Residential Duct Sealing Cost-Benefit Analysis

Technical Report

Residential Duct Sealing Cost–Benefit Analysis

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Final Report, June 2000

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REPORT SUMMARY

Residential air duct leakage can account for as much as 15% of a utility bill. Research has shown that houses with supply leakage fractions of 10% or greater are viable candidates for air duct sealing or retrofit. This report details the development of a regional program designed to measure and improve residential heating system distribution efficiency via air duct sealing and retrofits. The program consolidates the efforts of several utilities and coordinates a region-wide assessment of the cost-effectiveness of air duct retrofits.

Background

The Pacific Northwest homes in this sample represented two climate zones in four states—Idaho, Washington, Oregon, and Montana. These homes were heated by electric forced air furnaces and heat pumps, and supply air ducts were located primarily in unheated crawl spaces. On-site screening visits revealed that only about half of the 160 homes in the study had sufficiently leaky ducts to warrant a duct retrofit. Since this fraction was substantially lower than originally anticipated, the screening was expanded to include a review of heating system operation and maintenance (O&M) procedures. This study for the Oregon Office of Energy (OOE) was performed in cooperation with the Northwest Energy Efficiency Alliance (NEEA) and EPRI.

Objective

To determine the energy savings and cost-effectiveness of air duct sealing retrofits in a relatively large sample of Pacific Northwest homes.

Approach

Investigators divided the study into five steps. In the recruitment and marketing phase, they used various techniques to interest prospective homeowners in a duct review and retrofit. These techniques included direct mail, press releases, print advertising, and telephone follow-up. During the screening phase, they conducted a direct field review of prospective duct systems to determine each home's need for a duct retrofit. In some cases, this visit included a review of the heating and cooling equipment as well as evaluation of the duct system. The next phase, retrofit, applied to homes with substantial duct leakage. A contractor, who had participated in utility- or state-sponsored training and certification programs, provided duct sealing services. The quality assurance phase involved a post-retrofit review of the ducts, both for quality control purposes and to estimate energy savings. Finally, in the last phase, investigators analyzed energy savings using results of the screening and quality assurance reviews.

Results

Overall, duct sealings and retrofits result in a savings rate of about 12% of the space conditioning energy. This savings rate, which ranges from 1500-2300 kWh, is consistent among all large

samples drawn for this project and across climate zones. Using this rate as a guideline, payback periods range from 3-4 years for the duct retrofit measure. In cases where serious problems exist, savings two to three times the average observed levels could result in payback periods of as little as one year.

The results of this regional study, and of the individual studies comprising this sample, clearly indicate that retrofitting homes with significant duct leakage into unheated buffer spaces produces substantial savings. However, the relatively low number of homes with sufficiently high leakage levels—and the difficulty in identifying these homes without an expensive site visit—mean that a stand-alone duct sealing program is unlikely to be cost-effective.

A cost-effective program can be developed around a duct retrofit service combined with additional services. Anecdotal evidence from field crews indicates that customer interest in HVAC system evaluation and maintenance was at least as popular as the duct retrofit service itself. Performing routine O&M procedures on the heating equipment adds a benefit to the program that offsets the expense of visiting homes without cost-effective retrofit opportunities. Services offered can include a combination of some or all of the following: 1) Heating/cooling system and duct system inspection and assessment, 2) Routine maintenance services, including furnace tune-ups, 3) Review of natural gas safety and flue gas emissions, 4) Review of heat pump charge and function, perhaps with refrigerant addition or removal, 5) Review of thermostat, heat pump, and furnace controls, and 6) Assessment of insulation and weatherization opportunities. A program including some combination of these services is likely to be both cost-effective and popular with consumers.

EPRI Perspective

The development of a duct retrofit program in the Pacific Northwest meets the need for a market-based, self-sustaining enterprise modeled after regional market transformation goals. While the costs of duct retrofit measures are very attractive from the utility or consumer perspective, the expense of identifying a retrofit opportunity can equal or exceed the cost of the measure itself. This suggests the need to integrate HVAC system assessment into the overall program design so that the extensive screening requirements do not jeopardize the cost-effectiveness of the retrofit measure.

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Keywords

Ducts
Duct sealing
Cost benefit analysis
Residential buildings
Energy efficiency

ABSTRACT

The purpose of this research project was to determine the energy savings and cost-effectiveness of duct air sealing retrofits in a relatively large sample of Pacific Northwest homes. These homes were heated by electric forced air furnaces and heat pumps, and supply air ducts were located primarily in unheated crawlspaces. These homes were identified as having relatively leaky ducts during an on-site screening visit. Only about half of the homes were found to have sufficiently leaky ducts during the screening visit to warrant a duct retrofit.

A retrofit of the duct systems was conducted on those systems where a large enough amount of leakage was observed. A full accounting of the costs associated with these measures were maintained including the time and expense of the screening costs and other marketing and scheduling expenses.

Savings were estimated using a detailed model of distribution system performance. Average savings were on the order of about 12% of annual heating energy for 91 homes with sufficient detailed field data to allow modeling. A secondary finding of the study was that performing routine operations and maintenance procedures on the heating equipment, even when ducts are not found to be sufficiently leaky to warrant a retrofit, adds a benefit to the program which offsets the cost of visiting homes without cost-effective retrofit opportunities.

When the costs and benefits of the duct retrofit only were evaluated, the program was found to be cost-effective in some regions of the Pacific Northwest using current cost-effectiveness criteria. Adding benefits from the furnace operations and maintenance procedures improved the cost-effectiveness of the program.

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1
INTRODUCTION

This report details the development of a regional program designed to measure and improve heating system distribution efficiency through the use of duct testing and duct sealing. This program was designed to consolidate the efforts of several utilities and coordinate the development of a region-wide assessment of the cost-effectiveness of duct retrofits. Duct system reviews in residential buildings were conducted in all four states represented in the Alliance (Idaho, Montana, Oregon and Washington). Duct retrofits were performed for homes with high levels of duct leakage. Included in this sample are homes tested and retrofit under two separate utility programs adapted to meet the research needs of the regional effort. Puget Sound Energy (PSE) conducted its program beginning in 1997 (Davis et al., 1999). The Portland General Electric (PGE) program was conducted in 1998 (Baylon et al., 1999).

Other utilities, assisted by state agents, were involved in the program. These included Chelan County PUD, Benton County PUD in eastern Washington, Kootenai Electric Co-op in northern Idaho, Central Electric Co-op in central Oregon, City of Ashland in southern Oregon, Clark County PUD and Tacoma Public Utilities in western Washington. These utilities provided funds and coordination for State Energy Extension Service personnel to provide services to homeowners within their own service territories. In addition to these utilities, state agencies sponsored retrofits in southern and eastern Idaho. The utilities were informed of these efforts but did not participate directly in recruitment or the funding of retrofit activities.

In Montana, a subcontractor was engaged to review and provide services outside of both the state agency and the local utility. The efforts in Montana did not yield homes with sufficiently leaky or problematic ducts to warrant cost-effective retrofits. We included Montana's screening results because the contractor, under direct contract to the Oregon Office of Energy, performed testing functions similar to those performed by the State Energy Extension Services in Washington, Idaho and Oregon.

1.1 Goals and Objectives

The goals of this program were:

- To provide a sufficiently diverse sample of regional housing to determine the nature and size of the market for duct retrofits, based on home characteristics (especially duct location and floor / crawlspace insulation details) in the various parts of the region.
- To determine the energy impact of duct retrofits in various parts of the region, especially in colder climates.

- To develop a cost vs. benefit analysis for duct retrofits in various localities and to combine these data into a regional assessment of the cost-effectiveness of duct retrofits in heating systems. These reviews were confined to homes heated with heat pumps or electric furnaces. It was assumed that the duct construction, leakage characteristics and retrofit potential could be generalized from these electric heating subsets.
- To assess data collection and retrofit protocols that could be used both for training and general application to the duct sealing market. These protocols included the development of screening questions for telephone and mail assessment, and the development of screening techniques for application in the field.

1.2 Non-Energy Issues

In addition to the direct goal of establishing the cost-effectiveness of duct retrofits, several other issues were to be explored. These included investigating the possibility of developing a furnace and heat pump diagnostic approach, and evaluating the impact of adding air quality and comfort assessments.

The program was designed primarily to study the economic and energy impacts of duct retrofits. The equipment review was initially included as a safety measure to ensure that all of the equipment (especially gas appliances) was operating correctly before the field crews began working on the HVAC system. We also thought that data collected on the general state of the HVAC system would provide insight into the energy usage of a particular home. Early results indicated that the data being collected were quite valuable and revealed previously unsuspected maintenance issues. Furthermore, homeowner interest in the results of the safety review was at least as high as interest in the duct performance review. The review was modified and expanded early in the program to satisfy homeowner interest.

1.3 Business Development & Study Approach

This program began in late 1997 with the introduction of duct retrofit pilot programs by both PSE and PGE. These programs were approved by their respective regulators and were integrated into the regional study in its early phases. The nature of these services and the business model to be employed to deliver them evolved as the regional program progressed.

One key problem determined early in the PGE and PSE programs was the difficulty in identifying homes with sufficient duct leakage to ensure cost-effective retrofits. Previous studies had indicated that duct leakage was likely to be relatively severe in a large proportion of homes with ducts running through unheated crawlspaces. The initial recruitment process was designed to use mail or phone surveys to ask homeowners about the characteristics of their homes and duct systems.

Early in both the PSE and the PGE programs, it became clear that many of the duct systems installed in unheated spaces (usually crawlspaces) in the Seattle area and Portland area did not show sufficient leakage to justify a duct retrofit. Early results from retrofits and screening efforts suggested that no more than 50% of the homes with ducts located in unheated spaces could be retrofit cost-effectively. The PGE program restricted the recruiting to homes with relatively high electric bills, on the assumption that these elevated levels of consumption would be the result of inefficiencies and would indicate which homes would benefit most from an investment in duct retrofits. This screening approach did not result in a significantly higher proportion of viable retrofit candidates (based on subsequent duct leakage tests).

Since the number of homes that actually required duct sealing was a substantially lower fraction than was originally anticipated, the screening was expanded to include a review of heating system operation and maintenance procedures. The evolution of this part of the project occurred over the entire course of the program and no systematic data were collected on most of the functions performed. The only subset of homes where systematic reviews were conducted is the gas furnace set in the Puget Sound Energy program. Deferred maintenance and other operational considerations were reviewed and data regarding the potential benefits of burner adjustments, filter cleaning and replacement, and venting problems were collected. The O&M data were used to determine the desirability of including an O&M review in the regional duct program business plan.

In 1998, the State of Oregon instituted a tax credit for duct improvements. This program included a training and certification program for HVAC contractors that was tracked through submission of contractor invoices to OOE. These records were used to review the services offered by participating contractors, and showed the potential for including a variety of maintenance and installation services in an expanded program. These other services could offset duct screening costs.

The cost-effectiveness analysis evolved to include screening benefits and recruitment costs. All these factors must be considered in order to establish a true picture of the cost-effectiveness of the contractor-delivered services required to screen, repair and maintain the efficiency and effectiveness of heating systems in the Pacific Northwest.

2
METHODOLOGY

2.1 Study Approach

The study approach employed the use of various service delivery mechanisms. These mechanisms focused on the use of State Energy Office and Energy Extension Service personnel to provide training, recruitment and coordination for various utilities. Individual utilities were targeted that had previously expressed direct interest, had already developed duct retrofit programs, or that desired training, recruitment and other input from the regional duct program. The goal was to evaluate a diverse group of homes representative of a particular geographic area. Individual utilities were targeted in eastern Washington, southern Idaho, southern Oregon and eastern Oregon in addition to the PSE and PGE pilot programs.

The general approach was divided into five steps:

Recruitment and Marketing. This phase used various techniques to interest prospective homeowners in a duct review and retrofit. Depending on the utility, these techniques included direct mail, press releases, print advertising, and telephone follow-up.

Screening. A direct field review of prospective duct systems was conducted to determine the need for a duct retrofit for a particular home. This visit included a review of the heating and cooling equipment in some cases as well as the review of the duct system.

Retrofit. For those homes with substantial duct leakage, a contractor provided duct sealing services. These contractors had participated in utility- or state-sponsored training and certification programs.

