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Evidence of Increased Levels of Space Heat Consumption and Air Leakage Associated with Forced Air Heating Systems in Houses in the Pacific Northwest

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ABSTRACT

This paper examines energy consumption and airtightness data from 820 electrically heated houses built since 1980 in the Pacific Northwest. Half of the buildings were energy-efficient structures built to the Model Conservation Standards (MCS) developed in the region. The rest of the sample were conventional new houses intended to be representative of current building practices. The houses were monitored for a period of one year with the structures audited to determine insulation levels and occupancy characteristics. In the analysis of the monitored data we found that heating system type plays a large role in determining the relative efficiency of electrically heated houses. Residences with electric forced-air heating systems used an average of 1.40 kWh/ft² (15.1 kWh/m²) more space heating energy than those without them. We also discovered through the use of fan pressurization and perfluorocarbon tracer gas tests (PFT) that houses with forced-air systems exhibited substantially higher levels of air leakage. The tracer gas tests indicated an average of 70% higher levels of air change rate in the control houses with forced-air space heat as opposed to baseboard systems.

INTRODUCTION

With the Northwest Power Act of 1980, Congress stipulated that Model Conservation Standards (MCS) be created that would improve current building practices and help to preserve the inexpensive hydroelectricity resource indigenous to the Pacific Northwest region. These standards were designed to be flexible to account for regional differences in climate severity and to allow different construction methods. The MCS generally feature increased levels of insulation for the building envelope components. One of the major elements of the proposed MCS was to save a large amount of heating electricity through the use of house-tightening measures followed by mechanical ventilation with heat recovery.

Proof of the efficacy of the standards was demonstrated by the Bonneville Power Administration's Residential Standards Demonstration Program (RSDP). More than 400 energy-efficient houses were built and monitored for a full year in the four-state region. The program compared the performance of the energyefficient houses with an equal-sized group of new, but conventional houses. The RSDP houses were built primarily in 1984 and monitored in the 1985-1986 heating season. Included in this monitoring process were fan pressurization blower door tests of each house and perfluorocarbon tracer gas tests on a subset of the houses. These two tests were aimed at determining the relative level of air leakage in the two groups of buildings.

As expected, the thermal performance of the MCS houses was superior, using an average of 2.55 kWh/ft² (27.5 kWh/m²) less space heat electricity than the control group. More details of the construction characteristics and monitored thermal performance of the houses are given in Parker (1989).

INFILTRATION AND VENTILATION ASSUMPTIONS IN THE MCS

In developing the MCS, it was assumed that the air change rate in conventionally built houses averaged about 0.6 air changes per hour (ach)—theoretically presenting a large opportunity for energy conservation savings. Thus, the MCS houses were designed to be airtight with sealed polyethylene vapor barriers and air-to-air heat exchangers. The planning assumption was that the as-built MCS houses would have a natural air change rate (induced by wind and temperature difference) of about 0.1 ach with another 0.5 ach of ventilation provided by air-to-air heat exchangers with 60% of the heat effectively being recovered. This results in a net reduction of 0.3 ach over the conventional houses. The overall space heat energy savings were estimated to be more than 2000 kWh/year for an average new Northwest home even after accounting for energy use by the air-to-air heat exchanger.

INFLUENCE OF HEATING SYSTEM TYPE ON SPACE HEAT CONSUMPTION

Past analysis of air infiltration in residential buildings has found evidence of increased air leakage associated with forced-air and combustion heating systems. Lipschutz et al. (1982) found a 15% to 20% greater level of effective

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TABLE 1

Space Heat Against Primary Heating System Type for MCS Houses
kWh/ft² (kWh/m²)

