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DUCT LEAKAGE INVESTIGATION:

MONITORING OF CONSERVATION RETROFITS

FINAL REPORT

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for ~~the~~

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OAK RIDGE NATIONAL LABORATORY

Oak Ridge, Tennessee 37831

Managed ~~Operated~~ by

Martin Marietta Energy Systems, Inc.

for the

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Under Contract DE-AC05-84OR21400

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OAK RIDGE NATIONAL LABORATORY
OPERATED BY MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE U.S. DEPARTMENT OF ENERGY

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OAK RIDGE, TENNESSEE 37831

February 14, 1992

Mr. Les Lambert
Lambert Engineering, Inc.
601 NW Harmon Blvd.
Bend, Oregon 97701

Dear Mr. Lambert:

Final Report for Residential Duct Leakage Investigations - MMES Contract No. 86X-SA727V

This is in regard to the final report for the Residential Duct Leakage Investigation study. Since you have not submitted the final "camera ready" copy of your report after receiving my final comments on your draft report in July 1991, I have been attempting unsuccessfully to contact you by phone for the last two months. Since I requested only relatively minor changes to the text, I expected that you could have completed them by now. In spite of the fact the Martin Marietta Energy Systems has paid you the full amount for this subcontract, we certainly expect you to complete your contractual obligation by submitting a "camera ready" final report for publication.

Please contact me at (615) 574-5179 with information on your progress toward submitting your final report.

Sincerely,

James O. Kolb

James O. Kolb
Energy Division

JOK\jth

cc: W. R. Mixon
E. Freeman, DOE
File - RC

Acknowledgements

This project has been supported by grants from Oregon Department of Energy (No. C90023) and the U.S. Department of Energy through a subcontract managed by the Oak Ridge National Laboratory. The Bonneville Power Administration (BPA) permitted use of previously collected RSDP data.

ODOE funded the field investigation on which this report is based. The U.S. DOE funded the continued monitoring of the sites as well as further statistical investigation of the RSDP database. The respective contract officers, Gary Curtis and Mike Karnitz, have kindly assisted with contract arrangements.

Peter Lagus of S-Cubed Company provided information on gas chromatography procedures. Mark Modera of Lawrence Berkeley Laboratory has provided useful assistance with the complex problem of interactive air flows. Rectorseal Corporation provided samples of their duct sealant product for trial.

ABSTRACT

Ducted forced-air heating systems are used in over half of U.S. residences. Field data focussed on duct losses was sparse prior to this work. This project performed two studies to assess the energy impact of ducted heating systems. The first was a statistical analysis of existing monitored data to identify energy impacts in a large sample of homes from BPA's RSDP program. The second was a field test and retrofit repair of a sample of the RSDP homes. These homes were monitored for another year after the repair in an attempt to identify associated energy savings.

The statistical study analyzed over 500 recent vintage homes using submetering, blower door and tracer gas testing. Results showed:

- Ducted homes have 12% to 26% more leakage.
- Heating energy use per square foot averages 13% to 40% higher for homes with ducted heating systems.
- Duct losses are higher in "current practice" (control) homes than in energy-efficient homes.

The field investigation of ducted systems was conducted on 20 RSDP homes using blower door and tracer gas testing. Most of the homes were from the control group. Results showed:

- Duct leakage is highly variable. 10% of homes showed no significant leakage. 10% showed severe problems.
- The homes studied indicated an estimated average of 12% loss of heating system efficiency through duct leaks.
- The presence of heating ducts increases the apparent leakiness of the house by about 10% as measured with blower door testing (4 Pa ELA and 50 Pa air exchange).
- About one quarter of the duct leakage could be repaired.
- Tracer gas tests showed that fan-driven losses dominate infiltration while the furnace fan operates, causing an increase of about one half air change per hour.
- Flow hood tests showed that return ducts leaked twice as much as supply ducts during fan operation. This typically caused a net pressurization.
- Interaction of fan-driven and natural infiltration appeared to be more consistent with linear addition of air flows rather than addition of flows in quadrature.

- Estimates of energy savings from repairs based on short term tests averaged 375 KWh per year. The retrofit repairs have a simple payback of about four years.

From the above results, it was concluded that duct repairs are a cost-effective retrofit measure, especially if weatherization is taking place at the site anyway. Utility weatherization programs should include a duct repair component. Building code standards should require ducts to be located within the heated volume of the house or mandate better inspection of heating ducts in new construction.

Long term Post-repair monitoring was conducted to identify energy savings, but results were not conclusive. The amount of variation in residential heating usage was sufficient to mask the expected level of savings. Thus, there was little statistically significant evidence for energy savings from the retrofit repair.

Recommendations were made for further research. Whole-house blower door testing does not appear to be an appropriate investigation tool. Direct pressure testing of the isolated ducts is a variation initiated during this project. It appears to provide a higher level of precision. Tracer gas testing was useful but subject to weather-induced uncertainty. Testing a larger sample of residences, including gas furnace homes, would be advisable.

EXECUTIVE SUMMARY

This study was motivated by the suspicion that duct losses in the U.S. housing stock are widespread. Sparse pre-existing data suggested that duct leakage and resulting losses might be severe, and posed a retrofit opportunity.

Two separate studies were performed to gain knowledge of duct losses and duct leakage repair. A statistical review of pre-existing data was done to gain a large-sample perspective of duct leakage and losses. Also, field investigation of duct leakage retrofits was performed on a smaller sample of homes.

Statistical Study Sample and Methods

The statistical analysis used information collected for another project, BPA's Residential Standards Demonstration Project (RSDP). RSDP data was complete enough to support extensive test-reference comparisons of homes with ducted forced air heating and homes with zoned resistance heat (unducted homes). The comparisons focussed on two RSDP home groups. Four hundred Model Conservation Standard (MCS) homes featured above-code envelope insulation and air-tightness, and well insulated ducts, mostly inside heated space. The "control" group consisted of 400 post-1980 homes built to regional current practice.

Eight different indicators of whole-house air leakage, infiltration, and thermal losses were used in the comparisons. Four Pascal Specific Leakage Area, 50 Pascal Air Exchange Rate and Specific K Factor were the most useful indicators. Ducted homes proved larger than their unducted counterparts. Indicators that did not normalize for house size (4 Pascal ELA, 50 Pascal Airflow, K Factor) were less useful.

