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Effects of Ducted Forced-Air Heating Systems on Residential Air Leakage and Heating Energy Use

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ABSTRACT

Whole-house leakage and heating energy use of electric forced-air and room-heater-equipped homes in the Northwest are compared. More than 800 homes were tested to study energy savings from a proposed code. Air leakage was measured using fan pressurization and tracer gas. Energy use was submetered; inside-to-ambient temperature differential was monitored. Two home groups were tested: energy-efficient "MCS" homes and a "control" group of current practice homes.

Ducted and unducted heating systems were compared within homogeneous subsets of homes. Air leakages were compared using 4 Pascal air infiltration, effective leakage area, specific leakage area, and 50 Pascal ach. Heating energy was compared using specific K factor (Btu/h·°F·ft²).

Ducted forced-air homes were leakier and used more heat than unducted homes. Ducted control homes were 26% leakier than unducted controls and used 40% more heating energy. Ducted MCS homes were 22% leakier and used 13% more heating energy than unducted MCS homes.

INTRODUCTION

Losses due to air leakage and conduction have long been recognized as factors in the performance of ducted HVAC systems. The literature contains numerous anecdotal references to significant duct leakage discoveries in the course of field testing. Various investigations involving whole-house air leakage (Caffey 1979; Dickerhoff et al. 1982; Harrje and Born 1982; Lambert and Cramer 1986; Lipschutz et al. 1982; McKinstry and Lambert 1984) have reported evidence of duct leakage. The whole-house air leakage studies typically involved small to moderate samples of homes and did not focus specifically on duct losses. Due to small sample sizes and the inherently high variability of residential air leakage, these previously reported findings were of marginal statistical significance.

In similar fashion, systematic field investigation of the thermal impact of duct losses has been typified by small sample sizes or has been a footnote to investigation of other topics (Miller and Pearson 1986; Parker 1987). There has been a scarcity of statistically meaningful data on duct leakage and thermal losses.

The authors had participated in testing involving residential air leakage and field measurement of heating system efficiencies. They became convinced that duct losses warranted further study. When the Residential Standards Demonstration Program (RSDP) field testing was inaugurated, it was recognized as an opportunity to study duct losses. The work was undertaken with the expectation that resultant data would also provide the first large-scale study of residential duct leakage and thermal loss characteristics.

RSDP TESTING

RSDP field testing was intended to compare thermal efficiency and infiltration/indoor air quality characteristics of highly energy-efficient Model Conservation Standard (MCS) homes with a control group built to current regional practice. However, it also provided a unique chance to study duct air leakage and thermal losses on a large sample test-reference basis. Relevant aspects of the RSDP sample and testing protocol are described below.

The RSDP Sample

RSDP testing was structured as a test-reference investigation. The test group consisted of highly energy-efficient all-electric homes, subsidized by a federal power marketing agency in the Pacific Northwest. The MCS requirements included substantially above-code insulation, infiltration reduction measures, heat recovery ventilation, and well-insulated ducting. State energy agencies in the region reviewed house plans for MCS compliance and sometimes performed construction inspections. Program training materials encouraged builders to locate ducting within heated spaces.

Many of the builders of MCS homes were relatively small firms. They were evaluated as being above average in willingness to innovate, and usually perceived the overall quality of their housing as a marketing tool.

The reference group (controls) was selected from volunteers recruited by state energy agencies. Selection was for all-electric homes meeting or exceeding 1980 code or FHA requirements for energy efficiency. Control homeowners were paid an incentive for non-use of wood

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heating during the thermal test period. This introduced a bias into the control sample. Owners of larger homes tended to regard the incentive for non-use of wood heat as insufficient. Volunteer control homes tended to be significantly smaller than the MCS homes.

RSDP Test Protocol

Each MCS and control home was equipped with electric submeters, measuring space heat and water-heating energy use. Each home was also equipped with a two-channel temperature data logger which computed hourly heating or cooling temperature differentials, using actual inside temperature as the base. Homeowners were asked to report utility and submeter readings and temperature differentials weekly. All homeowners were asked to refrain from using wood heat during submetered data collection. (Some of the homeowners did not honor this request consistently.) The submetered data collection period continued for a minimum of one year.

One-time tests performed on all homes included fan pressurization testing. About one-third of the homes also were tested for average infiltration rates, using passive perfluorocarbon tracer gas techniques. Duct leakage investigation was not part of the sponsoring agency's funded agenda. Hence, the only data collection specific to duct leakage was recording of heating system type while on-site for other tests.