Heating System Type	Mean		Std Devn		Median		N
Baseboard Electric	3.19	(34.3)	1.29	(13.9)	3.10	(33.4)	115
Forced Air Electric	3.65	(39.3)	1.51	(16.3)	3.46	(37.2)	67
Heat Pump	3.52	(37.9)	1.64	(17.7)	2.34	(25.2)	19
Radiant Electric	2.62	(28.2)	1.51	(16.3)	2.41	(25.9)	10

leakage area (ELA) when testing a number of San Francisco, CA, and Eugene, OR, houses using a fan pressurization test. Accordingly, the 1985 *ASHRAE Handbook of Fundamentals* (ASHRAE 1985) indicates that heating-system-associated air leakage is from 3% to 28% of the total, with 15% being average. Field validation of a residential air infiltration model from several monitoring studies showed strong evidence of a link between furnace operation and increased air leakage (Cole et al. 1980). Goldschmidt (1986) examined various field studies of the relationship of heating system type and air infiltration and concluded that combustion systems with a flue would have air infiltration rates at least 0.10 ach more than those without them. A small case study of homes heated with forced-air gas systems in Canada (Shaw and Brown 1982) found similar results.

On the other hand, Gammage et al. (1986), studying air infiltration in 31 Tennessee homes, found that the air change rate in houses with forced-air systems was 77% greater when the duct fans were on (0.44 ach when off; 0.78 ach when on). Fan pressurization tests were also performed on the residential buildings. Similar to other investigations, effective leakage area in the forced-air-heated houses was only 15% greater than the non-ducted systems. This indicated that the leakage area of the duct system is not a good predictor of its relative effect on air leakage.

Finally, a recent sulphur hexafluoride (SF_6) tracer gas study in a hot, humid climate has found similar evidence of induced ventilation from air-conditioning systems (Cummings 1988). Tests in nine central Florida homes found that the infiltration rates in the houses averaged 0.22 ach with the air conditioner blower off and 0.62 ach when the blower was operating. Other experiments in this study found that the internal configuration of door closure in the houses would also affect the overall infiltration rate when the air handler was on.

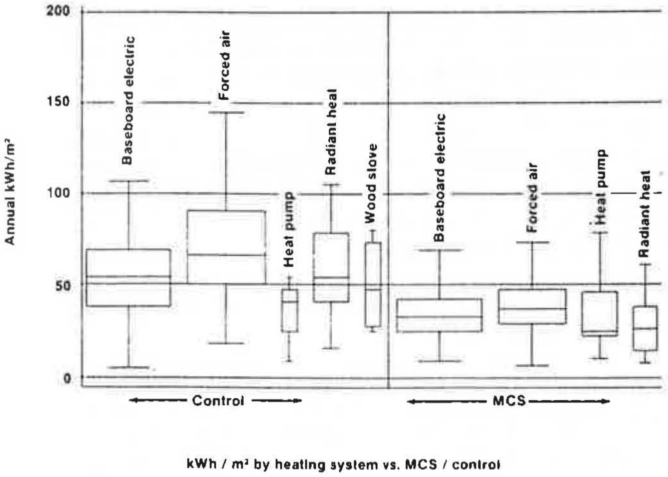

Figure 1 *Box plots of normalized space heat by heating system type for MCS and control houses*

In the analysis of RSDP houses we found that heating system type accounted for dramatic differences in electric space heat consumption. In particular, forced-air electric heating systems used considerably more space heat per m² than baseboard electric heating systems.

In the MCS houses, where attention had been paid to minimizing exterior duct runs and insulating them where they passed through unconditioned spaces, the average forced-air heating system used 17% more space heat (0.46 ± 0.36 kWh/ft² [5.0 ±3.9 kWh/m²]) than did the baseboard systems—barely of statistical significance.[1] This was also true of all differences in the MCS group. The group of energy-efficient structures is homogenous in character and only forced-air systems were significantly different. The relatively better performance of the forced-air MCS houses does suggest that duct losses in residential buildings may be minimized, subject to the skill and attention of the installer.

However, differences in electricity consumption between heating system types within the control group were greatly amplified. These results are shown by the variable-width box plots in Figure 1 (the width of the box indicates relative sample size). Other measures of central tendency and dispersion are given in Tables 1 and 2.

