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The Northwest Residential Infiltration Survey: Description and Summary of Results

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ABSTRACT

This paper summarizes results from a regional infiltration survey in which statistical and scientific validity received special emphasis. Tracer gas and house pressurization methods were used to estimate the heating season infiltration rate in a true random sample of 134 new all-electric homes in the Pacific Northwest. Regional average heating season infiltration rates were estimated to be 0.40 air changes per hour (ACH) using the gas tracer method, and 0.45 ACH using the Sherman-Grimsrud (LBL) infiltration model. Infiltration and leakage rates varied considerably, with standard deviations around 50% of the mean. Evaluated by ASHRAE Standard 119 (ASHRAE 1989), 17% of the homes failed to meet conditions for ventilation tightness, and 35% failed to meet ASHRAE Standard 62-1981 (ASHRAE 1981) for minimal ventilation rates. Homes with forced-air heating systems had infiltration air change rates that were 35% to 45% greater than homes with baseboards or wall heaters. Differences in building height, indoor temperature, and duct leakage appear to account for half the measured difference.

INTRODUCTION

Air infiltration is a major source of heat loss in residential buildings. It is also an important factor in indoor air quality. 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 Pacific Northwest. Special emphasis was placed on the statistical and scientific validity 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. A secondary experiment was designed to estimate the impact of central forced-air heating systems on infiltration rates while controlling for variations due to field contractors, climate, and local construction practices.

Two infiltration estimation techniques were employed: the first using blower-door leakage tests combined with the LBL infiltration model (Sherman and Grimsrud 1980) and the second using the time-averaged perfluorocarbon tracer (PFT) method (Dietz et al. 1986).

Field tests were conducted on 140 homes during the winter and spring of 1988. This paper summarizes the study design, statistical survey results, and field test results. Other topics in the survey report (Palmiter and Brown 1989b) include comparison of real-time multi-tracer infiltration measurements with the PFT and LBL model techniques in one home, and a detailed examination of various aspects of the LBL model. Due to space limitations, we exclude discussion of these topics in the main body, but conclusions are drawn from the complete analysis performed.

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STUDY DESIGN

Telephone Survey

The study design, telephone survey instrument, and a detailed description of the telephone survey results are given in Palmiter and Brown (1989a). A brief overview is presented here.

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

Although it is relatively easy for a utility to draw a random sample from customer billing records, it is more difficult to draw a sample for a regional power marketing agency with more than 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 that may be correlated with infiltration rates (wood use, number of stories, heating system type, draftiness), it was possible to assess selection bias of those agreeing to field tests on their homes. Responses to these questions from the final sample were compared with 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 tended 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 where homeowners expressed some interest in participating in the survey. A total of 140 access agreements were received, 20 fewer than the targeted 160 homes.

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 was 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 zone configurations; 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 (this is a protocol item that needs further attention). The blower door test results were adjusted for the difference between inside and outside temperatures using the square root correction given in CGSB (1986).

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 500 ft^2 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.

Since the PFT samplers measure the mass of tracer per mass of air, the PFT test results essentially measure the mass flow rate of air rather than the volume flow of air at site density (Dietz et al. 1986). For this study the raw PFT results have been corrected to site density. For example, some of the homes were located at elevations where the density of air was only 75% of that at sea level. For such a home the PFT air change rate was divided by 0.75 to give the volume flow corrected for absolute pressure. All PFT volumetric flows are for dry air at station pressure and at 68° F. Using flows at the density of outdoor air would reduce the PFT values by about 7%.

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 that 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 paper 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 that 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. 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.

In an earlier infiltration survey performed on homes in the Residential Standards Demonstration Program (RSDP), both PFT and blower door tests were administered 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.

RESULTS

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 January 1, 1980 and November 1, 1987 in the service area and a total of 124,771 with electric heat (Palmiter and Brown 1989a).

The disposition of the telephone survey sample is shown in Figure 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.

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. Are the infiltration characteristics of the homes of those agreeing to the field test the same as the larger population of eligibles? We made a number of statistical tests for bias, which are described in detail in Palmiter and Brown (1989a), based on the telephone survey questions and the field test results. None of the tests revealed any significant bias. It should be noted that without the larger base of the telephone survey, there would have been no means of making these tests.

Field Test Results

The field tests were done from January through April 1988, with the bulk of the tests done in February and March. 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 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, all three of which are used in the LBL model to predict infiltration.

The building height had been calculated using the rule-of-thumb "from the lowest leak to the highest leak." Homes with daylight basements were counted as full height even when the lower floor was half 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 some homes the highest leak was taken as the top of the chimney.

We believe the average stack height is a more appropriate input for the LBL model. We calculated the average stack height (height of column of warm interior air) using contractors' plans, elevations, and photographs. For a lower floor half below grade or for a two-story home in which the garage occupies half the lower floor, we counted half the height of the lower floor. For single-story homes, we took the average height of the heated space, rather than the height above grade. The new heights were 32% less on average, resulting in about a 12% reduction in LBL model predictions. In general, the homes with the greatest heights had the largest percentage reductions.