The fan pressurization testing was performed per ASTM E779-81, with homes tested in both the pressurized and depressurized directions. Test results are the average of flows in both directions. The sponsoring agency required fan pressurization test data to be reduced to seasonal air infiltration estimates, after Grimsrud et al. (1981). To facilitate alternate analyses, the raw airflow and pressure differential data were data-based for future use. House volume computations were performed during the on-site testing. While on-site, our technicians also collected data on house construction, such as substructure type and number of stories.

DUCT LOSS ANALYSIS METHODOLOGY

The present investigation seeks to determine the impact of ducted forced-air heating on house air leakage and thermal performance. A test-reference methodology is necessary, since no additional experimental treatments were given to any of the home groups tested. Ideally, one would like to compare otherwise identical homes, with and without forced-air heating. Since matched pairs were not available, matched group comparisons were the best alternative.

The MCS and control groups are strongly differentiated. However, homes were believed to be reasonably homogeneous within these two groups, with respect to characteristics other than presence or absence of forced-air heating. Also, comparative measures were sought which would normalize pertinent data with respect to highly variable characteristics such as size and local climate. To further test the assumption of homogeneity within groups, additional subgroup comparisons were made on the basis of factors such as substructure type and number of stories.

The effect of ducted forced-air heating was then determined by comparing whole-house normalized air leakage and thermal parameters of ducted and unducted homes within otherwise homogeneous groups. The measures and statistical methods used for comparison are described below.

Air Leakage Measures

Four Pascal Specific Leakage Area ("SLA")—Four Pascal Effective Leakage Area, computed after Sherman and Grimsrud (1980), is normalized for house size by dividing by house floor area. The floor area is inferred from house volume by assuming an average ceiling height of 8 ft. Units are cm^2 per ft^2.

Four Pascal Estimated Seasonal Infiltration ("Infiltration ach")—Computed after Grimsrud et al. (1981). Units are in air changes per hour (ach).

50 Pascal Air Exchange Rate ("50 Pa ach")—The average of airflow rates during pressurization and depressurization at 50 Pascals, divided by house volume. Units are in ach.

Perfluorocarbon Passive Tracer Gas Infiltration Rate ("PFT")—Capsules that slowly emit a tracer gas at a known rate are placed within the home. Average indoor tracer gas concentration is determined by measuring the amount of tracer gas adsorbed into passive sampling tubes over a known time interval. Details of the methodology are described by Dietz (1982). Units are in ach.

Thermal Loss Measures

K Factor (K)—The whole-house thermal loss coefficient was determined from analysis of measured space heat average energy use rate vs. inside to outside temperature differential over weekly intervals. Figure 1 is a plot of such data. The slope of the regression line is the K factor for the site. Units used in the analysis are Btu/h • °F.

Houses that were heated by heat pumps were excluded from the analysis. Houses that showed evidence of wood heat use (by excessive scatter in their K factor plots) were also excluded from analysis. Some homeowners had difficulty in consistently and accurately reporting meter readings. The final criterion for inclusion in the analysis was resistance heating with a K factor plot correlation coefficient of 0.9 or greater. Exclusion of heat pumps, wood

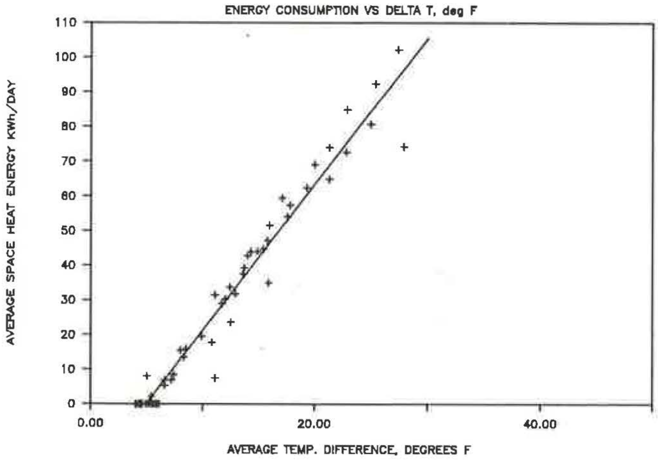

Figure 1 *Site 770: Energy consumption vs. Delta T, deg F*

TABLE 1
Statistical Comparisons of Ducted/Unducted Houses (see text for units)