Forced-air systems used 22% more space heat (1.40 ±0.62 kWh/ft² [15.1 ±6.7 kWh/m²]) than did non-forced-air resistance systems. Overall, this suggests that poor performance is likely unless forced-air electric systems are installed with attention to reducing duct losses. Analysis of the data indicated that with other factors held constant, forced-air systems in the control group may be achieving delivered heating system efficiencies of only 79% (±7%) relative to baseboard systems. These findings are all the more compelling in light of simulation results of forced-air system efficiencies by the ASHRAE SP43 committee (Jakob et al. 1986).

As expected, heat-pump-heated houses evidenced superior space heating performance even though all have air distribution duct work. Control group heat pump residences used only 57% of the space heat used by resistance-heated houses (a savings of 2.50 ±1.53 kWh/ft² [26.9 ±16.5 kWh/m²]). The implied average coefficient of performance (COP) for these houses was 1.74, a probable reflection of the impact of duct leakage and increased air infiltration on these systems. The relative

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[1] Uncertainty of all estimates were evaluated at a 90% confidence level.

TABLE 2

Space Heat Against Heating System Type for Control Houses
kWh/ft² (kWh/m²)

Heating System Type	Mean		Std Devn		Median		N
Baseboard Electric	5.28	(56.8)	2.63	(28.3)	5.01	(53.9)	108
Forced Air Electric	6.68	(71.9)	2.70	(29.1)	6.13	(66.0)	91
Heat Pump	3.37	(36.3)	1.83	(19.7)	3.86	(41.6)	4
Radiant Electric	5.37	(57.8)	2.11	(22.7)	5.09	(54.8)	19
Wood Stove	4.67	(50.3)	2.48	(26.7)	4.49	(48.3)	4

similarity of heat-pump-heated houses to other types for the MCS group reflects the fact that the MCS allow heat-pump-heated houses the option of using less stringent levels of insulation in the building shell. Most RSDP-MCS houses with heat pumps took advantage of this option.

Radiant electric heat systems also tended to use slightly less energy for space heat compared to baseboard units, although the differences were not statistically significant at any acceptable level due to the small sample size (29 houses) and the variability in the data.

The above findings were subjected to further statistical examination to establish their veracity. In Figure 2, a two-way residual plot shows the differences in space heat consumption with respect to both heating system type and MCS vs. control structures. The plot was constructed using a robust statistical procedure that iteratively removes medians to establish two-way effects (Tukey 1977). The result provides visual confirmation of our conclusion regarding both the savings of MCS houses and the relative effects of heating system type: forced-air heating systems evidence greater levels of normalized space heat consumption. These findings, coupled with the varied climatic distribution of results from the previously described studies, indicate that the interaction of air infiltration and space-conditioning systems in residential buildings is both significant and widespread.

FAN PRESSURIZATION INFILTRATION RATE ESTIMATES

All control and MCS structures had blower door fan pressurization tests performed to determine their relative tightness. The data collected from these tests were then used with the LBL infiltration algorithm to predict their seasonal natural air change rates (Sherman and Grimsrud 1980). The test estimates the effective leakage area (ELA) of the building. When normalized by floor area, the specific leakage area (SLA) is a common measure of relative house tightness. We found that the MCS group had approximately 40% less specific leakage area than did the control group.

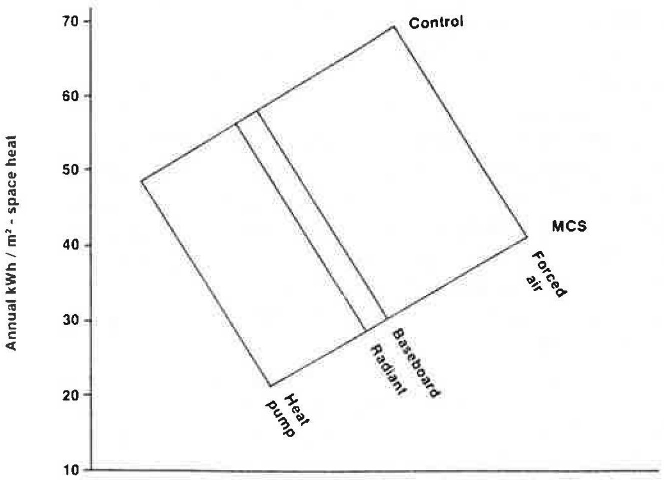

Figure 2 *Two-way residual plot of the effect of heating system type on MCS and control house annual normalized space heat consumption*

