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Field Investigation of Residential Infiltration and Heating Duct Leakage

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ABSTRACT

Field investigation and repair of residential ducted forced-air heating systems was conducted on more than 20 recent vintage homes. Fan pressurization, tracer gas, and flow hood measurements were made to quantify pre- and post-repair duct leakage. The homes studied were participants in the Residential Standards Demonstration Program (RSDP). Most of the homes represented the "current practice" control group. Results showed:

- *Variability of duct leakage is high. About 10% of homes showed little leakage; 10% showed severe leakage.*
- *Duct leakage added about 10% to house leakiness, measured by fan pressurization (4 Pa ELA and 50 Pa air exchange).*
- *Flow hood tests showed return duct leakage about twice that of supply ducts during normal furnace fan operation. This typically results in net pressurization of the house.*
- *Tracer gas tests showed that fan-driven losses dominate infiltration while the furnace fan operates, causing an increase of about one-half air exchange per hour.*
- *Duct leakage was only moderately repairable on a retrofit basis. Repairs reduced leakage by about one fourth.*
- *Engineering estimates indicated an average of 12% loss of heating system efficiency through air loss caused by duct leaks.*
- *Estimates of energy savings from duct repairs averaged 375 kWh per year. Such repairs would have a simple payback of about four years.*

INTRODUCTION

Central forced-air heating systems are the most common residential type. The heating system suffers energy losses from conductive heat loss and airflow leakage from the heating ducts. In addition to inefficiencies during operation, leaks in heating ducts can contribute to air infiltration. Some indication of the influence of duct losses has been noted in regional monitoring projects (Parker 1987).

Duct leakage reduction may be a relatively easy and cheap conservation measure. These considerations have led to two related studies of duct leakage. The first, discussed here, is a before-and-after study to identify residential duct leakage and determine the effects of retrofit repairs. The second is a test-reference experiment, comparing leakage and energy use of homes with and without ducting. The latter analysis relies on statistical inferences drawn from the large group of RSDP homes and is reported elsewhere.

Potentially complex interactions can occur between naturally driven and fan-driven infiltration. Consider the sketch in Figure 1. Natural infiltration occurs normally as a result of wind and stack effects driving air through the house. However, the natural infiltration can be affected when the furnace fan operates. The fan induces a net positive or negative pressure in the house when the duct leakage is larger on the return or supply side, respectively. Balanced leakage refers to a flow volume such that supply and return sides are the same. Thus, it is the minimum of either the supply or return leakage. The remaining flow, that is, the difference between the maximum and minimum of the supply and return leakage, is the unbalanced leakage. Unbalanced leakage, if it occurs, will affect natural infiltration. Modera and Peterson (1985) have suggested that the unbalanced portion of the airflow should be added in

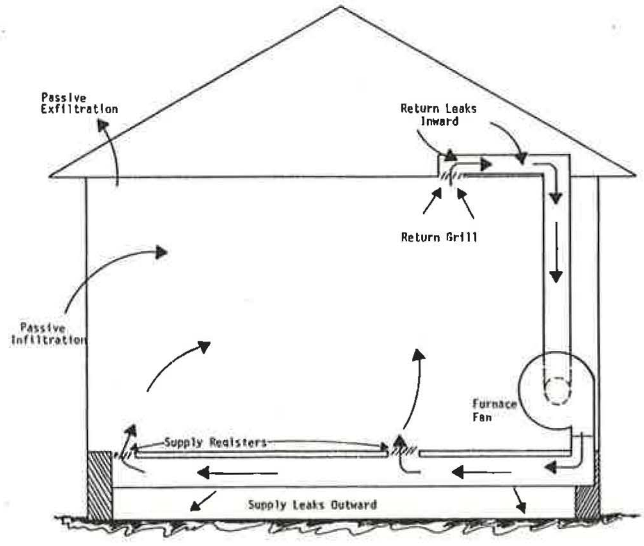

Figure 1

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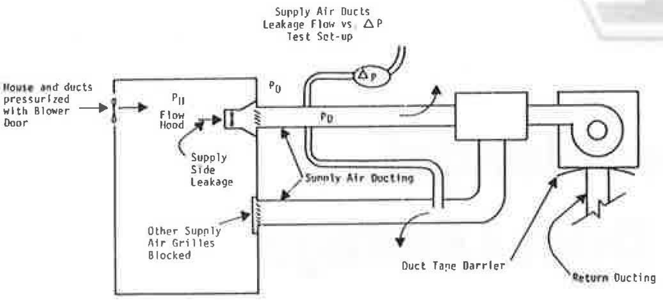

Figure 2a *Flow hood schematic—supply duct*

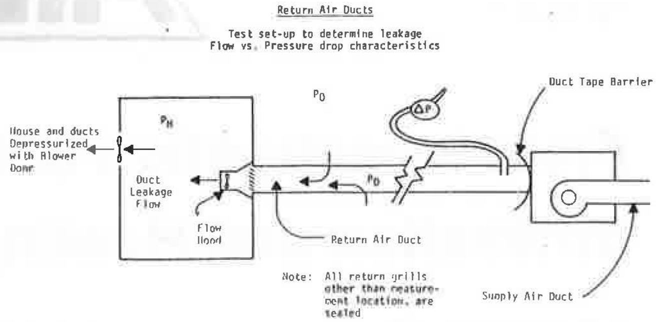

Figure 2b *Flow hood schematic—return duct*

quadrature with stack- and wind-induced infiltration. Kiel and Wilson (1987) have suggested that, for large fan-driven exhaust flows, simple linear addition of the flows is a better estimator.

Field test data allowing comparisons of duct leakage effects and the associated whole-house infiltration effects have been unavailable. Analysis of suitable data is desirable to evaluate the different models that have been proposed.