Statistical comparison of means (ducted vs. unducted homes) were done separately for the strongly differentiated MCS and Control groups.

Statistical Study Results

Evidence of duct losses was strong in both groups. Statistical significance was robust. Ducted homes showed greater leakiness, greater infiltration, and greater thermal losses in almost every comparison made.

The Control group showed greater duct losses than the MCS. Controls are more representative of U.S. housing stock than the MCS; their results are more germane to retrofit activities. Controls showed 26% greater leakiness, 26% greater infiltration, and 40% greater thermal losses for ducted homes.

The control group is of relatively recent vintage, and was self-selected from possibly energy-conscious volunteer homeowners. These factors suggest that duct losses could be greater than shown by the control group, in the U.S. housing stock.

Ducted MCS homes showed 22% greater leakiness and 13% greater thermal losses. Infiltration increases were marginally significant, showing ducted MCS as possibly experiencing more infiltration. The lower thermal losses of ducted MCS show that duct losses can be reduced by energy-conscious construction methods.

The magnitude of duct thermal losses in the control group was similar to MCS thermal savings, over controls. Duct losses are as important to energy use as a model energy efficiency code.

When the MCS and Control groups were partitioned into more detailed sample strata, ducted homes usually showed greater losses. Partitioning according to "substructure type" (basement vs. slab vs. crawlspace) showed that ducted controls with basements had unusually high thermal losses. Ducted basement MCS showed an opposite effect. Their thermal losses were not significantly different from unducted counterparts. Except for MCS homes with basements, results do not contradict a cause-and-effect relationship between duct leakage and increased thermal losses. Extremes observed for both basement comparisons suggest that other factors should be considered for ducted basement home thermal losses. Furnace-fan-driven structural leaks may be unusually significant factors in basement situations.

Field Retrofits of Duct Leakage

Twenty homes, mostly controls, were given duct repairs and tested for duct leakage using a before-and-after protocol. Short term tests were done with blower door, Sulfur Hexafluoride (SF_6) tracer gas, and a new technique using a high resolution airflow hood. Long term before-and-after energy use monitoring was also performed, but was inconclusive due to noisy data, small savings, and small sample size.

Methods

Blower door testing was marginally useful for unassisted measurement of duct leakage, due to limited precision of whole-house leakage results. Grills-open vs. grills sealed substractive determinations of duct leakage showed large scatter, in repeatability checks.

A new method of directly measuring duct leaks with a high resolution airflow hood was field tested. The home was pressurized by the blower door. Airflow into and from duct segments was then measured, using a high resolution flow hood, with substantially better accuracy than has previously been reported.

SF_6 testing per ASTM E741-83 was used to measure furnace-fan-driven infiltration before and after repairs, using fan-on and fan-off tests.

Manipulation of flow hood data into 4 Pascal ELA and 50 Pascal air change rate forms provided cross-checks with blower door data and SF_6 results. These checks support recommending the new technique for future duct leakage investigations.

Pre-and-Post Retrofit Results

"As-found", the test homes showed about 10% of whole-house ELA was attributable to duct leaks. Fan-driven incremental infiltration averaged about 0.5 ACH, nearly double the average fan-off value. Flow hood measurements showed return ducting volumetric leakage during fan operation averaged twice that of supply ducts.

The flow hood method made the component leakage measurements of supply vs. return duct segments possible. Unbalanced leakage flows between supply and return ducts imply house pressurization, and fan-driven structural leaks. (This may help to explain lower MCS thermal losses in spite of significant incremental duct leakage areas; MCS envelopes are much tighter).

The amounts of as-found duct leakage varied substantially. ~~10%~~ Ten percent of test homes had major leaks (e.g. ducts separated at the joints), and 10% had very little leakage.

Duct repairs eliminated about one quarter of volumetric duct leakage. This modest improvement was achieved with modest effort and materials requirements. Access to concealed ductwork was a significant barrier to higher repairability.

Long term monitored energy use data were inconclusive, but short-term test data supported energy savings estimates. Duct repairs were estimated to have an average energy saving of 375 KWh/yr, at a cost of about $70 to $80/site, for a simple payback of 3 to 4 years. With the present state-of-the-art in duct leakage diagnostics, agencies performing duct retrofits must expect uneconomic repairs at times. However, average results make duct leakage repair worthwhile, especially as an addition to ongoing weatherization activities.

Diagnostics and theoretical models associated with duct leakage and losses are still in a developmental state. Although this project achieved advances in measurement methods, there is room for improvement. There is no "silver bullet" diagnostic to reliably diagnose and pinpoint duct leaks for retrofit crews. Linear addition of fan-driven leakage to natural infiltration appears more accurate than "quadrature" addition techniques. However, theoretical models leave much to be desired, especially in dealing with fan-driven infiltration due to localized pressurization and depressurization of portions of homes.

Repair strategies start with visual inspection. Most gross leaks should be visible. Seams, joints, "y" fittings and elbows are prime suspects. Tell-tale dirt on fiberglass duct wrap is a sign of leakage at the dirty spot. Furnace filter slots should be inspected. Smokesticks can be helpful. Smoke intake indicates leaky ducts, but leaky ducts can also be overlooked using a smokestick. Measurable house pressurization or depressurization with respect to outside is an indicator of severe problems. However, this is also a symptom of balance problems that can occur with perfectly leaktight ducting.

Repair materials such as mastic or brush-on sealant should be used in preference to tape, since tape fails with time.

Conclusions and Recommendations

Duct-related losses are substantial in recent vintage housing. Apart from retrofit programs, this needs further ~~address~~ attention. With current practice, many new ducted homes are tomorrow's retrofit opportunities. However, repairability is low. New construction practices should address reduction of duct losses by locating ducts inside heated spaces, better balancing and workmanship, and careful inspection.

Duct leakage repair is an economically attractive retrofit. It is especially worthwhile as an addition to ongoing weatherization programs, where per-site travel and other costs are spread over other retrofits.

Further work on diagnostics and predictive models is needed to improve predictability of duct leakage. A better understanding of the thermal consequences of infiltration due to fan-driven local pressurization/depressurization zones within the same house is needed. This is important because in theory it can cause major losses with perfectly sealed ductwork. Short-term thermal diagnostics derived from electric coheating may circumvent difficulties with long term monitoring uncertainty. Thermography in conjunction with fan-on to fan-off alternations may be revealing as either a diagnostic or research tool.

