence intervals. Based on the available evidence, including the detailed case study, it is the authors opinion that the PFT results are the most reliable. If one feels the two techniques are of equal accuracy, it is reasonable to combine the intervals for the two techniques, resulting in an interval of 0.37 to 0.48 ACH as bounds for the population mean of typical heating-season infiltration rates.

We now present some of the results in more detail. An abbreviated tabulation of household characteristics for 134 homes is given in Table 2.2. It is interesting that nearly one third of the occupants report moisture problems in their homes, as increased ventilation, in one form or another, is a common mitigation measure for moisture problems. Also, note the prevalence of wood heat: 63% of households perceive wood as a significant source of heat and 40% of households give wood as their primary heat source.

Table 2.2. Survey characteristics for 134 homes

Description	Number of Homes	Percent of Total
Single-story	46	34.3
Ducted heating systems	70	52.2
Moisture problems	44	32.8
Wood a significant heat source (telephone survey)	85	63.4
Wood as primary heat source (field survey)	53	39.6

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Some of the primary results of the field audits are given in Table 2.3. The first block gives basic physical characteristics of the homes. The number of rooms of various types is pertinent to the application of several ventilation standards discussed below.

Occupancy factors are given in the second block of Table 2.3. The average home had more than three exhaust fans, including the dryer vent. About half the homes had fireplaces and the majority had wood stoves, with larger homes frequently having several wood-burning devices. Approximate hours per day of use of these devices is tabulated from the occupant activity record maintained daily for the duration of the PFT tests. Door or windows open is an average of the total time occupants reported at least one door or window as being partly open.

The third block of Table 2.3 contains temperature and wind speed data for the duration of the PFT tests. Start and stop dates and hours from the PFT tests were used to summarize the NWS weather data for each site. Also given are the corresponding TMY heating season values.

The fourth block of Table 2.3 gives several blower door test measures of leakage. The values given here are all based on the depressure tests only. The first is the LBL Effective Leakage Area (ELA) as defined by Sherman et al. [1982]. The LBL leakage area includes the discharge coefficient (i.e., it is the area for a discharge coefficient of unity). To approximate the physical leakage area, the ELA should be divided by 0.6.

The ELA is not easily compared across homes because it is strongly dependent on the size of the home. The Specific Leakage Area (SLA) as defined by Sherman et al. [1982] is 10,000 times the ELA divided by the floor area in consistent units. It is a better measure of the intrinsic tightness of the home. The Normalized Leakage Area (NLA) is that defined in Standard 119 [ASHRAE 1989]. It is equal to 1000 times the ELA divided by the floor area and then multiplied by a height correction factor (height over 8.2 feet raised to the 0.3 power). It is suggested in Standard 119 that the NLA is approximately equal to the natural air change rate.

The air changes at a pressure of 50 Pa (ACH50) is a common measure of tightness which is used in many building standards. The value of 9.3 can be compared with Scandinavian building codes which require a maximum of 3 ACH at 50 Pa for new homes. Dividing ACH50 by 20 gives another rule-of-thumb for predicting the natural air change rate.

The next to last block of Table 2.3 gives several air change estimates based on the NWS weather during the PFT tests. The Effective Air Change (EACH) for the PFT tests is the altitude-adjusted PFT value. The next entry is the EACH estimated with the LBL model. The next value, labeled air changes (PFT), is the EACH divided by the ventilation efficiency as estimated by the LBL model. It is our best estimate of the actual air change rate during the PFT tests and is the appropriate value for comparison with the LBL model air changes given in the next entry.

It should be noted that the actual air change rate is the pertinent quantity for heat loss purposes, while the effective air change rate is the pertinent quantity for indoor ventilation purposes (assuming the home is continuously occupied). The ratio of the two is the ventilation efficiency which averaged 95% for these homes, although for a few homes measured in mild weather it reached 79%.

Table 2.3. Summary of NORIS sample results (N=134)

Description	Units	Mean	Std.Dev.	Min	Max
Floor area	ft^2	1844	598	780	3612
House Volume	ft^3	15500	5620	6741	35009
Number of Bathrooms		2.31	0.72	1	4
Number of Bedrooms		3.19	.84	1	7
Rooms Not Kitchen or Bathroom		6.93	1.74	3	13
Stack Height	ft	11.71	3.46	7.5	22.0
Number of Occupants		3.35	1.37	1	9
Number of Exhaust Fans		3.52	1.51	0	7
Number of Wood Stoves		0.71	0.64	0	4
Number of Fireplaces		0.55	0.72	0	3
Exhaust Fan Use	h/day	1.26	1.22	0	8
Wood Stove Use	h/day	4.24	6.30	0	24
Fireplace Use	h/day	0.18	0.60	0	4.4
Doors/Windows Open	h/day	2.04	4.31	0	24
Inside Temperature	F	67.18	3.85	54.0	76.0
Outside Temperature (NWS)	F	43.23	4.29	25.9	52.1
Outside Temperature (TMY)	F	40.58	4.17	29.5	44.1
Temperature Difference (NWS)	F	23.95	5.52	7.9	39.2
Wind Speed (NWS)	mph	8.89	1.77	5.3	12.6
Wind Speed (TMY)	mph	9.10	1.50	4.2	11.7
Effective Leakage Area (LBL)	in^2	125	71	20	382
Specific Leakage Area		4.78	2.17	0.75	10.38
Normalized Leakage Area		0.527	0.245	0.075	1.219
Air Changes at 50 Pa (ACH50)	1/h	9.28	3.47	1.87	17.51
Air Changes at 50 Pa/20	1/h	0.464	0.173	0.093	0.876
Effective Air Changes (PFT)	1/h	0.368	0.178	0.105	0.945
Effective Air Changes (LBL)	1/h	0.408	0.179	0.085	0.939
Air Changes (PFT)	1/h	0.384	0.183	0.124	1.027
Air Changes (LBL)	1/h	0.427	0.186	0.087	0.967
Infiltration Air Flow (PFT)	cfm	99.8	64.5	21.1	333.8
Infiltration Air Flow (LBL)	cfm	110.6	64.9	20.1	317.4
Air Changes (PFT, TMY)	1/h	0.401	0.193	0.129	1.114
Air Changes (LBL, TMY)	1/h	0.446	0.202	0.090	1.175

The final two entries in the fifth block give the infiltration air flow in cubic feet per minute. The first is derived from the PFT ACH and the second is from the LBL model. These can be compared with typical bathroom fan flow rates of 50-80 cfm.

The last block of the table gives heating-season air change estimates based on Typical Meteorological Year (TMY) weather data. The LBL values are by direct calculation; the PFT values were estimated by multiplying the NWS PFT air changes by the ratio of the LBL-model NWS to the LBL-model TMY. These are our best estimates of the long-term heating-season infiltration rate.

Perhaps the most striking feature of Table 2.3 is variability of the infiltration measurements. All of them have standard deviations which approach 50% of the mean. The range from minimum to maximum is an order of magnitude or more.

2.5 Compliance with Ventilation and Leakage Standards

There are a growing number of standards relating to ventilation, indoor air quality, and air leakage. We evaluate the NORIS homes in terms of two of these: Standard 62 [ASHRAE 1981] and its revision Standard 62R for indoor air quality, and Standard 119 [ASHRAE 1989] for air leakage performance. The percentage of NORIS homes failing compliance with these standards is given in Table 2.4. These are given separately for ducted and nonducted heating systems as well as for the sample as a whole. The values are based on the PFT-based ACH and cfm.

Table 2.4. Percent of homes not meeting ventilation and leakage standards (N=134)

Description	Ducts	No Ducts	Total
Percent of Homes	52.24	47.76	100.00
Less than 10 cfm/room (Std. 62)	20.00	51.56	35.07
Less than 0.35 ACH (Std. 62R)	37.14	64.06	50.00
Less than 15 cfm/occ (Std. 62R)	5.71	35.94	20.15
Fail Std. 119	24.29	9.38	17.16

Standard 62 suggests minimum continuous ventilation of 10 cfm per room, excluding bathrooms and kitchens. Standard 62R has two compliance paths: a minimum whole-house ventilation rate of 0.35 ACH, or a minimum rate of at least 15 cfm per occupant. There are, thus, three ways of counting: by rooms, whole-house ACH, and per occupant. These give rather different results for the NORIS sample. By the criterion of 0.35 ACH, 50 percent of the homes fail, while by the criterion of 15 cfm per person only 20 percent of the homes fail. The criterion of 10 cfm per room is intermediate. By all three criteria, homes with nonducted heating systems have much greater failure rates than those with ducted systems.

Standard 119 addresses energy loss due to infiltration, and assigns leakage classes according to the normalized leakage area of a home. Acceptable class ranges are then given for locations throughout the U.S. and Canada. About 17 percent of the NORIS homes fail to meet Standard 119. The effect of heating system type is opposite to that for Standard 62 with a much larger percentage of ducted system homes failing the standard.

2.6 Findings and Conclusions

We present here a concise summary of the principal findings and conclusions from the NORIS project.

The final estimates for the average heating-season infiltration air change rates are 0.40 ACH for the PFT technique and 0.45 ACH for the LBL model.

There is tremendous variation in tightness as well as in measured air change rates. The NORIS sample of homes range from extremely tight to very leaky. Most of the homes fall into a grey area where natural ventilation may be inadequate and mechanical ventilation may be superfluous.

Most of the variation in infiltration air change rates is due to differing levels of tightness per unit size as measured by specific or normalized leakage area.

Homes with forced-air heating systems have infiltration air change rates which are 35 to 45% greater than homes with baseboards or wall heaters.

Depending on the criteria used, from 20 to 50% of the NORIS homes fail to meet current ventilation standards. For homes without forced-air heat, from 36 to 64% fail.

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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-related construction standards.

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3 INFILTRATION BASICS

Infiltration in residential buildings is a complex and poorly understood subject. It is convenient to divide the basic factors affecting infiltration rates into several categories.

Building Characteristics: These include the overall size of the leakage area, the nature and distribution of the leakage sites, the heights of various profiles of the building, the degree of local shielding from wind, the surrounding terrain and the internal connections of zones.

Weather Effects: These include the average outdoor temperature and wind speed, as well as their variation and correlation. Wind direction is also important.

Occupant Effects: These include thermostat settings, operation of fans, mechanical ventilation systems, combustion devices, and routine opening of windows and doors. An partially open window changes the leakage area, so the occupancy effects include time variation of the leakage area.

Heating System Effects: Operation of forced-air distribution systems may significantly increase infiltration rates due to duct leakage and differential pressurization of the home.

It should be noted that the categories are not exclusive and there are significant interactions across the categories.

There are two basic measurement approaches to residential infiltration: one based on pressurization testing which is aimed at estimating the leakage area of the home, and a second based on use of tracer gases to measure infiltration rates. The second approach captures occupant and heating system effects as well as weather effects and building characteristics.

3.1 Blower Door Tests

The blower door tests were done using eight points equally spaced on a logarithmic scale between 15 Pa and 60 Pa house pressure. Both pressure and depressure tests were done. In 48 of the 70 homes with ducted heating systems, a second depressure test was done with the heating system registers sealed. Fireplace and wood stove dampers were closed, heating system dampers were left as found, the exhaust fans were generally left unsealed. The protocol was in general agreement with the recommendations of the American Society for Testing and Materials [1985] and the Canadian General Standards Board [1986]. The blower door results were corrected for inside to outside temperature difference using the square root adjustment of the second reference.

Despite uniform instruction and protocol, there were significant variations between contractors in the number of exhaust fans which were sealed. Sealing and closing intentional openings can have a large impact on the blower door test; opening a single fireplace damper can increase the leakage area by as much as 100 in^2 which could easily double the leakage are of the home. The whole issue of proper and consistent preparation of homes for blower door tests requires more investigation.

The pressurization test leakage areas were on average 14% greater than those from depressurization. There were significant differences among contractors: with an average increase of 0% for one contractor, 8% for a second contractor, 14% for two contractors, and 25% for the remaining contractor.

Because the exhaust fans generally have backdraft dampers, one would expect to find some increase in the pressurization mode. The fans are only used for short periods, so the damper closed mode is more representative of the leakage area. Also, in the heating system comparison study where homes were randomly assigned to two contractors, the depressurization results for the contractors agreed much better than the pressurization results. For these reasons, we decided to base all of the results on the depressurization leakage areas.

3.2 PFT Measurements

The time-averaged PFT multizone measurement technique was developed at Brookhaven National Laboratory [Dietz et al., 1986]. Sources and samplers are deployed in each of the zones into which the home is divided. The sources are permeation devices which, for a constant temperature, release a PFT gas at a constant mass flow rate. The temperature sensitivity of the sources (about 4% per degree Celsius) is a significant source of error in the technique. An estimated temperature is required for each zone.

The samplers are small glass tubes with activated charcoal in the center. They operate on a diffusion principle, and therefore estimate the mass concentration of PFT per mass of air. This is also equal to the volume concentration of PFT per volume of air. Suppose air containing PFT is flowing through a pipe, and in the middle of the pipe the air is heated so that its volume expands by 30%. PFT samplers located upstream and downstream of the density change will then read the same. In effect, the PFT technique measures the infiltration mass flow rate.

Sampler contents are measured using a sophisticated gas chromatography technique. The sampler contents and the source type and temperature are input to a multizone matrix-based analysis method. The output from the multizone analysis are volumetric air flows between zones and to and from each zone to the outside. In our study, these volumetric flows were all referenced to a pressure of one atmosphere (29.921 in.Hg) and a temperature of 68 F.