Quality Assurance. A post-retrofit review of the ducts was completed, both for quality control and to allow energy savings to be estimated. In some cases, this review was conducted by the contractor and in other cases a more detailed review was conducted by Ecotope.

Savings Analysis. Using the results of the screening review and the quality assurance review, an estimate of the energy savings of the retrofit was developed.

2.2 Sample Design

The sample design was originally based on a target number of 160 fully evaluated and retrofit homes distributed throughout the region. A random sample of this size would be sufficient to characterize the two major climate zones. The methodology for delivering homes into the program was based on recruiting homes through utilities, state agencies and other methods and not through an actual random sample. Sampling and projecting these samples to population characteristics was more challenging than originally expected. However, the consistency of results in homes throughout the region (especially the consistency of the screening efforts) suggests that the requirements for a distributed random sample are not as great as originally thought.

Generalizations of the screening criteria and recruitment success to the overall residential populations are easily made using the sampling methodology developed here. Projecting regional savings is more risky, since the nature of the recruitment ensures that the sample is only representative of those people interested in duct retrofits. Nonetheless, enough consistency in duct retrofit results was observed to allow a reasonable level of generalization.

2.3 Telephone Screening and Recruitment

The screening questionnaire (Appendix A) is designed to gather key information on house, occupant and duct characteristics so that houses can be evaluated as potential retrofit candidates. The questionnaire is the first point of contact with the candidate, and is therefore also designed to answer their questions about the program. The questionnaire is designed to be completed in about 10 minutes, and is written with a combination of fill-in and open-ended questions to encourage the candidate to provide as much information as they wish. A version of the telephone screening questionnaire was used for mail-in responses by PGE.

The retrofit candidate is asked about the house age, house size (determines expected time needed for duct leakage tests and retrofit), number of stories (determines the percentage of ductwork that could be easily accessed by a retrofit crew), heating system type (furnace or heat pump), location of ducts, house insulation levels (affects potential savings, since houses with more insulation have a smaller heating load), presence of major appliances (affects non-HVAC energy consumption), presence of combustion appliances (which necessitate additional safety checks), and thermostat usage behavior (affects potential retrofit savings).

The candidate is also asked about problems they may have had with their heating/cooling system, including rooms that are cold or that overheat, recurring equipment problems, thermostat problems, etc. Depending on the severity of these problems, the house may not be a good candidate until mechanical or electrical problems are solved. However, if the problems seem mostly duct-related, the house might be an excellent candidate (assuming other criteria are met).

The most important information gathered by the screening questionnaire is the percentage of the supply ducts located in unheated spaces (usually the crawlspace). A house with all of its supply ducts in the crawlspace has a greater retrofit savings potential than a house with the same square footage of ducts running inside the building’s thermal shell, since conduction and air leakage losses for the first house are much greater. A house with owner-identified duct problems (disconnected ducts, low flow, low delivery temperature) is also given more consideration, since the aim of the program is to address these problems during retrofit.

2.4 Site Screening: Minimum Leakage Criteria

During the PSE field project, the retrofit/screening crew was given a target minimum leakage figure for deciding the suitability of a house for a retrofit. A minimum supply side leakage of 200 CFM_{50} to the outside was established; this would generally provide a supply leakage fraction (leakage to outside at normal operating conditions expressed as a percentage of system airflow) of about 10% in most homes.

Because of time constraints, the PSE crew could not always perform a duct leakage test at the time of screening; pressure pans were the only measurements taken at some homes. Homes with high average pressure pans were generally selected for retrofits; in most of these cases, a Duct Blaster™ test was done at the time of the retrofit to facilitate savings estimation.

To get a reliable estimate of savings, the air handler flow, duct area, and duct insulation level are also needed, as is the house heat loss rate. There is not enough time to get all of these data in a typical screening visit. However, during the regional project, the screening protocol was expanded so that air flow and system pressures could be measured directly (along with a Duct Blaster™ test). This enabled the field crew to estimate the supply leak fraction at the time of screening. (The detailed process for determining the leakage fraction is found in Appendix B).

The system operating pressure is important because it represents the average force pushing on the leaks in the ducts. Of course, the location of the leaks (and the pressure on these leaks) is very important. Since the Duct Blaster™ combines all of the leaks into a single figure, and because it is not practical to measure the static pressure at every point in the ducts, estimation is required to process the leakage and pressure measurements that are taken.

Generally, houses with leakage fractions under 5% offer very limited savings potential unless the leaks are obvious and accessible to the crew. Houses with supply leakage fractions of 10% or greater are better candidates, assuming at least half the leakage can be sealed in a reasonable time (one crew day) and the consumer economics pencil out (estimated a simple payback of 10 years or less).

2.5 Detailed Field Protocol

Ecotope developed an extensive field protocol for this project (Appendix C). Detailed duct tests were needed to facilitate the estimation of retrofit potential and to evaluate retrofit effectiveness in homes that had work done. The protocol typically takes a half-day or more to complete.

Earlier protocols have focused on one or two measurements of performance (house heat loss rate, house air tightness, etc.). The protocol used in this work includes these measurements and adds a suite of duct-related measurements. All houses going through the screening phase received at least a supply-side pressure pan test (return and supply temporarily split at the furnace). Direct measurement of duct leakage was strongly encouraged during the screening phase, as this enables a much more accurate estimation of retrofit potential.

The Duct Blaster™ test, while necessary to estimate retrofit potential, was not sufficient to evaluate retrofit cost-effectiveness. The protocol also required an estimate of air handler flow and measurement of operating static pressures in the duct system. The air handler flow was usually measured with a multi-point temperature rise test. Operating pressure information is extremely important, as the pressure acting on duct leaks is a major determinant of leakage during normal heating conditions. Technicians were also required to note duct insulation levels and to measure the ducts so that conductive loss could be estimated.

The protocol required the collection of additional data. Heating system nameplate information is recorded so that manufacturer's information can be consulted (especially useful for heat pumps). Technicians are encouraged to note operations and maintenance problems with the heating equipment, including obvious electrical problems and dirty filters.

For homes heated with heat pumps, a whole-house heat loss rate is needed in order to estimate the split between compressor/backup electricity consumption under various winter conditions.

The protocol also requires health and safety checks be performed. All houses are evaluated for their worst case depressurization potential; that is, the degree to which parts of the house containing one or more combustion appliances (woodstove, fireplace, gas fireplace, etc.) become depressurized as exhaust fans are turned on and interior doors closed. For houses with ducted combustion appliances, carbon monoxide levels were measured. Almost all the homes visited during the study were 100% electric, so the carbon monoxide issue did not require much attention.

3
RECRUITMENT AND SCREENING

The sample for reviewing the regional duct retrofit program is divided into two portions. The first and largest portion is the result of two utility pilot programs conducted by PSE and PGE. These two programs were approved by the respective state regulatory agencies (with certain distinctions based on the particulars of the utility filings). The overall screening results presented here are restricted to electrically heated single-family homes.

3.1 Utility Pilot Programs

The principal difference between the PSE and the PGE programs involved the recruitment strategies employed. Ecotope provided the recruitment, screening and duct retrofit services for the PSE program. Recruitment was based on advertisements, articles and other media promotions to reach individuals interested in having a duct review and potential duct retrofit at the utility's expense. In exchange, homeowners provided access to their homes as well as billing and other information required for program evaluation.

Since these techniques were fairly broad, a substantial fraction of the individuals who responded to the advertisements and press releases were ineligible or did not meet the heating system criteria. The PSE program retrofit ducts in homes heated by both gas and electricity. Assessments of both types of heating systems occurred in this program.

The PGE program used a direct mail utility marketing campaign to target homes with large energy loads. Homeowners received a questionnaire that they could mail back to the utility if they were interested in a possible duct retrofit. Since the recruitment required that potential participants fill out a full questionnaire and the utilities screened homes as part of their direct mail campaign, recruitment netted homes more likely to meet the criteria. However, the utility limited its participation to electrically heated homes and approximately two-thirds of the homes targeted were manufactured homes.

As a result of these recruiting efforts, certain homes were selected to receive a field screening. This protocol was designed to provide the information necessary to assess the impact of duct retrofits. Overall, the cost of recruiting and marketing was assessed based on the experiences in the PGE and PSE programs. While these two programs had noticeably different recruiting strategies, overall costs to recruit each potential candidate varied between about $18 and $40 per eligible home recruited. For purposes of the cost benefit analysis and overall program cost calculations, we used the higher rate of $40 per home. This is consistent with the PGE program, which tended to achieve a higher percentage of homes passing the screening tests.

3.2 Oregon Office of Energy Recruitment

Various cooperating utilities and State Extension Services conducted recruitment in this program. Recruitment was limited to single-family electrically-heated homes in target utility areas. This recruiting combined newspaper press releases and advertisements with direct bill inserts to clients. Previous weatherization program customers and similar clients were also contacted. This effort was fairly diffuse, since eight separate utilities were involved, in addition to the Washington and Oregon Energy Extension Services and the Department of Water Resources in Idaho. Tracking and costing of the recruiting was essentially impossible and largely incomparable between the various utilities. However, these methods were able to provide a list of homes that were likely to be good candidates for duct sealing.

3.3 Screening Results

The field screening process in all of the utility programs, including the PSE and PGE pilot programs, was the same. In all cases, a field crew was dispatched to conduct a pressure pan review of the duct system and perform a visual review of the heating system. In some cases, a Duct Blaster™ test was conducted, greatly improving the evaluation of the candidate for retrofit suitability. In the PSE program, an additional review was conducted on the furnace and the filter (and the combustion efficiency for a gas furnace). In all cases, filters and thermostat function were reviewed as part of the heating system and duct screening.

The most successful recruitment and screening effort occurred in the Benton County PUD service territory. This was due to the observation that all HVAC systems built by a particular installer were nearly 100% likely to require a duct retrofit. Thus, after a phone screening that ascertained the homes' installer, a screening could be scheduled with very high probability of success. While this was a fortuitous situation, it seems unlikely that it could be replicated.

The second most successful screening effort occurred in the PGE program, in which homeowners with higher-than-average bills filled out a mail-in survey. This approach eliminated some of the substantial failure rate observed in other localities. The Zone 3 homes (Idaho Falls and the state of Montana) were extremely disappointing: in no case was the recruiting or screening level successful enough to justify a stand-alone duct program. In Montana, even in relatively old homes with favorable configurations, ducts were sufficiently tight to negate the need for a retrofit, or the crawlspace in which the duct was located was unvented and heat loss from the duct was largely regained by the house.

In Zone 3 it is apparent from the success rate of less than 10% that a program focusing on the colder areas of the region, particularly the Montana service territory, is neither well advised nor likely to deliver any savings. Heating system review could still be applicable to these localities. For the cost-effectiveness evaluation, the recruitment percentage observed in Climate Zones 1 and 2 have been used to assess the overall cost of screening candidates for a successful duct retrofit.

In specific localities, such as Sun Valley, the use of vented, uninsulated crawlspace buffers seems to be a normal construction practice and so more eligible homes were observed in those localities than in most of the other colder areas of the region. However, the experience with the screening indicates that the focus of a duct retrofit program should be on warmer climates where vented buffer spaces more routinely contain a substantial fraction of the duct work.

Table 3-1 illustrates the results of the screening and recruitment efforts throughout the region. Only the OOE program was operated in eastern Washington, eastern Oregon and Idaho. Results for these areas characterized the level of effort achieved in the program by the participating member utilities. In western Washington and western Oregon, the PGE and PSE pilot programs each addressed about 2,000 homes in the recruitment process and field-screened over 300 single-family homes. Detailed data collection was performed for only a fraction of the homes in those programs. The cost-effectiveness analysis could only be conducted on that fraction.