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1. INTRODUCTION

Central forced-air heating systems are the most common residential type. Forced-air furnaces, both electric and gas, are the traditional installation and constitute the majority of older housing stock. Forced-air heating systems are, of course, required for heat pump heating systems. Forced-air systems are less often installed in new energy-efficient construction. The new homes have reduced heating loads, making small in-room resistance heaters more cost-effective. Since energy-efficient electric homes have not yet achieved high market penetration, forced-air systems continue to be installed in many new homes.

The use of forced-air systems leads to operating inefficiencies. The heating system suffers energy losses from conductive heat loss and air flow leakage from the heating ducts. Although recognized, there has been little research to quantify these energy losses. ASHRAE Standard 90 states, "There is no standard for leak testing of low pressure ducts. When low pressure ducts are located outside of the conditioned space (except return air plenums), all transverse joints shall be sealed using mastic or mastic plus tape."[1] This standard is somewhat permissive. Leaks in the retu rn air ducting can still be a significant problem, as will be discussed. It is not clear how effective the mastic sealants or tape are over long periods of time. Compliance by residential builders has not been investigated but is probably not frequent.

In addition to inefficiencies during operation, leaks in heating ducts can contribute to air infiltration. The cracks and crevices in the heating ducts increase the potential for small air leaks when the furnace fan is not operating. This mechanism is referred to as "passive" infiltration to distinguish it from the "active" air losses during fan operation.

Some indication of the influence of duct losses has been noted in regional monitoring projects. Bonneville Power Administration sponsored the Residential Standards Demonstration Project (RSDP) to document the performance of energy efficient homes. Homes in this program include Model Conservation Standards (MCS) homes, representing state-of-the-art energy efficiency. Another group of "current practice" homes were recruited as a control group. It should be mentioned that the current practice homes are not necessarily representative of new housing stock. There is some indication that those who volunteered for this program were already energy conscious individuals. Energy used for hot water, for example, appears to be less for the RSDP group than the norm.[2] The RSDP group has been shown to be younger and more professional.[3] As a result, the current practice homes are probably better constructed and more energy efficient than most new construction. In addition to these homes, another group called the residential ELCAP, included a sample intended to be representative of existing housing stock.[4] The current practice homes appear to fall midway in energy efficiency between the MCS homes and existing housing stock in ELCAP.[5]

Since the RSDP project was sponsored by an electric utility, all the homes were electrically heated. Study of electric homes is analytically convenient, since complexity due to combustion efficiency is avoided. Of course, the same duct leakage problems are expected to occur in fossil-fueled heating systems. Conclusions reached from study of the RSDP homes are expected to be even more significant for combustion heating systems. Such systems are predominantly forced-air distribution with relatively high discharge air temperatures. The high temperature is expected to result in larger system efficiency losses. Natural gas-heated homes have been exempted from aspects of regional energy conservation building codes. It is apparent in this study that energy-efficient homes are better constructed than "current practice" homes. It is likely that gas-heated homes are among those constructed with less care and attention to energy details. In review of the RSDP results, Danny Parker noted that forced-air heating systems consumed more energy than other heating systems under comparable conditions.[6] This difference was most pronounced in current practice homes. In one climate zone, the MCS houses did not show a significant difference due to forced-air heating. This suggests that heating duct losses may be a controllable variable, subject to the skill and care of the installer. This conclusion is not clear, since there were few forced-air systems in the MCS sample and some of these may have been miscoding errors in the database.

In another series of studies, duct leaks were found to account for a significant amount of the total infiltration leakage.[7] Homes in Eugene, OR showed 15% of Effective Leak Area (ELA) due to ducts. In San Francisco, the duct leakage was about 20%.[8] In both cases, the houses measured were intended to be well constructed, energy efficient homes.

The energy impact of duct leakage is complicated because warm air leaks into buffer spaces can still provide some benefit to conditioned spaces. Computer simulations have been developed to investigate such situations.[9] One recent simulation study reports that duct leakage on the order of 20% decreases heating system efficiency by 8%.[10]

The issue of air infiltration has emerged from the RSDP monitoring program as a major unknown. Infiltration predicted from blower door testing does not agree with that measured by long term tracer gas test. Both these methods have their limitations as discussed in Section 3. However, it is expected that forced-air homes have much larger air exchange as measured with PFT tracer tests.[11] This is because air leakage occurs during furnace fan operation.

The increased air exchange might be beneficial if indoor air quality were an issue. However, it might also be a detriment. In at least one case, increased radon levels were noted in a house which appears to have a leaky return duct running through a contaminated crawl space. The issue of combustion appliances and indoor air quality has not been studied. One Canadian researcher feels that carbon monoxide leakage into homes is a serious health problem caused by duct leakage.[12]

All these studies point to duct leakage as poorly studied and potentially important. Nevertheless, the magnitude of energy losses is not extremely large. Why then should duct leakage be studied? The answer is that duct leakage may be relatively easy and cheap to control.

Better articulation of installation requirements and training of installers would improve new construction. Furthermore, the existing housing stock is probably more leaky than the sample of homes studied. In this case, repair of the existing housing stock will yield significant savings with relatively little outlay. Retrofit repair of heating ducts is likely to be highly cost-effective. This suggests that utilities will want to include a duct repair component within their weatherization activities.

1.1. Objectives

These considerations have led to two related studies of duct leakage. The first is a test-reference study comparing leakage and energy use of homes with and without ducting. The analysis relies on statistical inferences drawn from the large group of RSDP homes. The second is a before-and-after study to identify residential duct leakage and determine the effects of retrofit repairs.

Oak Ridge National Laboratory (ORNL) supported a statistical evaluation of the existing RSDP monitoring data to identify characteristics attributable to forced-air systems. The primary goal of this test-reference investigation was to improve the accuracy of retrofit energy savings estimates. Engineering estimates of space heat energy are central to savings estimates and these estimates typically fail to offer good predictions of actual energy usage. Heating system inefficiencies may account for some of the discrepancy. The goal of the ORNL investigation was to develop improved estimating procedures.