Variable	Group	Mean	Ratio: Ducted/ Unducted	S. D.	Count	One-Tailed Significance
MCS Sample						
Infil. ACH	Unducted	0.2428		0.1719	134	.109
	Ducted	0.2721	1.12	0.1738	87	
50Pa ACH	Unducted	3.3898		2.1177	134	.088
	Ducted	3.7879	1.12	2.1299	86	
4 Pa ELA*	Unducted	268.87		194.61	134	.000
	Ducted	412.75	1.53	268.59	87	
4 Pa SLA	Unducted	0.1485		0.1069	134	.014
	Ducted	0.1813	1.22	0.1092	87	
K Factor*	Unducted	234.54		112.27	126	.000
	Ducted	329.19	1.40	163.38	66	
Specific K Factor	Unducted	0.1315		0.0596	125	.047
	Ducted	0.1484	1.13	0.0747	64	
PFT	Unducted	0.3164		0.2227	58	.356
	Ducted	0.3019	0.95**	0.1761	50	
Control Sample						
Infil. ACH	Unducted	0.5143		0.2301	169	.000
	Ducted	0.6046	1.18	0.2472	123	
50 Pa ACH	Unducted	7.3596		2.8190	167	.000
	Ducted	8.8822	1.21	3.0312	114	
4 Pa ELA*	Unducted	467.26		209.42	169	.000
	Ducted	726.96	1.56	282.41	123	
4 Pa SLA	Unducted	0.3222		0.1679	169	.000
	Ducted	0.4072	1.26	0.1610	123	
K Factor*	Unducted	304.50		153.33	159	.000
	Ducted	492.99	1.62	196.96	106	
Specific K Factor	Unducted	0.2005		0.0732	150	.000
	Ducted	0.2805	1.40	0.1101	106	
PFT	Unducted	0.3144		0.3765	86	.076
	Ducted	0.3949	1.26	0.1818	50	

* Denotes variable that is not normalized for size differences between groups.
** Indicated ratio lacks statistical significance.

heating, and inaccurately reported data left about 510 homes (220 MCS, 290 controls) suitable for this study.

Specific K Factor—After the samples were culled as described above, K factors were normalized for house size. As with SLA, floor area was inferred from house volume. Specific K factors are in $\text{Btu/h} \cdot {}^{\circ}\text{F} \cdot \text{ft}^2$.

Statistical Comparison Methods

The primary method of statistical analysis was comparison of means for leakage and thermal loss measures, between ducted and unducted subsets of homogeneous groups. Significance of differences in means was tested using one-tailed criteria.

The null hypotheses tested are that leakage and heating energy use of ducted homes are not greater than those of unducted homes. Use of two-tailed criteria would have tested the null hypotheses that leakage and thermal losses of the groups are equal. Use of two-tailed criteria was regarded as unnecessary and would have resulted in lower significance levels of reported results. Engineering judgment indicated ducting was unlikely to result in reduced air leakage or thermal losses.

The tabular results show means, standard deviations, and sample counts for various groups and subgroups compared. The comparisons are expressed as ratios of means (ducted mean divided by unducted mean) accompanied by a significance value. The significance value indicates the probability that the difference in group means is due to chance.

METHODOLOGY IMPLICATIONS

Some implications of the above methodology are noteworthy. On the negative side, the comparisons of thermal loss measures fail to explicitly distinguish losses due to duct leakage from those due to conduction. On the positive side, this study is possibly unique in comparing leakage and thermal losses of homes with ducting to homes without ducting.

Other work in the field has generally addressed various experimental treatments applied to houses with ducting. Typical examples are leakage testing with grilles sealed vs. grilles open, or infiltration testing with the HVAC fan on vs. off. We believe that such treatments fail to disclose the full impact of the presence of ducting. For example, running a grilles-sealed vs. grilles-open test of a home with ducting does not reveal leakage or thermal losses due to duct chase openings between heated and unheated spaces. Such differences are only detectable using a test-reference methodology, as reported here.