Table 3-1
Field Screening Rates for Single-Family Homes

Program	Reviewed	Accepted	% Accepted
Puget Sound Energy-Gas	166	74	44
Puget Sound Energy-Electric	71	53	74
Portland General Electric	524	271	52
Benton County PUD	12	8	75
Chelan County PUD	18	9	50
Ashland PUD	53	15	28
Kootenai Electric	8	5	62
Montana Power / Missoula Electric	24	1	4
Idaho Power	28	12	42
City of Idaho Falls	8	2	25
Clark / Tacoma PUD	10	6	60
Total	922	456	49
Climate Zone 1	824	419	51
Climate Zone 2	66	34	51
Climate Zone 3	32	3	9

In the Portland program, approximately two-thirds of the effort was expended on manufactured homes. In the PSE program, approximately two-thirds of the homes were gas heated. Both of these subsets provide insights into the nature of a retrofit program for the region but were excluded from the cost-effectiveness analysis for the regional program. This program was designed to focus on single-family, site-built electrically-heated homes.

Figure 4-1 shows the distribution of homes retrofit under the program and the geographic distribution of localities participating in the program.

4
DUCT RETROFIT EFFECTIVENESS

Duct retrofits were conducted within the programs throughout the region. The sample methodology targeted utility districts in the eastern half of Washington and Oregon, as well as in Idaho and Montana. The pilot programs in the PSE and PGE service territories in the Portland and Seattle areas were supplemented by the City of Ashland territory and some participation from Clark County PUD and Tacoma Public Utilities. To accomplish the research goals of this project and provide a well-developed first order estimate of savings, the Ecotope duct model was employed. This model was developed using the results of detailed metering and monitoring on homes in the Northwest region (Palmiter and Francisco, 1996) and has been extensively validated. However, the model requires extensive, high-quality data that cannot always be ensured in large-scale research endeavors of this type.

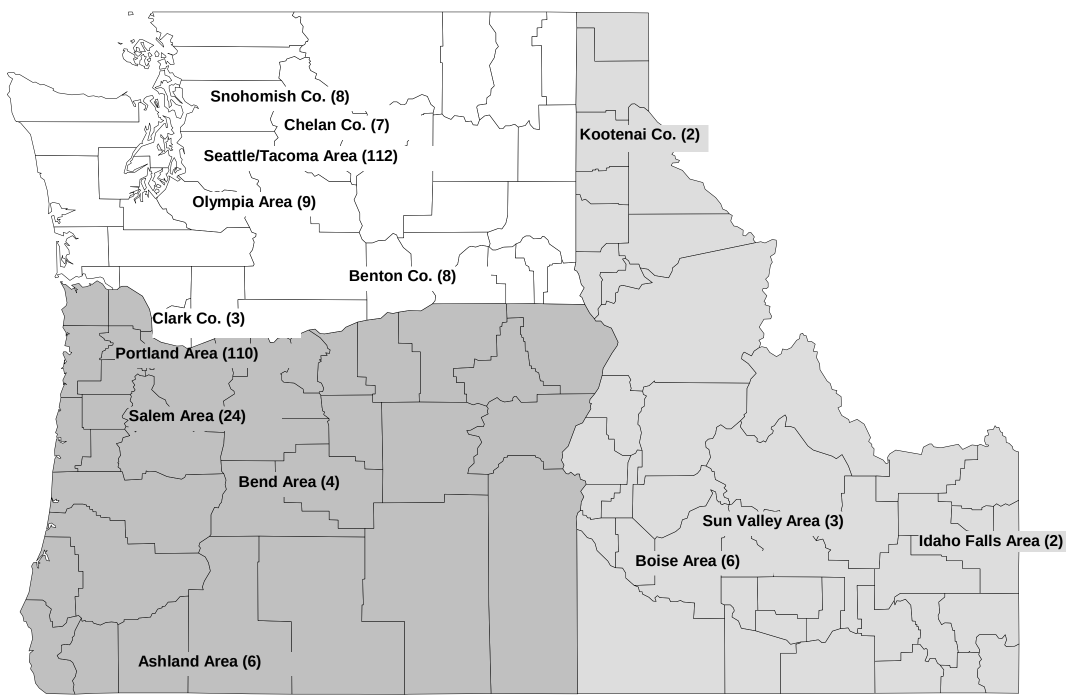

Figure 4-1
Geographic Distribution of Retrofits

Table 4-1 shows the number of homes modeled for a cost benefit analysis. Modeling was limited to homes heated with electric resistance furnaces or heat pumps and with sufficient information to employ the duct model. The PGE program included approximately 15 homes that were evaluated with a more simplified model based on Duct Blaster™ and air handler flow information only. This model used a standard set of modeling assumptions to develop a savings estimate. These homes were included here since they were integral to the overall study design for that pilot program. This simplified modeling technique was not employed by any of the other participating utilities, although a small increase in savings estimates might have been possible in some localities through use of this method.

Table 4-1
Homes Retrofit and Fully Modeled

Program	Retrofit	Modeled*
Puget Sound Energy	127	27
Portland General Electric	134	35
Benton County PUD	8	6
Chelan County PUD	7	3
Ashland PUD	6	5
Kootenai Electric	2	2
Montana Power	1	0
Idaho Power	9	8**
City of Idaho Falls	2	2**
Clark/Tacoma PUD	5	0
Central Electric Co-Op	4	4
Total	305	91

* Homes used in savings analysis and cost/benefit analysis.
** Some Idaho homes were in Zone 3 climates but were combined with Zone 2 homes for this analysis.

The most demanding evaluation methodology was based on Ecotope's duct model developed for the Bonneville Power Administration and the Electric Power Research Institute (Palmiter and Francisco 1997). This methodology uses detailed field data to assess energy savings from duct retrofit. However, a variety of conditions in the field can make it difficult to gather the information necessary to inform this model. Depending on the robustness of the available data, a variety of engineering methods were employed to evaluate each home. A detailed description of the model and analysis techniques is included as Appendix D.

The duct model methodology requires direct measurement of change in duct leakage, furnace air flow, duct system size and insulation levels. Since the protocol requires that the total furnace flow be measured (either by using a flow hood to measure flows at each register or by using another method such as temperature rise across the furnace), the retrofit contractor or quality control technician had to be extremely careful in performing these measurements before and after the retrofit. This proved to be much more challenging than anticipated, resulting in the loss of sites for modeling in several cases.

Table 4-2 summarizes the results of the modeling analysis. The 23 homes in Zone 2 receiving full modeling are the basis for the full savings calculations for Zone 2. The Ashland results were weighted with the PSE and PGE results (assuming that the Ashland climate zone represents 4% of the total population of Zone 1). This analysis has virtually no effect on the relatively large samples from PSE and PGE, although the billing analysis was used to derive the correction for sites which could be modeled but for which no billing analysis was conducted.

Table 4-2 is divided into two sections. The first section includes all the modeled homes from Eastern Washington, Oregon and Idaho that are considered the colder Zone 2 homes. The second section includes only those homes retrofit under the OOE program in Zone 1 that are all in the Ashland service territory. While other homes were retrofit in Zone 1 under this program, they were either part of the PGE and/or PSE program or did not receive enough detailed field review to be modeled using the procedures presented here.

Both the modeling results and the billing analysis results are presented in Table 4-2. The modeling results used heat loss information from the house to project a total heating and cooling load. A savings estimate was developed from this model. This approach assumes a constant 68° Fahrenheit set point throughout the heating season and no additional supplemental heat source. Wood heat, electric space heating, or other supplemental heat are not included in this analysis. While efforts were made to screen out homes with supplemental heat sources, some amount of wood heat was used in several of the retrofit homes.

Table 4-2
Savings Summary

ID Location	Equip.	Model Results		Billing Analysis		Savings kWh	Savings ratio
		Savings %	Savings kWh	Total kWh	Space kWh		
201 Nampa	3.5T HP	0.0	0	28920	17740	0	1.000
202 Caldwell	15 kW EFA	32.9	11487	50175	36471	11999	1.045
203 Melba	20 kW EFA	3.8	664	25889	13385	509	0.766
204 Nampa	2T HP	10.8	4195	38428	15740	1700	0.405
205 Nampa	15 kW EFA	13.7	3300	28416	15924	2182	0.661
206 Hailey	15 kW EFA	10.7	3183	32125	21673	2319	0.729
207 Sun Valley	25 kW EFA	17.3	7955	42993	31881	5515	0.693
208 Bellevue, ID	4T GSHP	9.4	785	55405	22553	2120	2.701
221 Chelan	3T HP	12.9	1788	30082	12014	1550	0.867
222 Wenatchee	15 kW EFA	6.3	1590	45630	20442	1288	0.810
223 Leavenworth	2.5T HP	26.6	4382	24051	15487	4120	0.940
241 Bend	2.5T HP	19.6	3720			3359	
242 Bend	20 kW EFA	6.5	1519	29991	21099	1371	0.903
243 Bend	25 kW EFA	3.6	1235	26161	9265	334	0.270
244 Bend	3T HP	5.9	863	19825	13757	812	0.941
245 Kennewick	20 kW EFA	34.0	10050	25360	15280	5195	0.517
246 Kennewick	15 kW EFA	3.2	689	46960	10960	351	0.509
247 Kennewick	15 kW EFA	12.6	2814	41720	18200	2293	0.815
248 Kennewick	20 kW EFA	14.2	2708	27970	6538	928	0.343
249 Finley	15 kW EFA	5.9	1271	57223	21091	1244	0.979
250 Kennewick	3.5T HP	11.5	2015	34432	19688	2264	1.124
271 Idaho Falls	20 kW EFA	2.2	583	39319	18991	418	0.717
272 Rathdrum	5T GSHP	3.2	179	40444	17996	576	3.217
273 Hayden	3T HP	18.8	2840			2565	
101 Ashland	1.5T HP	26.3	2591	19734	7026	1848	0.713
102 Ashland	3T HP	4.8	641	13726	6610	317	0.495
103 Ashland	2.5T HP	28.6	2684	19712	8876	2539	0.946
104 Ashland	1.5T HP	59.9	15362	14883	7323	4386	0.286
105 Ashland	30 kW EFA	5	850	26424	16860	843	0.992
Total Zone 2&3		11.9	2909.0			2292	
Total Zone 1*		24.9	4425.6			1987	
Total All Cases		14.1	3170.4			2239	

*not including the PGE and PSE pilot homes

The billing analysis was based on one to three years of historical billing records for each home (in two cases, no bills were available). Based on this billing analysis, savings were estimated using a median low bill approach (Kennedy 1994). This procedure is designed to gain a space heat estimate from the billing pattern and is considerably more robust than PRISM® or other regression analysis.

However, for homes with heat pumps, the estimates are substantially biased. A detailed analysis of the Portland and Salem areas conducted for PGE (Baylon, et al. 1999) showed an offset which totaled a 4,000 kWh/yr in homes with heat pump or air conditioning systems. This 4,000 kWh/yr includes approximately 2,500 kWh of space cooling and 1,500 kWh of bias introduced by the overlap between the cooling and heating seasons. In most billing analyses, values presented for space heating and cooling include a correction for this bias.

The billing savings analysis uses the results of the modeling multiplied by the estimated space-conditioning load (from the bills). Finally, a ratio between the savings estimates conducted directly from the modeling and the savings derived from the billing analysis is presented. The average ratio is .906, meaning the model underpredicts savings for this set of homes.

The results of the PGE and PSE programs were used to establish the overall impact of a regional duct retrofit program (Table 4-3). These two utilities dominate the Zone 1 climate zone, accounting for 96% of the savings from this program. (The remaining four percent was derived from the Ashland retrofits - see Table 4-2). The Zone 2 savings were used for the cost benefit analysis in cold climates (Section 6). Manufactured homes retrofit under the PGE program are not included in this analysis but are included for reference.

Table 4-3
Energy Saving From Duct Retrofits (kWh)

	Site Built Homes				Manufactured Homes	
	Heat Pump		Electric Furnace			
Utility	kWh	%	kWh	%	kWh	%
PGE	1389	11.00	1261	10.00	1310	14.30
PSE	1687	14.00	1739	13.00		

5
RETROFIT AND SCREENING COSTS

The cost analysis conducted for these data used labor and retrofit materials costs provided by the retrofit contractors. In most cases, this estimate included a post-retrofit quality review conducted by the contractor. The quality review included a Duct Blaster™ analysis or a pressure pan analysis designed to inform the contractor and homeowner of the success of the retrofit. Using an average field billing rate of $40 per person per hour, the overall cost of retrofits in this program averaged $382 for the 27 homes for which these data were available. This compared to $368 a home in the PGE program (that did not include any on-site quality control) and $420 in the PSE program (that did include on-site quality control). For purposes of this analysis, an estimate of $400 per home per retrofit (including contractor-performed quality control) was used. Substantially greater or lesser costs could be anticipated depending on the difficulties encountered at a particular house.