Oregon Department of Energy (ODOE) sponsored a field study to investigate duct leakage in a small number of the RSDP homes with a forced-air system. The homes studied tended to be current practice homes. Those MCS homes included tended to utilize a heat pump heating system. A site visit was made to these homes and attempts were made to identify duct leakage by several different methods. Technicians then attempted retrofit repairs on duct leaks and repeated the test procedures. The goal of the study was to examine the following questions:

(1). How much of the total leakage is attributable to the forced-air heating system?

(2). Where are the major heating system air leaks?

(3). What is the repairability of forced-air heating system leaks?

(4). What are the best preventative and repair strategies?

(5). Do heating system characteristics help predict significant air leakage or practically repairable leakage?

In addition, ORNL sponsored a later phase of the same study -- an analysis of monitored energy usage affected by duct losses. The group of homes that participated in the ODOE field study were candidates for before and after monitoring. The RSDP data were particularly useful for this purpose since they included the period before the field visit. ORNL supported further monitoring after the field visit to document any improvements.

Directly determining the energy impact of duct leakage requires evaluation of two seasonal quantities:

- Estimation of additional passive infiltration, during fan-off conditions, due to the presence of heating ducts.
- Estimation of additional fan-driven ventilation, and its net temperature difference, due to furnace fan operation.

Similarly, impact of duct leakage repairs requires assessment of changes in these quantities. However, the precision of available seasonal estimators of ventilation and infiltration is still being debated. Therefore, other indicators of duct leakage are of interest. These indicators include instantaneous leakage characteristics, short-term air exchange rate (ACH) measurements and seasonal energy usage.

2. STATISTICAL ANALYSIS OF THE RSDP SAMPLE

Statistical analysis of already-existing RSDP data was performed with two major objectives in mind. First, a better understanding of the extent of duct-related losses was needed. Second, after the assumption of large losses was proved correct, information relevant to duct retrofit activities was desired. Analysis of RSDP data was opportunistic. That is, RSDP data had been collected for other purposes -- evaluation of a proposed model residential code. Although not optimized for duct loss study, RSDP data was complete enough to provide substantial insights without a new (and enormously expensive) data collection effort.

RSDP data analysis was done in several stages. Preliminary analysis was done with the largest suitable sample sizes. This maximized the statistical "power" of analyses, and gave a broad overview of duct-related losses. This stage indicated duct losses were significant and probably widespread. Subsequent stages of analysis were done on smaller subsets of RSDP data, with two goals: (1) determine if duct losses are associated with house characteristics available in RSDP data, and (2) confirm, insofar as possible, that presence of ducting is responsible for higher losses (as opposed to some other underlying factor).

2.1. Statistical Analysis Methods

The primary analysis method was statistical comparison of means of whole-house leakage, infiltration, and heating energy use indicators, for ducted versus unducted home groups. The statistical significance of such comparisons improves as the variability (standard deviation) of indicators used decreases. This consideration led to two strategies intended to reduce random variability within home groups. The first was selection of relatively homogenous groups, reasonably matched except for ducting (or lack thereof). The second was preferential reliance on indicators that normalized for characteristics that varied widely within otherwise homogenous groups.

The RSDP sample consists of two strongly differentiated groups. MCS homes had previously been shown to have better thermal efficiency and less air leakage than the Control group. Lumping these two groups together for ducted vs. unducted home comparisons would have introduced unwanted variability from non-duct-related causes. Therefore, all comparisons of ducted versus unducted homes treat MCS and Control groups separately.

All of the comparisons of means were tested for statistical significance using t-tests. The presence of ducts is expected to increase air leakage and thermal losses, or at least not decrease them. For this reason, a one-tailed significance test was used. The null hypothesis tested is that ducted homes are not significantly leakier or "lossier" (have greater thermal losses) than unducted homes. Each comparison of two home groups includes a significance level. Significance level indicates the probability that random variation accounts for observed differences in the means. A significance of 0.10 means there is a 10% chance that random variability accounts for the observed effect.

Appendix B shows extensive statistical summaries and comparisons for the RSDP homes. Multiple linear regression and analysis of variance (ANOVA) techniques were also used on an exploratory basis. Results are included in Appendix B.

2.2 Air Leakage and Thermal Loss Indicators

Relevant RSDP data consists of whole-house data on air leakage, space heat energy use, and (for some homes) air infiltration. The air leakage data were obtained using blower door testing, per ASTM E779-81. Space heat energy use data was obtained from space heat submeters. Coincident values of inside-to-outside temperature difference were measured by two-channel temperature loggers. Both space heat meter readings and temperature differences were reported by homeowners at weekly intervals. The infiltration data, for approximately one third of the homes, were obtained using Perfluorocarbon tracer gas, using methods developed by R. Dietz[13]

These data were used to determine four air leakage indicators, two infiltration indicators, and two thermal loss indicators. The air leakage indicators are:

- Four Pascal effective leakage area (4Pa ELA), computed as described by Sherman and Grimsrud[14], in CM^2
- 50 Pascal airflow rate (Q50), the average of whole-house pressurization and depressurization flows at 50 Pascals pressure difference, in CFM
- Four Pascal specific leakage area (4 Pa SLA), the value of 4 Pa ELA divided by house floor area, in CM^2/FT^2
- 50 Pascal air change rate (50 Pa ACH), the value of Q50 (expressed in cubic ft/hr) divided by house volume, in ACH

The later two air leakage indicators are normalized for house size. Since the ducted and unducted home groups were not controlled for size, the size-normalized indicators are considered to be more accurate indicators of leakiness. They have been used in preference to the unnormalized indicators of air leakage.

The two infiltration indicators used are:

- Infiltration ACH, the estimated seasonal infiltration rate, based on 4 Pa ELA and average weather data for a nearby weather station, using methods described by Grimsrud et. al.[15]

- PFT ACH, using whole-house values of seasonal infiltration determined using PFT testing

The infiltration ACH uses weather data that are only approximations to actual site weather. It is subject to greater variability than the direct measures of air leakage, to the extent these weather approximations are incorrect. These variations are in addition to any inaccuracies that may be inherent in the estimating method itself.