In order to obtain true volumetric flows, the raw PFT values need to be adjusted for density changes due to altitude. We multiplied the raw values by the ratio of 29.921 in.Hg to the station pressure (absolute pressure) in inches of mercury. The station pressures were taken from NWS data concurrent with the PFT test and adjusted for the estimated altitude of the home. We call the altitude adjusted value the effective PFT air change rate (EACH). For all 134 homes the average increase was only 1.4% because the great majority of homes were located near sea level. For some homes, the increase was over 20%.

The relationship between actual and effective air change rates and the concept of ventilation efficiency are discussed in detail in Section 10. We used the LBL model run hourly to estimate the ventilation efficiency. The altitude-adjusted PFT values were then divided by the efficiency to estimate the actual air flow rates. Over all 134 homes, this adjustment resulted in an average 4.4% increase in PFT-based infiltration rates; for some homes, the increase was over 20%.

In summary, the raw PFT infiltration rates were adjusted for two factors: density differences due to altitude of the home and estimated ventilation efficiency. The average increase due to the combined factors was 5.9%.

3.3 The LBL Model

The basic premise of the LBL infiltration model [Sherman and Grimsrud, 1980] is that infiltration can be modeled as the product of two factors: a leakage factor and a weather factor. The leakage factor is the Effective Leakage Area (ELA) which is determined from blower door tests. The ELA, as used here, includes the discharge coefficient. To get the physical leakage area, the ELA should be divided by 0.6.

The weather factor includes wind speed, house height, shielding and terrain classes, wind speed and inside and outside temperatures. The weather factor has separate wind and temperature terms. A fundamental assumption of the model is that the wind effect and the stack effect can be added in quadrature. In equation form:

$$Q = \sqrt{Q_w^2 + Q_s^2}$$

where Q is the overall infiltration rate and Q_w and Q_s are the separate wind and stack effects.

It is important to understand the effect of adding in quadrature. This is easily done by noting that this is simply the equation for the length of the diagonal of a rectangle whose sides are equal to Q_w and Q_s. If the rectangle has one side very much longer than the other, then the diagonal is about the same length as the longer side. For practical purposes, when one term is three or more times larger than the other, the effect of the smaller term is negligible.

The complete LBL model is presented as a flow chart in Fig. 3.1. The equation at the bottom corresponds to the one given above. Note the use of two heights: one for wind effect and one for stack effect. All of the analysis presented in this report uses a single height for both terms. Our final estimates use a calculated average stack height for both terms.

The other inputs shown in the figure are outside temperature, inside temperature, wind speed, terrain class, weather site terrain class, shielding class, and two leakage ratios: X and R.

The leakage ratios are difficult to estimate or measure. For this study, we used default values of R=0.5 and X=0 for all homes. This is equivalent to assuming that half of the total leakage area is in the walls and that the floor and ceiling leakage areas are equal. This is an aspect of the LBL model which requires further work.

The terrain and shielding classes affect only the wind term of the model. The verbal descriptions associated with each of these classes in the original paper are poor. The estimated classes are rather subjective, as we show elsewhere. Unfortunately, the LBL model is quite sensitive to the terrain and shielding class assumptions. The wind-related aspects of the model require considerable further investigation. Many aspects of this issue are discussed in detail later in the report.

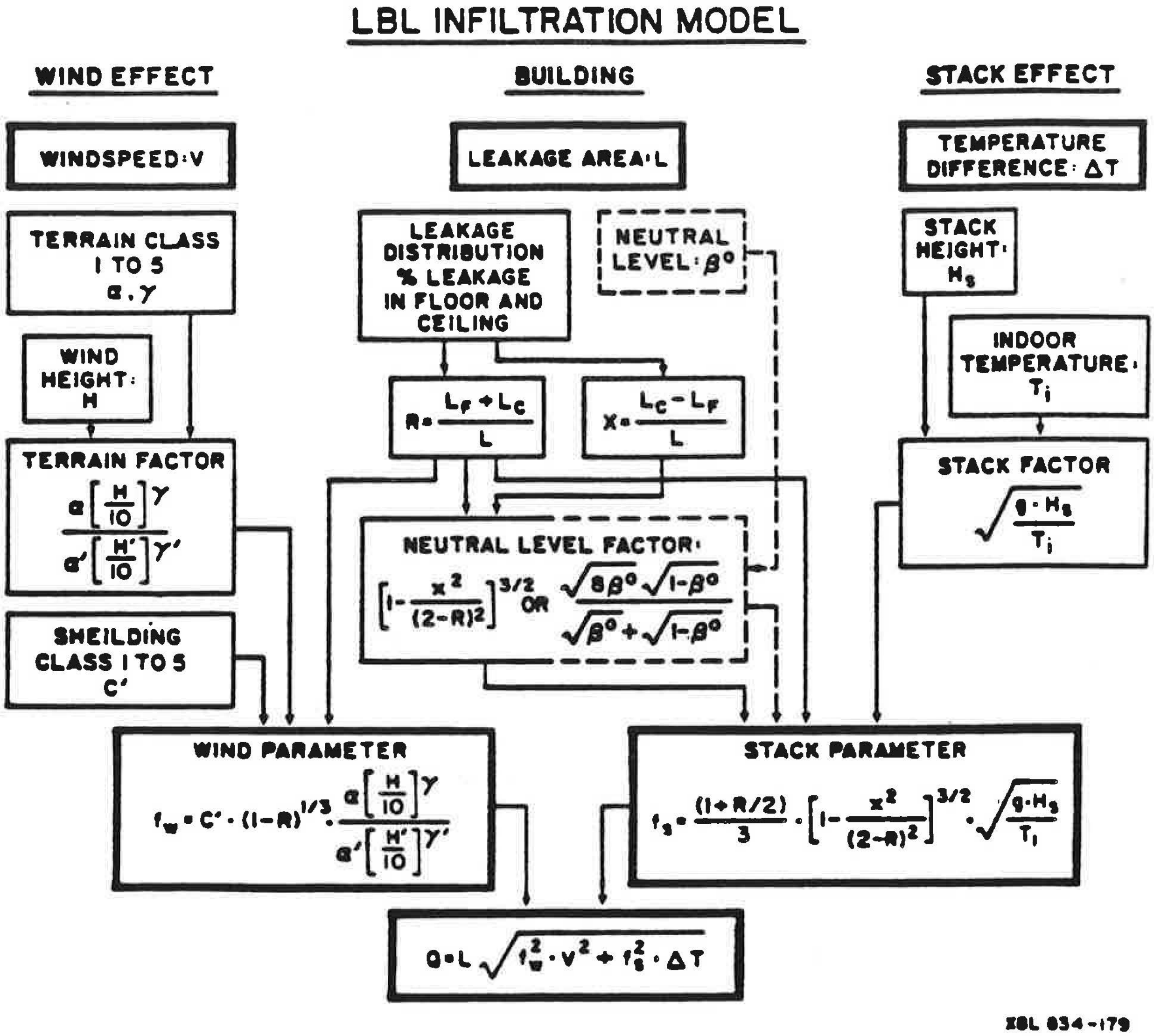

Figure 3.1. Schematic representation of LBL infiltration model [Modera et al. 1983]

4 DETAILED CASE STUDY

In order to gain a more detailed understanding of residential infiltration, a special study was conducted on a typical two-story, electrically-heated home. We will refer to this home, which was not part of the NORIS sample, as the test home for lack of a better term. In view of the wind-related difficulties evident in the NORIS analysis, it is particularly important to see what light this detailed study can shed on the problem. It also provides insight into the nature and magnitude of occupancy effects on infiltration.

The special study used a newly developed real-time MultiTracer Measurement System (MTMS) developed at LBL [Sherman and Dickerhoff, 1989]. This system is considered to be sufficiently accurate to act as a reference for evaluating the accuracy of other methods of estimating infiltration rates. The home was divided into three zones: 1) an upstairs bedroom zone, 2) an upstairs living, dining, kitchen zone and 3) the lower floor (family room and extra bedrooms). A one week, three-zone PFT test using the same three zones was conducted concurrently with the MTMS measurements. Although the MTMS system was in place for several days before the start of the PFT test and there was an additional PFT test performed after the removal of the MTMS, the analysis in this report is restricted to the one week comparison period.

Some pertinent facts about the test home are given in Table 4.1. The home is located less than a quarter mile from the open waters of Puget Sound toward the east. The floor area, volume, and height are very similar to the average for two-story homes in the NORIS sample.

Table 4.1. Test house data

Floor area	2213	ft^2
Volume	17589	ft^3
Number of stories	2	
Average stack height	13.5	ft
Heating system	Heat pump with air handler	
Foundation type	Vented crawlspace	
Year built	1979	
Location	Olympia, WA	
Duration of PFT test	168 hours	
Start/Stop dates	1/12/88-1/19/88	
Start/Stop time	2:15 PM	
Number of occupants during PFT test	2	
Terrain class	3	
Shielding class	2	
Leakage ratios	$X = 0, R = .5$	
Wind tower height	30	ft
NWS wind tower height	20	ft
ELA depressure	170.5	in^2
Specific leakage area (SLA)	5.35	
Normalized leakage area (Standard 119)	0.621	

Blower door tests were performed by LBL technicians; the blower door results are also shown in Table 4.1. The SLA and NLA are somewhat greater than the NORIS average for homes in the Puget Sound area. The average stack height and the terrain and shielding classes are LBL estimates.

Wind speed and indoor and outdoor temperatures were measured 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 Table 4.2. 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.

The last block of Table 4.2 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% while the wind effects differ by more than a factor of two.

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 airport speeds to those at the home. Prediction of the factor of 2.5 reduction at the 30 foot site tower requires a terrain class of 5 or greater at the site, which is beyond the range of conventional terrain class assignments given the generally open nature of the site.

Table 4.2. Summary of hourly weather data and infiltration results for the duration of the PFT test. (N=168)

Variable	Units	Mean	Std. Dev.	Min	Max
Temperature at site	F	40.98	4.79	32.18	53.38
Temperature at NWS station	F	39.99	5.96	27.86	53.78
Wind speed at site	mph	3.73	2.48	0	11.18
Wind speed at NWS station	mph	9.40	5.96	0	29.97
Temperature - Zone 1	F	66.96	1.59	62.87	69.76
Temperature - Zone 2	F	65.63	1.84	61.11	69.04
Temperature - Zone 3	F	66.08	1.59	62.42	69.80
Average indoor temp	F	66.22	1.64	62.21	68.69
Multitracer method	cfm	160.2	30.0	99.6	240.6
Full LBL Model	cfm	160.6	23.5	116.2	257.7
Full LBL Model, NWS	cfm	232.5	73.1	127.9	558.1
LBL Model, stack	cfm	134.6	12.3	103.2	156.5
LBL Model, stack, NWS	cfm	137.0	14.6	101.7	167.8
LBL Model, wind	cfm	74.9	49.9	0	224.7
LBL Model, wind, NWS	cfm	169.9	107.7	0	541.5

The wind and outdoor temperature data are shown in the upper two panels of Fig. 4.1. During the first four days the sky was completely overcast and it was generally warm, windy and wet. The site temperatures track the NWS temperatures very closely during this period. During the last three days there were periods of clear sky, particularly at night, with little wind and colder temperatures. The moderation of temperature variation at the site relative to that at airport during the last three days is likely due to the proximity of open water.

Several features of the weather data deserve comment. The temperature curves are very smooth compared to the wind curves, which have many sudden large changes; the average temperatures at the two locations are very close, while the average wind speed differs by a factor of two; the two temperatures track fairly closely, while the wind speeds show little resemblance beyond being greater at both sites during the first four days.

The last panel in Fig. 4.1 shows the average of the three indoor zone temperatures. There is a prominent setback at about 11 PM and setup at about 6 AM with the result that the heating system does not operate during the setback period. The temperature drop after setback is larger on days 16 and 17 due to the lower outdoor temperatures.

Our initial analysis compared the average whole-house infiltration for the week from the MTMS with the PFT results and LBL model predictions. The LBL model was run hourly using hourly wind speed, and indoor and outdoor temperatures. Runs were also made using the NWS temperature and wind speed assuming, as we have throughout this analysis, that the airport is terrain class 2. The results of this initial effort are shown in Table 4.3 as both air changes per hour and as cubic feet per minute. The MTMS and PFT volumetric flows are for dry air at 1 atm pressure and at 68 F temperature, the same convention used for the PFT results in the NORIS sample.

It is remarkable that the 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.

Table 4.4 compares the individual zone infiltration rates for the PFT and MTMS measurements. For zones 1 and 2, the discrepancy is about 35%. The magnitude of the zone discrepancies suggests that the exactness of the agreement of the whole-house MTMS and PFT estimates is largely fortuitous.

Table 4.3. Test home air flow estimates

Description	ACH	CFM
MTMS	.546	160.2
LBL Model	.548	160.6
PFT	.545	159.8

Table 4.4. MTMS and PFT zone infiltration rates

Zone	MTMS	PFT
1	40.8	56.4
2	30.2	22.5
3	89.2	81.0
Total	160.2	159.8

It is very instructive to examine the MTMS and site-weather LBL model results on an hourly basis. These are shown graphically in Fig. 4.2. Since the outdoor temperatures (and also therefore the stack effect) are smooth, we use the stack effect as a reference for the other flows. The upper panel shows the MTMS flows compared with the predicted stack effect, the second panel shows the full LBL model predictions compared with the stack effect, and the bottom panel shows the wind effect 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. The closeness of this tracking of the lower boundary is about the same during the first four days when it is windy 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 and a smaller one late on the afternoon of day 16. The wide peaks generally start just before midnight and drop significantly around 7 AM.