The specific K factors presented here have the same units as would result from calculated loss coefficients using standard heat loss methodologies. However, they should

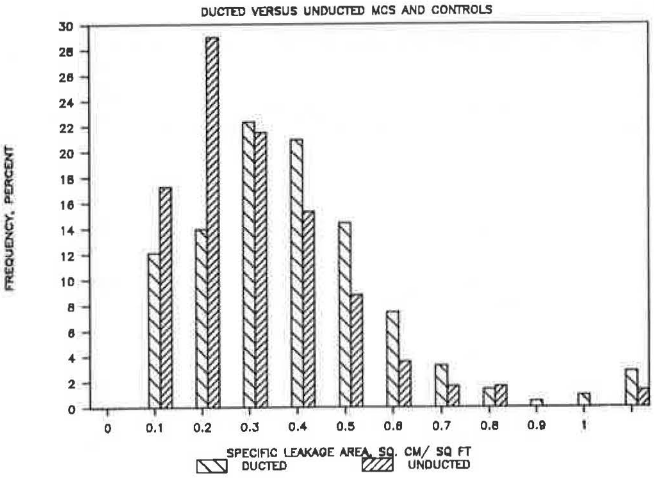

Figure 2 *Distribution of specific leakage area: ducted versus unducted MCS and controls*

not be considered as exact equivalents. Other work (Conner and Lortz 1986) suggests that calculated loss coefficients tend to be higher than experimentally determined values.

RESULTS

First, ducted vs. unducted MCS and ducted vs. unducted controls were compared using various leakage and thermal loss measures. The results are shown in Table 1. In addition to the size-normalized measures, two unnormalized measures are shown; four Pascal ELA (effective leakage area) and K factor. The changes in means after normalization to SLA and specific K factor are substantial, and confirm the importance of size normalization. These changes also demonstrate that ducted subgroups were typically larger than unducted subgroups.

It is noted that the specific K factors obtained in this study agree well with those obtained by Miller and Pearson (1986). Their investigation dealt with MCS and controls equipped with data loggers rather than submeters, and employed sensors to detect wood heating use. Their analysis excluded periods of wood heat use and their results do not distinguish ducted from unducted homes. They reported specific K factors of 0.137 (MCS, n = 52) and 0.195 (controls, n = 27). Their sampling of controls over-represented cold areas (DD65 > 6000) compared to the authors'.

For every comparison except PFT ach within the MCS, the ducted subgroup is significantly leakier and "lossier" (has a higher specific K factor) than the unducted subgroup. The effect of ducting is more pronounced in the control group than in the MCS group. This shows in both the means ratios and the higher significance levels for controls.

The high standard deviations for the various measures illustrate the inherently high variability of house characteristics. Figure 2 shows frequency distributions of SLA for ducted and unducted homes. Both distributions are near-normal, with some skew to the right side. The high variability shown in both distributions emphasizes the importance of large samples when attempting statistical comparisons. Small samples are likely to lack significance. This imposes a limit on what can be accomplished by further breakdowns of our sample into small subgroups.

Of the leakage indicators, 4 Pascal SLA showed higher significance than either 50 Pascal ach or infiltration ach. This result suggests that this indicator is better at distinguishing duct leakage effects of interest. The PFT ach and infiltration ach are not shown in subsequent comparisons, due respectively to the smaller number of houses tested with PFT and less ability to indicate differences. The unnormalized indicators were also dropped as misleading.

To test the null hypothesis that ducted vs. unducted differences shown in Table 1 were due to systematic differences other than ducting, additional comparisons were made. Two variables were analyzed—substructure type and number of stories. For the substructure differentiation, homes were categorized as basement, crawlspace, or slab. Table 2 shows ducted vs. unducted comparisons for these subgroups. As before, ducted homes were leakier and lossier than unducted ones, where the results had statistical significance. The significance levels are lower (compared to levels in Table 1), probably due to diminished sample sizes. Nonetheless the null hypothesis—that differences in Table 1 are due to substructure type rather than ducting—is not supported.

A similar set of comparisons was made based on number of stories. The results (not shown) again indicated ducted groups as leakier and lossier than unducted ones. The null hypothesis—that Table 1 differences were due to number of stories rather than ducting—was not supported.

DISCUSSION OF RESULTS

Although the results are based on volunteer samples rather than random samples, null hypothesis testing indicates that results are valid. Homes with ducted heating systems are leakier than homes without ducted heating systems. Homes with forced-air electric resistance heating systems use more heating energy than electrically heated homes without ducted systems. These conclusions are no surprise, since all but perfectly sealed, perfectly insulated ducts will experience losses. What is noteworthy is the magnitude of the observed effects associated with ducting.