A federal power marketing agency sponsored the Residential Standards Demonstration Project (RSDP) to document the performance of energy-efficient homes. Homes in this program include Model Conservation Standards (MCS) homes representing state-of-the-art energy efficiency. Another group of "current practice" homes represents a control group. The field study discussed herein investigated duct leakage in a small number of these RSDP homes. A site visit was made to these homes and attempts were made to identify duct leakage by several different methods. Technicians then attempted retrofit repairs on duct leaks and repeated the test procedures. In addition, these homes were monitored for one year post-retrofit to identify any change in energy usage that could be attributed to duct repairs. An advantage of using the RSDP participants is that pre-retrofit monitoring data were already available for the 1984-1986 period. Objectives of the field study were:

(1) Measurement of house duct leakage characteristics, "as found."
(2) Diagnosis and repair of accessible duct leaks and measurement of repair effects.
(3) Assessment of the predictability and economics of energy savings from duct leakage repairs.

The primary goal of this before-and-after investigation is to improve the accuracy of retrofit energy savings estimates. Engineering estimates of space heat energy typically fail to offer good predictions of actual energy usage. Heating system inefficiencies may account for some of the discrepancy. Determination of the energy impact of duct leakage requires evaluation of two seasonal quantities—estimation of natural infiltration due to the presence of heating ducts and estimation of additional fan-driven ventilation due to furnace operation.

METHODOLOGY

Because of the multiple thrusts of the investigation, there are several aspects to the methodology. The field leakage measurements applied existing fan pressurization and tracer gas concentration decay techniques. Also, a refinement of component leakage testing methods—isolating duct segments and measuring duct leakage with a flow hood at various pressure differentials—was used.

Analysis and interpretation of the field leak test data required dealing with imperfect measurement precision and repeatability in both fan pressurization and tracer decay data. Analysis also involved considering ways to use field measurement to understand long-term infiltration and energy use implications of duct leakage phenomena.

Fan Pressurization Testing

The blower door is a way to measure the airflow vs. pressure difference characteristics of a structure. To the extent that the ductwork can be "shut off" or isolated, a sequence of measurements with ducts open and ducts sealed can be made. By subtraction, a rough idea of the flow vs. pressure difference characteristics due to the ductwork is obtained. One measure of house leakiness is the 4 Pascal (0.016 in w.g.) effective leak area (ELA). An alternative leakiness measure is the volumetric flow rate, Q50, at 50 Pascals (0.20 in w.g.) pressure difference. The Q50 parameter was preferred in this study because it occurs within the range of experimentally measured airflows. The ELA results from an extrapolation to a pressure differential outside the experimental range.

Flow Hood Testing

Understanding of the duct-leakage-related infiltration can be substantially improved by determining the distribution of leaks between supply and return ducting. Further understanding can be gained from knowing the fan-induced pressures driving leakage of supply and return ducts.

In this study, we improved on a variation of blower door testing, which may be a useful field technique. The desired information from blower door testing is a plot of log Q vs. log ΔP for the duct leaks only. The blower door information for the whole house is of limited utility because the flow quantities are imprecisely determined. It is more useful to measure duct leakage flows directly. For this purpose, a specially fabricated flow hood suitable for measuring low flow rates was used, as shown in Figures 2a and 2b. The flow hood was designed and calibrated for low flow rates in both directions.

TABLE 1
Percentage Increase of Whole-House Leakage Parameters Due to Duct Leakage Before Duct Repair

	Pressure	Depressure	Average P&D
ELA Fraction (n=17)			
Blower Door Method			
Mean	4.9%	16.6%	9.3%
S. D.	9.0	15.7	6.5
Flow Hood Method			
Mean	3.3%	6.2%	4.4%
S. D.	1.4%	2.9	1.6
Q50 Fraction (n=17)			
Blower Door Method			
Mean	6.3%	13.0%	8.8%
S. D.	10.1	7.0	5.2
Flow Hood Method			
Mean	8.9%	9.6%	9.6%
S. D.	3.6	3.1	3.4

The supply and return sections of the ducts were isolated from each other by applying a seal at the furnace fan. Then all the registers and grilles were sealed except for one supply register and one return grille. The house was pressurized and depressurized with the blower door. This allows airflow into and out of the open grille to be measured directly with a flow hood. Repetition at various house (and duct) pressure differentials established flow vs. pressure differential curves for supply and return ducts. For this latter determination, it was necessary to measure the pressure in the duct, since house and duct pressure differentials may not be the same. With some experimentation, it appeared that an effective average pressure could be measured which was representative of the entire duct.

This procedure isolates the supply and return ducting from wholehouse leakage effects. Having isolated values for duct ELA, 50 Pascal air exchange rate, etc., for various house differential pressure facilitates evaluation of duct leak effects on natural infiltration. More importantly it allows close estimation of supply and return duct leakage flow rates during furnace fan operation.

Tracer Gas Testing

Sulfur hexafluoride tracer gas tests were used during the field study to measure fan-driven air exchange directly. Comparison of the fan-on and fan-off ach measurements gives an indication of the net change in ventilation due to fan operation. Tracer gas concentration decay tests, per ASTM E741-83, were run first with the furnace fan on, then off. Interior doors were left open. The fan-on test was run first to achieve good mixing. It was immediately followed by the fan-off test, without additional tracer gas. This sequence was followed to minimize variation in weather-driven infiltration between fan-on and fan-off tests. During the testing, a fan was operated inside the house to ensure thorough mixing. Crawlspaces and garage areas were vented to the outside. Distortion of the results due to tracer gas leaking back from the crawlspace into the house is a possible problem. However, these tests were conducted on calm, mild days on which stack effects are expected to be minimal.