The thermal loss indicators are:

- K factor, the slope of the regression of space heat energy use rate versus inside-outside temperature difference, BTU/°F-HR

- Specific K factor (Sp. K), the K factor divided by house area in square feet, BTU/°F HR FT^2

Obtaining suitable values for K factor and specific K factor involved several considerations. A complete, accurate house data set tends to produce reasonable correlation between space heat energy use rate and temperature difference. Figure 1 shows an example plot of "clean" regression data. However, some homeowners had difficulty reporting meter readings correctly. Others used wood heat at times, in spite of being paid to refrain from doing so. Some data sets were incomplete due to temperature recorder malfunctions. Incomplete or incorrect data, and wood heat use, tended to produce poor correlations between space heating and temperature difference. For these reasons, only sites showing strong regression results were used in the comparisons. An F-test significance level of 0.1 or less was used as the criterion for inclusion in the comparison groups.

The K factor for a home is a composite value that represents both shell losses and heating system efficiency (COP). In terms of engineering units, it is similar to UA/efficiency. The objective of comparing K factors for ducted versus unducted homes is to detect differences due to duct-related losses, with all else held as constant as is practical. Using ducted groups that include heat pumps tends to defeat this comparison, since unducted homes used resistance heat (COP =1.0) and heat pumps have COPs greater than 1. For this reason, homes with heat pumps were excluded from the K factor and specific K factor comparisons.

Specific K factor was used in preference to K factor, since it better accounts for uncontrolled variations in house size.

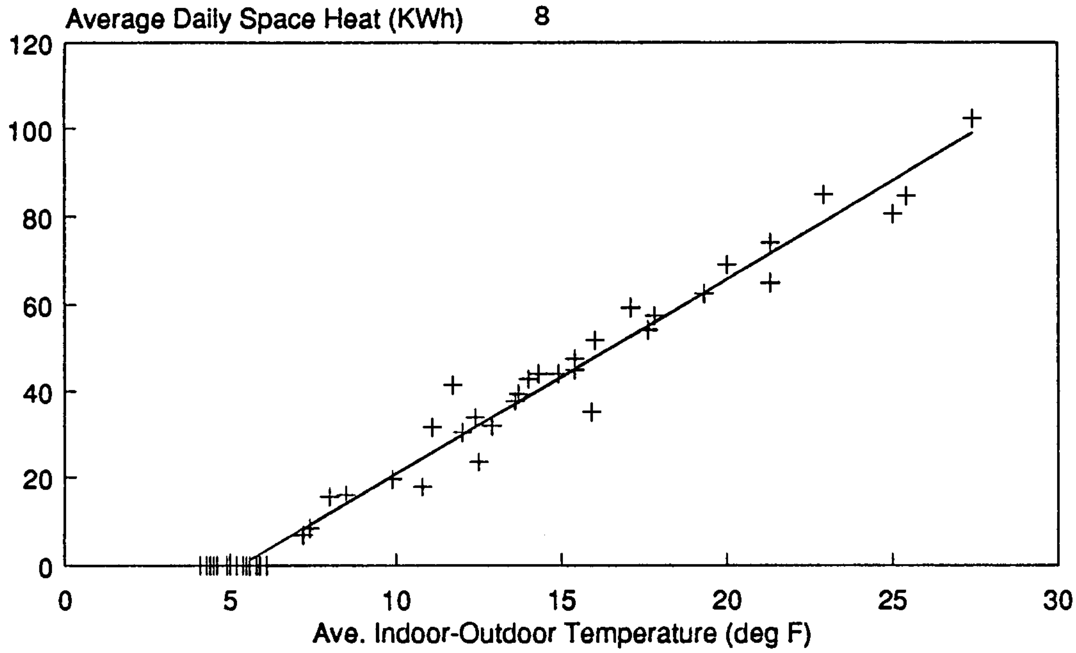

Figure 1. K Factor regression example - monitored space heat energy use vs temperature difference, site 770

2.3 Large Sample Comparison Results

Results of the large sample comparisons are shown in Table 1. As previously noted, separate comparisons are made for the MCS and Control groups.

The overall trend is quite clear. With the exception of PFT-measured infiltration for the MCS group, ducted homes are leakier, experienced greater infiltration, and used more space heat than unducted homes. The significance levels indicated that presence of ducting is very likely to be associated with greater leakage and thermal losses.

The main instances where significance levels are less robust are for the PFT comparisons, and infiltration ACH in the MCS group. The less robust significance for PFT comparisons may result, at least in part, from the smaller sample sizes available for comparisons. The significance level for infiltration ACH may be adversely affected by additional variability introduced by the estimating method used to determine infiltration ACH.

The extent of differences between ducted and unducted homes can be roughly assessed by normalizing each comparison. The normalizations shown in Table 1 were accomplished by dividing means of indicators for ducted groups by means of corresponding unducted groups. The resulting ratio is not exact, since it fails to account for uncertainty of either mean. However, it provides a useful indicator of approximate duct effects for each comparison.

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

Variable	Group	Mean	Ratio: Ducted/ Unducted	S. D.	Count	One-tailed Significance
MCS Sample						
Infil.ACH	Unducted	0.2428		0.1719	134	.109
	Ducted	.2721	1.12	.1738	87	
50Pa ACH	Unducted	3.3898		2.1177	134	.088
	Ducted	3.7879	1.12	2.1299	86	
4 Pa ELA*	Unducted	268.87		194.61	134	.000
	Ducted	412.75	1.53	268.59	87	
4 Pa SLA	Unducted	0.1485		0.1069	134	.014
	Ducted	.1813	1.22	.1092	87	
K Factor*	Unducted	234.54		112.27	126	.000
	Ducted	329.19	1.40	163.38	66	
Specific K Factor	Unducted	0.1315		0.0596	125	.047
	Ducted	.1484	1.13	.0747	64	
PFT	Unducted	0.3164		0.2227	58	.356
	Ducted	.3019	.95**	.1761	50	
Control Sample						
Infil.ACH	Unducted	0.5143		0.2301	169	.000
	Ducted	.6046	1.18	.2472	123	
50 Pa ACH	Unducted	7.3596		2.8190	167	.000
	Ducted	8.8822	1.21	3.0312	114	
4 Pa ELA*	Unducted	467.26		209.42	169	.000
	Ducted	726.96	1.56	282.41	123	
4 Pa SLA	Unducted	0.3222		0.1679	169	.000
	Ducted	.4072	1.26	.1610	123	
K Factor*	Unducted	304.50		153.33	159	.000
	Ducted	492.99	1.62	196.96	106	
Specific K Factor	Unducted	0.2005		0.0732	150	.000
	Ducted	.2805	1.40	.1101	106	
PFT	Unducted	0.3144		0.3765	86	.076
	Ducted	.3949	1.26	.1818	50	