Days 17 and 18 have low wind speeds and low wind effect; from the middle panel it is clear that when the wind effect is added in quadrature to the stack effect, the increase in infiltration is negligible (i.e., 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, during the first four days, there are many periods when wind effect is large; however, 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. The activity record also notes two hours of dryer use on day 16, which is Saturday.

To a first approximation, a partially open window can be treated as an increase in the ELA of the home. The MTMS peaks are typically about 40% greater than the stack effect suggesting a comparable increase in the ELA. The ELA is 170 in^2, so the physical leakage area is about 283 in^2 and a 40% increase would be 144 in^2. This would correspond to opening a three foot high bedroom window about three inches, an entirely reasonable supposition.

Further insight can be gained by examining the discrepancy between the full LBL model and the MTMS during hours when the occupancy effect is small. We used the time periods after 8 AM and before 11 PM, with days 16 and 17 excluded. The discrepancy is shown in Fig. 4.3.

The upper panel shows the discrepancy plotted versus wind effect, while the lower panel shows a plot versus stack effect. From the upper plot, it is clear that the discrepancy averages around zero for wind effect less than about 50 cfm. Since the stack effect is about 135 cfm, this is about where the effect of adding in quadrature reduces the wind effect to negligible. Above this point the discrepancy is a tight and nearly linear function of wind effect.

In the lower panel, the discrepancy approaches zero at high stack effect (when the quadrature effect is strong) and otherwise shows a good deal of scatter. Taken together the panels suggest that the discrepancy is caused almost entirely by a wind effect which is too large and is related to stack effect only indirectly through the addition in quadrature.

More 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. For a 60% reduction in site wind speed, the full LBL model predicts 139 cfm, compared with 135 cfm for stack effect only and 160 cfm for the MTMS. Wind thus increases the infiltration by about 3% over stack only, and occupancy effects produce an additional increase of 15%.

The time-averaged LBL model agrees with the time-averaged MTMS 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. For this home and this time period, the required adjustment to wind speed makes wind effect negligible.

For this test case, where we have detailed infiltration data, we draw the following conclusions. There is no evidence for 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%. The LBL model, when used with NWS data, overpredicts by 45%; when used with weather data measured at the test home, it overpredicts by about 15%. Almost all of the overprediction error is due to failure to get the wind effect right, and with the wind suitably adjusted, its effect is negligible.

This is a very interesting set of high quality data which may yield additional valuable insights on further analysis. We strongly recommend further experiments of this type be carried out in the Pacific Northwest. They can be easily be further enhanced by designing special sub-experiments to examine such effects as those of the furnace air handler, exhaust fans, mechanical ventilation systems, closing interior doors, wind direction, and window opening on infiltration. If these experiments are carried out in *representative* homes, and in each case a concurrent PFT test is made, it would soon be apparent to what degree the PFT technique may be biased. It is clear that such experiments, again on *representative* homes, are a promising means of improving the LBL model to the point where it can be relied on for practical field work.

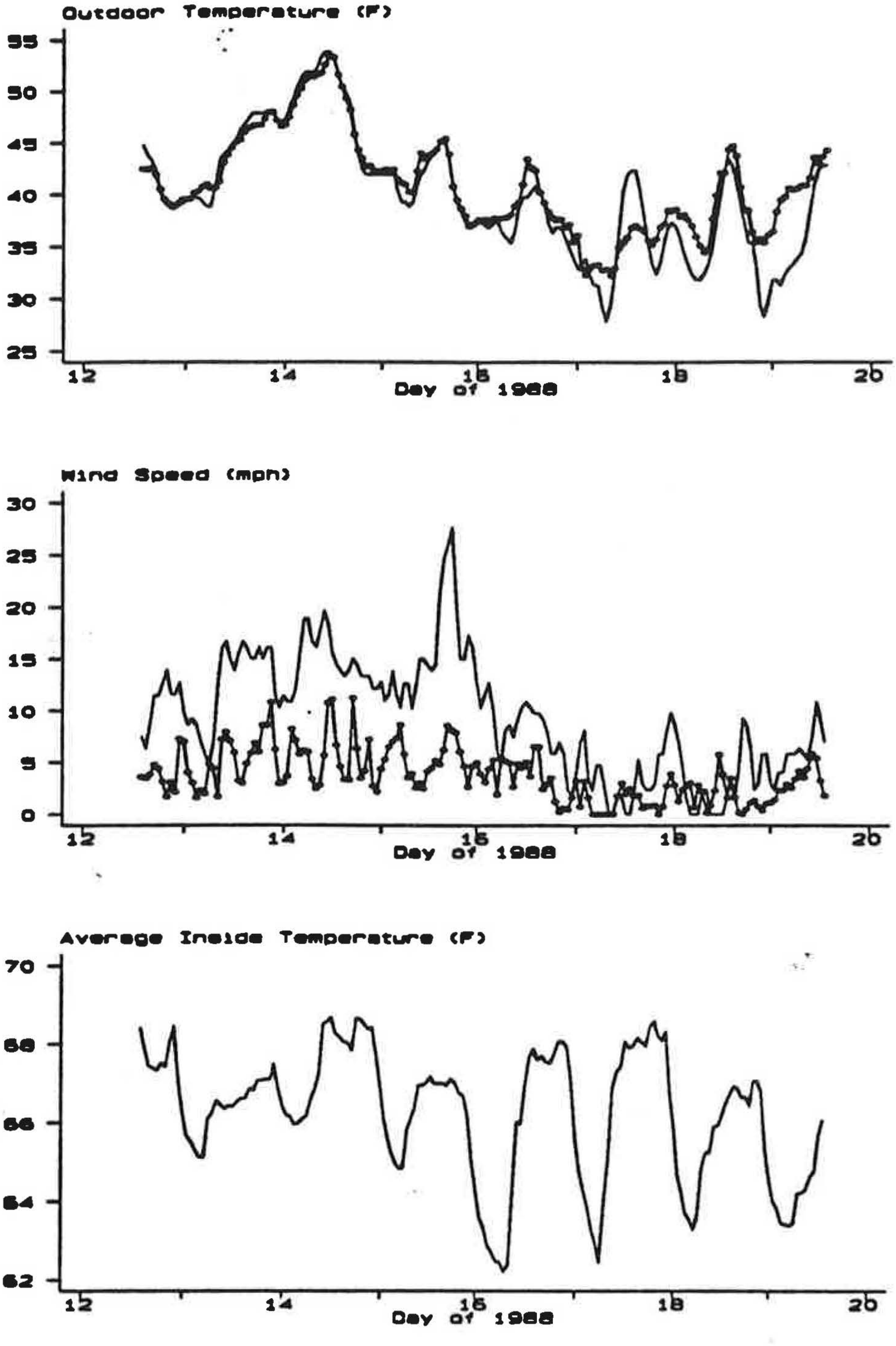

Figure 4.1. Comparison of weather data measured at case-study home (circles) with NWS airport data (plain line)

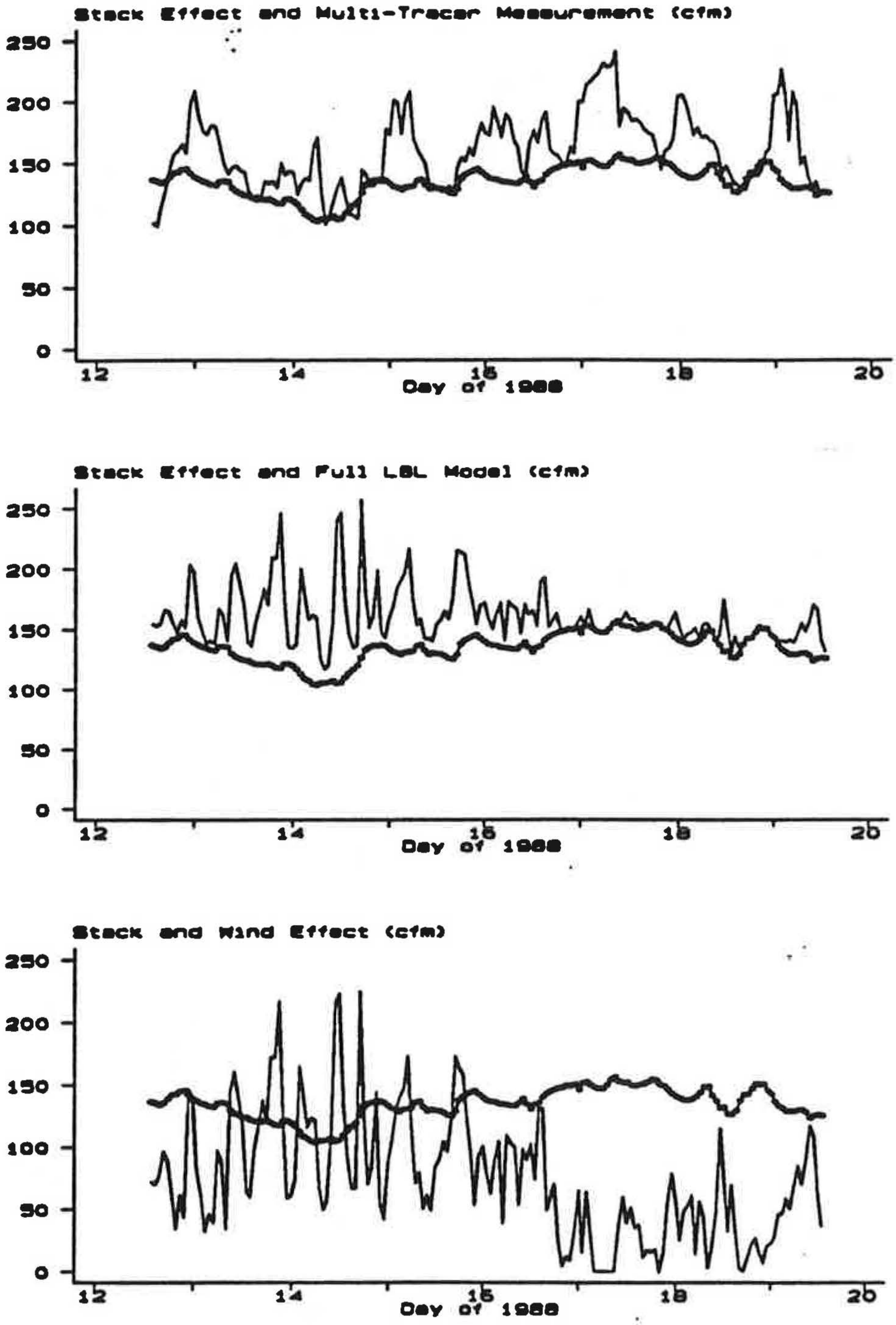

Figure 4.2. Comparison of LBL model and multitracer measurements
Each panel shows the LBL-model stack effect marked by circles. Other measurements are marked by a plain line: the top panel shows MTMS results, the middle panel the full LBL model results, and the lower panel the LBL-model wind effect.

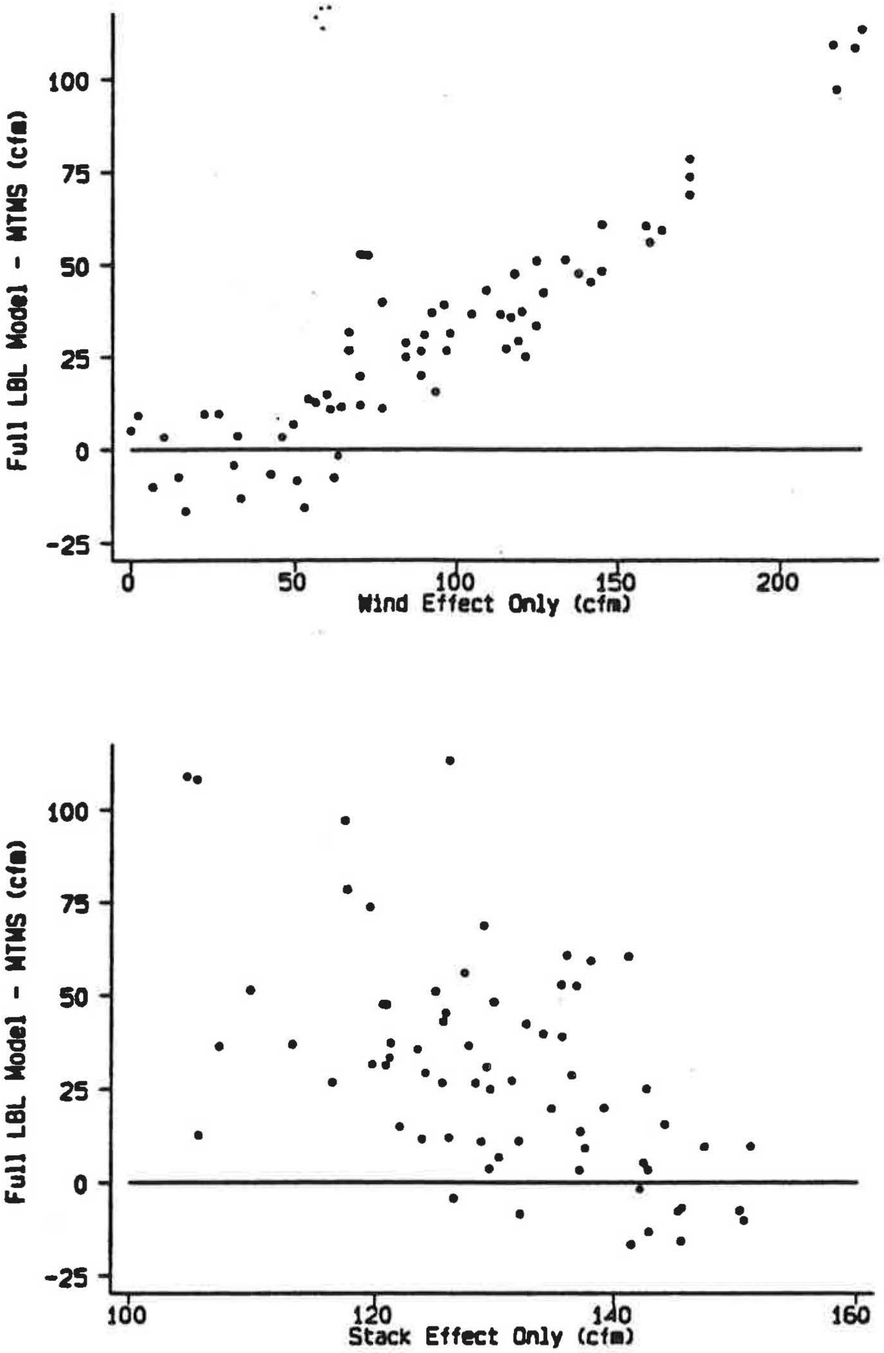

Figure 4.3. Difference between full LBL-model and MTMS versus stack and wind effects