Energy Use Monitoring

A primary goal of the project was to reconcile energy estimating procedures and monitored energy usage. A

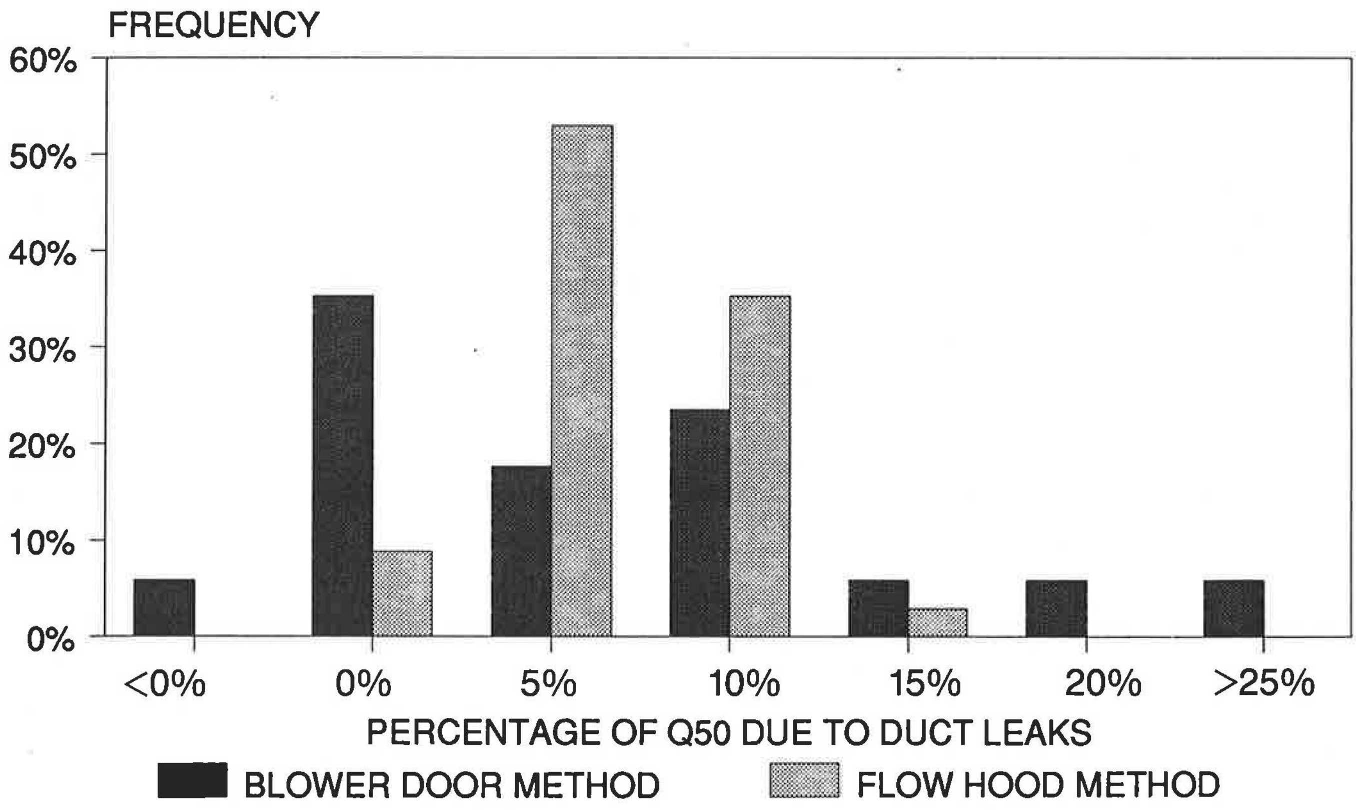

Figure 3 *Distribution of duct-related Q50*

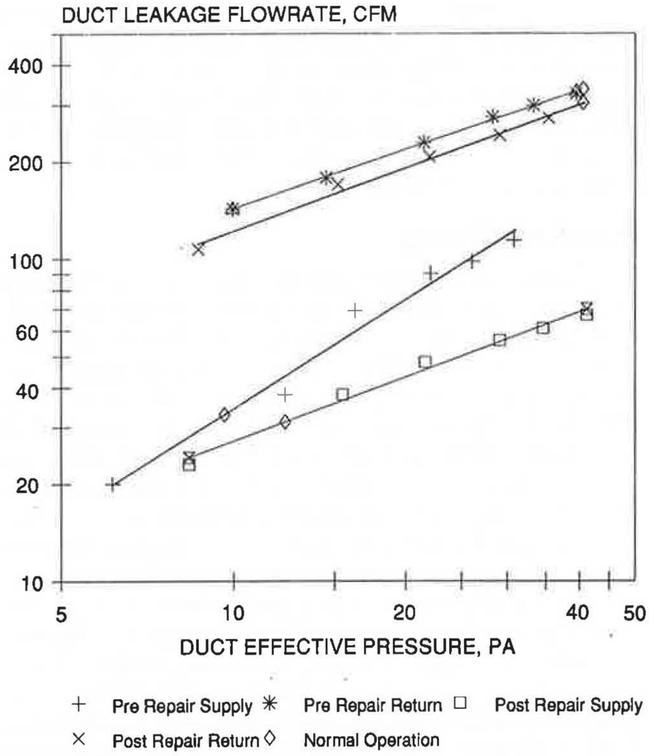

Figure 4 *Duct leak flows vs. duct delta P*

preliminary method of estimating the energy impact of duct losses has been developed. However, predicted energy changes were small and beyond the resolution of the monitoring to detect.

Sample Selection

The field investigation was conducted on a sample of the RSDP homes because monitored data were available on their previous energy usage. RSDP homes are generally of 1980 vintage or later. No attempt was made to select a representative sample from the general housing population. Homes were selected based on the presence of a ducted heating system outside the conditioned area. The typical configuration consists of supply ducts located in a vented crawl space and a return duct in a vented attic. An initial blower door test was conducted to screen for significant duct leakage. Homes warranting repair were defined as having duct-related ELA of at least 50 cm^2 (7.75 in^2). Four of 27 (15%) of the initial sample did not meet the screening criteria for significant leakage. Most of the homes were from the control group, although some MCS homes with heat pumps were included. All homes were electrically heated. The homeowners tended to be energy-conscious, as evidenced by their ongoing participation in an energy research project. The homes are probably better constructed than the norm. Thus, the leakage impacts identified in this study are probably conservative. A random sample of existing homes would probably show more severe duct leakage.