Terrain and shielding classes are used to estimate wind-induced infiltration. 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 that requires considerable further work. New terrain and shielding classes for each home were estimated by Dr. Sherman using photographs of the homes. Combined with the height adjustments, these changes reduced the LBL model predictions by 36%. More details are given in Palmiter and Brown (1989b).

An abbreviated tabulation of household characteristics for 134 homes is given in Table 1. 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.

Some of the primary results of the field audits are given in Table 2. 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. 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 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 typical meteorological year (TMY) heating season values, which include the months of October through April.

The fourth block of Table 2 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). This differs from the Canadian leakage area in using a reference pressure of 4 Pa vs. the 10 Pa of the Canadian standard (CGSB 1986). The LBL leakage area also includes the discharge coefficient (i.e., the area for a discharge coefficient of unity). To approximate the actual leakage area, the LBL leakage area 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 ASHRAE 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 ft 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 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 PFT technique measures the average tracer concentration that is proportional to the *harmonic* average of the hourly air change rates (Dietz et al. 1986). The actual average air change rate, however, is the *arithmetic* average of the hourly air change rates. Since the harmonic average of any set of numbers is less than or equal to the arithmetic average (equality holding only for a steady flow), the PFT results are biased low (Sherman 1989). This is illustrated in 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 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%.

To partially compensate for this effect, we used the LBL model with the hourly weather data to predict both the actual and the effective air change rate. The PFT effective ACH was then multiplied by the model-predicted ratio of the two quantities to predict the actual PFT-based air change rate.

The next-to-last block of Table 2 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%.

The final two entries in the fifth block give the infiltration airflow in cubic feet per minute (cfm). 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 to 80 cfm.

The last block of the table gives heating season air change estimates based on 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 is the 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.

The LBL model results using the modified parameters are compared with the PFT results in Figure 2. 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.

The final estimates for the regional average infiltration rates are given in Table 3. 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.

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 a detailed case study in Palmiter and Brown (1989b), it is the authors' opinion that, in the NORIS study, the PFT results are the most reliable.

ASHRAE Standards Compliance

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 62-1981 (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 to comply with these standards is given in Table 4. These are given separately for ducted and non-ducted heating systems as well as for the sample as a whole. The values are based on the PFT-derived ACH and cfm.

Standard 62-1981 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. Thus, there are 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% of the homes fail, while by the criterion of 15 cfm per person only 20% of the homes fail. The criterion of 10 cfm per room is intermediate. By all three criteria, homes with non-ducted 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% of the NORIS homes fail to meet Standard 119. The effect of heating system type is opposite to that for Standard 62-1981, with a much larger percentage of ducted system homes failing the standard.

Heating System Comparison Results

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 5. The first block gives various home characteristics which show that homes with ducted vs. 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%. 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 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.

The remaining blocks of Table 5 give various infiltration parameters, which have the same meaning as described for Table 2. 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 Figure 3 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. There is some indication that the PFT air change rates have greater variability for the ducted systems.

Two physical reasons 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 vs. 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), both of 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. Based on the PFT-measured cfm, only 3 out of 20 homes with ducted systems failed to meet Standard 62-1981, 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 6. 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 oversampled 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.

FINDINGS AND CONCLUSIONS

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 homes range from extremely tight to very leaky. 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.

Depending on the criteria used, 20% to 50% of the NORIS homes fail to meet current ventilation standards. For homes without forced-air heat, 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%. Most of the homes fall into a gray area where natural ventilation may be inadequate and mechanical ventilation may be superfluous.

Homes with forced-air heating systems have infiltration air change rates that are 35% to 45% greater than homes with baseboards or wall heaters. 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 62-1981, 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 also affect infiltration rates. In the study as a whole there are strong correlations of heating system type with climate; for instance, almost all homes in western Montana have baseboard heat. This type of correlation may have influenced the RSDP results.

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 results 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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Table 1. 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

Table 2. 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

Table 3. 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

Table 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

Table 5. 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.