5 WEATHER DATA

The initial weather data to be used for the analysis was selected from a network of residential meteorological sites established for the Electrical End-Use and Load Assessment Program (ELCAP) run by Pacific Northwest Laboratory.

Close examination revealed several problems with the hourly ELCAP wind data. The data logger resolution is low, resulting in bins about 2 mph wide; for some sites there were only 3 or 4 distinct wind values. The anemometers have been in the field for several years without maintenance. The manufacturer does not publish a cut-in speed for this inexpensive model. The resolution and cut-in considerations would be of little importance in an exposed site like an airport, where wind speeds are generally above 5 mph and average 8 to 12 mph.

For a sheltered location the average wind speed is much lower, and the resolution and cut-in speed become very important factors in determining the correct average wind speed. Both of these factors will result in excessive numbers of zeros and a tendency to underestimate the average wind speed. In addition, the instruments at several of the sites appear to be malfunctioning with almost all hourly wind speeds equal to zero.

The ELCAP weather data are riddled with periods of missing data ranging from a few hours to weeks or months in a row. Even with the choices made to minimize missing data problems, we found up to 10% missing hours for the period of weather assigned to some homes.

For these reasons we decided to use National Weather Service (NWS) hourly data. The homes were assigned to one of 12 NWS sites based on the county in which the home was located. The assignments are shown in Table 5.1. These NWS stations were also chosen to be identical to stations for which Typical Meteorological Year (TMY) data was available, so that the TMY assignments are the same as the NWS assignments.

The NWS wind and temperature data are instantaneous values read on the hour. The wind speeds are given to the nearest knot (about 1.15 mph). The cut-in speed is 3 knots and values less than this are generally recorded as zero.

For a given home the NWS weather data used covers only the period of the PFT test for that home. Homes assigned to a given NWS site generally have different weather data, although there are a few cases where two homes have nearly identical start and stop times. It is important to keep in mind that, whenever NWS data are referred to in this report, it means a different two to three week period for each home. No analysis was done using the entire January through April NWS weather data.

All of the TMY results are based on the heating season, defined as the months of November through April. No summer or whole year analysis was done.

Table 5.1. National Weather Service stations and county assignments

NWS	County	State	Number of Homes	
Seattle	Island	WA	2	
	King	WA	13	
	Kitsap	WA	5	
	Skagit	WA	4	
	Snohomish	WA	32	
	Whatcom	WA	3	59
Olympia	Pierce	WA	16	
	Thurston	WA	6	22
Portland	Clackamas	OR	1	
	Multnomah	OR	1	
	Washington	OR	4	
	Clark	WA	8	14
Salem	Benton	OR	1	
	Marion	OR	2	3
Medford	Jackson	OR	1	
	Josephine	OR	1	2
Yakima	Benton	WA	2	
	Chelan	WA	1	
	Douglas	WA	1	
	Okanogan	WA	1	
	Yakima	WA	1	6
Redmond	Deschutes	OR	2	2
Spokane	Kootenai	ID	3	
	Spokane	WA	4	7
Boise	Ada	ID	2	
	Asotin	WA	1	3
Pocatello	Blaine	ID	1	
	Bonneville	ID	2	3
Missoula	Flathead	MT	2	
	Lincoln	MT	1	
	Missoula	MT	2	
	Ravalli	MT	2	7
Helena	Gallatin	MT	5	
	Lewis & Clark	MT	1	6
Total			134	134

6 SHIELDING AND TERRAIN

Terrain classes vary from 1 to 5, with class 1 defined as a surface of an "ocean or other body of water with at least 5 km of unrestricted expanse." Class 5 is described as similar to the "center of a large city, e.g., Manhattan" [Sherman & Grimsrud, 1980]. Shielding classes also range from 1 to 5, with class 1 having no obstructions or local shielding whatsoever, and class 5 having heavy shielding close to the home. Terrain class is meant to describe the general surface roughness of the surrounding land, and shielding accounts for local obstructions close to a building. Tables 6.1 and 6.2 show terrain and shielding classes and their descriptions.

Table 6.1. Terrain parameters for standard terrain classes

Class	γ	α	Description
1	0.10	1.30	Ocean or other body of water with at least 5 km of unrestricted expanse
2	0.15	1.00	Flat terrain with some isolated obstacles (e.g. buildings or trees well separated from each other)
3	0.20	0.85	Rural areas with low buildings, trees, etc.
4	0.25	0.67	Urban, industrial or forest areas
5	0.35	0.47	Center of large city (e.g. Manhattan)

Table 6.2. Generalized shielding coefficient vs. local shielding

Shielding Class	C'	Description
1	0.324	No obstructions or local shielding whatsoever
2	0.285	Light local shielding with few obstructions
3	0.240	Moderate local shielding, some obstructions within two house heights
4	0.185	Heavy shielding, obstructions around most of perimeter
5	0.102	Very heavy shielding, large obstruction surrounding perimeter within two house heights

The terrain and shielding classes have been changed from Roman to Arabic numerals.

Blower door contractors were instructed on how to choose terrain and shielding classes by Max Sherman of LBL. Although terrain and shielding attempt to account separately for global and local conditions affecting wind speed, there is a strong correlation between the two classes for values chosen by the contractors, as shown in Table 6.3.

Table 6.4 shows cross-tabulations of terrain and shielding classes. For any given terrain class, the most often chosen shielding class is the same class. In all, terrain classes 2 and 3 accounted for 83% of the homes and shielding classes 2 and 3 accounted for 84%. Contractors picked these two classes the most, cutting across all geographic locations.

Table 6.3. Terrain and shielding class assignment correlations

	Contractor terrain	LBL terrain	Contractor shield	LBL shield
Contractor terrain	1.0000			
LBL terrain	0.1116	1.0000		
Contractor shield	0.5774	0.1655	1.0000	
LBL shield	0.1579	0.3448	0.2556	1.0000

Table 6.4. Contractor terrain and shielding class cross-tabs (percent of 134 homes)

	Shielding					
Terrain	1	2	3	4	5	Total
1	2.24	2.24	0.75	0.00	0.00	5.22
2	1.49	26.12	15.67	0.75	0.00	44.03
3	0.00	6.72	27.61	4.48	0.00	38.81
4	0.75	0.75	4.48	5.22	0.00	11.19
5	0.00	0.00	0.00	0.00	0.75	0.75
Total	4.48	35.82	48.51	10.45	0.75	100.00

Table 6.5. LBL terrain and shielding class cross-tabs (percent of 134 homes)

	Shielding					
Terrain	1	2	3	4	5	Total
2	1.49	3.73	6.72	2.24	0.75	14.93
3	1.49	1.49	4.48	3.73	0.75	11.94
4	1.49	2.99	3.73	8.96	1.49	18.66
5	0.00	4.48	14.93	27.61	7.46	54.48
Total	4.48	12.69	29.85	42.54	10.45	100.00

While some of the invariance within terrain classes can be explained by contractors' general testing locales, it is clear that the assignments are not as well distributed as they should be. In April of 1989, Dr. Sherman came to Ecotope to review the terrain and shielding classes. During this week we chose a randomly selected subset of NORIS homes in the Seattle area (which contained the bulk of the NORIS homes) as well as a random sample of homes from the full database of 140 homes to study in detail. Elevations, sections and pictures of these homes were examined for stack height, terrain and shielding. We then visited six of the Seattle area homes.

It was concluded that the terrain classes and shielding classes recorded by the contractors were in error and that average stack height would be more appropriate than the contractor values (see Section 7 for the discussion of stack height).

Dr. Sherman subsequently estimated terrain and shielding classes for all 140 homes. This was done primarily by inspection of the background in photographs of the home. Generally, four pictures of a house were taken from different perspectives. Terrain and shielding classes were estimated as well as possible from the photographs. In retrospect, it would have been advantageous to have instructed contractors to take four pictures of the site, with their backs to the house rather than facing it. We would then have a much better idea of the surrounding terrain and shielding.

Ten sites had no photographs at all; the pictures were either lost or never taken. Terrain and shielding were assigned to these homes according to the predominant classes for homes in similar areas. Pictures for 37 homes did not adequately show the surrounding terrain, and best guesses were made.

The results are shown in Table 6.5. Terrain classes 4 and 5 account for 73% of the homes. Table 6.3 shows the correlation between terrain and shielding as 60% less than that of the contractor choices. There is also very little correlation between contractor terrain classes and LBL terrain classes, and contractor shielding classes and LBL shielding classes.

Terrain and shielding assignments were also highly dependent upon contractors, as shown in Tables 6.6 and 6.7. There was a strong tendency for contractors to choose one terrain class and use it for all the homes. All contractors used only one terrain class for more than 50% of the homes assigned to them; the most noticeable is contractor 5, with 96% of the homes recorded as class 2. The same is true of shielding with a slightly greater variation; 45% to 82% of all homes were recorded under one class.

The distribution of terrain classes by homes east and west of the Cascades is shown in Fig. 6.1. The left graph is contractor assigned terrain classes with the left bar representing homes east of the Cascades and the right bar homes west of the Cascades. The right graph shows LBL choices for terrain. The vertical axis represents the percentage of homes for each terrain class. There is practically no variation from east to west for the contractor values. Classes 2 and 3 contain more than 80% of the homes, and class 5 appears only east of the Cascades for one home (shown as 3% of homes east). LBL values show a clear east-west trend with no homes in class 1. Almost all class 2 homes are east of the Cascades, and the large majority of class 5 homes are west of the Cascades.

Table 6.6. Terrain class by contractor

	Contractor					
Terrain	1	2	3	4	5	Total
1	0	0	1	5	1	7
2	8	3	12	9	27	59
3	11	12	2	27	0	52
4	2	1	4	8	0	15
5	0	0	1	0	0	1
Total	21	16	20	49	28	134

Table 6.7. Shielding class by contractor

	Contractor					
Shielding	1	2	3	4	5	Total
1	1	0	1	4	0	6
2	5	5	9	6	23	48
3	13	8	6	33	5	65
4	2	3	3	6	0	14
5	0	0	1	0	0	1
Total	21	16	20	49	28	134

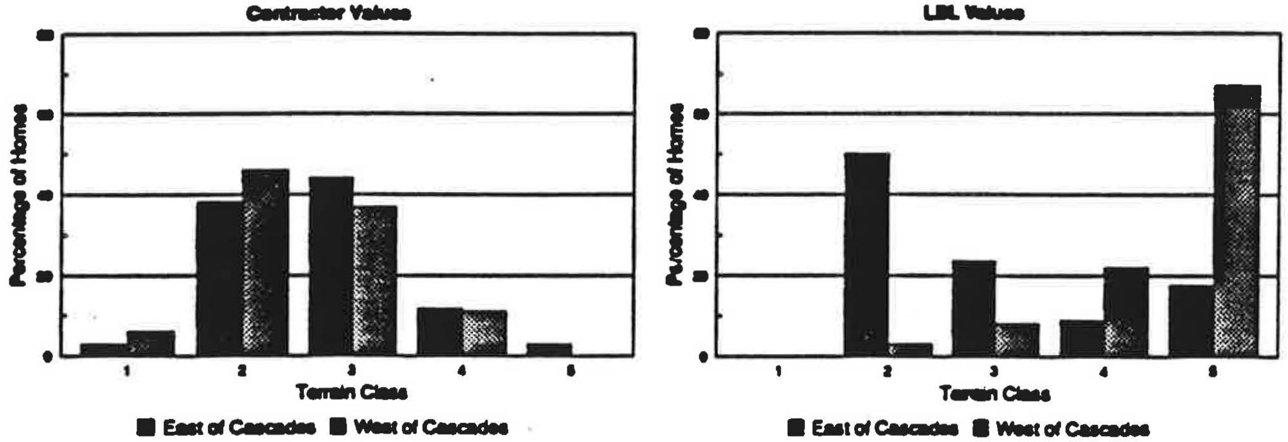

Figure 6.1. Terrain class assignments by contractors and LBL for homes east and west of the Cascades.