TABLE 2
Percentage Increase in Whole-House 50 Pascal Flow Rate Due to Supply and Return Ducts Average Pressure/Depressure—Before Repair

n = 17	Supply Duct	Return Duct
Mean	3.9%	6.4%
S.D.	1.2	3.1

RESULTS

Duct Leakage Contribution to Whole-House Infiltration

The amount of air infiltration due to leakage through ductwork was estimated by several methods: (1) whole-house ELA measured by blower door with ducts open and ducts sealed; (2) Q50 airflows measured similarly by blower door; (3) duct contribution to ELA extrapolated from flow hood measurements; and (4) duct contribution to Q50 extrapolated similarly.

All the methods were consistent, showing an increased infiltration of approximately 10% due to ducts. Table 1 lists results for sites studied. There was a marked difference in the experimental variation between the two methods. This is indicated by the large standard deviation using the blower door method. The blower door method produced a much wider range of results. Distribution of the two methods is compared in Figure 3. There was considerable variation between sites. About 10% of sites suffered from serious installer errors that were easily repaired. Examples included broken or missing ductwork and major holes in sheet metal.

Whole-house blower door measurements are subject to limited accuracy. Comparison of initial and final duct-sealed pressurization tests showed results reproducible to about 8%. This is the expected variability due to temperature, weather, and instrument error. Unfortunately, the uncertainty is the same order of magnitude as the duct leakage. The flow hood method gives similar aggregate results, but with some improvement in reducing variability, as shown by the reduced standard deviations in Table 1.

Disaggregation of Supply and Return Duct Leakage

Attempts to isolate leakage of supply and return ducts were not successful using the whole-house blower door method, due to the subtractive comparison of two imprecise measurements. However, the flow hood method has sufficient resolution and accuracy to separately measure supply and return duct leakage and to detect changes due to repairs. Figure 4 shows an example of flow hood measurements for one site. The plots show two sets of supply and return duct leakage measurements. One set is prior to repair and the other is after repair. The plotted data illustrate low scatter compared to subtractively determined data from whole-house blower door testing. The points indicated as "normal operation" show the static pressure measured in the duct during operation of the furnace fan.

Table 2 shows measured leakages for supply and return ducts using the flow hood. The leakages are shown as percentage increases in whole-house leakage compared to values with ducts sealed. 50 Pascal data are

TABLE 3a
Effective Duct Pressure During Fan Operation
Duct-Outdoor Ambient Pressure Difference (Pascal)

Site	Before Repair Supply	Before Repair Return	After Repair Supply	After Repair Return
135	9.6	40.6	12.3	40.6
210	50.8	93.6	57.1	96.8
609	3.2	30.8	4.1	30.6
610	25.2	21.6	26.8	21.1
613	45.7	30.1	46.3	50.9
655	24.7	7.8	21.7	43.8
677	32.5	53.2	34.9	63.5
679	47.8	109.4	38.0	149.2
710	12.2	75.4	21.4	92.0
711	45.4	37.0	44.9	44.9
745	4.8	44.4	7.1	46.0
750	6.0	47.5	7.0	39.7
754	26.8	47.3	34.4	49.2
Average	25.7	49.1	27.4	59.1
% Change			+6.4%	+20.3%

TABLE 3b
Fan-Driven Duct Leakage—Interpolated Airflows (n = 20)

Before Repair	Supply Duct		Return Duct	
Mean	40.6 L/s	(86.2 cfm)	84.1 L/s	(178.1 cfm)
S. D.	21.9	(46.4)	45.9	(97.3)

TABLE 4
Whole-House Air Infiltration (n = 20)

Flow Hood Method		Qbalanced	Qunbalanced
Before Repair			
Mean		.415 ach	.441 ach
S. D.		.249	.273
After Repair			
Mean		.324 ach	.398 ach
S. D.		.150	.363
Tracer Gas Method	**Fan On**	**Fan Off**	**Difference**
Before Repair			
Mean	.817 ach	.275 ach	.542 ach
S. D.	.447	.124	
After Repair			
Mean	.682 ach	.316 ach	.366 ach
S. D.	.279	.150	

TABLE 5
Air Infiltration Rate (n = 20)

	Gross Flow Estimate	Quadrature Model	Linear Model	Tracer Measured
Before Repair				
Mean	.856 ach	1.19 ach	0.690 ach	0.817 ach
S. D.	.57	.40	.282	.447
After Repair				
Mean	.722 ach	1.14 ach	0.640 ach	0.682 ach
S. D.	.49	.51	.263	.279

shown since they more accurately reflect duct operating conditions than do 4 Pascal data. The predominance of return duct leakage over supply duct leakage confirms subjective impressions formed in the field. It appears that installers are more careful to seal seams on supply ducts.

Leakage During Fan Operation

The fan-driven air exchange was investigated by two methods: (1) interpolation or extrapolation of flow hood measurements to the operating static pressure produced by the fan and (2) direct measure of whole-house air exchange using tracer gas.

The primary assumption of the flow hood method is that a single static pressure measurement point can be considered typical of the entire duct. This single pressure point, measured during both the fan pressurization test and normal furnace fan operation, is referred to as the effective duct pressure. The leakage flow rate is then calculated by extrapolating the log Q vs. log ΔP plot to the point representing fan-on effective duct pressure.

Some experimentation was conducted on early sites to validate this assumption. The assumption is quite reasonable for the return duct, with large duct diameter and relatively little lengthwise change in static pressure. It is less reasonable for the supply ducts. These ducts experience a larger change lengthwise in static pressure. The static pressure appeared to change most rapidly at the supply plenum and the delivery register. In between, for long duct lengths, the static pressures tended to stay relatively level. The field inspections tended to support the conclusion that a midrange measure of static pressure could be representative of the effective pressure.