The ELA from the fan pressurization test is coupled to weather data and a series of calculations to predict a seasonal air change rate. The Sherman-Grimsrud method has been widely used to estimate the relative air leakage of residential buildings and comparisons to sulfur hexafluoride tracer gas tests have shown reasonable agreement of predicted vs. actual air exchange rates (Sherman and Modera 1986). However, other research has found some evidence that wind-driven infiltration may be overestimated by the Sherman-Grimsrud model (Hamilton et al. 1983). This issue has yet to be completely resolved. In addition, we briefly outline some other notable limitations of the Sherman-Grimsrud infiltration model:

1) The algorithm represents a simple single-zone model of infiltration and may not accurately account for multiple-zone effects.

2) The model assumes that the building leakage area is uniformly distributed over the building, only differentiating between horizontal and vertical leakage ratios.

3) The model does not account for air exchange created by mechanical conditioning or ventilation systems.

4) No allowance is made for occupant-induced ventilation such as opening windows, doors, or fireplace dampers.

5) Simplifying assumptions are made for the interaction of balanced and unbalanced flow components of overall building air leakage.

We used the fan pressurization test results, audit data, and the correlation technique along with 30-year normal weather data for October through March to estimate the seasonal infiltration rates. The data for the overall sample of all satisfactorily tested buildings are summarized in Table 3.

TABLE 3

Estimated Seasonal Air Change Rates for RSDP Houses from Fan Pressurization Tests

Group	Mean	Std Devn	Median	Min	Max	N
Control	0.55	0.26	0.52	0.06	1.59	331
MCS	0.28	0.21	0.23	0.02	1.83	292

TABLE 4

Comparison of Fan Pressurization and PFT Air Change Estimates for the Control Group Houses

Group	ACH	Std Devn	Median	N
Fan Pressurization	0.53	0.25	0.51	161
PFT Test	0.31	0.16	0.28	161

As expected, the MCS houses were quite a bit tighter than the control houses, although more leaky than the target natural air change rate of 0.1 ach. Also, the blower door tests showed that the control houses were somewhat tighter than anticipated (0.6 ach).

One significant bias was encountered in application of the Sherman-Grimsrud methodology. Assessment of the appropriate terrain and shielding class parameters to use with the fan pressurization data is somewhat subjective. In 90% of the sites, the technicians recorded shielding and terrain class III—the middle value. However, subsequent reevaluation of site-specific data has shown that most often the shielding classes were type IV—typical suburban shielding in developed areas. Based on an analysis of the sensitivity of the Sherman-Grimsrud method to this input assumption, we estimate that the mean and median air change rates estimated above are too high by approximately 10%.

PERFLUOROCARBON TRACER GAS MEASUREMENTS

A subset of more than 200 houses had in situ air change rates measured with the perfluorocarbon tracer gas (PFT) technique (Dietz et al. 1986). According to the PFT measurements, the average (as operated) air change rate of the MCS houses was about 0.35 ach. Of course, this figure includes the ventilation supplied by the air-to-air heat exchangers so it is impossible to determine the natural ventilation rate for the energy-efficient houses.

Using the PFT technique, the average air change rate in the control group was 0.31 ach during the period December 1985 through March 1986. However, the developer of the PFT test procedures has estimated that due to non-uniform mixing and closed-off rooms in the RSDP sample, the results of the PFT test should be increased by an average of 34% (Dietz 1986). This adjustment results in an average estimated air change rate of 0.42 ach for the monitoring period for the control group of houses. A rudimentary comparison of the uncorrected PFT with fan pressurization data is given in Table 4.