Table 6.8 shows a simple summary of terrain and shielding classes. For the whole sample of 134 homes, the mean LBL terrain class is 1.55 classes greater than that of the contractors. The mean LBL shielding class is 0.75 classes greater than that of the contractors.

Table 6.8. Summary of terrain and shielding assignments

Variable	Obs	Mean	Std. Dev.	Min	Max
Contractor terrain	134	2.58	0.79	1	5
LBL terrain	134	4.13	1.12	2	5
Contractor shield	134	2.67	0.75	1	5
LBL shield	134	3.42	0.99	1	5

The discrepancy between contractors and with the LBL choices for terrain and shielding indicates that the selection of these classes is very subjective. The written description of the classes in Tables 6.1 and 6.2 are too simple and vague. Terrain class assignments may also vary depending on the prevailing wind direction for a specific site. Moreover, meteorologists generally agree that the power or log laws used for estimating the effect of height on wind speed are valid only at heights above 35 to 40 feet.

It seems likely that if another group of people were trained using the same definitions as above, and all were sent to the same sites to estimate terrain and shielding, we would end up with a variety of classes for each site. Considering the present form of the LBL model and its sensitivity to wind speed, such subjectivity is clearly not acceptable. Unambiguous definitions of terrain and shielding classes are needed before the model can be used properly.

7 STACK HEIGHT

ASHRAE Standard 119 [ASHRAE 1989] defines a building's height as "the vertical distance from the lowest grade level to the highest ceiling of building space. In cases where this is uncertain, the vertical distance from the lowest to the highest leakage site within the building envelope shall be used." The standard then uses the height, leakage area and floor area to calculate the normalized leakage of a building.

For a home which is half single-story and half two-story, the above definition will result in a height of about 16 feet. We believe that a more appropriate height for estimating stack effect would be the average of the two heights (about 12 feet) because the magnitude of the stack effect, for a fixed temperature difference, is approximately proportional to the average height of the column of warm indoor air which is displacing cold outdoor air.

Contractors' estimates for building height tended to follow the "lowest leak to highest leak" rule. Homes with daylight basements were counted as full height even when the lower floor was partially below grade, homes with a single skylight penetrating the ceiling were given a height to the top of the skylight, homes in which a single room had a cathedral ceiling were given a height to the peak of the cathedral ceiling, and for a few homes the highest leak was taken as the top of the chimney.

We recalculated the heights based on the average stack height, i.e., the average height of the column of warm interior air, using contractors' plans, elevations and photographs. For a lower floor half below grade, we counted half the height of the lower floor. For homes in which the garage was under a living area, we took the average height of the interior heated space. For combinations of the two, we weighted portions of the home with similar heights by the areas of the footprints. For single story homes we took the average height of the heated space rather than the height of the ceiling above grade. The new heights were 32% less on average. In general the homes with the greatest heights had the largest percentage reductions.

The histograms in Fig. 7.1 show contractor heights and new heights for single and multistory homes. Heights varied about 8 feet to 18 feet with a fairly even distribution for what contractors considered to be single story homes. Multistory homes had heights ranging from 16 to 40 feet.

The stack height for single story homes is predominantly 8 feet. For multistory homes, the distribution of the contractor estimates of building height has a strong mode at about 17 feet. The stack heights have a mode at 12 or 13 feet, reflecting the predominance of split level construction, daylight basements, and integrated garages. There is a secondary mode at 17 feet, reflecting true two-story buildings. Note that some multistory homes have new heights as low as 8 feet; this can happen for homes that have split level entries with half of the upper level living space located over a garage, and the lower level space predominantly below grade. The average stack height is close to that for a single story home.

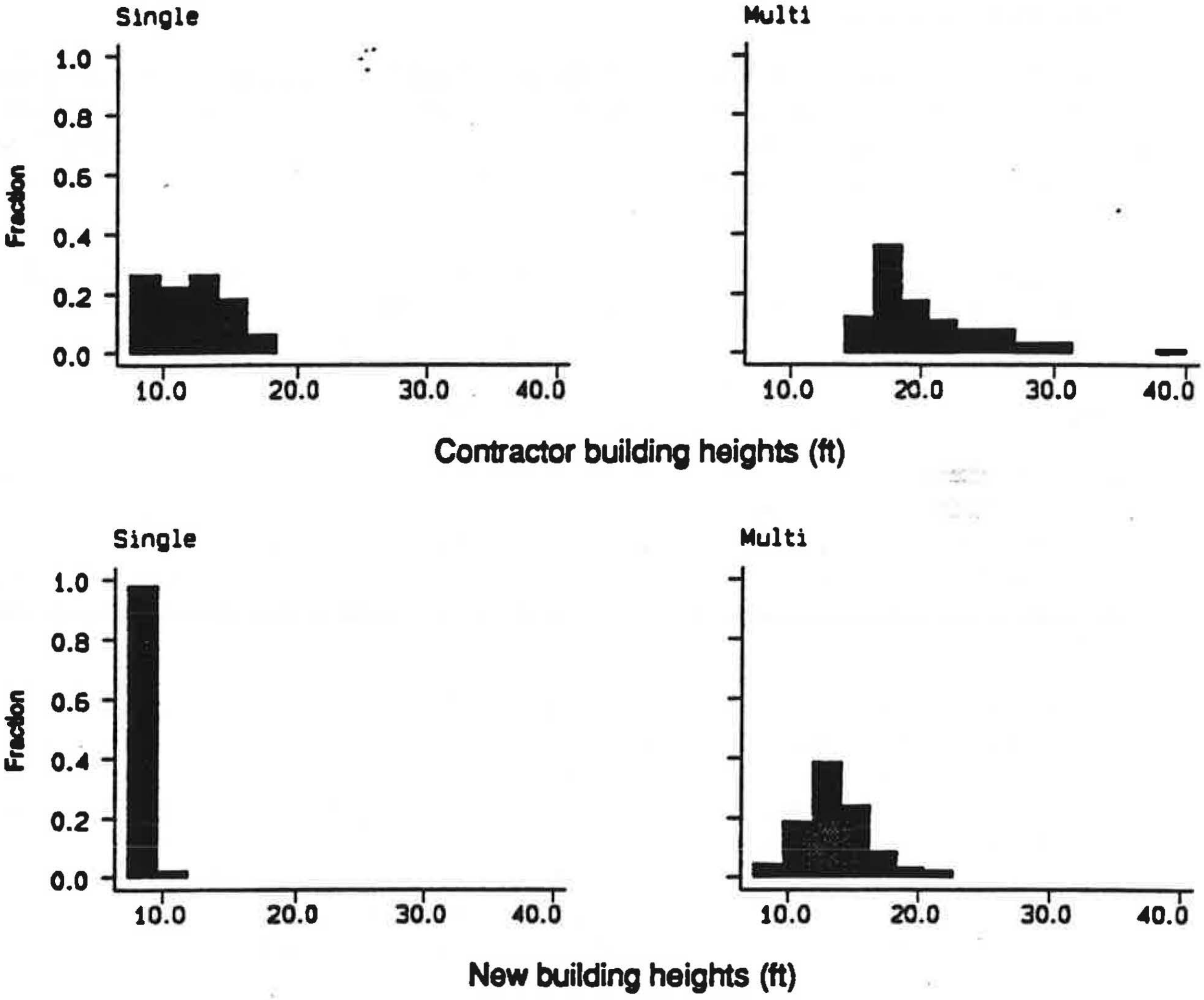

Figure 7.1. Histograms of contractor and new building heights by single or multistory homes

8 LBL MODEL RESULTS

Infiltration predictions were generated with the LBL model for two sets of weather data: NWS and TMY. The NWS predictions are for the exact period of the PFT test for each individual home. The NWS results are for direct comparison to the PFT results. The TMY results are typical long-term heating season results.

Two sets of LBL model results were generated for each weather set: one using the original contractor estimates for terrain, shielding and height, and a second one using the modified parameters. Altogether there are four sets of LBL model results.

For each of the four runs hourly averages of several variables were calculated: outdoor temperature, wind speed, infiltration rate, reciprocal infiltration rate (to estimate effective ventilation), stack effect only, and wind effect only. In addition, the average wind speed and temperature were used in a single calculation of the infiltration rate. The results of these calculations are summarized for 134 homes are given in Table 8.1.

The first entries in the table give the average temperature and wind speed. The TMY temperature is lower then the NWS temperature by about 2.5 F. This is primarily due to the fact that a number of homes in Montana (a very cold climate) were done late in the spring when outdoor temperatures were much greater than the heating season average. The wind speeds for the two weather sets are quite close. Overall, the PFT tests were done in weather very similar to long-term heating season conditions.

The next block of the table gives the average hourly infiltration rates. The parameter modifications have reduced the NWS rates from 0.67 to 0.43 ACH, or about 36%. The TMY rates are about 4% higher in each case. The parameter adjustments result in much larger changes than the choice of weather data. The average hourly infiltration based on the modified parameters and the TMY weather data, 0.446 ACH, is our best LBL-model estimate of typical heating season infiltration.

The next block in the table gives effective infiltration rates. These were calculated by taking the reciprocal of the average hourly reciprocal infiltration rates. It accounts for the reduction in ventilation efficiency due to variation in infiltration rates caused by wind and temperature variation.

The ratio of the effective infiltration to the hourly average value is the ventilation efficiency which is given in the block below. The ventilation efficiency is about 91% for the original parameters and about 95% for the modified parameters. The ventilation efficiency is used to adjust the PFT-based infiltration rates upward for comparison with the LBL infiltration rates.

The next block gives the results of a one-shot (a single application of the LBL model to average temperature and wind speed) calculation. Most of the practical applications of the LBL model use either a one-shot or monthly calculations. For the TMY data, this is a single estimate using average weather for the entire heating season. These values are slightly below the hourly average values.

Table 8.1. LBL model results for original and modified parameters (N=134)

Variable	Units	Mean	Std.Dev.	Min	Max
Weather data					
Outside temperature, NWS	F	43.2	4.3	25.9	52.0
Outside temperature, TMY	F	40.6	4.2	29.5	44.1
Wind speed, NWS	mph	8.9	1.8	5.3	12.6
Wind speed, TMY	mph	9.1	1.5	4.2	11.7
Average hourly ACH					
NWS, original	1/h	0.667	0.323	0.098	1.730
TMY, original	1/h	0.704	0.350	0.109	1.867
NWS, modified	1/h	0.427	0.186	0.087	0.967
TMY, modified	1/h	0.446	0.202	0.090	1.175
Average effective ACH					
NWS, original	1/h	0.618	0.298	0.088	1.505
TMY, original	1/h	0.635	0.308	0.107	1.556
NWS, modified	1/h	0.408	0.179	0.085	0.939
TMY, modified	1/h	0.424	0.189	0.088	1.019
One-shot calculation ACH					
NWS, original	1/h	0.645	0.314	0.091	1.689
TMY, original	1/h	0.676	0.338	0.108	1.816
NWS, modified	1/h	0.417	0.181	0.087	0.944
TMY, modified	1/h	0.434	0.197	0.091	1.124
Stack effect only ACH					
NWS, original	1/h	0.416	0.204	0.058	1.039
TMY, original	1/h	0.434	0.209	0.082	1.072
NWS, modified	1/h	0.341	0.156	0.039	0.792
TMY, modified	1/h	0.357	0.161	0.056	0.836
Wind effect only ACH					
NWS, original	1/h	0.474	0.264	0.031	1.531
TMY, original	1/h	0.496	0.294	0.030	1.656
NWS, modified	1/h	0.215	0.131	0.010	0.733
TMY, modified	1/h	0.222	0.144	0.010	0.933
Ventilation efficiency					
NWS, original		0.926	0.034	0.787	0.991
TMY, original		0.908	0.039	0.817	0.980
NWS, modified		0.952	0.042	0.787	0.993
TMY, modified		0.949	0.029	0.837	0.986
Specific infiltration					
NWS, original	ft/min	197	42	107	337
TMY, original	ft/min	207	43	109	360
NWS, modified	ft/min	131	35	73	270
TMY, modified	ft/min	136	35	83	259

All NWS values are calculated from period spanning PFT tests for each home. All TMY values are calculated for the heating season (November through April).

The next block gives hourly average values for stack effect only (i.e., wind speed set to zero). The change of 18% from the original to the modified parameters is due the change in house height.
The next block gives the hourly average wind effect only (i.e., temperature difference set to zero). With the original parameters, the wind effect is slightly greater than the stack effect; with the modified parameters it is about half the stack effect.

The last block gives specific infiltration in feet per minute. The value of 136 ft/min for the modified parameters and TMY data can be compared with the reference value of 140 ft/min given in Standard 119.

9 SENSITIVITY ANALYSIS OF THE LBL MODEL

A simple sensitivity analysis of the LBL model can be made by removing the effect of ELA and house volume. The predicted air change rate multiplied by the volume and divided by the ELA, in consistent units, has dimensions of velocity. This quantity, specific infiltration, can be interpreted as the average velocity of infiltration air flow through a hole of the size of the leakage area (assuming unit discharge coefficient).