Both effective duct pressure measurements and extrapolated leakage flows are shown in Table 3. An example of the flow hood log-log plots for one site is shown in Figure 4.

As indicated in Table 3b, leakage during fan operation is frequently unbalanced, resulting in a net pressurization of the house. Balanced and unbalanced flow components from Table 3 (flow hood method) are compared to whole-house air exchange rates measured using tracer gas in Table 4. For simplicity, results are normalized to the house volume. Units are house air changes per hour (ach). As expected, the tracer gas ach is at least as large as the balanced flow. Most but not all of the unbalanced flow contributes to the air change measured with tracer gas.

It is useful to compare the experimental results and those expected from the infiltration models. These comparisons for fan operation are shown in Table 5. The gross flow estimate is the sum of balanced and unbalanced flows (or the maximum flow rate) measured with the flow hood. On average, the gross flow estimate appears very close to tracer gas ach. This relationship does not hold up as well for individual houses. The scatter for individual houses could be due to measurement imprecision or to operation of other factors. Which is the case is not known. The quadrature model overestimates exchange rates. This may be due to assumptions regarding stack and wind components and not necessarily to the quadrature assumption. The linear model shows better agreement with tracer gas tests but underestimates slightly. Comparison of the two models with tracer measurements is shown in Figure 5.

Repairability of Duct Leaks

Since the volumetric amount of duct leakage is small, the best information on changes attributable to repairs comes from the flow hood method. Repair of duct leaks can significantly change static pressure and consequently duct flows and pressure drops. This requires that both duct leakage flow vs. pressure differential and duct normal operating pressure be retested after repair. With this information, an estimate of post-repair duct leakage can be made.

Figure 4 illustrates this process. Note the change in the supply duct plot as a result of the repair. For this site, the post-repair plot of leakage flow vs. pressure differential is