The results for controls are probably more representative of mainstream residential construction practice than MCS results. We speculate that ducting effects may be even larger for older housing stock and housing in areas with a milder climate. We see no reason why our results should not be considered qualitatively applicable to fossil-fueled forced-air systems as well. Likewise, they are probably qualitatively applicable to ducted air-conditioning systems.

The 26% air leakage effect (in terms of SLA) and 40% heating energy effect observed in ducted controls is substantial. It suggests that current construction practices associated with forced-air heating systems should be reviewed. The lower duct effects shown by the MCS group (22% leakier, 13% lossier) illustrate that substantially better performance of ducted systems can be attained.

The obvious next question is, what are the problem areas with forced-air heated homes, and what are the potential remedies?

TABLE 2
Comparison of Ducted and Unducted Homes by Substructure Type

Category	Dependent Variable	Duct Type	No.	Mean	Means Ratio*	S.D.	One-Tailed Significance Level
Control	Basement SLA	Unduct	22	.2632		.151	.101
		Duct	18	.3162	1.20	.094	
Control	Slab	Unduct	47	.2539		.100	.000
		Duct	32	.3609	1.42	.141	
Control	Crawl	Unduct	89	.3765		.187	.014
		Duct	58	.4431	1.18	.164	
MCS	Basement	Unduct	19	.1222		.064	.173
		Duct	14	.1568	1.28**	.139	
MCS	Slab	Unduct	47	.1493		.108	.210
		Duct	29	.1674	1.12**	.098	
MCS	Crawl	Unduct	58	.1586		.117	.034
		Duct	35	.2040	1.29	.110	
Control	Basement ACH50	Unduct	22	6.078		2.971	.165
		Duct	16	6.917	1.14**	2.074	
Control	Slab	Unduct	45	6.139		1.985	.000
		Duct	30	8.378	1.36	2.918	
Control	Crawl	Unduct	89	8.269		2.853	.010
		Duct	54	9.435	1.14	2.905	
MCS	Basement	Unduct	19	2.879		1.494	.485
		Duct	13	2.857	0.99**	1.926	
MCS	Slab	Unduct	47	3.333		2.169	.421
		Duct	27	3.432	1.03**	1.821	
MCS	Crawl	Unduct	58	3.657		2.240	.067
		Duct	35	4.405	1.20	2.432	
Control	Basement Sp K	Unduct	20	.1715		.076	.001
		Duct	17	.2805	1.64	.121	
Control	Slab	Unduct	47	.1660		.062	.000
		Duct	30	.2428	1.46	.099	
Control	Crawl	Unduct	89	.2295		.070	.000
		Duct	45	.3009	1.31	.100	
MCS	Basement	Unduct	19	.1170		.048	.443
		Duct	12	.1145	0.98**	.043	
MCS	Slab	Unduct	43	.1098		.058	.123
		Duct	19	.1277	1.16**	.048	
MCS	Crawl	Unduct	54	.1525		.056	.020
		Duct	24	.1879	1.23	.092	

* Ducted/Unducted
** Indicated ratios lack statistical significance.

It is apparent from other studies that leakage of the ductwork itself is a significant part of the problem. It is also apparent that conduction losses from ducting must play some role in the thermal losses. There are other factors that may also warrant consideration. Additional examination of our data and of the differences between MCS and control homes indicates some possibilities for consideration.

Leakage vs. Conduction Losses

Our results do not explicitly partition thermal losses between leakage and conduction. However, one would expect that if all else were equal, the leakier groups would also have higher thermal losses. Figure 3 shows the general kind of relationship between thermal losses and duct leakage one might expect for a matched quartet of homes. It assumes duct leakage and conduction losses are the only duct-related thermal loss factors operating. Hypothetical homes A, B, C, and D are identical except for the amount their ducts leak. House A has no duct leaks, house B has moderate duct leakage, and house C has severe duct leakage. House D has baseboard heat. The axes show the ratios of losses and leakage, compared to those of house D. House D experiences no duct losses. House A experiences only conduction losses. Houses B and C experience increasing thermal losses due to leakage, as well as conduction losses.