The specific infiltration is a function of the remaining inputs for the LBL model. A simple linear regression of specific infiltration in feet per minute on these inputs is given in Fig. 9.1. This regression uses the TMY data and the modified parameters. The results using the original parameters were quite similar. The upper section summarizes the variables. The average specific infiltration of 136 ft/min is similar to the standard value 140 ft/min assumed in Standard 119. The regression explains about 95% of the variation in specific infiltration.

```
(N=134)

Variable                       Units      Mean   Std.Dev.        Min        Max
----------------------        ------    ------    -------    -------    -------
Specific infiltration         ft/min    135.74      34.83      82.63     258.61
Terrain class                             4.13       1.12       2.00       5.00
Height                            ft     11.71       3.46       7.50      22.00
Shielding class                           3.42       0.99       1.00       5.00
Outside temperature                F     40.58       4.17      29.53      44.08
Inside temperature                 F     67.18       3.85      54.00      76.00
Wind speed                       mph      9.10       1.50       4.18      11.66

  Source |       SS        df       MS              Number of obs =      134
---------+-----------------------------             F( 6,    127) =   416.86
   Model |  153584.654     6  25597.4424            Prob > F      =   0.0000
Residual |  7798.45833   127  61.4051837            R-square      =   0.9517
---------+-----------------------------             Adj R-square  =   0.9494
   Total |  161383.113   133  1213.40686            Root MSE      =   7.8361

Variable                   Units  Coefficient   Std.Error      t   Prob>t    Beta
----------------------    ------   ----------   ---------  -----   ------   -----
Specific Infiltration     ft/min
----------------------    ------   ----------   ---------  -----   ------   -----
Terrain class                          -16.46         .77  -21.3    0.000   -.529
Height                        ft         4.71         .20   23.5    0.000    .468
Shielding class                        -10.80         .76  -14.2    0.000   -.307
Outside temperature            F        -2.48         .21  -11.8    0.000   -.297
Inside temperature             F         1.70         .18    9.2    0.000    .188
Wind speed                   mph         5.26         .49   10.7    0.000    .226
Constant                               124.00       14.67    8.4    0.000       .
------------------        ------  -----------   ---------  -----  -------  ------
```

Figure 9.1. Sensitivity analysis of the LBL model

The coefficients have simple interpretations, for instance, the specific infiltration increases by 5.26 ft/min for a 1 mph increase in wind speed, and decreases by 16.46 ft/min for an increase of 1 terrain class.

Since the variables all have different units and variability, it is more revealing to examine the dimensionless beta coefficients given in the last column. The beta coefficient is the change in specific infiltration (measured in standard deviations) produced by a one standard deviation change in the variable. For instance, a one standard deviation increase in wind speed (1.50 mph) produces an increase of 0.226 standard deviations in specific infiltration (0.226 times 34.83 or 7.872 ft/min).

The beta coefficients indicate the relative importance of the input variables. Thus, the most influential variable is terrain class, followed by height and shielding class. The LBL model is thus quite sensitive, for these homes and these climates, to terrain and shielding, which are the least understood and most subjective inputs to the model.

10 VENTILATION EFFICIENCY

Ventilation efficiency is the ratio between the effective infiltration rate (EACH) and the actual infiltration rate. It is that constant infiltration rate which would result in the average pollutant (or PFT) concentration actually observed. It is also the ratio of the *harmonic* average of hourly infiltration rates to the *arithmetic* average. If one is interested in heat loss, the actual infiltration rate is the quantity of interest. The unadjusted PFT results tend to be biased low (although they are true measures of the effective infiltration rate). The ventilation efficiency is therefore also a measure of PFT bias. For a more detailed discussion of ventilation efficiency and PFT bias, see [Sherman 1989].

This is illustrated by the following example. Suppose a home has a constant 0.5 ACH for 168 hours (one week). For unit source strength, the tracer concentration for each hour is then 1/0.5, the average concentration for the week is 2, and the reciprocal of the average concentration (the EACH) is also 0.5 ACH.

Now suppose the ventilation rate is 0.2 ACH for 161 hours, and for each day in the week, windows are opened for an hour, resulting in 7.4 ACH during that hour. The average tracer concentration in this case will be [161(1/0.2) + 7(1/7.4)]/168 = 4.797. The actual ACH for the measurement period is still 0.5 = [161(0.2) + 7(7.4)]/168), but the PFT results will indicate an effective ACH of only 1/4.797 = 0.21. The heat loss will be that for 0.5 ACH, but pollutant concentrations will be the same as for a continuous ventilation rate of only 0.21 ACH. The ventilation efficiency is only 42%.

It should be noted that although the actual air change rate is the pertinent quantity for heat loss purposes, the effective air change rate is the pertinent quantity for indoor ventilation purposes (assuming the home is continuously occupied). The discussion above shows that more effective ventilation is obtained with a steady flow than with a highly varying flow (i.e., for a given heat loss, steady flow provides more ventilation). The ventilation efficiency for these homes averaged about 95%, although for a few homes measured in mild weather it fell to 79%.

It is instructive to examine the contribution of wind and stack effect to ventilation efficiency for this representative sample of Pacific Northwest homes. For a given weather station, the ventilation efficiency is a well defined function of the ratio of the stack effect to the wind effect. Fig. 10.1 shows the relationship for 61 homes assigned to the Seattle TMY using the original model parameters. The efficiency only falls below 95% when the wind effect is greater than the stack effect. Other climates produce similar curves which have significant displacements from the Seattle curve.

The reason for this is evident in the weather graphs given in the case study section. During the heating season the hourly variation in wind speed is much greater than the hourly variation in outdoor temperature. Since the efficiency measures the effect of variation in infiltration, one should expect that homes with wind dominated infiltration will show low efficiency relative to those which are stack dominated. The smoothness of the curve in Fig. 10.1 is partially due to the tendency of the contractors to estimate the same shielding and terrain classes for different homes.

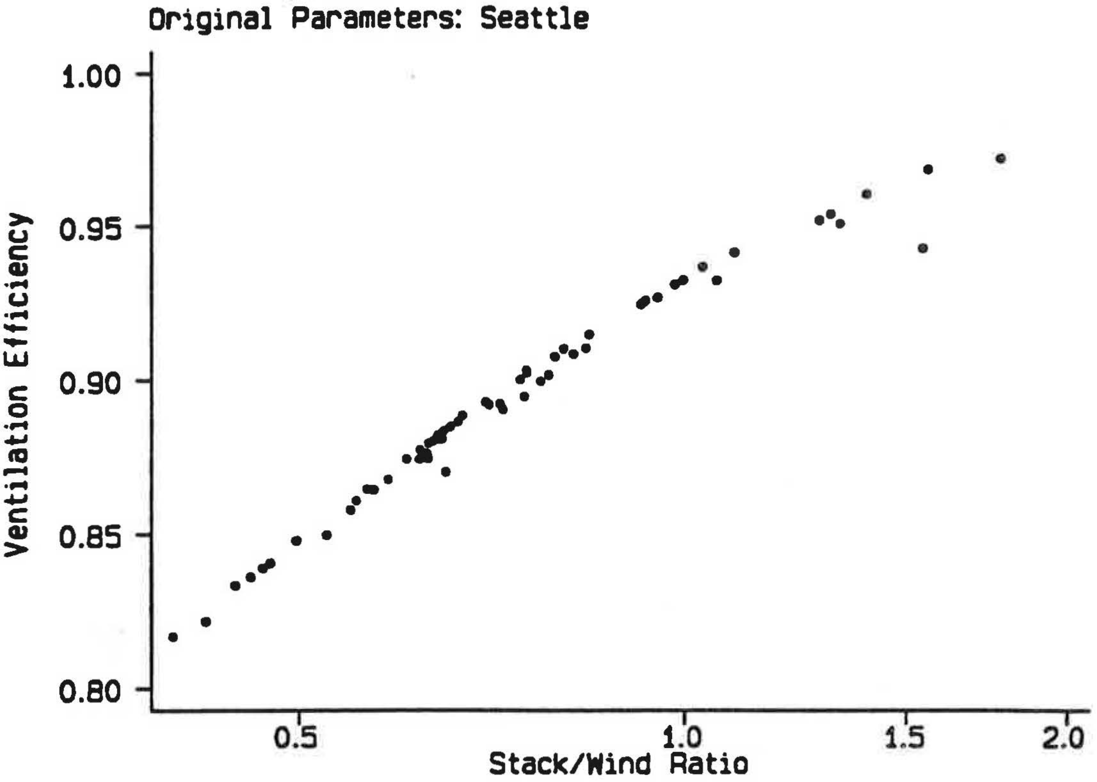

Figure 10.1. Ventilation efficiency versus stack to wind ratio for Seattle TMY

The dependence on wind effect is shown clearly in Fig. 10.2 which shows box plots of efficiency versus terrain and shielding class for all 134 homes when using TMY weather. The upper graphs are for the original parameter estimates, while the lower ones are for the modified parameters. The modified parameters result in generally higher efficiencies. There is a clear tendency in all of the plots for the efficiency to increase with terrain or shielding class.

The important point is that ventilation efficiency (and therefore PFT bias) depends strongly on the magnitude of the wind effect. In order to estimate the efficiency, it is necessary to get the wind effect right.

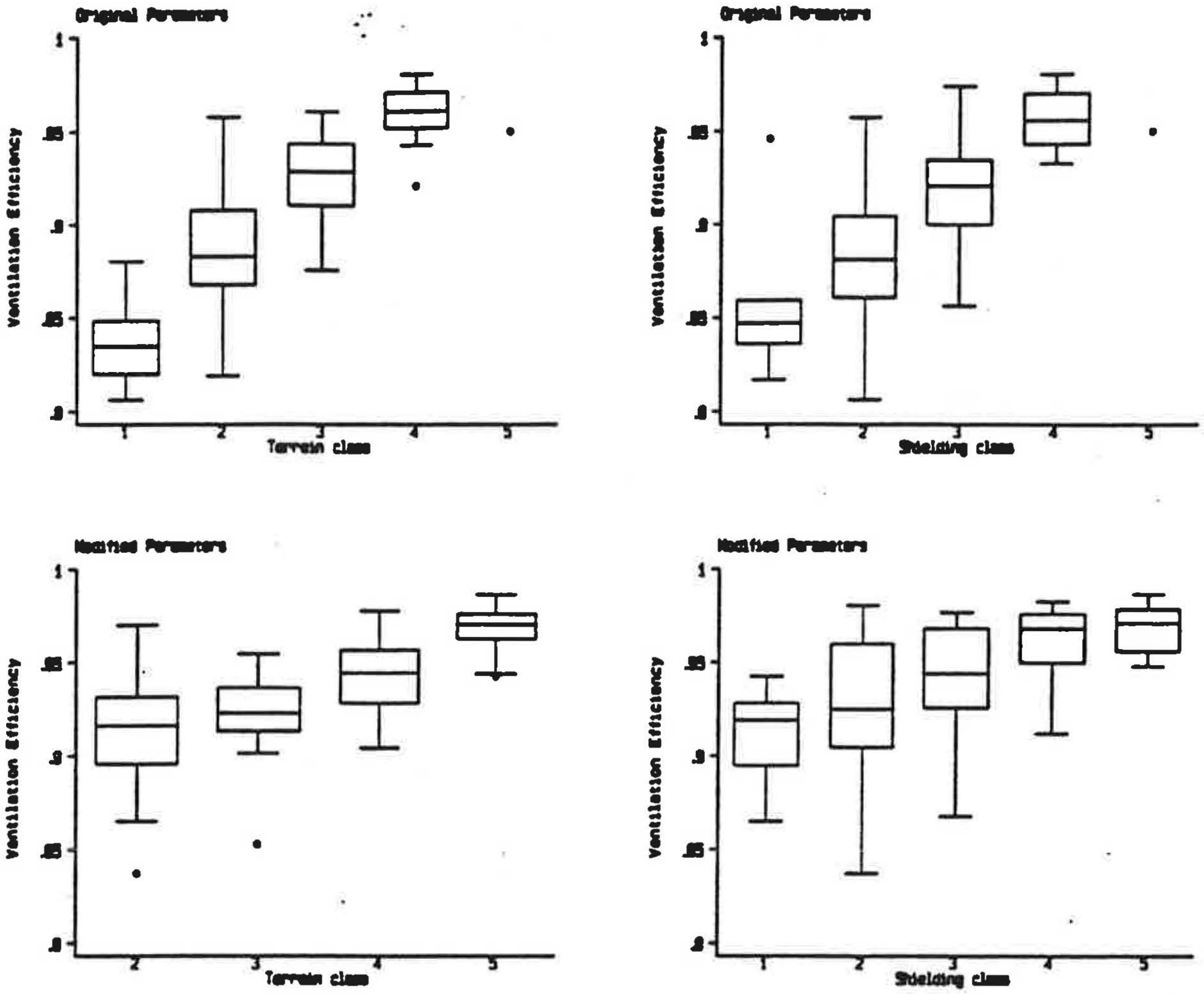

Figure 10.2. Ventilation efficiency box plots by terrain and shielding class.

The top graphs use the original terrain and shielding classes assigned by the contractors. The bottom graphs show the results after terrain and shielding classes and heights were revised.