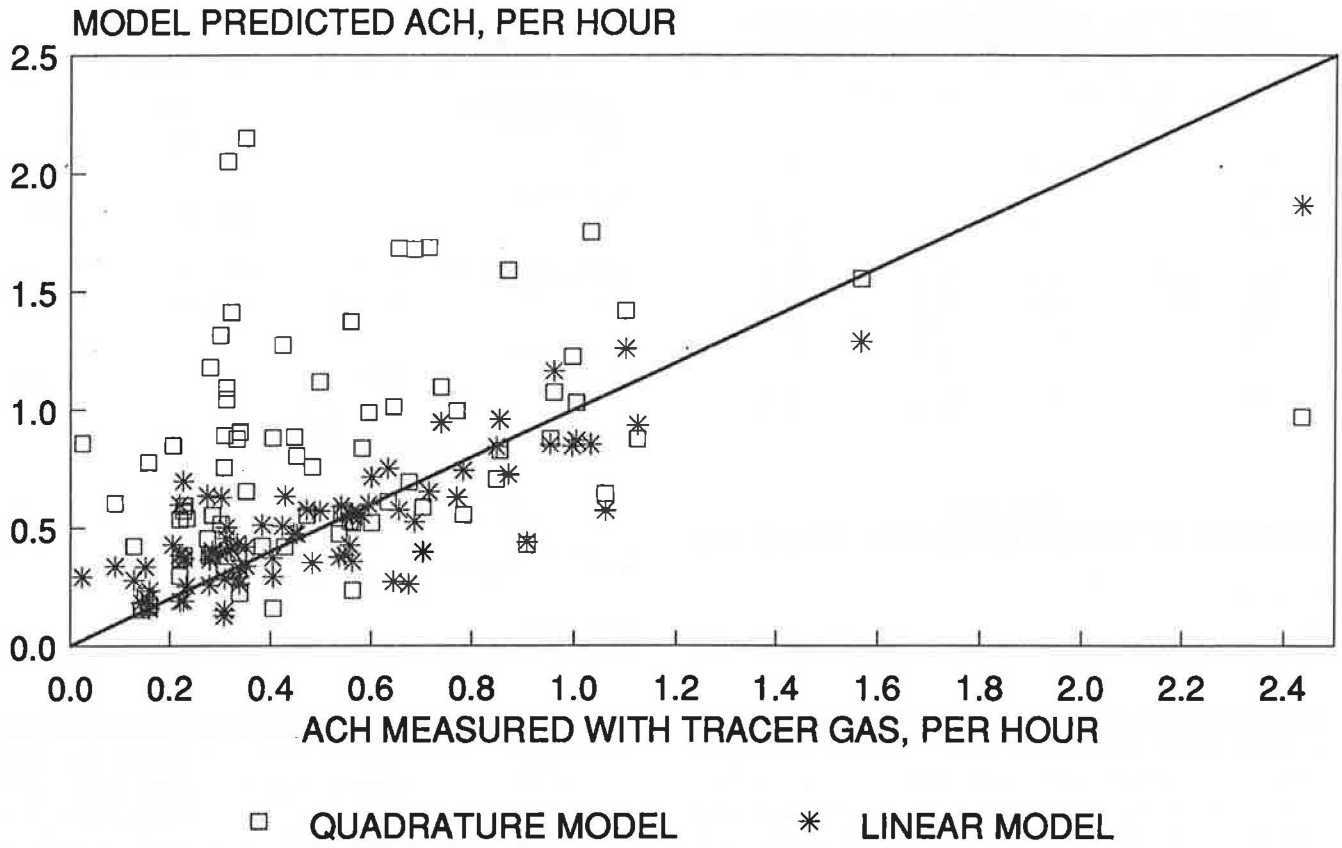

Figure 5 *House ach—quadrature and linear models*

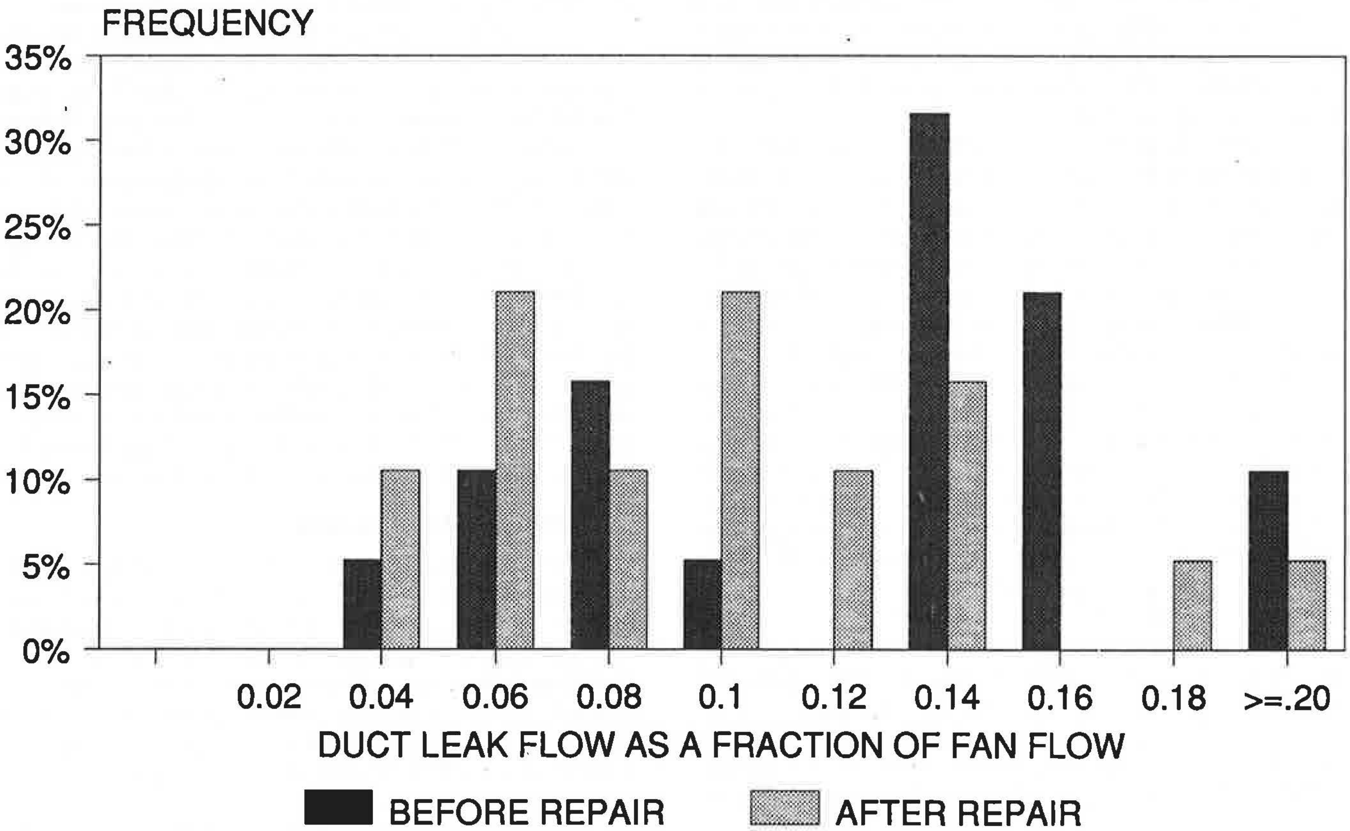

Figure 6 *Duct leak flow as a fraction of fan flow*

TABLE 6
Repairability of Duct Leaks
Duct Leakage as Percentage of Total Fan Flow

	Before Repair	After Repair	Fraction Repaired
(n = 19)			
Mean	12.2%	9.7%	.236
S. D.	6.3	6.1	.231

significantly lower than for the pre-repair case. This indicates a measurable reduction in leak area. However, this is not the final measure of leakage flow reduction during fan operation. The repaired duct now loses less air. With approximately constant fan volume, increased duct flow results in higher friction losses. As a result, the normal operating pressure in the duct increases. This has the effect of driving more air through the remaining leaks. Thus, the reduction in duct leak area does not produce a one-for-one reduction in leakage volume. The improvement due to repair is deceptively small—about 20%.

It is instructive to consider the duct leakage flows as a percentage of furnace fan total airflow. For this reason, the air loss is reported as the fraction of total fan airflow in Table 6. There is considerable variability between individual sites. The amount of improvement varied from 3% to 60%. This variability is shown in Figure 6, which indicates the distribution of duct leakage divided by total fan flow before and after repairs.

Repair Strategies

Part of the leakage problem lies in poor standards for installers. The building code does not require specific sealing measures. The general contractor does not always check on the quality of the subcontractor's work. The first requirement is for at least a visual inspection of the installation. All of the serious errors observed were direct and obvious. Any inspection of the crawlspace would have noted the errors.

Visual inspection is facilitated by noting that errors tend to occur with specific components. Right-angle elbows can fall apart. Seams at Y-joints may be ripped. Obvious dirt on fiberglass duct insulation is a sign of air leakage. Furnace filter slots are usually poorly sealed. The ends of flexible duct are often poorly sealed. The longevity of duct tape is questionable. Duct tape is inadequate for sealing butterfly or finger joints where a round duct is butted into a square distribution plenum. For this application, good results were observed using a commercial latex sealant designed for heating applications.

Identification of useful diagnostic tools other than visual inspection was not successful. The field investigation tested return air temperature as a measure of leakiness. It was not useful due to thermal capacitance of the duct metal. An unbalanced pressure test is possible comparing house-to-ambient static pressures with the fan on and off. When a change was observed, it indicated a serious installer error apparent to visual inspection. Smoke stick tracing during blower door tests correctly identified some of the leaky ducts. However, there were equally leaky ducts where the technician failed to note smoke traces.