These costs do not include the screening costs done before the retrofit. In this regional analysis, as in the PSE and PGE programs, screening was conducted by the utilities separately and costed separately. In the regional program, actual screening costs were not collected since these costs were mostly incurred by various Energy Extension Office personnel. Therefore, the experience in the PSE and PGE programs was used to establish screening costs for this analysis. Table 5-1 summarizes the costs associated with the entire regional program and used in the cost/benefit analysis.

Table 5-1
Cost Data

Cost Components	
Marketing / Recruiting	$ 40
Screening	$ 150
Measure	$ 350
Quality Control	$ 50
Consumer Benefit (*subtracted)*	$-100
Total (with screening and marketing)	$ 490

Marketing and screening costs are combined to describe the cost per home identified in the screening as being eligible for a cost-effective duct retrofit. The number of homes that must be screened to yield a retrofit candidate varies substantially between climate zones and utility programs. An average screening ratio of 51% was observed across the entire program. This reflects the impact of an all-electric program in most localities but also largely shows the probability of ducts requiring a retrofit once they have been determined to be in unheated buffer areas. Zone 3 was not included in this analysis, since the screening ratio in Zone 3 suggests a duct retrofit program is impractical.

Another benefit, while much more intangible, is very important to the overall program design. The fact that there are numerous opportunities to market services to homeowners beyond duct retrofits should be attractive to contractors and serve as a benefit from the screening process that significantly outweighs the cost of this service. Neither of the utility programs was designed to understand this potential benefit.

To understand this better, a data set generated from contractors participating in the Oregon duct retrofit tax credit program was reviewed. Invoices from the early stages of this program detail the services offered and purchased as a by-product of marketing duct retrofits through the current Oregon certification program. The sample here is small, 50 homes, but Figure 5-1 illustrates the distribution of invoiced services. These data indicate that about 65% of the sales were not associated with duct evaluation or duct sealing.

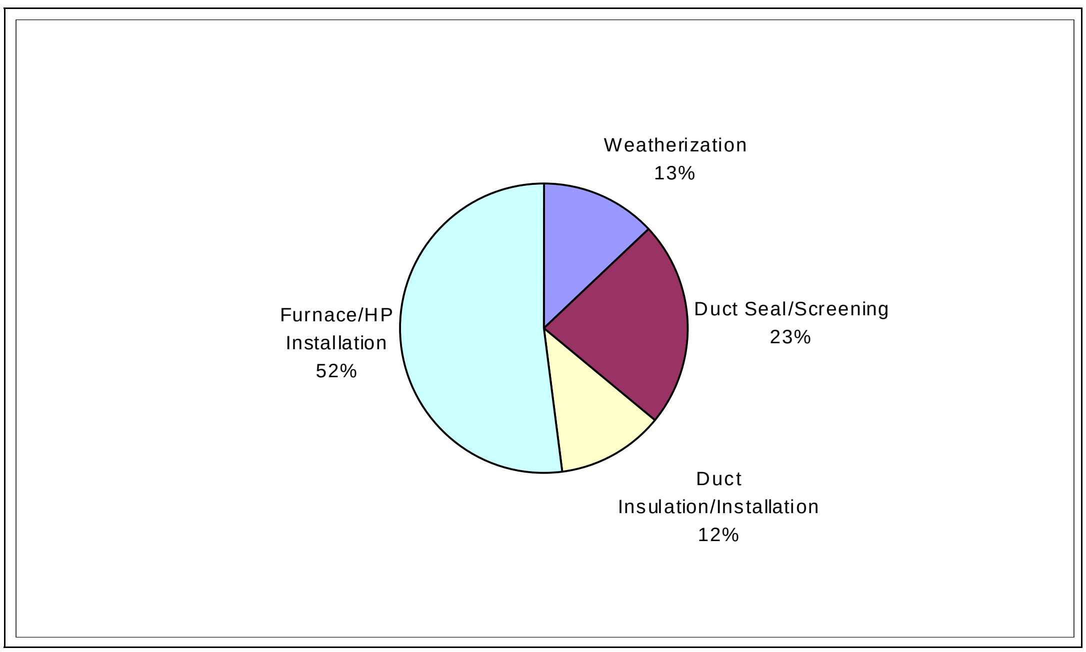

Figure 5-1
Invoiced Services

A benefit analysis was conducted on the screening using information derived from a more extensive market-based program conducted in Oregon under the Oregon tax credit program. This analysis suggests that only about a third of the cost of screening should be applied to the actual duct retrofit. The remaining cost could be described as a benefit to both the consumer and the contractor, both in identifying marketing opportunities for other services and in providing health, safety and maintenance reviews not directly related to ducts. For example, a consumer would benefit from knowing that their system filters are dirty and need cleaning, or that an electrical relay or thermostat is malfunctioning. Or the house may need a new furnace or more insulation and since the contractor was already at the house to look at the ducts, he would not have to return for a second visit to bid a new heating system or weatherization job. For this analysis, a benefit of $100 was assumed for the screening.

6
RETROFIT COST - BENEFIT ANALYSIS

The overall cost-benefit analysis for a duct retrofit is divided into three parts:

1. The cost and benefit of the retrofit measure itself is evaluated. In this case, a cost of $400 was assumed for the duct retrofit. The retrofit costs in the PGE program averaged $368 per home and in the PSE program averaged $420 per home. These costs, when averaged with the other Oregon retrofit costs, average $382 per home. These costs are reasonably comparable, but some screening and quality control costs were peculiar to individual programs. Given this uncertainty, overall cost of $400 per home seems to best represent the experience of the PGE, PSE and NEEA programs.

   Percentage savings were derived from the modeling analysis and applied to the bills collected in each home. This technique includes the effects of supplemental heat on the electric bill and thus reduces the savings estimates in cases where there is significant supplemental heat, since the modeling assumes all heat is provided by a central furnace or heat pump. An energy savings analysis was done for each of the localities in the region and in each of the pilot programs. Zone 3 was not included as a separate analysis since only three homes were retrofit and since screening costs in Zone 3 were extremely high. The retrofit homes in Idaho that are in Zone 3 climates are included in the Zone 2 results.

2. The second cost-benefit analysis attempts to use costs associated with screening and marketing to assess the overall cost-effectiveness of this program. The additional costs of screening and marketing are applied to all homes that received a screening review as a result of a utility or private marketing campaign. Since only half of these homes would be eligible for a duct retrofit, this cost is doubled when applied to the individual retrofit.

3. The third analysis takes into account the benefits identified from screening beyond the identification of duct leakage; namely health and safety benefits and other marketing opportunities for heating system replacement and building envelope weatherization. A value of $100 per home screened (roughly the cost of a gas furnace review in the Seattle area) was assigned to partially account for the potential benefits that might accrue. This service includes filter cleaning and general assessment of heating system function. The benefit applies to all houses not just those retrofit, since all houses visited may benefit from the O&M services. Therefore, the benefit is effectively doubled for each house retrofit, since only 50% of the houses visited need retrofits.

Table 6-1 summarizes the cost-benefit analysis for these three approaches from the utility's perspective.

Table 6-1
Utility Costs vs. Benefits

Cost-Benefit Per House Retrofit	Zone 1	Zone 2
Number of homes modeled	67	24
Savings (kWh)	1597	2291
Cost (measure only)	$400	$400
Cost/Benefit (mils/kWh)	16	11
Cost (w/ screening and recruiting)	$780	$780
Cost/Benefit (mils/kWh)	32	22
Cost (w/ screen, recruit, & benefits)	$580	$580
Cost/Benefit (mils/kWh)	24	16

Table 6-2 provides the same analysis from a consumer perspective. In this perspective, the consumer is assumed to only pay for services provided directly to their home, thus the screening cost is not multiplied by any additional screening factor, but is priced to include both the screening and marketing costs associated with the individual homes. Using the results from Table 5-1, this adds $190 per home to the measure cost of $400. As with the utility review, an operating and maintenance benefit of $100 is assumed, leaving a net cost of screening review of $90 per house.

Table 6-2
Customer Costs vs. Benefits

Customer Simple Payback (yrs)		
Retrofit	**Zone 1**	**Zone 2**
Retrofit measure only	4.2	2.9
Retrofit measure plus screen with benefits	4.7	3.3

(Energy cost of $0.06/kWh.)

As can be seen from reviewing Tables 6-1 and 6-2, duct retrofits are cost-effective from a utility point of view. The measure cost is 16 mils per kWh in Zone 1 and 11 mils per kWh in Zone 2. These costs double when the full cost of screening and marketing are taken into account (from a utility perspective). However, with the additional benefits identified, overall utility costs are about 24 mils in Zone 1 and 16 mils in Zone 2.

Consumer payback periods of about three years are typical for the measure costs in Zone 2. This is largely a function of the relatively colder climate and larger amounts of cooling loads in Zone

2, while in Zone 1 the measure costs require slightly more than a four-year payback period. When screening costs and benefits from screening (viz. a $100 credit) are added in, payback periods rise to approximately five years in Zone 1 and just over three years in Zone 2. (No utility recruiting costs are included in the customer cost analysis.)

7
CONCLUSIONS AND RECOMMENDATIONS

The development of a retrofit duct program throughout this region has been based on the need to create a market-based, self-sustaining enterprise modeled after the regional market transformation goals. While the measure costs of duct retrofits are very attractive from the perspective of the utility or the consumer, the cost of identifying a retrofit opportunity can equal or exceed the cost of the measure itself. This suggests the need to integrate screening and heating system assessment into the overall program design so that the extensive screening requirements do not jeopardize the cost-effectiveness of the retrofit measure.

In the PSE program, up to 30% of the gas furnaces reviewed had significant safety or health problems that required immediate attention in the form of furnace and burner tune up, cleaning or even furnace replacement. The energy savings from this could easily have been equivalent to the duct savings but rectification of health and safety issues often outweigh the immediate energy savings. In heat pump programs, especially in eastern Washington and the Ashland area, several noticeable problems suggest the need for periodic review.

The Oregon duct improvement tax credit data shows only about a third of the overall consumer expenditures were directly related to ducts (HVAC contractors marketed and installed weatherization and heating system upgrade services as part of duct assessment). Customers often upgraded their heating systems at the time the duct improvements were performed. Many customers received the duct retrofit as an added service from the installer of new heating equipment. This model provides cost-effective benefits for the customer, the utility and the HVAC contractor.

Overall program results suggest a savings rate of about 12% of the space conditioning energy. This savings rate is consistent among all of the large samples drawn for this project and consistent across climate zones. The savings levels represented are about 1,500 kWh in Zone 1 and about 2,300 kWh in Zone 2. Using this as a guideline, individual consumers can be offered a system with payback periods of three to four years for the duct retrofit measure. In cases where serious problems exist, savings two to three times the average observed levels could be expected. This can result in payback periods of as little as one year.

The results of this regional study, and of the individual studies comprising this sample, clearly indicate that substantial savings are available from retrofitting homes with significant duct leakage into unheated buffer spaces. However, the relatively low number of homes with such leakage levels and the difficulty in identifying these homes without an expensive site visit indicate that a stand-alone duct sealing program is unlikely to be cost-effective.

A cost-effective program can be developed, however, around a duct retrofit service that is combined with additional services. Anecdotal evidence from the field crews indicate that customer interest in HVAC system evaluation and maintenance was at least as popular as the duct retrofit service itself. These services to offered can include a combination of some or all of the following:

- Heating/Cooling system and duct system inspection and assessment
- Routine maintenance services, including furnace tune-ups
- Review of natural gas safety and flue gas emissions
- Review of heat pump charge and function, perhaps with refrigerant addition or removal
- Review of thermostat, heat pump and furnace controls
- Assessment of insulation and weatherization opportunities

A program including some combination of these services is likely to be both cost-effective and popular with consumers.