11 COMPARISON OF PFT AND LBL RESULTS

The LBL model results using the modified parameters are compared with the PFT results in Fig. 11.1. The line indicates equality. The two methods track one another reasonably well although there is considerable scatter. The variability of infiltration rates increases at higher levels of infiltration and both distributions are skewed positive. Large negative deviations from the one-one line may indicate homes with large occupancy effects.

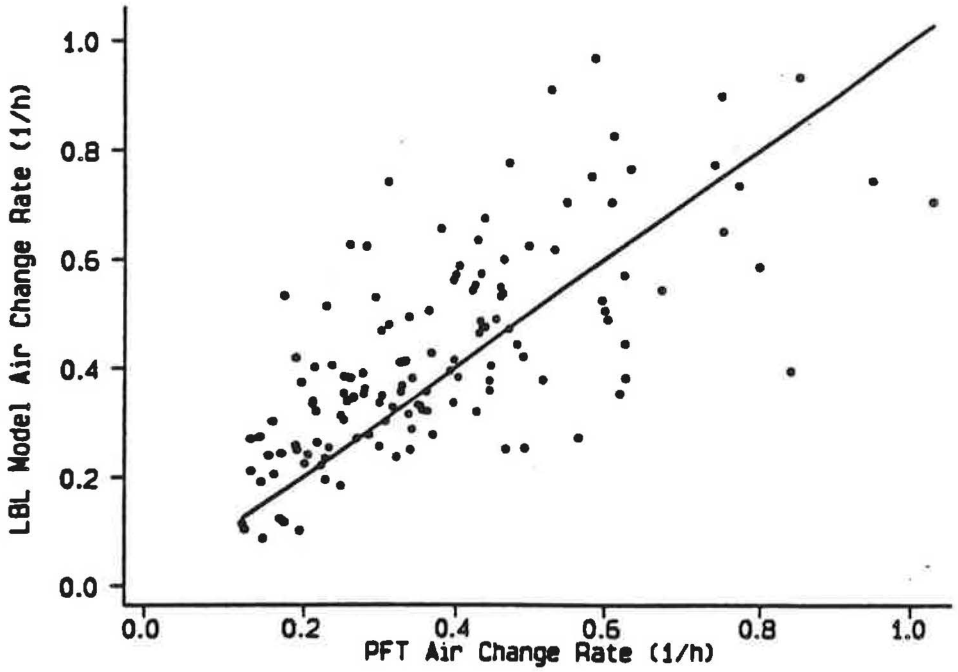

Figure 11.1. Comparison of PFT and LBL model results
LBL hourly predictions used National Weather Service data for the duration of the PFT test. The line indicates equality.

It is instructive to relate the discrepancy between the PFT and LBL infiltration rates to the wind and stack effects. Fig. 11.2 shows the discrepancy for both the original and modified parameter estimates plotted versus the corresponding stack and wind effects. The discrepancy for the original parameter estimates is highly correlated with the wind effect, and to a lesser extent and considerably more scatter with the stack effect.

With the modified parameters, there is still some correlation with wind effect while the correlation with stack effect is very small. This suggests that the height adjustment has removed most of the relation of discrepancy to stack effect. The remaining correlation with wind effect suggests the wind term is still being estimated too high.

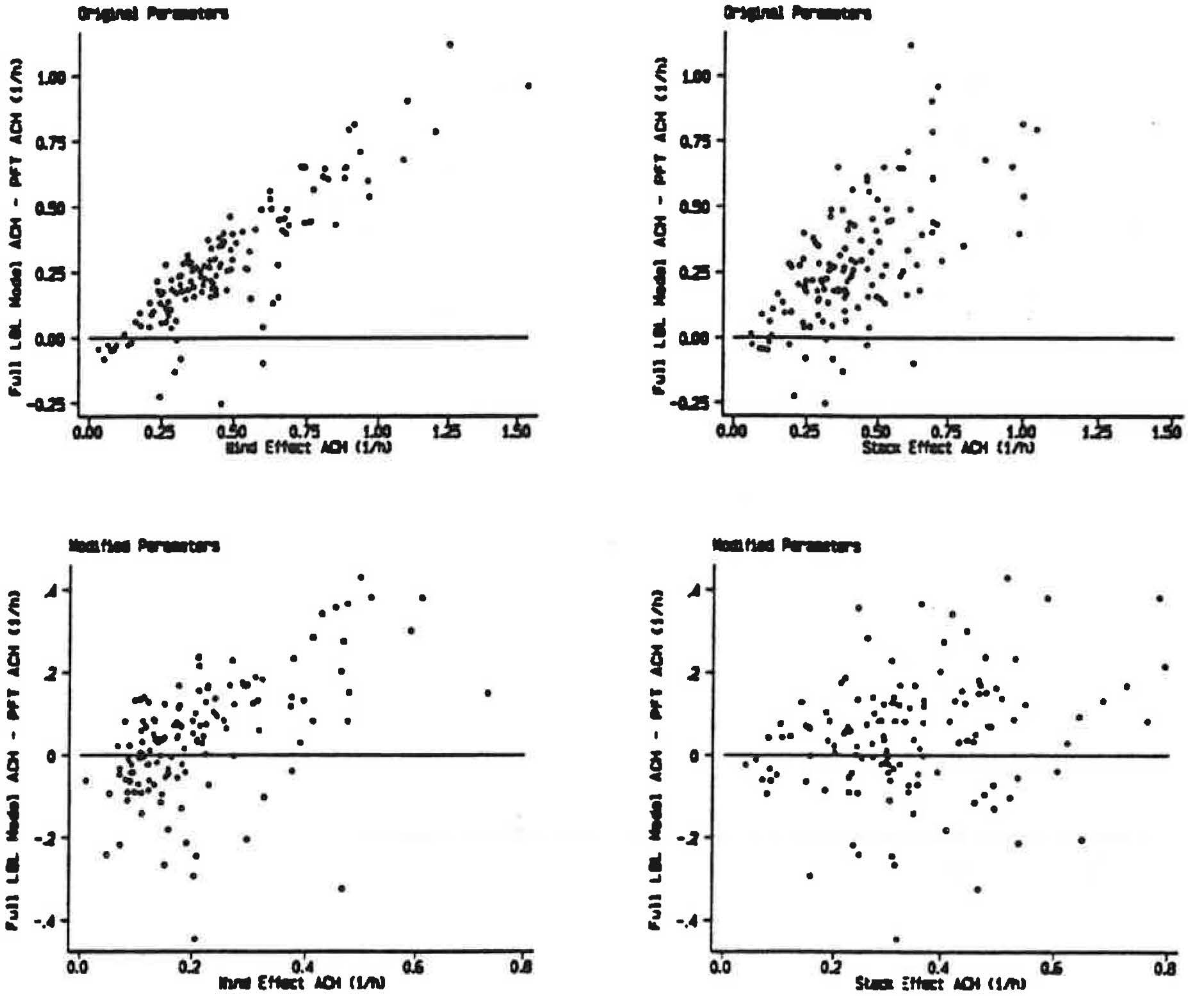

Figure 11.2. LBL and PFT difference versus wind and stack effects
The top graphs are for the original parameters; the bottom graphs are for the modified parameters.

These suggestions can be further explored by examining the relationship between the discrepancy and the shielding and terrain classes. Fig. 11.3 shows box plots of the discrepancy by shielding and terrain class for both the original parameters and the modified ones. With the original parameters there is a strong decreasing discrepancy with increasing class for both terrain and shielding. The errors for terrain class 1 and shielding class 1 are particularly large.

The discrepancy is much smaller with the modified parameters. The effect of terrain class has been greatly reduced. There is still a systematic decrease in discrepancy with increasing shielding class, suggesting that the LBL model results would be improved by increasing the shielding class, particularly for classes 1 and 2.

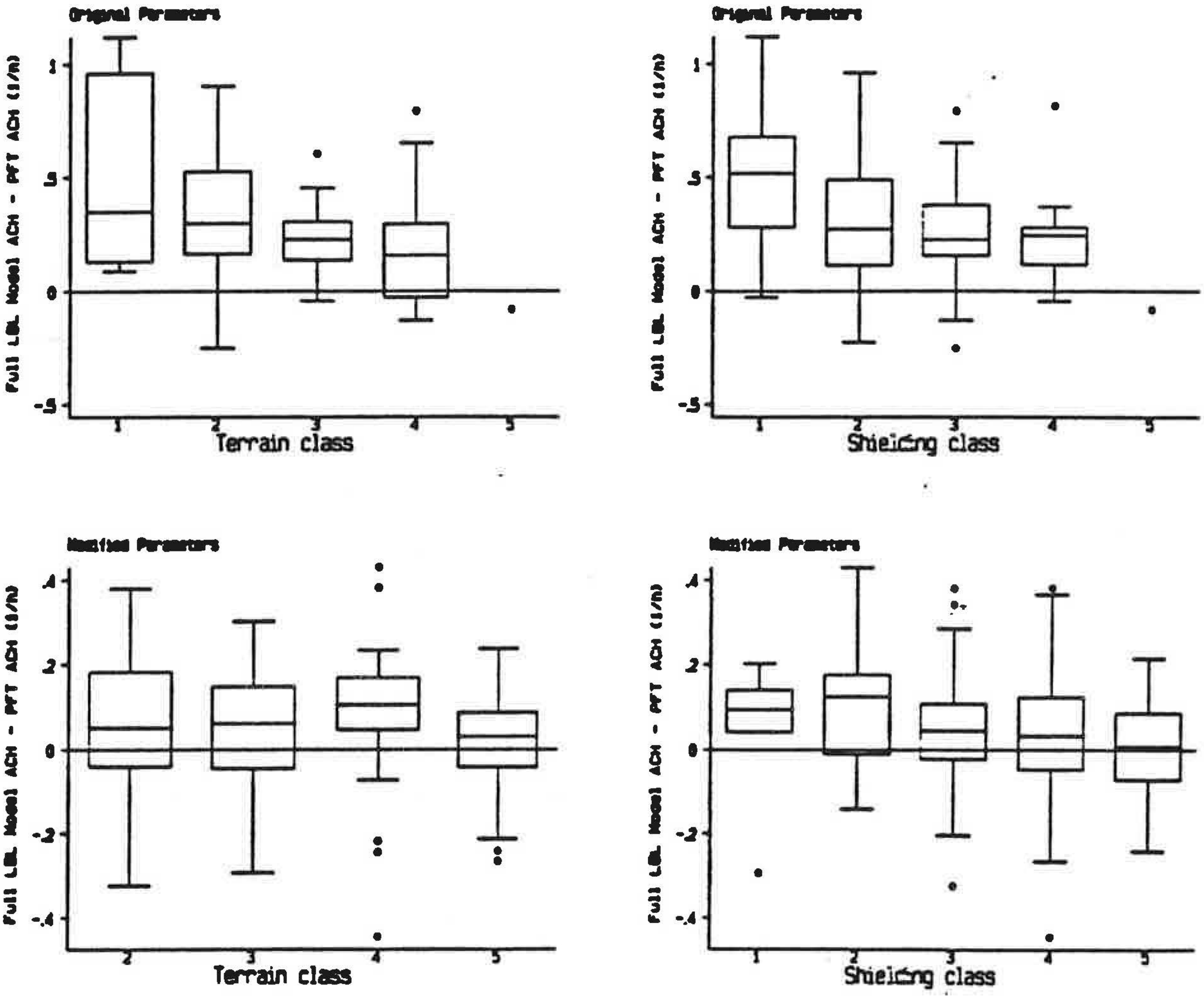

Figure 11.3. LBL and PFT difference versus terrain and shielding classes
The top graphs show results using the original terrain and shielding classes; the bottom graphs show results using the modified classes.

12 HEATING SYSTEM EFFECTS

In an earlier infiltration survey performed on homes in the Residential Standards Demonstration Program (RSDP), the BPA administered both PFT and blower door tests on 161 post-1978 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]. 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]. Neither of these studies was a probability sample, however, and due to local construction practices there is a tendency for correlation between heating system type, house type, tightness, and climate.

In order to make a more scientific test of the effect of ducted systems, we embedded an experiment within NORIS. An equal number of randomly chosen ducted and non-ducted homes were randomly allocated to two contractors and three time periods. Thus both field contractor and weather differences were blocked out. Homes for this experiment were all located in a single area, in order to minimize differences due to local construction practices. The Seattle area was chosen for this subset, since there were many sample homes available.

Before discussing the heating system comparison, it should be noted that many of the homes with ducted systems had the duct work entirely within the envelope. The duct leakage is best expressed as a percentage of the total leakage area. The median duct leakage percentage was 7%, however, in 10% of the homes the leakage exceeded 22%. Unfortunately, the portion of ductwork exterior to the envelope was not included in the audit form.

The results of the heating system experiment are given in Table 12.1. The first block gives various home characteristics which show that homes with ducted versus non-ducted heating systems differ in a number of other respects. Homes with ducted systems have 35% larger floor areas, are predominantly multistory, and tend to have daylight-basement or split-level construction with slab-on-grade foundations. The increase in average stack height of 24% will produce a change in LBL model predictions of about 10%.

Occupancy factors are in the second block of Table 12.1. The number of wood stoves and fireplaces and their hours of use are listed. "Doors/windows open" is the number of hours per day occupants listed at least one door or window as open. The hours of wood stove use differ by roughly the same percentage as the floor area and volume, suggesting that about the same fraction of wood heat was used in each group.