It is important to note that the two tests measure two different characteristics. The fan pressurization test determines the relative leakage area of the structure, not including mechanical or occupant-induced ventilation. Conversely, the PFT test measures the effective concentration of the tracer gas over time. Since ventilation and the concentration of pollutants are inversely related, tracer gas techniques measure the reciprocal of infiltration—the rate of dilution. This has been termed the "effective" ventilation rate.

As a result, unless the ventilation rate does not vary during the test period, passive tracer techniques will tend to underestimate the average actual ventilation rate of the building (Sherman 1987). The magnitude of this error depends in large part on the air leakage rate and the magnitude of its fluctuation over time. Thus it seems likely that the PFT test in the RSDP sample was biased low. On the other hand, since the concentration of pollutants is strongly related to the rate of dilution, the PFT results may be the better quantity with which to determine the impact of house tightening on indoor air quality.

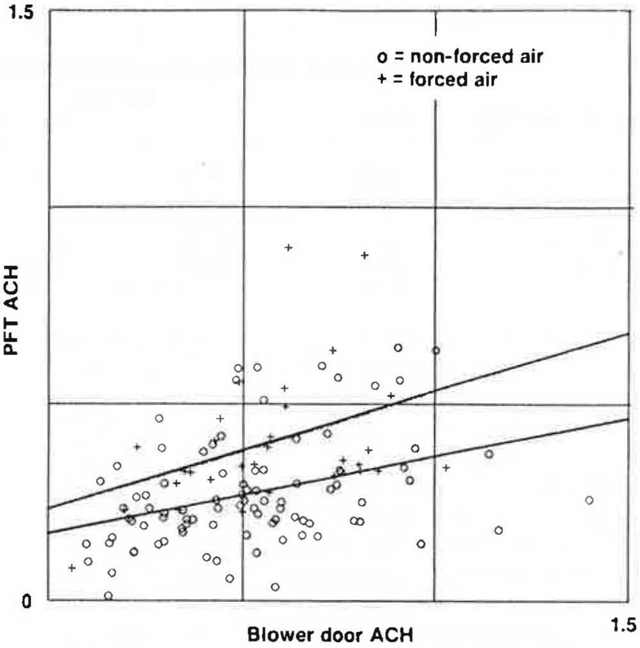

Figure 3 *Estimated building air change rate: comparison of fan pressurization and perfluorocarbon tracer gas test estimates*

CLIMATIC INFLUENCES ON THE PFT MEASUREMENTS

The period of December 1985 through March 1986, when most of the PFTs were in place, was both warmer and less windy in the Pacific Northwest than the long-term average weather conditions. When the fan pressurization correlation is used with average values for house volume, effective leakage area, and the actual Seattle weather data, the Sherman-Grimsrud algorithm predicts an average air change rate for the houses of 0.46 ach.

Thus, the two tests can be shown to give average air change estimates within roughly 20% of each other provided that actual weather data are used and the PFT test procedures are carefully planned and executed. However, this level of agreement may be misleading since the overall sample includes both forced-air and non-forced-air heated houses. If the comparison is confined to non-forced-air heated buildings then the Sherman-Grimsrud model seems to overpredict the air change rate estimated by the PFT procedure by 42% (Sherman-Grimsrud = 0.44 ach; PFT = 0.31 ach).

The disagreement on individual cases is also very great and is as yet unresolved. Figure 3 presents a scatterplot of PFT ach vs. that estimated by the fan pressurization tests. The data points are labeled by heating system type. Visual inspection of the data shows more similar values between the two tests on forced-air systems, but substantial bias for zoned electric baseboard systems. Two