Our test data, for what could be loosely termed matched groups, can be plotted in the same fashion. Figure 4 shows data points for several "matched groups" listed in Table 2. The crosshairs centered on each data point are error bars. They represent one standard error of the mean for ducted homes in each direction from the mean. The mean of unducted homes in each group was used for normalizing data. This method of normalizing is not statistically rigorous, since it fails to account for error in unducted means. To rigorously test for significance of the relationships shown, analysis of variance (ANOVA) techniques were employed. ANOVA analysis confirmed that where the error bars do not overlap, the group differences shown are statistically significant.

It is not to be expected that these groups should all fall on the same line, since there are substantial differences between the groups. Each point shown represents a single point on a separate plot line for its group.

The test data do not provide enough information to complete the plots for each group. However, each line goes to a point on the Y axis, which represents zero duct leakage. Logical boundary conditions can be imposed on

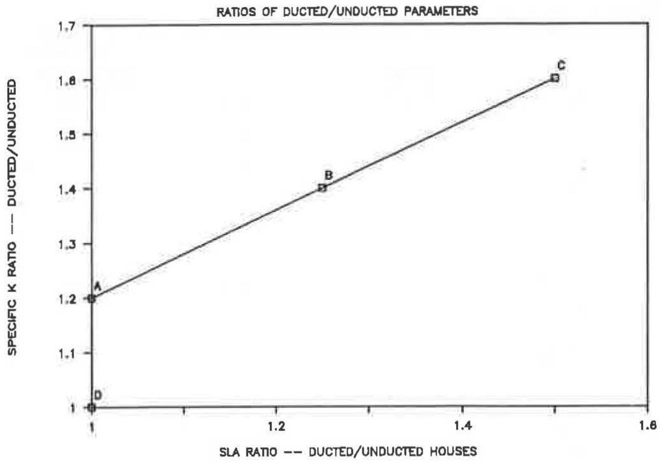

Figure 3 *Ratios of ducted/unducted parameters*

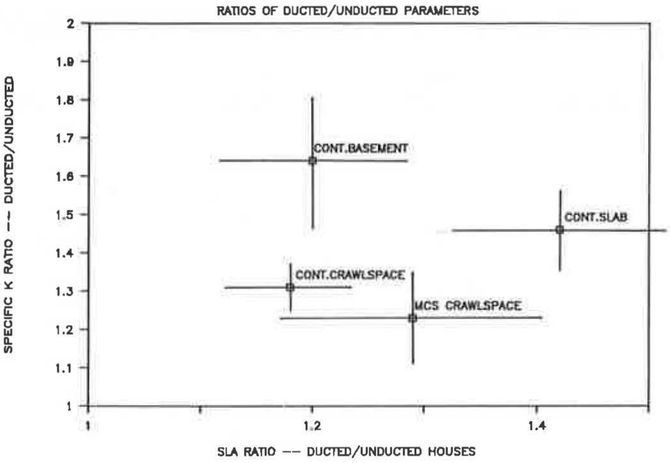

Figure 4 *Ratios of ducted/unducted parameters*

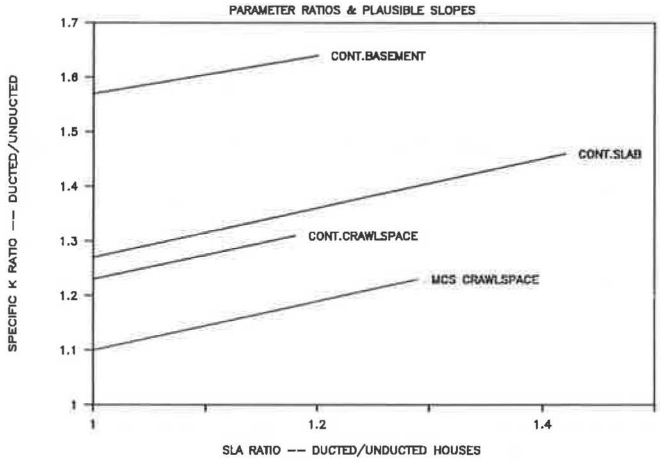

Figure 5 *Parameter ratios & plausible slopes*

the slopes of these lines. Zero slope would represent no sensitivity of losses to leakage, and is unlikely. The slope required to produce a 1,1 intercept would imply no conduction losses, again unlikely. The actual lines must lie between these extremes. Within the extremes, one would expect that slopes would be steeper for leakage of ducts in colder spaces (attic ducting for slab homes, crawlspace ducting for crawlspace homes). A less steep slope would be expected for relatively mild basement environments. In addition, the conduction losses of MCS crawlspace homes, with better insulated ducting, are probably lower than those for crawlspace or slab controls, implying a lower Y intercept.