* Denotes variable that is not normalized for size differences between groups

** Indicated ratio lacks statistical significance

Two of the un-normalized indicators, 4 Pa ELA and K factor, have been included in Table 1. Comparison of the means ratios of these indicators to their normalized counterparts (4 Pa SLA and specific K factor) shows a difference. The means ratios are smaller for the normalized indicators. Review of the data showed this is due to a systematic difference between ducted and unducted home sizes; ducted homes tended to be larger. The un-normalized indicators (4 Pa ELA, Q50, and K factor) are therefore shown to be biased. For this reason, subsequent discussions and analysis deals primarily with the normalized indicators. However, normalizing by floor area may not completely eradicate systematic group differences attributable to size. It is reasonable to expect that both SLA and specific K factor should decrease with size (all other factors remaining constant). This is because the ratio of surface area to floor area is expected to decrease with size. If larger homes are less "lossy", the duct impacts may be larger than is indicated by the difference in means.

2.4 Large Sample Conclusions

Based on the means ratios, the presence of ducting is associated with greater leakage and greater thermal lossiness in both groups. Duct effects appear to be more pronounced in the Control group than in the MCS group (this conclusion supports the a priori decision to treat the two groups separately).

For the MCS group, ducting was associated with 12% to 22% greater whole-house leakiness (based on 50 Pa ACH and 4 Pa SLA, respectively). Ducting was associated with 13% greater thermal lossiness (based on Sp K) in the MCS group. Ducting may have been associated with 12% more infiltration ACH, but the significance level was not as conclusive as for the other indicators. PFT data was inconclusive for MCS homes.

For the control group, ducting correlates with 21% to 26% greater leakiness (using 50 Pa ACH and 4 Pa SLA). Ducting also correlates with 40% greater thermal lossiness (based on Sp K). Infiltration was also 18% to 26% greater in ducted homes (using infiltration ACH and PFT, respectively).In both groups, 4 Pa SLA showed higher significance levels than either 50 Pa ACH or infiltration ACH. This suggests that this indicator may be the superior one (of these three) for distinguishing duct leakiness effects.

It should not be expected that all indicators will show the same extent of duct effects. This is because the various indicators include effects of different physical parameters. The leakage indicators (4 Pa SLA and 50 Pa ACH) reflect whole-house leakiness at different pressure differentials. Neither accounts for furnace fan pressure rise or duty cycle. In contrast, Specific K factor implicitly includes the effects of fan-driven air leakage from the ductwork and house envelope. Also, it must be recognized that specific K factor differences between ducted and unducted homes are partly due to conductive heat loss from ducts. The observed effect cannot be attributed entirely to volumetric air loss. Location of ducts can mitigate this impact. Ducts located partially or entirely inside the conditioned space would reduce much of the conduction impact.

The infiltration indicators also differ, in that infiltration ACH, as it was computed for this study, does not include furnace-fan-driven air leakage. In contrast, PFT-measured infiltration implicitly includes furnace fan effects. It is worth noting that PFT values for ducted homes are subject to the uncertainty caused by the "average of the inverse" problem. The ducted houses would have more error if there is a large change in exchange rates due to furnace fan operation. This may partly obscure the expected higher air exchange rate for the ducted houses. For this study, it is not clear that attempts to compare blower door and PFT infiltration will provide useful information.

For these reasons, the variety of different duct impacts, from indicator to indicator, should not be interpreted as inconsistency of results.

The results also show that all indicators used exhibit high variability. An example plot, Figure 2, shows frequency distribution of 4 Pa SLA for the entire sample, for ducted vs. unducted homes. This is significant for at least two reasons. First, the high standard deviations for all the various measures illustrate the inherently high variability of building characteristics. In Figure 2, the unducted homes show an approximation to a normal distribution. The ducted homes are skewed to higher values by the presence of serious outliers. The fact that not all the homes are affected shows that ducted homes can be tightly constructed in some cases. Secondly the high variability in both distributions emphasizes the importance of large samples when attempting statistical comparisons.

Both the high variability within groups, and the generally lower duct losses in the MCS group show that ducting does not inherently imply severe losses. Some homes in both groups experienced relatively low duct losses. The MCS group in particular showed lower levels of duct-related losses. The RSDP data are not detailed enough to pinpoint which aspect(s) of the MCS might explain lower MCS losses. However, it seems very likely that there is a cause - and-effect relationship. Systematic differences between MCS and control homes are:

- Duct location - MCS builders were encouraged to locate ductwork within heated spaces, when feasible.

- Duct insulation - MCS required all ducts to be insulated to R-11. By code, control duct insulation could vary from none in basements to R-4 or R-8 in attics, crawlspaces, and garages.

- o MCS homes had significantly higher levels of envelope insulation than controls.

- o MCS homes used continuous vapor barrier construction and low air leakage windows as infiltration reduction measures. These were not required for controls.

A graphical overview of leakiness, infiltration, and thermal lossiness of both groups is useful. Figures 3 through 6 show relative differences between groups for selected variables. The PFT ACH is not shown due to the smaller number of sites tested by this method and the lack of statistical power with small samples. The variables examined are normalized to building size to facilitate comparisons.