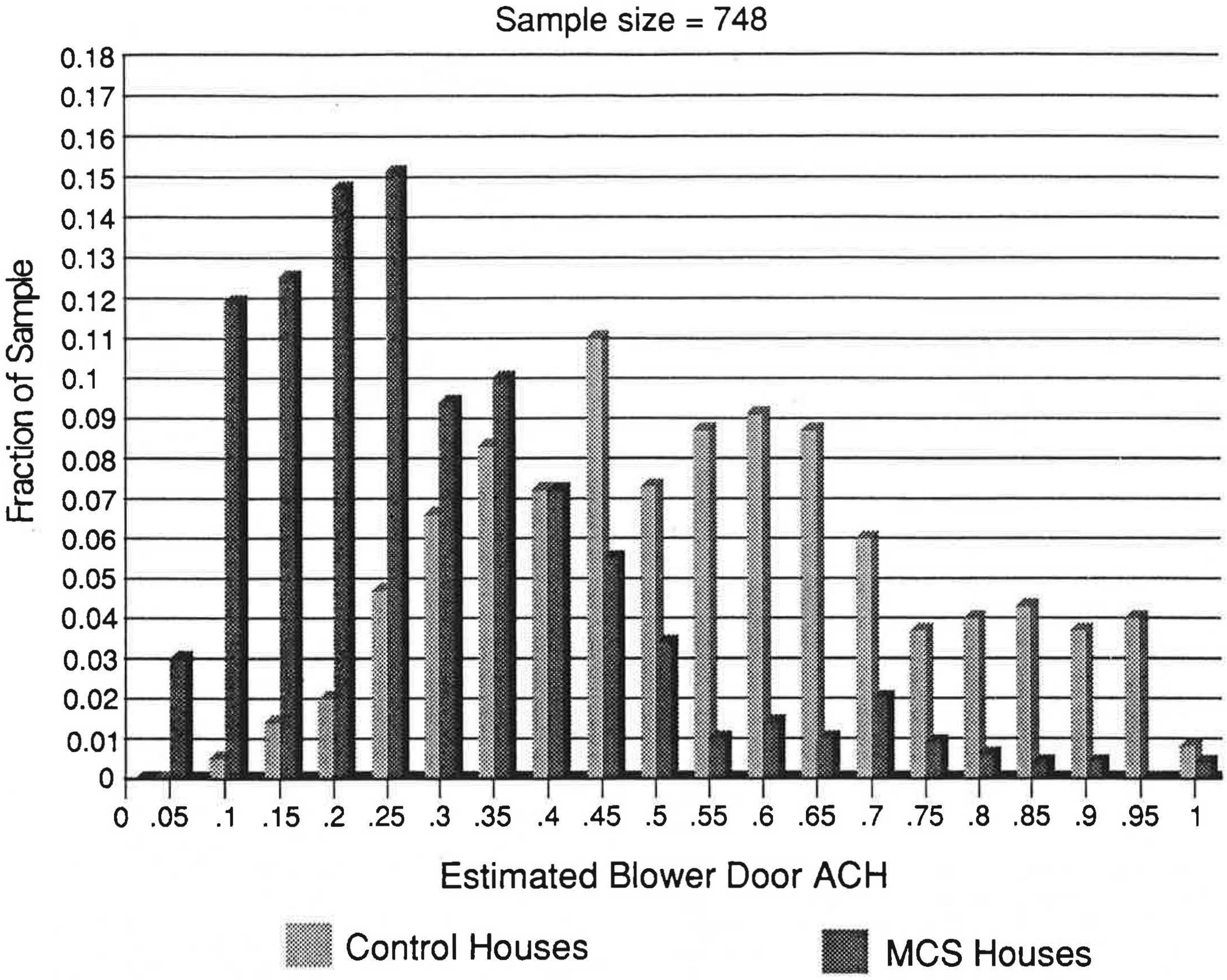

Figure 4 *Frequency distribution of estimated blower door air change rates for MCS and control houses*

regression lines are plotted on the graph; the upper line represents the relationship between the indicated blower door ach and the PFT ach for forced-air heated houses; the lower line shows the relationship in ach with non-ducted systems. An investigation is under way to examine some of the reasons for the rather extreme differences. This project, the Northwest Residential Infiltration Study (NORIS), is to be completed in 1989.