Recommendations are: (1) in new construction, locate ducts inside the conditioned space; (2) visually inspect installations for obvious errors; (3) use sealant on duct joints and seams; (4) pay special attention to specific components (elbows, Y-joints, flexible duct, finger joints); and (5) seal floor penetrations with caulk.

Energy Savings

A major goal of the investigation was to estimate the change in space heating energy usage caused by duct leakage. The expected energy impact was calculated using engineering assumptions. This method analyzed monitored energy use before the repair. The building's specific K-factor was calculated as the regression slope of space heating energy against average indoor minus outdoor temperature using weekly observations. The predicted change in heating efficiency was then estimated based on apparent improvement in three factors. These factors were duct "volumetric efficiency" (fan flow less fan-induced duct leakage, divided by fan flow), reduced infiltration, and improved duty cycle. The results are shown in Table 7. The repairs are estimated to be quite cost effective. Levelized costs were computed using a 6% real discount rate. The program costs were computed with and without the "dry hole" sites where repairs were not deemed necessary due to low initial duct leakage.

Comparison with Monitored Energy Usage

To identify the experimentally induced change, recently monitored energy usage data were regressed and the regression coefficient compared both to the previous and the predicted new coefficient. Homes with heat pumps were examined for cold-weather outliers due to the use of resistance strip heaters. Such data points were not used. An example comparing before and after results is shown in Figure 7. The results of the monitoring are disappointing. Statistical significance is determined by a t-test based on the pooled standard deviations. Significance of changes varies depending on the number and variability of the monitoring data. At some sites, large changes occurred but lacked statistical validity. In fact, if changes had oc-

TABLE 7
Energy Savings Estimates

	Annual Energy Saved	Retro Cost	Simple Payback	Benefit Cost Ratio	6% Level Cost
n = 19					
Mean	376 kWh	$67.25	3.6 Years	5.1	$0.010/kWh
S.D.	604	19.71			
n = 23					
Including "dry hole" costs					
		$80.92	4.3	4.2	0.013