The specific K factor comparisons shown in Figure 6 are particularly revealing. The additional lossiness of ducted controls (over unducted controls) is slightly larger than the savings achieved by unducted MCS as compared to unducted controls. Stated another way, **duct losses appear as important as the effects of a model energy efficiency code.**

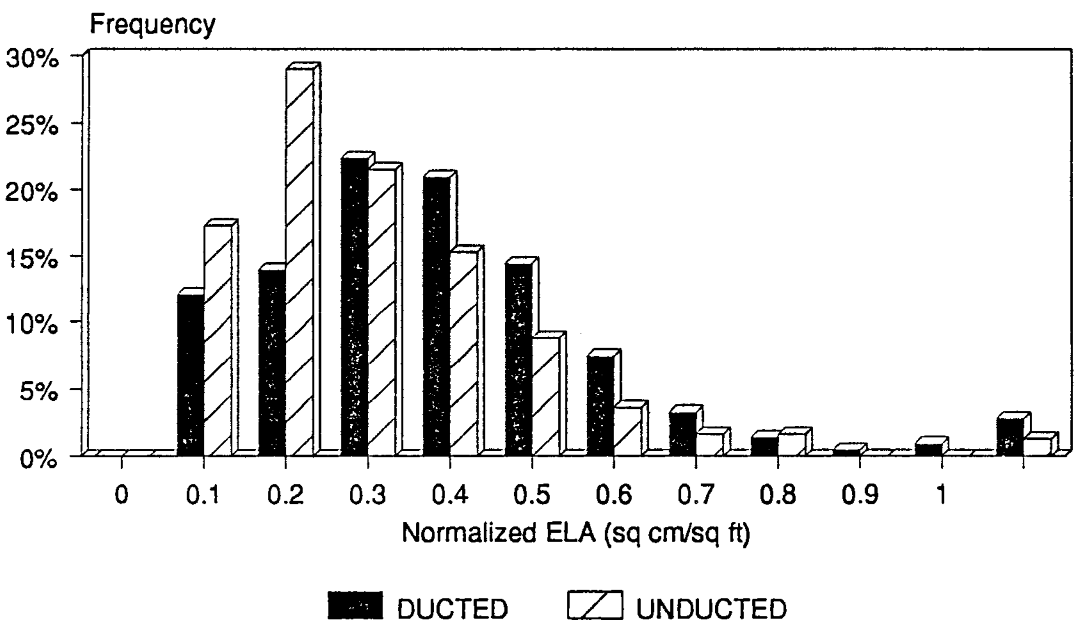

Figure 2. Distribution of specific leakage area - combined MCS and control groups

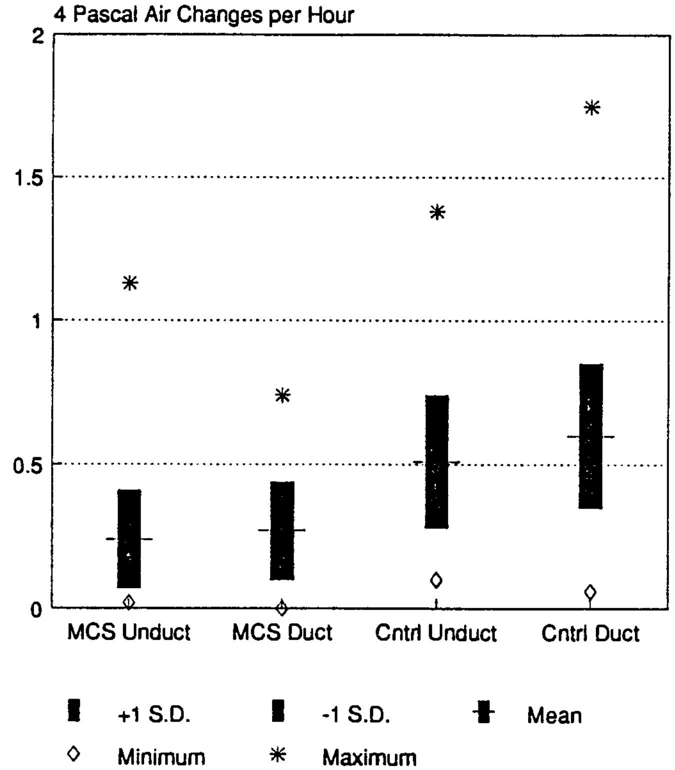

Figure 3. Natural infiltration rate.

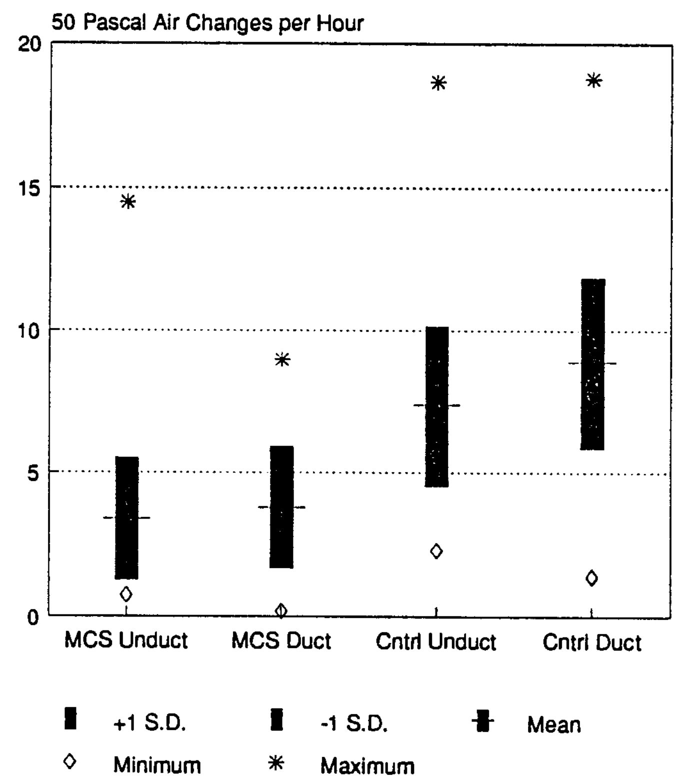

Figure 4. 50 Pascal Air Exchange Rate.

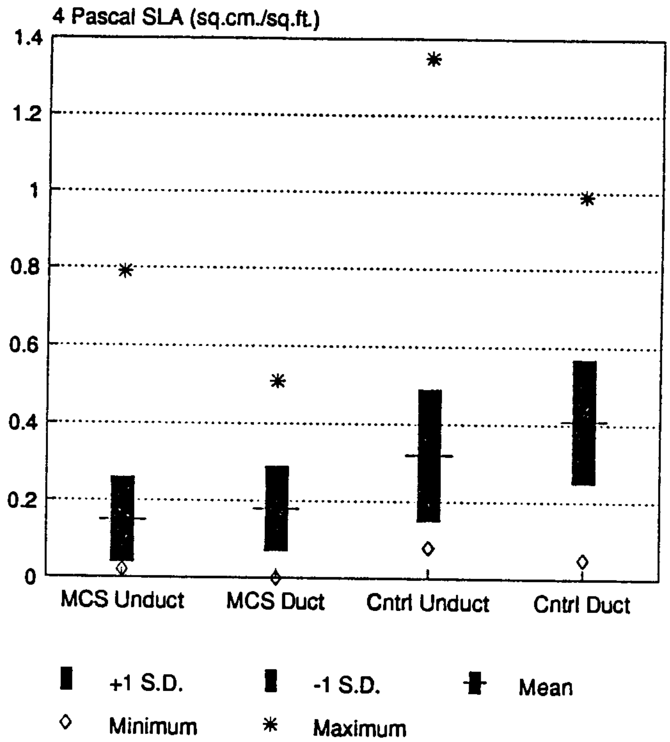

Figure 5. 4 Pascal specific leakage area (SLA).