The outside temperatures and wind speeds in the third block were very similar for the two groups and compare closely with TMY heating season values in the Seattle area (Seattle and Olympia TMY data). About half the homes in each group had inside temperature recorders installed in one zone. The average inside temperatures for ducted system homes were 1.0 F warmer, resulting in a 5% increase in average temperature difference.

Table 12.1. Results of heating system comparison study for 42 homes

Description	Units	No Ducts	Ducts	Percent Difference
Number of homes		22	20	
Percent Single Story	%	59.1	10.0	---
Percent Crawl Space Foundation	%	72.7	30.0	---
Floor Area	ft^2	1513	2037	35
House Volume	ft^3	12081	16874	40
Number of Bathrooms		2.09	2.45	17
Number of Bedrooms		3.09	3.15	2
Rooms Not Kitchen or Bathroom		6.09	7.15	17
Stack Height	ft	10.44	12.93	24
Number of Occupants		3.50	3.40	-3
Number of Exhaust Fans		3.59	3.65	2
Number of Wood Stoves		0.68	0.65	-4
Number of Fireplaces		0.36	0.85	136
Exhaust Fan Use	h/day	1.45	1.48	2
Wood Stove Use *	h/day	3.91	5.09	30
Fireplace Use *	h/day	0.05	0.16	220
Doors/Windows Open	h/day	3.47	1.29	-63
Inside Temperature	F	66.33	67.33	---
Outside Temperature (NWS)	F	43.38	43.25	---
Temperature Difference	F	22.95	24.08	5
Wind Speed (NWS)	mph	9.40	8.98	-4
Effective Leakage Area (LBL)	in^2	94	145	54
Specific Leakage Area		4.48	4.92	10
Normalized Leakage Area		0.474	0.559	18
Air Changes at 50 Pa (ACH50)	1/h	9.37	9.80	5
Air Changes at 50 Pa/20	1/h	0.468	0.490	5
Effective Air Changes (PFT)	1/h	0.312	0.427	37
Air Changes (PFT)	1/h	0.321	0.437	36
Air Changes (LBL)	1/h	0.375	0.435	16
Air Changes (LBL, Stack)	1/h	0.308	0.384	25
Air Changes (LBL, Wind)	1/h	0.190	0.177	-7
Infiltration Airflow (PFT)	cfm	62.7	128.1	104
Infiltration Airflow (LBL)	cfm	75.5	123.9	64
Less than 10 cfm/room (Std. 62)	%	50.0	15.0	-70
Fail Standard 119	%	4.5	5.0	11

*Includes homes without device.

The fourth and fifth blocks of Table 12.1 give various infiltration parameters. The LBL model results were based on hourly calculations for the period of the PFT test using the average inside temperatures in the homes, and the hourly outside temperature and wind speed from two NWS stations.

The PFT air change rates differ by 36% between the two groups, while the LBL model predictions differ by 16%. Differences in height, indoor temperature, and the duct leakage appear to account for about half of the PFT-measured difference. These air change rates are compared graphically in Fig. 12.1 for the two groups separately and for the two groups combined. The LBL model predictions are close to the PFT for homes without ducts, and under-predict for the homes with ducts. Stack and wind effect air flows are shown for the LBL model. The wind effect does not change much between ducted and non-ducted homes and its direction of change has an opposite sign compared to the other infiltration parameters, but wind speed for ducted homes is slightly less. However, the stack effect changes by 25%. There is some indication that the PFT air change rates have greater variability for the ducted systems.

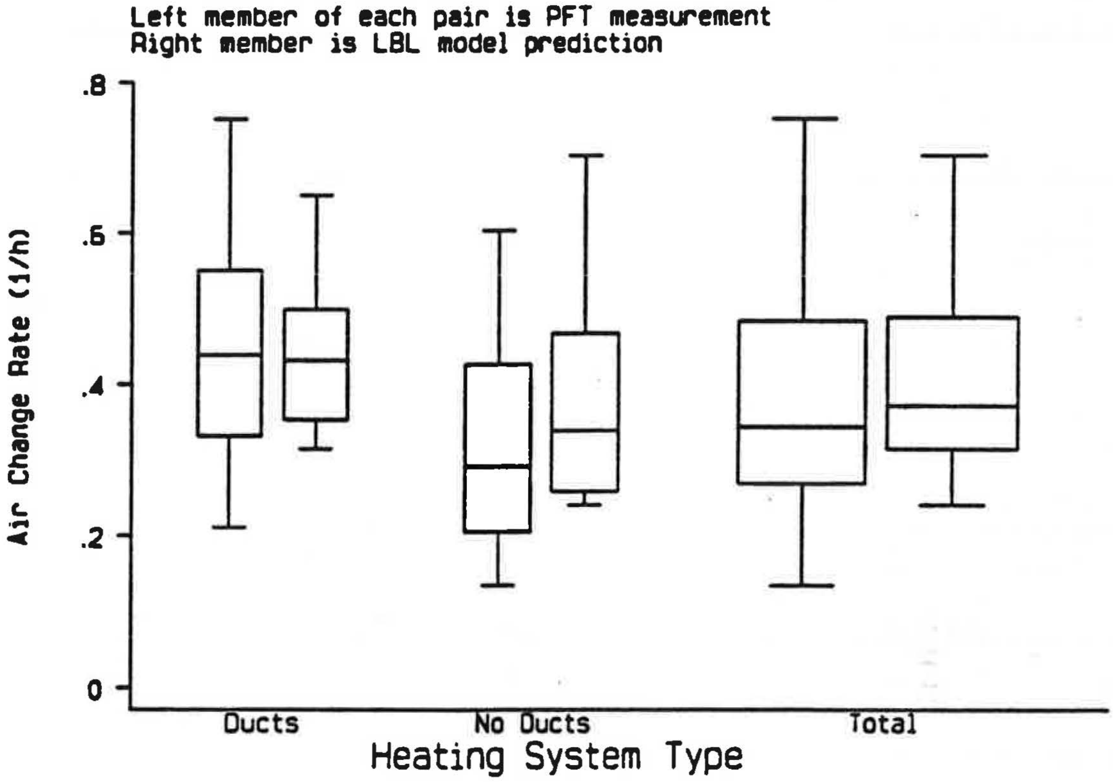

Figure 12.1. Effect of heating system type on air change rates

There are two physical reasons which might be expected to produce these effects. First, 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 4 to 15 Pa), thus producing greater leakage than predicted by the LBL model. Second, residential systems are rarely balanced and are strongly affected when doors in the home are closed (e.g., bedrooms with a supply, but no return), which can create differential pressures between rooms and across the envelope of about the same magnitude as natural driving forces. For a more detailed review see [Modera 1989].

Of the simple leakage indicators, the NLA captures the difference between homes best, due to the height correction. Measures based on air changes at 50 Pa predict only a 5% change between groups, and are therefore somewhat misleading. Compliance with Standards 119 and 62 is shown in the last block of Table 12.1. Based on the PFT-measured cfm, only 3 out 20 homes with ducted systems failed to meet Standard 62, while 11 out of 21 homes with non-ducted systems failed. Only one home in each group failed to meet Standard 119.

Several additional heating system comparisons are given in Table 12.2. For the NORIS sample as a whole (134 homes), there is a 43% difference which is comparable to the 60% difference for the RSDP control homes. This can be partially explained by the fact that Montana was over-sampled in the RSDP study, and homes in Western Montana tend to be very tight and are almost exclusively heated with baseboards. The R-2000 study shows the same magnitude of effect as the NORIS substudy. Note that in all cases, the standard deviation is about 50% of the mean.

Table 12.2. Heating system comparison for four studies (ACH)

	No Ducts			Ducts			
Study	No.	Mean	Std. Dev.	No.	Mean	Std. Dev.	Percent Change
R-2000 Control Homes	7	0.28	0.22	18	0.37	0.22	32.1
RSDP Control Homes	69	0.248	0.126	44	0.396	0.168	59.7
NORIS All Homes	64	0.314	0.140	70	0.448	0.194	42.7
NORIS Sub-Sample	22	0.321	0.132	20	0.437	0.148	36.1

The heating system comparison reinforces the findings of other studies (see [Parker 1989] for further citations) that forced air distribution systems have a significant impact on tracer-measured air change rates. This brings into question the relevance of uniform application of Standards 119 and 62, and suggests the need for further research and possible modifications of the standards to accommodate heating system effects.

The heating system comparison also shows the dangers of simple categorization of broadly based survey data. Although the PFT air change rate does change dramatically in both the sample as a whole and in the heating system sub-study, it is clear that there are a number of other aspects of the homes which are correlated with heating system type and which also affect infiltration rates.

In the study as a whole there are strong correlations of heating system type with climate and tightness of home (almost all homes in western Montana were very tight and had baseboard heat). This type of correlation may have influenced the RSDP results.

Although the comparison sub-study is too small to draw sweeping conclusions, it appears that, for the sub-study homes, about half of the differential may be due to differences in leakage area, height, and indoor temperatures.

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15 APPENDIX A

Data Corrections and Outliers

During review of the NORIS database, certain errors and discrepancies were noticed for individual sites. This section catalogs changes made to the data by site and the rationale for doing so. Whenever a change was made, all dependant variables were also corrected.

ID 15 was originally split into three zones for the PFT test. Zone 3 was a shop area on the ground floor of the home. It was noted in the site booklet that the zone was closed off from the rest of the home, and there was no mention of any heat source for the zone. From the sketches, it seems that the only entry to the shop area is through the garage. A PFT source was placed in Zone 3, but with no samplers. Both the blower door test and PFT analysis were correctly done without Zone 3, and the correct zone temperatures were used in calculating the PFT source strengths for Zones 1 and 2. However, the average whole house temperature incorrectly included the temperature for Zone 3 (54 F). The resultant average indoor temperature was 66 F. It has been replaced with 72 F, the correct average. This change has a large effect on the stack term of the LBL model, and results in a much lower LBL air change rate.

ID 122 had an incorrectly entered whole house volume. All zone volumes were correctly entered and used for both the LBL and PFT analysis. This change affected only subsequent calculations using volume that were done by Ecotope.

ID 271 was originally classified as having three zones. Zone 3 included a "hobby room" above one of two garages, which was accessible only from an outside staircase. The other portion of the zone was a study on the ground floor adjacent to the garage, which had a door connecting it to the rest of the house. As there was no way for the hobby room to be included in the blower door test, the contractor attempted to correct for the whole house volume by subtracting the volume of the hobby room. This results in the PFT test and the LBL model measuring two different configurations. In addition, it was obvious from the sketches that the hobby room volume was incorrectly calculated.

We recalculated the volume for Zone 3 using only the study area. The zone volume changed from 21618 ft^3 to 4500 ft^3. From the sampler concentrations, it was obvious that the ventilation for the whole house was well mixed for the source in Zone 1. We redid the PFT analysis using only the source in Zone 1 and including the study volume. The whole house average temperature, area, volume and total number of rooms were also changed to reflect the exclusion of the hobby room.

ID 218 had anomalous blower door results. The orifice configuration for the Infiltec blower door was listed as 1 on the blower door tapes and 2.75 on the information sheet in the site booklet. Battelle chose to use 1 in their analysis, and the LBL prediction was four times larger than the PFT results. Using 2.75 resulted in a closer agreement with the PFT, so we replaced all blower door results with numbers calculated from using the smaller orifice.

ID 36 had a discrepancy in the number of sources placed in Zone 2. Floor plans showed 4 sources, and the PFT sheets showed 3. The Battelle analysis used 3 sources. We redid the PFT analysis using 4 sources to obtain a more believable ACH.

ID's 50, 136 and 208 were also large outliers. All three had anomalously large LBL air change rates and small air change rates from the PFT analysis. We could find no correlation for the error (ACH[LBL]-ACH[PFT]) with any occupant activity factors, nor could we find any correlation with factors having an affect on the LBL prediction, that would explain the discrepancies.

ID 50 was missing the uncap time for the samplers, and Zone 1 (bedroom area) had sources but no samplers, and was noted as being closed off at the bottom of a stairwell all the time. The PFT analysis used only Zones 1 and 2 (first floor), but the blower door analysis used a house volume which included Zone 3. As there were no samplers in that zone, it was impossible to reconcile the two tests.

ID 208 had one source and the temperature recorder in Zone 2 located in a sunspace for the duration of the test. The average recorded temperature for the sunspace was 54.2 F, and the one-time contractor value for the zone was 73 F. A total of 4 sources were placed in Zone 2, and 54.2 F was used to calculate the source strengths for all 4 sources. Even after we corrected the temperature for the zone and redid the PFT calculations the result was still bad. Compounding problems that were not correctable included Zone 3, a hallway running the length of the house. The hallway was not a part of the living area, but acted as a buffer zone to Zone 2. Attached to the hallway was a "fruit room" which was labeled as having an outside air source. Since such a situation should result in an over-prediction from the PFT and an under-prediction from the LBL model, the two tests are not reconcilable.

ID 136 listed 3 sources for Zone 2, and 4 are clearly shown on the floor plans. We redid the PFT analysis using 4 sources, which increased the PFT ACH, but the new figure still kept the site as a large outlier. This site also had too few house pressure stations taken during the blower door test, and all were taken on the low end (<40 Pa) of the scale. ELA's ranged from 733 in^2 to 937 in^2, the third largest in the whole sample, and the SLAD was the largest of the sample. It seems likely that either the blower door test was done with a window or door open or that there was something wrong with the PFT tests that is not apparent from the booklet. This ID kept reappearing as an outlier with no explanation, so we dropped it from the sample.