8
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A
SCREENING QUESTIONNAIRE

Duct Sealing Candidate Telephone Interview

Status ________________________

Contact name ________________________ Interviewer
Name/org.________________________

Address/phone
____

Date of call _____________ Time of call ________________

Intro: Good day. This is _____________________calling from ______________________. I am contacting homeowners in this area to tell them about an energy conservation program offered through Montana Power. The program's purpose is to fix leaky ducts and measure the energy savings. We are looking for houses with electric forced-air heating systems and ductwork that runs in unheated areas such as crawlspaces and attics. As part of the program, our crew will also evaluate your home for indoor air quality and other health factors. The diagnostic and retrofit work is provided free of charge by the utility.

All work will be performed by licensed, bonded contractors. The crew will be able to inform you of the general condition of your heating system and related issues when they visit your home.

We would like to take a look at your most recent 12 months of billing information just to get an idea of how much heating energy you are using. This information will be kept confidential. Is this all right with you? ____yes ____no.

If you are selected for the program, we will make a short visit to your house to measure the duct leakage and perform other measurements. Depending on the results of these tests, we will schedule you for a retrofit.

I have several questions to ask which should take about five minutes of your time. Can we do this now or should we reschedule a time?

Rescheduled time ___________________________

Contact's phone (home and/or work?) ______________________

Interview

1. Type of house? single family ______ apartment _______ mobile _____
   if apt or mobile home, **END interview**

2. What type of heating system do you have/use? (Check all that apply- Indicate the percentage of each that you typically use)

_____% electric forced-air *location*_____________
_____% gas furnace *location* ___________________
_____% heat pump *indoor unit location* __________
_____% baseboard electric heat
_____% wall space heaters
_____% cable ceiling heat
_____% kerosene or propane heaters **(vented? __________)**
_____% portable plug-in electric space heaters
_____% fireplace/woodstove *location* ____________
_____% gas log/fireplace **(vented? _________)** *location* _____________________
_____% through the wall/window heat pump *location* __________________

If >75% of heat not provided by central system, home is unsuitable for the study. Thank homeowner for their time and end the interview.

3. Type of foundation? crawlspace ___ slab on grade _____ basement _____
If basement, ask if majority of ducts in basement, if so **END interview**

4. Where are the warm air ducts mostly located? If split between different locations, indicate rough percentage in each zone: basement ____ crawlspace _____ attic _____ garage ______ inside house (between floors or otherwise) _____

5. What is the approximate square footage of your home? ________

6. How many people live in the home? _________

7. When was the home built? ____________

8. Number of stories? one ____ two _____three _____ split level Y ____N _____

9. Do you have frequent moisture build-up problems such as condensation on your windows and/or mold/mildew growth? Y ____ N____ in which room(s) does this happen?
____

10. Do you have any natural gas/LPG appliances (other than furnace/fireplace/log)?
water heater _____ oven/cooktop ____ dryer ____
location of gas water heater ___________

11. (If water heater not n. gas/LPG) What type of water heater(s) do you have?
electric ______ other (specify) ______________________

12. What are the insulation levels in the home (R-values or inches):
    wall _______ attic/vault ______ floor _______ ducts______
    window type _______

    Any other details (utility wx program participation, etc.)
    ____
    (Encourage homeowner to do their best; many will not know some/all of these values)

13. Do you have any mechanical cooling equipment (air conditioning). If so, what type of cooling system do you have/use? (Check all that apply- note how often each used.)

_____ whole house air conditioner (works with same ducts as furnace
use_________________

_____ through the wall/window air conditioner
use_________________

_____ evaporative cooler ("swamp cooler")
use_________________

14. Any heating/cooling problems (hot/cold rooms) to report (including equipment problems)? Describe:

    (use back of page as necessary)

Any major appliances used more than once per week? Indicate number of each and note operation schedule if used frequently.

_____ hot tub (fuel type/use: __________/_________)
_____ spa use ___________
_____ swimming pool (heater fuel _________)
_____ green house with lights/ electric heat; use ___________
_____ pumping or watering equipment; use____________
_____ welding/shop/kiln equipment; use ____________
_____ extra refrigerator/freezer; use ____________

16. At what temperature do you maintain your house during the heating season? Approximately how many hours/day do you use this setpoint? when home (#hrs)? ____ (___) when sleeping (#hrs)? ____ (___)

Thank you for your time. We will review the information and call you back if you qualify to schedule a field visit to measure your duct leakage.

B
PROCEDURE FOR ESTIMATING DUCT LEAKAGE FRACTION

Outline of Procedure for Figuring the Leakage Fraction

1. Measure register flows and pressures. Use flowhood calibration equation to condition raw flows. Correct each flow to standard conditions of temperature and pressure using the SCFM.xls spreadsheet.) Sum register flows. (Alternately, use the temperature rise method to estimate air handler flow. For HPs, the test must be conducted in resistance-only mode.)

2. Determine flow exponent (*n*) and coefficient (*C*) for total (to inside and outside) duct leakage. Refer back to the field data from the total duct leakage test. Use the power law equation ($Q = C\ \Delta P^n$) to do this, putting in measured values for Q and ΔP and solving first for the flow exponent and then for the coefficient. For example, if the test pressures are exactly 50 and 25 Pa WRT out,

   $$Q_{50} = C(50^n) \text{ and } Q_{25} = C(25^n)$$

   (Note the testing pressure differentials may not be exactly 50 and 25 Pa; the exact testing pressures must be used.) Equating $Q_{50}/50^n$ and $Q_{25}/25^n$ (they both equal C) and then solving for *n*, we get

   $$n = \ln(Q_{50}/Q_{25})/\ln(50/25)$$

   Substitute in the values from the test to find *n*. Once *n* is determined, use it in the power law equation, along with known values for ΔP and Q, to find *C*. Write down the power law expression for total duct leakage with the *C* and *n* you have found.

3. Determine system operating pressure (crucial). Measure static pressure at both the supply plenum and all registers. A long (12”) Pitot tube is best. Come up with a weighted average pressure; we generally give the registers 75% of the weight and the plenum 25%. Example: if the average of the supply register statics is 5 Pa and the supply plenum static is 35 Pa, the weighted average system operating pressure is

   $$0.75(5\text{ Pa}) + 0.25(35\text{ Pa}) = 12.5\text{ Pa}$$

4. Substitute the calculated system operating pressure into the flow equation from Step 2. This gives you the total duct leakage at operating pressure.

5. Add the value from step 4 to the sum of the register flows. You now have the air handler flow. (If using temperature rise method for determining AH flow, skip this step.)

6. Repeat Steps 3 and 4 for duct leakage to the outside. That is, determine the flow equation for exterior duct leakage, use the system operating pressure as the P in the power law equation, and calculate the duct leakage to outside at operating pressure.

7. Divide the result of Step 6 by the air handler flow (step 5). You now know the leakage fraction.

Here is an example of how this goes. **Note this is for the supply system only,** as that's what we'll be mostly dealing with in this program. (The steps would be the same for the return, we are just calling your attention to the fact that we are only dealing with one side of the distribution system):

Measurements (this is what you would have from doing the field protocol; I just chose some plausible round numbers):

Test	Leakage @ test P WRT out	Leakage @ test P WRT out
Supply leak total	625 CFM @ 52 Pa	390 CFM @ 27 Pa
Supply leak to out	300 CFM @ 50 Pa	190 CFM @ 25 Pa

Sum of register flows (corrected to standard conditions with spreadsheet): 625 CFM
(This is Step 1 of "finding the leakage fraction" procedure described on the previous page.)

Average of register static pressures: 6.5 Pa
Supply plenum static pressure: 32 Pa

Step 2: Determine power law equation for total leakage and correct total leakage down to standard operating conditions:

General form of equation $Q = C\,\Delta P^n$ -- we first solve for *n*, then solve for *C:*

$n = \ln [Q_{near\ 50}/Q_{near\ 25}]/\ln [\Delta P_{near\ 50}/\Delta P_{near\ 25}] = \ln (625/390)/\ln(52/27) = 0.472/0.655 = 0.720$

(Note "ln" is natural (base *e*) log. Also note this is also how we find the flow exponent for checking how good a blower door or duct blaster test has turned out)

$$Q = C\,\Delta P^n \quad \text{so } C = Q/\Delta P^n \quad \text{and in this case } C = 625/52^{0.72} = 36.34$$

So the flow equation for total duct leakage in this house is $Q = 36.34\ \Delta P^{.72}$. Next we need to find the pressure to put into the equation; that is, what is pushing on those duct leaks?

Step 3: Determine average static pressure in supply system:

> This requires some heroic assumptions. We have found through looking at coheat results that a pretty good approximation of average system pressure is found by giving 75% of the weight to the registers and 25% weight to the supply plenum. However, if you know where the leaks are (that is, if you know almost all the leakage is near the plenum, for example) the plenum pressure should get more of the weight. This is a judgement call.

For our case, we will use the 25:75 split:

Avg system static = 0.75(6.5 Pa) + 0.25(32 Pa) = 12.9 Pa

Step 4: Determine total leakage at average static pressure ("operating conditions") in supply system:

$$Q_{total,\ oper.\ P} = 36.34(12.9)^{.72} = 229.1\ \text{CFM.}$$

Step 5: Add supply leakage at operating conditions to sum of register flows (from Step 1) to get air handler flow (denominator of supply leakage fraction ratio):

229. 1 CFM + 625 SCFM = 854.1 CFM

Step 6: Determine power law equation for exterior leakage and estimate leakage to outside at operating static:

This is the same thing we did in Step 2 but we use the results from the duct leakage to outside test to get *n* and *C* this time around.

$$n = \ln [Q_{near\ 50}/Q_{near\ 25}]/\ln [\Delta P_{near\ 50}/\Delta P_{near\ 25}] = \ln (300/190)/\ln(50/25) = 0.457/0.693 = 0.659$$

$$C = 300/50^{.659} = 22.78$$

$$Q_{to\ out,\ oper.\ P} = 22.78(12.9)^{.659} = 122.9\ \text{CFM.}$$

Note how our whopping 300 CFM to out at 50 Pa has diminished to only 123 CFM at normal operating conditions.

Step 7: Determine supply leakage fraction (SLF). This is the percentage of conditioned air which is not making it into the house through the expected duct pathway:

SLF = leakage to out at operating pressure/air handler flow = 112.9 CFM/854.1 CFM = 14.4%

Discussion

Now what? We generally consider a 15% SLF as a pretty good bet for a cost-effective retrofit, because there's room for improvement and we can expect to actually see something in the bills. But in order to go ahead we still have to consider a few things. (Note this list is not exhaustive, but it reflects what I usually consider in the majority of cases where a decision is being made whether to proceed):

- Do we think our crew can get rid of half the leakage? Can they get to the leaks in a reasonable time? They will need to get about half of the SLF to make a difference. Most crews should be able to do this, but someone needs to make sure the ducts are accessible and there are no other impossible conditions.
- Is there at least R-8 between the buffer space containing the ducts and the inside of the house? If not, quite a bit of the "waste heat" will return to the house. If the buffer space is uninsulated, we would like to see at least a 20% SLF to start. If we have perimeter insulation and uninsulated joist bays, regain is close to 100% so very high leakage is needed for electric furnaces (>40% SLF) and houses with heat pumps need at least a 25% SLF.
- If the house is two story or split-level, at least half the potential savings go away because at least half the ducts are inaccessible without surgery. So the crew needs to be very thorough on the remaining half of the system that is accessible. If the starting point is a 15% SLF, the crew has to be thorough to get the 50% reduction in SLF.
- Even if the crew may not be able to get half of the leakage, they can still do some homes with lower SLFs (say 10%) if the heating load of the house is sizable. For example, if we have a house with an estimated annual heating load of, say, 15000 kWh, and the crew gets half of a 10% SLF, or 5 points on the 1-100 efficiency scale, the relative savings (expected to be seen in the utility bill) are (0.95 – 0.90)/0.90 = 0.055 = 5.5%, and the annual dollar savings are estimated at (0.055 * 15000 kWh * $0.05/kWh) = $41. This means we have a payback on the work of about 10 years if the retrofit cost (no overhead) is $400. This is borderline but probably a go.
- Not every house has to provide a cost-effective retrofit to make the overall program economics favorable. Still, we should attempt to get cost-effective retrofits on a case-by-case basis.

I hope the example and notes have provided you with sufficient material to see more of the guts of the SLF and decision-making process. Again, this is still in development, so your questions and comments are encouraged and appreciated.