VARIATION OF AIR LEAKAGE IN THE SAMPLE

Based on the data from both infiltration tests, we conclude that the average RSDP control house will have an air change rate of about 0.4 ach under normal weather conditions in the Northwest. This average assumes a mix of forced and non-forced air-conditioning systems. This conclusion is generally consistent with another study of air change rates of the RSDP control houses and a separate sample of residential buildings in the Hood River Conservation Project (Gardner et al. 1988). However, the average air change rate was found to be a poor statistical descriptor; the relative air leakage of Pacific Northwest houses varied tremendously. Figure 4 shows the blower door correlation estimated air change rates for the MCS and control houses. The shapes of the two distributions are quite different. The MCS distribution reflects the fact that these houses were built to be tight and more often than not, achieved that goal. The control group shows a much more normal distribution. However, in either case, the air change rate of individual houses varies 10 to 1.

VARIATION OF AIR LEAKAGE WITH HEATING SYSTEM TYPE

We found the air change rates estimated by either test procedure varied considerably depending on heating system type. This is one of the most important results to be obtained from the RSDP data. Table 5 shows how the PFT

TABLE 5

Average PFT Air Change Rate Against Primary Heating System Type Control Houses

Heating System	Mean Value	Std Devn	Median	N
Electric Forced Air	0.409	0.177	0.345	31
Baseboard Electric	0.241	0.107	0.221	45
Radiant Electric	0.224	0.111	0.243	10
Wood Stove	0.180	0.197	0.168	4

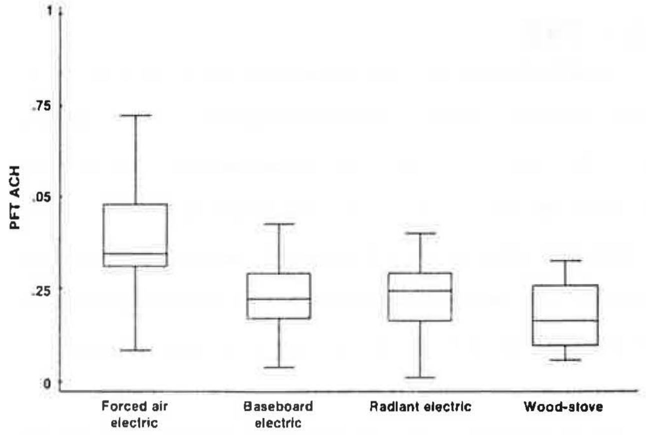

Figure 5 *Estimated air change rate by perfluorocarbon tracer gas tests: comparison against heating system type*

air change rate varied with heating system. Figure 5 further illustrates the range and variability of the data using box plots by heating system type.

The difference between the baseboard electric and forced-air systems of 0.168 (±0.054) ach is statistically significant at better than a 99% confidence level. The indicated air change rate predicted by the PFT test is 70% greater for houses with forced-air heating systems.

Since the blower door test will also pressurize the ductwork in forced-air houses, we would expect to see evidence of increases in ELA from duct leakage when using this procedure on the houses. This is verified in the values shown for the same sample for the blower door results in Table 6.

Although both estimating methods show that forced-air houses are leakier, the PFT test indicates a greater magnitude in this difference. There may be several reasons for this. In terms of the PFT estimates, non-uniform mixing of interior air, a potentially significant problem with tracer gas measurements, is likely to be minimized with forced air systems. The Sherman-Grimsrud method has no way of accounting for the fact that leakage in the duct system is under considerably higher pressure differences than is leakage located in the building shell. When operating, typical residential duct systems are under pressures ranging from 0.1 to 0.3 in of water (24.9 to 74.7 Pa)—far greater than the pressures the envelope encounters in the process of natural air infiltration. At the same time, the fraction of time that duct fans are on is correlated with the building thermal load and colder ambient temperatures so that induced infiltration from forced-air systems tends to have a disproportionate impact upon load relative to natural air infiltration.

On the other hand, a good portion of the duct leakage area may be contained within the conditioned space so that some of the leakage of the conditioned air is not lost in terms of thermal loads. The portion of ductwork exterior to the conditioned envelope appears to be correlated with the building foundation type, although information on this fraction was not collected in the audit data.