Figure 5 shows plausible approximations to the true plots based on these premises. Although not exact, these plots provide useful information. The relationships between slab and crawlspace controls and crawlspace MCS do not contradict expectations. Duct leakage thermal effects appear significant relative to conduction losses. However, the thermal losses for basement control homes were unexpectedly large. The plot suggests either that duct conduction losses in these homes are quite large, or that some other loss mechanism is operating. An increase in duct conduction loss coefficient would be expected for uninsulated basement ducts as compared to insulated ducts in crawlspaces and attics. We had expected this to be significantly offset by the milder duct environment in basements. If the indicated losses were in fact primarily due to conduction, one would expect infiltration patterns similar to other control groups with similar incremental duct-related leakiness. PFT results for control basement homes were reviewed in search of additional insight.

Valid PFT data were available for only 10 of these homes—five each ducted and unducted. Means of PFT ach for ducted and unducted basement controls were compared using a small-sample t-test. The mean for ducted homes was 84% higher than for unducted ones. On a one-tailed basis, the difference in means was significant at a 95% confidence level. Also, PFT testing is known to underindicate air exchange rates when the rates vary substantially with time. Large intermittent furnace-fan-driven air change rates to ambient would cause more underindication in ducted homes. By comparison, the incremental PFT ach due to presence of ducting for the entire control group is 26%, as shown in Table 1. For our small sample of ducted basement controls, incremental PFT ach was about three times that for the entire ducted control group.

It is risky to draw firm conclusions from such limited data. However, the results suggest that fan-driven air exchange with the outside (as opposed to the immediate duct environment) is a factor in the ducted basement control thermal losses. Interaction between house envelope leaks and fan-induced space pressure differentials is suspected. This may warrant further investigation. Alternately, duct conduction losses in unconditioned basements may be substantial.

Comparison of MCS and Controls

Leakage and especially thermal losses due to presence of ducting are lower in MCS than control homes. Reviewing group differences suggests possible reasons why this is so.

Duct Location. The MCS builder training sessions and training materials encouraged MCS builders to locate ducts inside heated spaces. The actual impact of these exhortations on duct location in MCS homes was not determined. However, it may be a factor.

Duct Insulation. The MCS called for duct insulation to R-11. By contrast, 1980 code required R-4 to R-8 (depending on code jurisdiction and climate zone) for ducts in crawlspaces, attics, and garages. Codes required no insulation of basement ducts of controls.

Envelope Insulation. MCS insulation requirements were substantially greater than 1980 code, in all climate zones. This had the effect of requiring substantially lower energy delivery by space heating equipment in MCS homes. Less energy input to ductwork in MCS homes probably translated directly to lower duct losses. In particular, lower fan duty cycles may partially account for the lower thermal loss per unit leakage in the MCS group.

Infiltration Reduction Measures. The MCS required infiltration controls not imposed by code. Many MCS homes employed continuous vapor barrier construction. It is plausible that ducted systems can cause slight localized pressurization or depressurization of house spaces during fan operation. To the extent this occurs, interaction with house envelope leaks could take place, even with perfectly sealed ductwork. Where fan-induced pressures are additive to natural stack effects, infiltration exchange with the outside could be increased.

In a companion study of 20 ducted homes (Robison and Lambert 1989), measured leakage of return ducts was about twice that of supply ducts. Such a leakage pattern, with return ducts in unconditioned space, would tend to pressurize the heated spaces. This could be a factor contributing to the losses shown by basement control homes. However, continuous vapor barrier construction would tend to reduce furnace-fan-induced infiltration through the envelope.

Heat Recovery Ventilation. Most MCS homes were equipped with heat recovery ventilation (HRV) systems. Whether use of HRV systems in the MCS homes is related to the relatively lower thermal losses due to presence of ducting is not known.

Other Losses

Loss mechanisms other than those discussed above exist and should be considered.

Duct Penetrations. Although not directly subject to fan-forced leakage, duct penetrations and chases can contribute to leakage and passive infiltration. Some fan pressurization investigations using grilles-sealed vs. grilles-open methodology have arrived at duct leakages as low as 10% of whole-house leakage (Robison and Lambert 1989). Sample sizes and methodology variations complicate direct comparisons. However, the larger percentage of leakage due to presence of ducting in our data suggests significant leakage due to duct penetrations.