C
FIELD PROTOCOL

Regional Duct Program Data Collection Protocol **ID_______**

Name:	**Date:**
Address:	**Technician(s):**
Phone:	**Organization:**

Homeowner Acknowledgment:

I acknowledge that I have given permission for <agency name> or its representative to test and perform work on my house as part of <name of program>.

____
Homeowner signature

Tests on the first five pages (after this one) are designed to be performed at first point of contact (screening visit). Additional tests may or may not be performed during the screening visit, but the protocol should be completely filled out for retrofit sites. Blower door, duct leakage, CAZ and pressure pan tests must be performed before and after the retrofit. If you have any questions, call Bob Davis at Ecotope: (206) 322-3753.

Order of tests

1. Visual inspection of heating system and ducts.
2. Worst case depressurization tests.
3. Combustion appliance safety tests (where appropriate).
4. Pressure pan and blower door tests (ducts unsealed).
5. (Some cases)
   - Duct Blaster test
   - Blower door test (ducts sealed)
   - Temperature rise/air flow/static pressure tests

Tools needed for all tests

____Hand tools (screwdrivers, nutdrivers)
____Blower door and frame, plus speed controller, hoses and operation manual
____Pressure pan

____Flashlight or headlamp and extra batteries
____Safety gear (crawl suit, gloves)
____Cardboard scraps
____Utility knife
____Digital thermometer with 24” probe (wooden dowel or similar) and sensitive (36 ga) thermocouple wires
____Digital pressure gauge(s)
____Cordless drill
____Duct tape
____2” masking tape (utility grade and Long Mask) and masking paper (for returns)
____Tape measure

Additional tools

____Electrical multimeter (for checking element continuity and element amps
____CO meter (if any gas appliances to be tested)
____Duct pressurization fan, speed controller, hoses, instruction manual
____6” and 12” Pitot tubes (long tube needed for measuring register static pressure)
____15 mil butyl tape (for patching holes in sheet metal)

Visual Inspection

Fill in the following basic information at point of first contact.

Site name:		Floor/duct R-value (enter inches of insulation if easier)	/
City:		Crawl vented (more than 6 open vents)?	Y N
House type:	*Rambler* *2 story*	Note any combustion appliances which must be tested:	
	Split level attached garage		

Confirm type of primary heating system (circle below). Turn up thermostat and check furnace/heat pump operation. Check to see warm air is coming out of ducts and (where applicable) whether the line in from the outdoor unit heats up and the outdoor fan comes on. Confirm thermostat operates properly (Is it level? Any signs of overheating circuitry?) Ask homeowner about any perceived problems with heating system.

Confirm primary heating plant type: Electric furnace Heat pump Gas furnace
Location of furnace/indoor unit: Garage Inside house Basement Crawl
Other ________________________

Furnace/indoor unit make/model/capacity (kW, tons, or Btuh)______________________________________

Heat pump or AC outdoor unit ______________________________________ *(verify whether HP or AC by setting thermostat to call for heat and checking whether refrigerant line from outside heats up)*

Filter type/condition ____

Unit operates properly (note any problems):

Perform brief assessment of ducts. Describe system briefly. Note factors which would make standard retrofit difficult.

Supply system type (circle one): graduated trunk radial ("octopus")
other____________ Location(s) of supply ducts:

Retrofit suitability notes:

Brief description of return grilles and ducts; include location of returns:

Combustion Zone Worst Case Depressurization Tests

The purpose of worst case depressurization tests is to evaluate the possibility of any combustion appliance being exposed to negative pressures sufficient to cause backdrafting of exhaust gases.

The ability of a chimney or flue to draw properly is a function of many factors, including

- height of the stack
- outside and inside temperature
- design of flue, condition of the flue
- other appliances sharing the same flue
- wind speed & tightness of the house
- exhaust fan operation
- duct leakage
- location of the cold air return(s)
- condition of the combustion itself
- homeowner interactions

In other words, there are many conditions under which combustion appliances backdraft. Depending on climatic conditions the worst case is likely to change on a day-to-day basis.

It is possible to configure most newer homes so that the negative pressure in a CAZ will exceed safe limits. Determining likely scenarios vs. extremely unlikely scenarios is the key to getting useful data so that corrective measures can be recommended where needed.

Worst case depressurization should not be confused with fuel spillage or draft testing. These tests are separate tests that should be conducted on all fossil fuel appliances. ***Because it is possible to backdraft combustion equipment during this test you must ensure all combustion equipment cannot come on during these tests***. Backdrafting appliances can produce large amounts of CO very quickly, endangering the technician and homeowner.

Preparing the house for CAZ tests. (Note testing conditions on the next page):

1. *Are all registers normally open or are some normally closed? Ask the homeowner.*
2. *Are windows in rooms without returns normally open at night? If so leave them open for the test.*

3. *Are there two combustion appliances in the same zone? If so are they used at the same time? A fireplace can draw between 300 to 500 cfm. The blower door can be used to simulate a roaring fire.*
4. *Clean the lint trap on the clothes dryer.*
5. *Clean or replace furnace filter.*
6. *Determine the configuration of the buffer zones. Is the garage door usually open or closed? Are the crawl space vents usually open or closed?*
7. ***Make sure any combustion appliances cannot come on during the test.***
8. *Identify the zone containing the combustion appliance. This is referred to as the CAZ.*
9. *Identify exhaust fans. These may include, but are not limited to, bath fans, kitchen fans, clothes dryers, attic fans.*

Doing the CAZ test:

1. *Close all exterior doors and windows (with the exception of those windows normally open). If the blower door is in place, plug the fan hole (unless being used to simulate a fire in fireplace.)*
2. *While standing in the CAZ, place one end of the air tube outside, and attach the other end to the reference tap on side "B" of the digital pressure gauge. Switch the mode selection knob to pressure. An extra long hose is very handy for this test.*
3. *Close the interior doors to zones that do not contain return grilles.*
4. *Read the pressure of the house with respect to (WRT) outside. Record____________.*
5. *Turn on the air handler. Set the fan to the highest speed by activating the "fan" setting at the thermostat or at the furnace itself (fan switch on housing). If the system has AC, turn the thermostat to a cooling setting to activate the high speed fan.*
6. *Read pressure gauge. If gauge is reading negative, the house is being depressurized. Record this number: __________.*
7. *Turn on fans that are in the CAZ.*
8. *Turn on fans located behind interior doors that were shut for step # 3.*
9. *While watching the gauge, open these doors one at a time. If the CAZ goes more negative (for example -5 Pascals to -6 Pascals) keep the door open. If the CAZ becomes less negative (for example -5 Pascals to -4 Pascals) shut the door. Repeat this procedure for each room containing a fan. Record these numbers and any notes as you proceed:________________.*
   ____
   __
10. *Turn off air handler fan. Repeat step 8 (successive interior door openings). Record numbers as you proceed: ____.*
11. *The highest negative number achieved is the worst case. Determine the highest negative number from line 8 or 9. Record here:_______________*

CAZ house configuration worksheet (mark all appropriate conditions)

Combustion appliances in CAZ	Fireplace, woodstove, water heater, furnace, gas log/FP
Location of CAZ	
Interior doors closed (list rooms)	
Air handler speed	High, low, med.
Furnace filter condition	Clean, dirty

Dryer lint trap condition	Clean dirty
Crawl space vents	Open closed
Garage door	Open closed
Door to basement	Open closed
List registers closed (list rooms)	
Circle exhaust fans on for worst case test	Kitchen, m bath,bath2, bath3, Jenn-aire, laundry, dryer, other

IMPORTANT: If the house has natural gas or LPG appliances, you must perform combustion safety tests on furnace, water heater, and other gas appliances as needed before proceeding to pressure pan test. See Sun Power protocol for details on these tests.

Once these are complete (if applicable) proceed to the pressure pan test.

Split System Pressure Pan Test

The purpose of this test is to get a quick assessment of duct leakage. The pressure pan does not directly measure the leakage but it gives the ratio of the leakage to the buffer space containing the ducts to the total duct leakage. You can get an idea of where the big leaks are with this test, and it also tells you if you are having an effect with a retrofit. ***The pressure pan is not a substitute for a direct measurement of duct leakage.***

The "split system" test means the supply and return sides of the duct system are "split" at the furnace. This is usually done by taking out the furnace filter and taping in cardboard at the furnace slot or EAC. For gas furnaces, some ingenuity and perseverance may be required to insert the split.

Leakage from the duct zone to the inside of the home ("boot leakage") will also show up as exterior duct leakage if appropriate measures are not taken. Tape off obvious boot leaks or take pressure measurements through a foam block placed in the boot.

The test is usually performed with the house at –50 Pa WRT outside. This means the blower door must be set up and the following procedure followed:

<u>Pressure Pan Test Set-Up and Testing Procedure:</u>

1. *Close all exterior doors and windows.*
2. *Open all interior doors and supply registers.*
3. *Turn off furnace and exhaust fans.*
4. *Turn all gas appliances to pilot. (If elec. furnace or heat pump, turn breakers off.)*
5. *Remove furnace filter. Clean or replace if very dirty.*
6. ***Block return side from supply side with cardboard or plastic and tape.***
7. ***Close furnace door**. Tape off obvious holes into furnace cabinet (knockouts, etc.).*
8. *Check for fireplace(s) and seal closed. This is important to keep ashes from being sucked into the house.*
9. *Run pressure tap(s) to zone(s) containing ducts (crawlspace, attic, etc.).*

10. *Record pressure of house WRT outside during pressure pan test (usually –50 Pa)_________*
11. *Record (below table) pressure of duct buffer zone(s) WRT house when house at testing pressure.*
12. *Record if boots taped and/or foam block used.*
13. *Number registers starting at the front door and moving clockwise.*
14. *Do not put unusual pressure on the pan when taking a reading.*
15. *Note any unusual registers (toe kicks, long, skinny registers, register partially blocked by furniture, etc.).*
16. *Record sizes of registers (in inches) and estimate net free area (usually 50% for standard louvered registers).*

Pressure Pan Data

Register # (note location of register(s), as needed. Note toe-kicks, etc.)	**Pan test 1 (status:** ___________)**	**Pan Test 2 (status: _________)**	**Pan Test 3 (status: _________)**	**Boot taped/foam block used?**	**Reg. size (inches) (l x w)**	**Net Free Area (%)**
S1*						
S2						
S3						
S4						
S5						
S6						
S7						
S8						
S9						
S10						
S11						
S12						
S13						
S14						
S15						
S16						
S17						
S18						
S19						
S20						
Sum of supply pans						
Avg supply pan						

*“S” denotes supply register

**”Status” refers to screen, post-retrofit, or retest (applies if a second test performed during the same visit after, for example, a mid-stream change is made to the test (big boot leak sealed, partially closed register opened, etc.)

***Flow data are optional. They may be performed in some cases to offer an additional measurement of air handler flow or to address distribution/comfort issues.

Pressure(s) to buffer zone(s) containing ducts WRT house (specify zones and record pressures):

2-Point Blower Door Test (ducts unsealed)

Once the pressure pan test has been performed, it is quite simple to perform a two point blower door test (in depressurization mode). The house is depressurized to near 50 and 25 Pa with respect to outside and the flow through the fan determined with lookup tables or the pressure gauge. **Note the house pressure WRT outside doesn't have to be exactly 50 or 25 Pa; the actual values will be corrected to 50 Pa during analysis.**

Make and model of blower door used ____

Blower Door (BD) Depressurization Test Procedure:

1. *Close all windows and doors to the outside. Open all interior doors and supply registers.*
2. *Close all dampers and doors on wood stoves and fireplaces.* ***.*** *Seal fireplace or woodstove as necessary to prevent ash disaster.*
3. *Make sure furnace and water heater can not come on during test. Make sure all exhaust fans and clothes dryer are off. Make sure any other combustion appliances will not be backdrafted by the blower door.*
4. *Make sure doors to interior furnace cabinets are closed. Also make sure crawlspace hatch is on, even if it is an outside access. Check attic hatch position. Put garage door in normal position.*
5. *Set fan to depressurize house. Run pressure tap out through door shroud.*
6. *Depressurize house to –50 Pa or thereabouts. Record house pressure, BD flow pressure, and BD ring (below). If you cannot reach –50 Pa, get as close as possible and record information.*
7. *Now take the house down to –25 Pa WRT outside and record information.*

Blower Door Tests	Condition (screen, post-retro, retest, etc.)	House P near 50 Pa (P_{50})	BD fan pressure	BD Ring	BD flow near 50 Pa (Q_{50})	House P near 25 Pa (P_{25})	BD fan pressure	Ring	BD flow near 25 Pa (Q_{25})
Test 1									
Test 2									
Test 3									
Test 4									

8. *To check test, calculate the flow exponent, n. Use the following formula,* $n = \ln(Q_{50}/Q_{25})/\ln(P_{50}/P_{25})$. *Note* Q_{50} *and* Q_{25} *are the flows through the blower door at the testing pressures (which are denoted* P_{50} *and* P_{25}*. Depending on the test, you may not get the house to exactly –50 or –25 Pa WRT outside. Use the exact* ΔP *you measure when checking the flow*

exponent. For example, if the house gets to –48 Pa for the high ΔP, use this as the P_{50} in the equation. If the flow exponent is not between 0.50 and 0.75, repeat the test.