A recent detailed study of residential duct leakage in the RSDP houses found similar results to the above findings (Lambert 1988; Robison and Lambert 1988). The average air change rate, estimated by the Sherman-Grimsrud method, was 0.60 ach for ducted systems and 0.51 ach for non-ducted ones. The Lambert study also found that: 1) duct leakage varied considerably from one installation to the next; 2) relative heating system efficiency of ducted systems was degraded by about 12% compared to non-ducted systems; 3) the duct systems increased apparent leakiness of houses by about 10%; and 4) about one-third of the leakage could be remedied by retrofit repairs saving an average of 375 kWh per year. Simple paybacks of the studied retrofit repairs averaged about four years.

TABLE 6

Average Estimated Blower Door ACH Against Primary Heating System Type Control Houses

Heating System	Mean Value	Std Devn	Median	N
Electric Forced Air	0.561	0.221	0.567	31
Baseboard Electric	0.484	0.259	0.447	45
Radiant Electric	0.556	0.362	0.535	10
Wood Stove	0.651	0.222	0.608	4

ADEQUACY OF THE SAMPLE

The limitations of this study should be understood when interpreting these results. An obvious limitation is the regional character of the data; it comes from the Pacific Northwest, which often is climatically dissimilar to other areas. Given their variability, the data are considerably more representative of a number of houses than they will be for a single structure. The examined housing stock was new; most of the houses were built after 1980. Finally, the RSDP project was not designed as a scientific experiment. Builders and occupants were self-selected in the demonstration project, which may add bias to the estimates. Thus, we have no guarantee that the demonstration MCS homes actually represent what would be obtained for MCS houses from builders more experienced with the construction techniques; we have less assurance that the control houses actually represent current building practices in the Pacific Northwest.

CONCLUSIONS

The study of 800 homes in the Pacific Northwest provides evidence that heating system type plays a large role in determining the relative efficiency of electrically heated houses. Forced-air heating systems used an average of 17% to 22% more space heat than non-forced-air electric resistance systems. In the control houses with forced-air systems, this represented an additional consumption of space heat electricity of 1.40 ± 0.62 kWh/ft^2 (15.1 ± 6.7 kWh/m^2) more than baseboard systems. The study also demonstrated a strong link between forced-air heating systems and air leakage in the houses. Use of Sherman-Grimsrud fan pressurization tests showed effective leakage areas averaging 16% greater in houses with forced-air systems. However, this relatively small increase in overall leakage area has a powerful influence on overall building air change rate. According to the perfluorocarbon tracer gas tests (PFT), the air change rate of forced-air heated houses was 0.168 (+.054) ach greater than in the baseboard homes—a 70% increase.

Robust statistical analysis methods have been used to scrutinize the data to establish the veracity of the above conclusions. The results suggest that forced-air heating systems are strongly linked with increased levels of residential space heating as well as relatively higher levels of air leakage. Other studies performed in other regions of the U.S. suggest that the phenomenon is general and widespread (Gammage et al. 1986; Robison and Lambert 1988; Cummings 1988). To summarize, the results suggest:

1) Duct air leakage and associated heat transfer are likely to be significant in terms of building space-conditioning energy budgets. Although the increased effective leakage area from duct systems may only be about 15% greater than in houses without ducts, the overall increase in air leakage and associated space-conditioning energy consumption is likely to be much greater.

2) Induced air leakage from combustion systems with chimneys would probably be greater than the results shown in this study since only flueless electric forced-air systems were examined.

3) Differential pressures within the building envelope caused by unbalanced air distribution, closed interior doors, and attempted zoning in forced-air heating systems may be responsible for a portion of the increased levels of air leakage.

As yet, no comprehensive study has sufficiently examined the factors responsible for these phenomena. Since most computer simulations currently being used to determine conservation measure thermal performance do not consider these influences, significant improvements in prediction accuracy would be available with greater understanding of the processes involved. A comprehensive research agenda is recommended.

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