Equipment Leakage. In a subsequent study, the authors have noted that forced-air furnaces sometimes leak. Slide-in filter openings and loose-fitting service access panels can be significant leaks.

Other Construction Practices. The work done by other building trades can contribute to leakage. The authors have observed plumbing and electrical penetrations in ducts that contribute to leakage. "Box joist" ducts in basements are particularly vulnerable. Gypsum-board-lined "wall stacks" are vulnerable to leakage through plate holes for wiring.

Inadequately undercut doors can cause rooms without return ducts to have airflow balance and leakage problems. With doors closed, supply branch duct pressure may go up, causing increased supply duct leakage. If the room's envelope is leaky, infiltration to the outside can also increase.

The practices of using "box joist" and gypsum-lined wall stack type ducts are questionable from a leakage and thermal efficiency standpoint. Problems with crawlspace plenums for supply or return air are best addressed by avoiding this practice.

Potential Remedies

Given that presence of ducted forced-air heating results in greater leakage and thermal losses, what can be done to reduce duct losses? The test data and engineering judgment suggest a number of remedies.

Use of Ducting. Where use of ducting is optional, such as in electric-resistance-heated homes, duct losses may be best avoided by choosing room heaters.

Duct Location. Avoidance of ducting through unconditioned spaces, whenever practical, will reduce both leakage and conduction losses. The thermal losses associated with ducting indicate interior duct chases are worth considering as alternates to crawlspace, attic, and garage ducting.

Duct Sealing. Use of leak-prone products and practices for ducting, particularly in unconditioned spaces, should be avoided.

Duct Insulation. Insulation of ducts in unconditioned spaces to above-code values may be warranted. Some insulation of basement ducts appears warranted for basements that are not fully conditioned spaces.

Construction Practices. Duct penetrations through the structure should be sealed against air leakage. Plumbing and electrical penetrations of ducting and plenums should be avoided or thoroughly sealed. Rooms without return air ducts should have adequate door undercuts or transfer grilles. Use of crawlspace plenums should be avoided. Use of box joist or gypsum-lined wall stack ducts should be limited. Since some construction practices affecting duct losses are not within the control of HVAC installers, general contractor and building inspector education is appropriate.

Envelope Insulation and Sealing. In addition to obvious load reduction advantages, these measures appear to reduce duct losses.

Equipment Improvements. Installation of forced-air equipment with leaky enclosures in other than fully conditioned spaces should be avoided. Manufacturers might gain a market advantage by producing and promoting product options with minimal air leakage.

Further Investigation. Interaction between envelope leakage and forced-air HVAC could produce significant duct losses with perfectly sealed ducts. The extent to which this is a factor in observed losses is unknown. Experimental determination of the importance of such interaction would be useful in evaluating continuous vapor barrier construction and duct sealing options.

CONCLUSIONS

Firm conclusions from this study are:

1. Homes with ducted forced-air heating have more whole-house air leakage than homes without ducting. The difference averaged 26% for "current practice" homes.
2. Whole-house thermal losses of ducted homes are greater than for unducted homes. The difference averaged 40% for current practice homes.
3. The incremental leakage and thermal losses due to presence of ducting were substantially lower in highly energy-efficient homes. Incremental leakage and thermal losses were 22% and 13%, respectively.
4. Engineering judgment and test data indicate thermal losses due to leakage in homes with ducting in unheated spaces is significant.
5. Test data indicate thermal losses in ducted homes with basements are large.
6. Incremental leakage and thermal loss due to presence of ducting was reduced by construction features used in the energy-efficient homes tested. The relative importance of these features is not explicitly determined. The features are:
   - duct location preference to heated space
   - above-code duct insulation
   - above-code envelope insulation
   - continuous vapor barrier construction
   - heat recovery ventilation.

Tentative conclusions and topics for further consideration, suggested by the data and/or engineering judgment, are:

1. Duct penetrations through the structure may be a significant cause of leakage in ducted homes.
2. Air handler leakage may contribute significantly to ducted home leakage.
3. Work of other construction trades can contribute to leakier ducted homes. Plumbing and electrical penetrations of ducts and plenums and inadequate door undercuts can cause losses outside the control of HVAC installers.
4. Investigation of interaction between house envelope leaks and HVAC fan-driven local pressure variations inside homes may be warranted.

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