Note testing conditions (if windy, inaccessible room(s), garage door open or closed, etc):

Exit Protocol (if finishing at this point):
____ ***Remove split system device at furnace!!*** *Remove fireplace seal.*
____ *Turn breakers on where applicable and confirm furnace operation.*
____ *Turn any gas appliances back ON and confirm operation.*
____ *Inspect home, garage, crawlspace, attic for any equipment, garbage, etc.*

Duct Pressurization Tests (Total and Exterior Duct Leakage)

Duct pressurization tests provide the most conclusive evidence of the suitability of a house for retrofit. The exterior duct leakage test indicates what amount of heated (or cooled) air is lost to the buffer space and therefore not available to heat or cool the home**. This is the leakage we are trying to eliminate with the retrofit**. Generally, a duct pressurization test should be performed if the average pressure pan reading is over 2 Pa, or if one reading is over 5 Pa (assuming the pan test is done with most boot leakage eliminated).

The key to these tests is keeping track of what pressure differences are to be measured. The duct pressure WRT outside must always be measured. Duct pressure is usually measured into the supply plenum, although it may also be useful to measure the pressure elsewhere in the system. This is especially true if there are disconnects near the plenum. That is, even if the pressure in the plenum is near 50 Pa when testing, the pressure down the line may be much less because of the big leaks. Taking some extra pressure measurements at other registers (when taped) will help in interpreting the results.

Duct pressure must also be referenced to house for the exterior leakage test. If the furnace is in the garage, you must find a way to measure back in to the house. Usually this is done by placing a non-crushable probe (small diameter metal tube such as Pitot tube or the tube supplied with the digital pressure gauge) under the garage-to-house threshold.

Set-up procedure for duct pressurization tests:

1. *Set blower door to pressurize house. May have to turn around fan (from normal BD test position) if house is leaky.*
2. *If system is not already split, block return side from supply side with cardboard or plastic and tape.*
3. *If testing supply side, attach duct tester fan to furnace cabinet with cardboard and tape or directly to blower mount. (If blower removed, be careful with wires and record how to re-connect them.)*
4. *If testing return side, attach duct tester to return grille.*
5. *Tape all registers. Use appropriate tape (Long Mask) for friable surfaces.*
6. *Set up pressure tubes so that pressure gauge can read duct pressure WRT outside, duct tester fan pressure, and house pressure (for exterior duct leakage test).*

7. *Measure duct pressure in plenum or register. If you select a register, make sure it is not disconnected from the rest of the duct system. Specify on protocol sheet where duct pressure is measured. Use Pitot tube or static pressure tap for this measurement.*
8. *Make sure crawlspace access door is on (even if access is from outside house).*

Performing total duct leakage test:

1. *Pressurize supply or return side to about 50 Pascals WRT outside with smallest flow ring possible.*
2. *Check pressure in other side of system WRT outside. (Check return if testing supply; supply if testing return.) This pressure should be close to zero. If not, check system split.*
3. *Measure the duct system pressure WRT outside. Record in table (next page).*
4. *Measure duct tester fan pressure. Look up flow in table, use gauge* ***(make sure the pressure gauge you are using is paired with the right duct tester)*** *or use flow equation.*
5. *Repeat steps 1-3 with ducts at 25 Pa WRT outside.*
6. *Check flow exponent. (Formula on next page.) Repeat tests as needed.*
7. *Note any unusual testing conditions (wind, etc.):*

Total Duct Leakage Data (note duct pressure WRT outside does not have to be exactly 50 or 25 Pa)

	Pre-Retrofit				Post-Retrofit			
	Supply		Return		Supply		Return	
	50 Pa	25 Pa	50 Pa	25 Pa	50 Pa	25 Pa	50 Pa	25 Pa
Duct P	____	____	____	____	____	____	____	____
Ring	____	____	____	____	____	____	____	____
Fan P	____	____	____	____	____	____	____	____
Flow	____	____	____	____	____	____	____	____

Note position of pressure tap(s) in supply and return system:

To check each test, calculate flow exponent as for the blower door test (previous page). The flow exponent, n, = $\ln(Q_{50}/Q_{25})/\ln(P_{50}/P_{25})$. If flow exponent not between 0.50 and 0.75, repeat test.

Performing exterior duct leakage test:

1. *Exterior house doors and garage doors should be* <u>*closed*</u> *for exterior duct leakage test.*
2. *Pressurize the house to about 50 Pascals WRT outside.*
3. *Pressurize duct system to about 50 Pascals with smallest flow ring possible.*
4. *Measure pressure of ducts WRT house. Make sure blower door flow does not impinge on pressure tap measuring house pressure.*
5. *Adjust duct tester speed controller so that duct pressure WRT house is zero or very close.*
6. *Re-check pressure of ducts WRT outside.*
7. *Measure duct tester fan pressure. Look up flow in table, use gauge* ***(make sure gauge is paired with the right duct tester)*** *or use flow equation. Record duct pressure WRT out, DB fan pressure, DB fan ring.*
8. *Repeat steps 2-7 with house and ducts at about 25 Pa WRT outside.*
9. *Check flow exponent (as above).*
10. *Note any unusual testing conditions (wind, etc.):*

Duct Leakage to Outside Data (note duct pressure WRT outside may not be exactly 50 or 25 Pa)

	Pre-Retrofit				Post-Retrofit			
	Supply		Return		Supply		Return	
	50 Pa	25 Pa	50 Pa	25 Pa	50 Pa	25 Pa	50 Pa	25 Pa
Duct P	____	____	____	____	____	____	____	____
Ring	____	____	____	____	____	____	____	____
Fan P	____	____	____	____	____	____	____	____
Flow	____	____	____	____	____	____	____	____

Blower Door Test (ducts sealed)

This test will assist in determining the amount of house infiltration induced by the air handler fan. The test is quickly performed just after the duct pressurization tests. Keep all registers (including returns) taped. If duct tester attached to supply or return, make sure inlet is taped or otherwise air-tight**. Cover duct tester inlet if duct tester fan is still attached to supply or return**. Do a two point (50 and 25 Pa) blower door depressurization test as before.

Sealed Blower Door Tests	Condition (screen, post-retro, retest, etc.)	House P near 50 Pa (P_{50})	BD fan pressure	BD Ring	BD flow near 50 Pa (Q_{50})	House P near 25 Pa (P_{25})	BD fan pressure	Ring	BD flow near 25 Pa (Q_{25})
Test 1									
Test 2									

1. *Note any unusual testing conditions (wind, etc.):*

2. *To check test, calculate the flow exponent, n. Use the following formula,* $n = \ln(Q_{50}/Q_{25})/\ln(P_{50}/P_{25})$.

Reconstruction Protocol (after all fan tests are complete and prior to static pressure/flow tests):

1. ***Remove split system device at furnace!!***
2. *Untape all registers.*
3. *Remove fireplace seal.*
4. *Turn furnace breakers ON (or gas valve and power to furnace ON where applicable.) Turn gas valves to other appliances* ***ON*** *and confirm operation.*

Additional details to be collected for all retrofit homes (note floorplan and duct sketch can be performed while retrofit is underway):

Describe repairs made and materials used:

Crew performing the retrofit:

Crew hours required for the job (include travel):

Confirm square footage and volume of house (sketch below or on grid paper as needed). Also, sketch duct system, indicating R-values, dimensions and lengths of runs (to nearest foot):

Register Flow & Static Pressure Measurements

The purpose of these tests is to document airflow and system pressures so that duct leakage data can be scaled to normal operating conditions. If only exterior duct leakage is measured, the air handler flow should be measured with the temperature rise method (see pages c-14 to c-15). ***Even if register flows are not measured, supply plenum pressure and at least 5 register pressures should be taken in order to describe system operating pressure.***

Static pressure measurements are to be taken with a static pressure probe such as a Pitot tube or similar device. Proper use of the probe minimizes erroneous readings (which will include some component of velocity pressure). For plenum measurements, insert the tube through a found or drilled hole and bring the tube back to near the inside wall of the plenum. Measure static pressure upstream and downstream of the filter on the return side.

Expected upstream return readings are in the range of -30 to -100 Pa. Lower readings indicate the fan is on low speed and/or the filter is very restrictive and/or dirty. Downstream return static pressure can be as high as –200 Pa if the filter is totally blocked. Supply side static pressure generally ranges between 15-70 Pa. Higher readings can mean the fan is on high speed (heat pumps), the system uses a small plenum with many small diameter take-offs, etc.

Drill holes as needed in the plenums to take measurements. Patch these later with butyl tape.Record the following plenum pressures before and after retrofit:

	Before retrofit	After retrofit
Upstream return plenum pressure		
Downstream return plenum pressure		
Supply plenum pressure		

Measuring Register Flows, Temperatures, and Static Pressures

Measuring register flows will be necessary to find air handler flow if the temperature rise method cannot be used. We assume a residential size flowhood will be used. It is important to know what the calibration curve is on the hood or know if it can be calibrated. Measurement of temperatures is also important, since hot air is less dense than cool air. Do not rely on the temperature sensor supplied with some flowhoods; use a separate digital thermometer with precision of 0.1 °F. The flows will be corrected to standard conditions by the analyst.

Measurement of register pressures is also important so that the average system pressure can be estimated. This is crucial to correcting duct leakage numbers taken at standard testing pressure differentials (50 and 25 Pa) down to standard operating conditions (often closer to 10-20 Pa).

<u>Procedure for Measuring Register Flows, Temperatures, and Pressures</u>

1. *Take measurements in the "as-found" configuration. In some homes, many registers will normally be closed by occupants.*
2. *Turn up the thermostat high enough so that the furnace fan will operate for some time. Do not use fan switch at thermostat to operate fan. Start measuring immediately.*
3. *For flows, make sure the hood is centered over the register. Note in table if it is not centered.*
4. *Measuring flows from toe-kick registers is especially tricky. Do your best.*
5. *For measuring pressures, use a long (12") Pitot tube pointed into the supply air stream. If a register is normally closed, take measurement through louvers. If you get a negative reading no matter how you point the tap, make note on protocol.*
6. *For measuring temperatures, place the temperature probe at the outflow from the flowhood. You may have to make your best guess at the temperature if it is fluctuating.*

Note flowhood used and calibration (if known):_________________________________

Register Flows, Temperatures, and Pressures

Supply reg #	Toe kick? Normally partially or fully closed? Other notes:	Pre-retro flow (CFM)	Pre – Static P (Pa)	Pre-temp (F)	Post-retro flow (CFM)	Post - Static P (Pa)	Post-retro temp (F)
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							
19							
20							

Measuring Air Handler Flow With the Temperature Rise Method

In using this technique, you are figuring out the flow of the system's working "fluid" (air) by measuring the amount of temperature rise across the equipment and combining this with the energy put into the airstream by the furnace.

This approach requires measurement of temperatures on each side of the elements, heat exchanger or evaporator coil and measurement of electricity used by the furnace (found by clocking the electric meter). For heat pumps, run the equipment in emergency mode (no compressor) to uncomplicate the process.