Table 6. 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

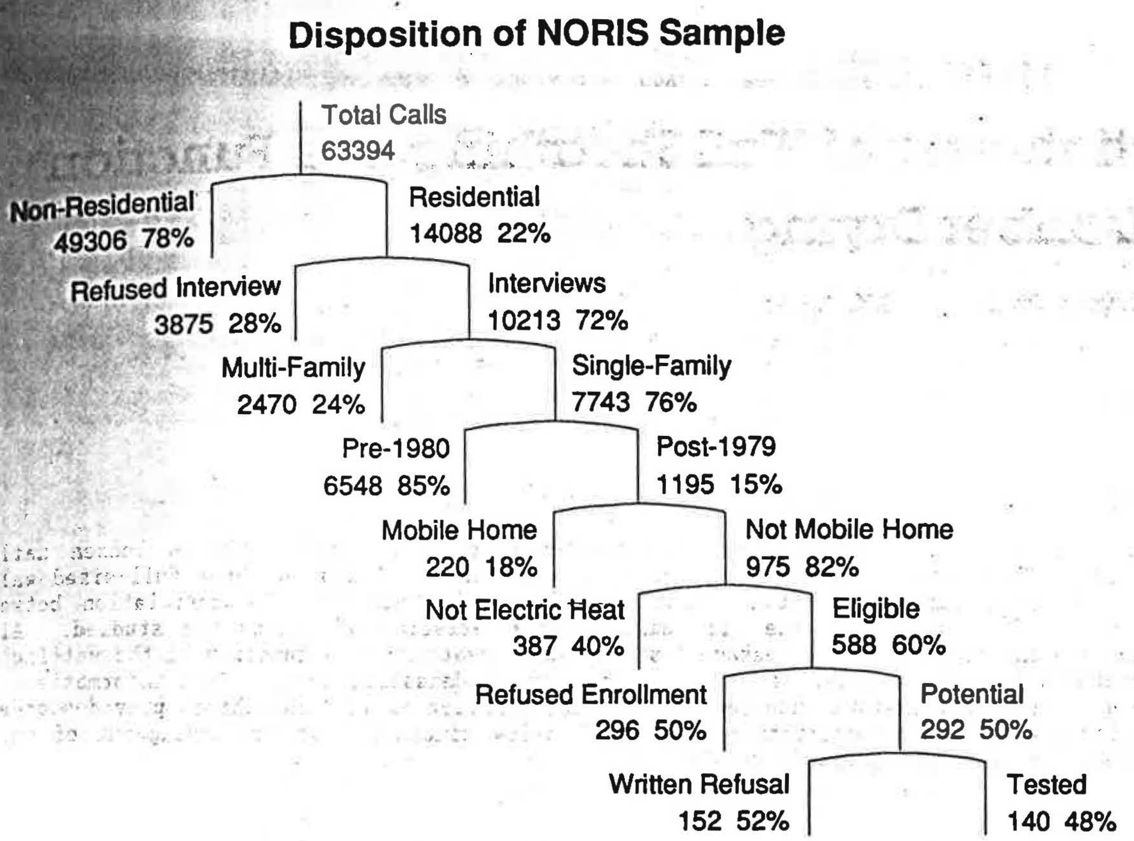

Figure 1. Disposition of telephone survey sample

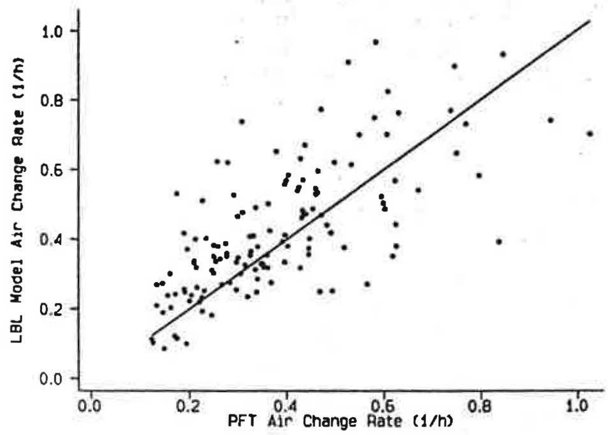

Figure 2. Comparison of PFT air change rates adjusted for efficiency with LBL model hourly simulations using National Weather Service data for the duration of the PFT test. The line indicates equality.

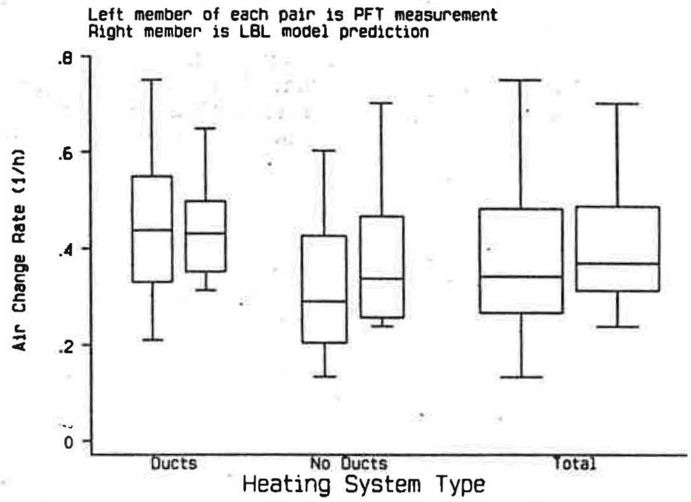

Figure 3. Comparison of heating system type hourly air change rates