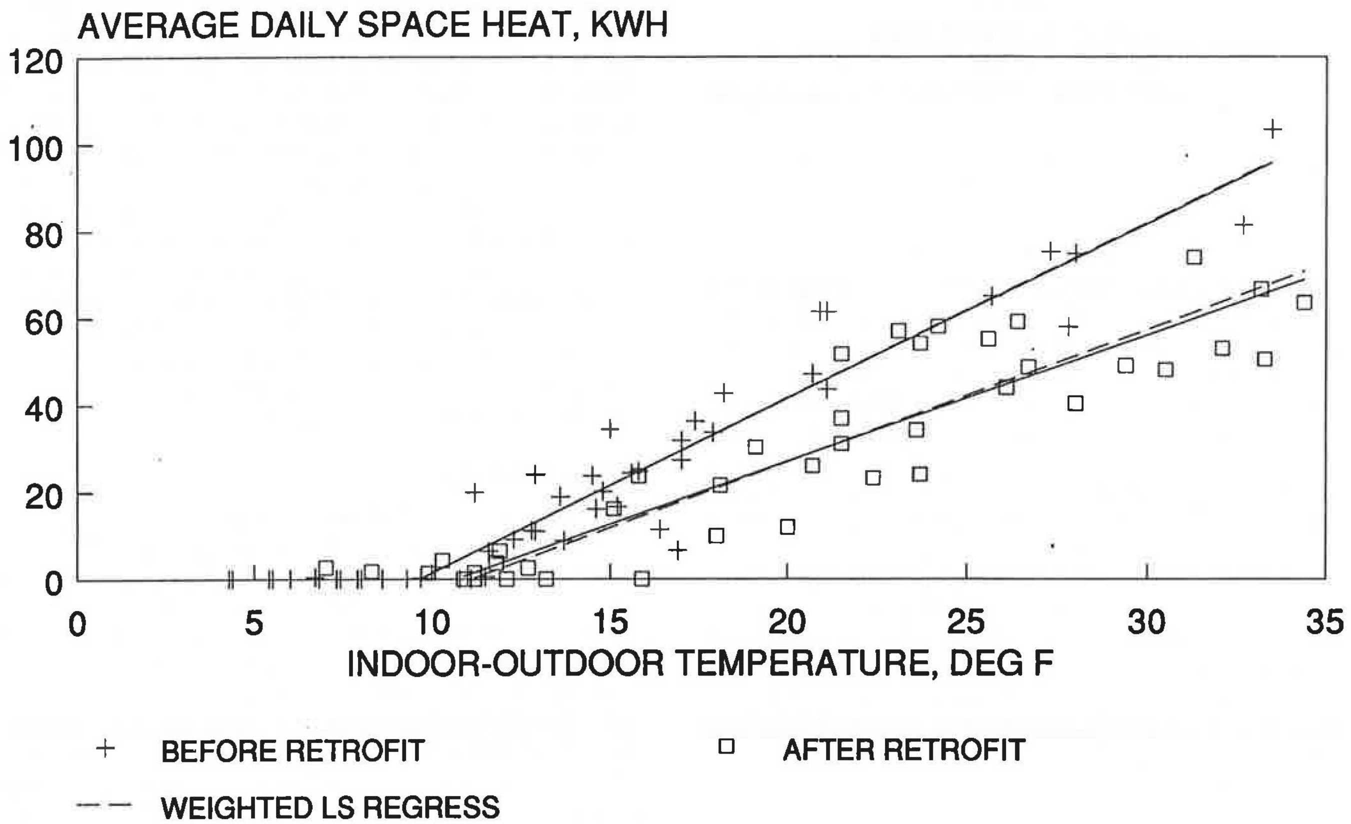

Figure 7 *Monitored space heat energy usage*

TABLE 8
Monitoring Results

Verification of Savings

Site No.	Pre-Retrofit K Factor kWh/Day °F	Post-Retrofit K Factor kWh/Day °F	Significance Level t-test	Comments
Control Sites				
134C	2.55	1.77	0.15	
705C	0.387	0.295	ns	
723C	2.98	2.82	ns	
770C	4.38	4.13	ns	
Control Sites with Structural Changes				
183C	2.39	0.920	ns	changed AAX
217C	2.21	0.563	0.06	changed AAX
170C	2.71	3.88	0.15	finish basement
Experimental Sites				
610	1.80	1.29	ns	
613	5.41	5.53	ns	changed Tb
625	4.29	4.63	ns	
655	4.99	4.21	0.15	fix break
664	5.25	5.77	-0.15	
677	2.25	2.55	ns	
695	4.00	2.90	0.02	fix break
710	4.86	4.67	ns	
735	2.37	2.60	ns	
745	4.15	4.30	ns	
754	5.84	4.36	0.0	wood use?
135	4.46	3.80	0.15	

Comparison With Prediction

Site No.	Monitored K Factor kWh/Day °F	Predicted K Factor kWh/Day °F	Significance Level t-test	Comments
610	1.29	1.73	ns	
613	5.53	5.38	ns	changed Tb
625	4.63	4.26	ns	
655	4.21	3.74	ns	fix break
664	5.77	5.15	ns	
677	2.55	2.12	ns	
695	2.90	3.88	0.05	fix break
710	4.67	4.55	ns	
735	2.60	2.39	ns	
745	4.30	4.14	ns	
754	4.36	5.64	0.0	wood use?
135	3.80	4.39	ns	

curred as predicted by the energy estimation methodology, they would usually have been too small to observe given the experimental variability. Monitoring results are listed in Table 8.

The first question is whether a measurable savings has occurred. Those savings are expected to be apparent in retrofit sites but not in control sites. Of 12 retrofit sites, 6 showed savings but only 3 were statistically significant. Six

TABLE 9
Monitoring Results

Site No.	t-test Significance	Percentage Savings Observed Savings Percentage	Expected Savings Percentage	
Control Sites				
134C	0.15	30.6%	0%	
705C	ns	23.7	0	
723C	ns	5.4	0	
770C	ns	5.6	0	
Average		16.4	0	
Control Sites with Structural Changes				
183C	ns	61.5%	0%	
217C	0.06	74.5	0	
170C	0.15	-43.1	0	
Experimental Sites				
610	ns	28.2%	3.9	
613	ns	- 2.4	0.6	
625	ns	- 7.9	0.7	
655	ns	15.6	25.0	few data
664	ns	- 9.9	1.9	
677	ns	-13.2	5.8	
695	0.05	27.6	3.0	fix break
710	ns	3.7	6.3	
735	ns	-10.0	- 1.2	
745	ns	- 3.7	0.1	
754	0.0	25.4	3.4	wood use?
135	ns	14.8	1.6	
Average		7.7	4.8	

sites showed negative savings, however only one proved to be statistically significant. Two additional sites were not useful because homeowners supplied poor or inconsistent data. Thus, it would be more correct to say that of the 12 sites, 8 showed no savings, 3 showed significant positive savings, and 1 showed significant negative savings. Of 7 control sites, 4 showed no savings, 2 showed significant positive savings, and 1 showed significant negative savings. These results demonstrate problems with experimental "noise" in the monitoring data. Of the 3 control sites with significant changes, 2 can be explained by structural changes in the home.

The second question is whether the savings agree with those predicted. The experimental "noise" interferes with drawing firm conclusions. Of the 12 experimental sites, 2 showed savings larger than expected. All the others showed savings which were not significantly different from those predicted. It must be pointed out that the savings expected from the retrofit repair are small. In fact, when the expected savings are compared to the dispersion of monitoring data, it appears that only one site would be expected to have a statistically significant observable result. This is consistent with observed results. The expected change in energy usage was expected to average about 5%. This small change would not be observed considering the variation in monitored usage. The observed average of about 8% change cannot be distinguished from experimental noise. Table 9 shows the expected changes expressed as a percentage change in energy usage.

Site 655 received a major repair and should have demonstrated a sizable change. However, it suffered from few data points and correspondingly poor resolution. Site 695 was one of the most successful. At this site, a major break was discovered and repaired. This apparently resulted in even greater savings than expected. The occupants of site 754 may have used a wood stove— their data appear suspect due to high variability. Overall, the small sample size and variation in the data prevent drawing statistically valid conclusions.

CONCLUSIONS

(1) Duct leaks increase the blower-door-measured ELA of a house by an average of about 10%. The average distribution is 4% in supply and 6% in return ducts.

(2) This amount of leakage is consistent with that observed for both the 4 Pascal ELA and the 50 Pascal air exchange rate as measured with a flow hood.

(3) The flow hood measurements are consistent with, but more precise than, whole-house blower door testing. The precision of whole-house blower door testing to measure infiltration is questionable. Further testing of whole-house airflow is not recommended as a technique to quantify the small airflows involved in duct leakage. The flow hood technique initiated in this study shows potential as a more accurate method for quantifying duct leakage.

(4) Differences in leakage produce a net pressurization in most homes during furnace fan operation. Fan-induced leakage in return ducts was substantially greater than in supply ducts.

(5) Interactions between fan-induced air exchange and natural air infiltration appear more consistent with linear addition of airflows rather than addition in quadrature.

(6) It is cost effective to include duct repair in residential retrofit programs, such as utility-sponsored weatherization. Code requirements should articulate and enforce duct installation standards for any new housing that includes forced-air heating systems.

(7) More research is needed to quantify the impact and extent of duct leakage in current housing stock. The homes in this study are probably better constructed than the norm. In particular, there has been no study of natural-gas-heated homes. Models to understand the complexities of interacting airflows in buildings are not adequate. Further research could provide very beneficial insight into low-cost opportunities for energy conservation.

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