Step-by-step procedure

1. *Tell homeowner you will drill holes in their sheet metal. Drill holes big enough to admit temperature probe, if you have not already done this for the static pressure measurements. On the supply side, taking at least four measurements is advised, especially when the blower is offset on the plenum.*
2. *Turn down water heater and other electric loads. Note hot water heater setting and loads turned off* ____
3. *If some loads cannot be turned off, clock meter to determine baseload (skip to step 8, below) or use other methods of measure. Record baseload* _______ *kW.*
4. *Turn up the thermostat and let equipment run for at least 5 minutes.*
5. *Record return plenum temp* ______ *(specify °F or °C)*
6. *Record supply temps in table (specify °F or °C)*

Back

Front

7. *Remeasure return plenum temp* _______ *(°F or °C)*

8. *Record revolutions of the smallest dial and time needed for these revs. Use the meter constant printed on the face of the meter (usually 7.2). An additional multiplier will be needed for CT-type meters, and is usually the product of the metering transformer's ratios. Use the following formula to get watts consumed by the heating system:*

$$W = (3600 \times k_h \cdot \text{Mult} \times \text{rev})/t$$

Where k_h = meter constant on face of meter (watt-hrs per revolution (usually 7.2))
Mult = multiplier (as needed) for certain meters
t = time required for revolutions counted (in seconds)

Record baseload (as needed) __________ *watts*
*Record watts consumed by furnace (subtract baseload first)*_________ *watts*

9. *Average return plenum temps; record average as* T_r ________ *(°F or° C)*

10. *Average supply plenum temps; record average as* T_s ________*(°F or °C)*

11. *Air flow calculation:*

Airflow in standard CFM (SCFM) = (energy in (from Step 8) · conversion factors)/ $(T_s – T_r)$

OR

SCFM = (Watts in · **constant)**/$(T_s - T_r)$

Where the **constant** is either 3.16 (if using °F) or 1.75 (if using °C)

Show work:

12. *Turn back on any appliances you turned off earlier and patch holes in the plenums*.

D
USE OF FIELD MEASUREMENTS TO DETERMINE SAVINGS: EFFICIENCY MODELING

Use of Field Measurements to Determine Savings: Efficiency Modeling

This section describes the process by which raw field data are processed into measurements of duct distribution efficiency both before and after the retrofit. Data from 69 homes were processed using some or all of the procedures described below; results from 60 of the homes were judged sufficiently reliable for estimating retrofit savings. The distribution efficiency data were then applied to consumption data for use in cost-effectiveness calculations (see Section 5).

The two primary mechanisms for heat loss from ducts are conduction and leakage. The delivery efficiency, which is defined as the fraction of energy provided by the equipment that actually gets delivered through the building envelope by the duct work during steady-state conditions, can be expressed as

$$\eta_0 = \alpha_s \beta_s - \alpha_s \beta_s \left(1 - \alpha_r \beta_r\right) \frac{\Delta T_r}{\Delta T_e} - \alpha_s \left(1 - \beta_s\right) \frac{\Delta T_s}{\Delta T_e} \quad (1)$$

where η_0 is the delivery efficiency

- α_s is the fraction of the air handler flow that is delivered to the house by the supply ducts
- β_s is the conduction efficiency of the supply ducts
- α_r is the fraction of the air handler flow that is taken from the house by the return ducts
- β_r is the conduction efficiency of the return ducts
- ΔT_r is the temperature difference between the return register and the air around the return duct
- ΔT_s is the temperature difference between the return register and the air around the supply duct
- ΔT_e is the temperature change across the conditioning equipment

In these definitions the return register temperature is identified with the house temperature. This expression of the delivery efficiency has the properties that each term is dimensionless and that the supply and return temperature differences are separated and linear. In addition, the only temperature measurements required are those at the return register and in the zones where the supply and return ducts are located. Eq. (1) is identical to that found in Standard 152P for delivery effectiveness, which has the same definition as delivery efficiency. For a detailed derivation of this equation, see Palmiter and Francisco (1997). Note that this definition of delivery efficiency differs from that found in ASHRAE (1993), which says that the delivery efficiency is the ratio of the energy delivered through the registers, not through the building envelope, to the equipment output capacity.

While the delivery efficiency is an important measure of efficiency, in large part because it indicates the fraction of energy supplied by the equipment that is delivered via the intended paths, it usually does not represent the fraction of the supplied energy that actually goes to satisfying the load of the house. The fraction of supplied energy that is delivered to the house as useful heat is called the distribution efficiency. Two primary factors that result in a distribution efficiency different from the delivery efficiency are the interaction of unbalanced duct leakage with natural infiltration, and the effect of regain. Regain is energy that is lost by the ducts to unconditioned spaces but is recovered as useful energy by the building. Some of the primary mechanisms through which regain occurs are conduction through the envelope, air leakage directly from ducts to the conditioned space, and the reduction in loss from the conditioned space to the buffer space due to an increase (or, in the case of cooling, a decrease) of buffer space temperature resulting from the duct losses.

The distribution efficiency η can be expressed as

$$\eta = \eta_0 + f_s\left(1 - \eta_0 + \left(\frac{f_r}{f_s} - 1 - \beta_r\left(\frac{f_r}{f_s} - \alpha_r\right)\right)\frac{\Delta T_r}{\Delta T_e}\right) - \eta_{in} \qquad (2)$$

where f_s is the fraction of supply losses that is recovered to the house
f_r is the fraction of return losses that is recovered to the house
η_{in} is the effect of the interaction of unbalanced duct leakage and natural infiltration

The form of the infiltration interaction term depends on whether the unbalanced leakage is greater than or less than twice the natural infiltration rate (based on Palmiter and Bond [15, 16, 17] and incorporated by ASHRAE [14]). If the unbalanced leakage is less than twice the natural infiltration rate,

$$\eta_{in} = \frac{1}{2}(\alpha_r - \alpha_s)\frac{\Delta T}{\Delta T_e} \qquad (3)$$

where ΔT is the temperature difference between inside and outside.

If the unbalanced leakage is more than twice the natural infiltration rate,

$$\eta_{in} = \left[\alpha_{\max} - \alpha_s - \frac{m_{nat}}{m_e}\right]\frac{\Delta T}{\Delta T_e} \qquad (4)$$

where $\alpha_{\max}$ is the greater of α_s and α_r
m_{nat} is the natural infiltration mass flow rate
m_e is the mass flow rate of air through the air handler

The infiltration interaction term has the property that, in the case of return-dominated leakage ($\alpha_s > \alpha_r$), the distribution efficiency increases with increasing return leakage compared to ignoring the infiltration interaction term. In extreme cases, such as a return leak in a hot garage in a heating season situation, this increase can offset all of the other losses, resulting in a distribution efficiency greater than 1. Similarly, if the leakage is sufficiently supply-dominated, the additional infiltration can create a higher load that the equipment is unable to meet and the distribution efficiency can be less than 0.

Note that the delivery efficiency and distribution efficiency only include the effects of ducts on the heat required of the equipment by the house. Neither efficiency measure includes the efficiency of the equipment itself, such as the combustion efficiency of a gas furnace or the compressor efficiency of an air-conditioner or heat pump.

Application of the Model to Detailed Audit Data

The two most challenging aspects of applying the model to the measured data were estimating the flow through the air handler and determining the leakage at operating conditions. There is currently no good way to get an accurate measurement of air handler flow. One common method is to measure the temperature change across the equipment and the energy output, from which a flow rate can be calculated. However, temperatures are rarely very uniform in the supply plenum, so a single temperature measurement may not reflect the actual bulk temperature, resulting in a poor estimate of flow.

To obtain the air handler flow rate, Ecotope used the sum of the measured supply register flows and added the total supply leakage at operating conditions. The result was compared to the flow obtained using the energy output and the temperature change across the equipment based on the average supply temperature from the multiple measurements (typically nine points) taken in the plenum. The median temperature was also considered, and at the minimum the supply plenum temperature implied by the sum of register flows and total supply leakage needed to be within the range of temperatures measured at the various points in the plenum. Based on this analysis, we arrived at a best estimate of air handler flow.

It is still problematic, however, to determine what the operating conditions are in a given system. Duct leakage tests are performed at prescribed pressures that are not typically representative of the situation when the air handler is operating. In previous studies, Ecotope has found that a simple rule of thumb works reasonably well for most houses. This rule of thumb takes one-quarter of the plenum static pressure and three-quarters of the average register static pressures (as measured with a pitot tube) and adds the two results together. The result is then used as the operating system static pressure in the leakage curves obtained from the duct leakage tests. In some houses, where a large amount of leakage is known to occur at one end of the system or the other (say a disconnect at either the plenum or at one register, with no other notable leakage), these weights may be modified. Using this pressure in the total supply leakage curve allows an estimate of air handler flow, whereas using the pressure in the leakage to outside curve allows an estimate of leakage fraction.

Since these tests were done both pre- and post-retrofit, this procedure was done in both cases and the results were compared. Since most blowers operate at a place on the fan curve such that the flow is fairly independent of external static pressure, the pre- and post-retrofit results should be at least close to each other except in the most extreme cases. This was typically the case, and a single flow rate that seemed reasonable for both the pre- and post-retrofit cases was chosen. Once the air handler flow was estimated, it was simple to calculate conduction efficiency based on this flow and the measured duct surface area and insulation levels.

For seasonal savings estimates, temperature differences between the house and the buffer spaces were based on the characteristics of the buffer spaces (e.g. size and insulation levels) and the duct losses into each space. These were evaluated using a computer worksheet developed at Ecotope. This worksheet also evaluated the regain factors based on the same characteristics of the buffer spaces. In cases where ducts ran in multiple locations outside of the conditioned space, the results were weighted by the fraction of surface area of the ducts in each space.

For the infiltration interaction, the unbalanced leakage was compared to the infiltration predicted by a model developed at Lawrence Berkeley Laboratory (Sherman and Grimsrud 1980) based on stack effect only. Effects due to wind were not considered. Previous work by Ecotope (Palmiter and Bond 1991; Palmiter and Bond 1994; Palmiter, Francisco, and Bond 1996; Palmiter and Francisco 1996) has shown that the wind portion of this model greatly overestimates the impact of wind, and that in most cases wind effects will actually be small.

All of these parameters were used in the computer worksheet mentioned previously, which uses a bin calculation procedure to determine seasonal efficiency. This worksheet accounts for such items as fractional runtime and the interaction between heat pump compressors and backup resistance elements. A number of different weather stations were used to most closely simulate the temperatures found at each house.

Basic Audit Data and Results

In addition to the detailed pre- and post-retrofit audits, some additional basic audits were performed post-retrofit. Most of these were performed on houses on which pre-retrofit duct leakage tests had been performed. These audits were performed partly as quality control and also in part with the hope that it would be possible to estimate savings due to the retrofits. Since not all items required for full modeling were measured in these basic audits, it is not possible to get a good estimate of actual efficiency. However, because the retrofits only addressed supply-side leakage (in most homes), the idea was that it might be possible to correlate the change in supply leakage with savings.

The primary factors that would make the savings different for two houses with identical supply leakage reduction and in the same general location are:

- conduction efficiency
- buffer space characteristics
- the interaction of unbalanced leakage with natural infiltration.

Since no return-side leakage measurements were made, only the first two of these were considered in the attempt to correlate leakage reduction to savings. As conduction efficiency decreases, the potential for savings due to leakage reduction increases; as the buffer space becomes more well-connected to the house (i.e. lower levels of insulation under the floor and/or in the attic) the potential for savings due to supply leakage reduction decreases.

Data from the detailed audits were used to try to obtain the correlation. Conduction efficiency was found to be only a small factor in the potential for savings in these houses, so the focus turned to the levels of insulation in the buffer spaces. This was found to be a large factor. For a similar leakage reduction, the percentage savings for homes with uninsulated buffer spaces was only about half as large as for homes with insulated buffer spaces. Therefore, regressions were done for each of the two cases, and the resulting curves were applied to the data from the basic audits.

For the basic audit homes, the leakage fractions were determined in the same manner as for the detailed audits, with the exception of being able to compare air handler flow estimates to ones based on plenum temperatures and energy output. It should be noted that, without all of the information required to fully implement the model, there is likely to be a significant amount of scatter for the basic audit results. In addition, the sample size from the detailed audits is small and also shows some scatter, so it is possible that a different population of homes would show a different result.

Target:

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