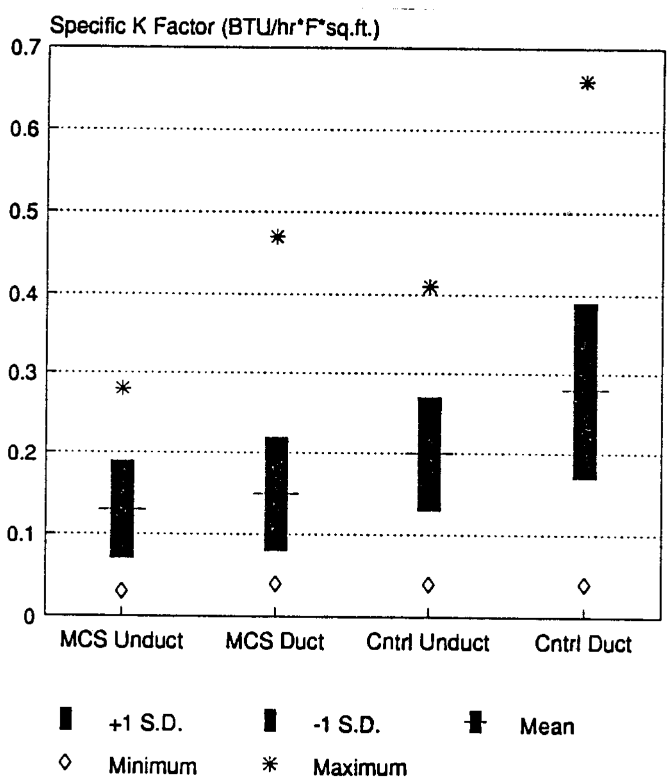

Figure 6. Specific K factor.

2.5 Analysis of RSDP Data Subsets

The large sample comparisons show significant duct effects, but they are not uniform. This raises issues relevant to energy use estimation and to retrofit considerations.

If duct losses are more prevalent in certain classes of homes, energy use estimating methods should account for them. Where RSDP house characteristics support examining duct losses by house type, this should be explored.

In any program addressing duct leakage repairs, retrofit targeting and retrofit effectiveness are issues. If particular classes of homes exhibit especially high duct losses, they may be preferred targets for retrofitting. Also, performing duct leakage repairs presumes a cause-and-effect relationship between duct leakage and thermal losses. This presumption should be checked, if possible.

These issues can be addressed, to some degree, by examining duct losses as a function of house characteristics. RSDP data supported examination of duct-related losses by structure type.

The structure types examined were: substructure type (slab/finished basement, unfinished basement, crawl space) and number of stories (single story, two or more stories). The experimental variables were 4 Pascal Specific Leak Area (SLA), 50 Pascal Air Change Rate (ACH50), and Specific K Factor (Sp K). These variables are normalized for house size or volume with units as previously stated. As before, Specific K Factor analysis was limited to non-heat pump sites with strong regression results.

Tabular results for ducted versus unducted comparisons by substructure type are shown in Table 2. Figures 7 through 12 show the comparisons in graphical form.

Eleven of the eighteen comparisons show strongly significant elevations of leakiness or thermal losses for ducted cases. The remaining seven comparisons show weaker statistical significance. Comparisons showing weaker significance could signify that duct effects are small for that comparison. The weak significance could also result from small sample size. Sample sizes in Table 2 are substantially lower than those in Table 1. Comparisons showing the least significance (MCS basement cases) are those with the smallest sizes.

In the MCS group, ducted crawlspace homes are significantly leakier and significantly lossier. In the control group, all three substructure types show significantly higher losses for ducted homes. The trend is that presence of ducting virtually always is accompanied by greater leakiness and greater thermal losses. This persistent trend strongly suggests that there is a cause-and-effect relationship between ducting and losses.

Table 2. Comparison of Ducted vs Unducted Homes for Various Substructure Groups

Category	Dependent Variable	Duct Type	No.	Mean	Means Ratio*	S.D.	One Tailed Significance Level
Cntrl Basement	SLA	Unduct	22	.263		.151	.101
		Duct	18	.316	1.20	.094	
Cntrl Slab		Unduct	47	.254		.100	.000
		Duct	32	.361	1.42	.141	
Cntrl Crawl		Unduct	89	.377		.187	.014
		Duct	58	.443	1.18	.164	
MCS Basement		Unduct	19	.122		.064	.173
		Duct	14	.157	1.28**	.139	
MCS Slab		Unduct	47	.149		.108	.210
		Duct	29	.167	1.12**	.098	
MCS Crawl		Unduct	58	.159		.117	.034
		Duct	35	.204	1.29	.110	
Cntrl Basement	ACH50	Unduct	22	6.08		2.30	.165
		Duct	16	6.92	1.14**	2.07	
Cntrl Slab		Unduct	45	6.14		1.99	.000
		Duct	30	8.38	1.36	2.92	
Cntrl Crawl		Unduct	89	8.27		2.85	.010
		Duct	54	9.44	1.14	2.91	
MCS Basement		Unduct	19	2.88		1.49	.485
		Duct	13	2.86	0.99**	1.93	
MCS Slab		Unduct	47	3.33		2.17	.421
		Duct	27	3.43	1.03**	1.82	
MCS Crawl		Unduct	58	3.66		2.24	.067
		Duct	35	4.41	1.20	2.43	
Cntrl Basement	Sp K	Unduct	20	.172		.076	.001
		Duct	17	.281	1.64	.121	
Cntrl Slab		Unduct	47	.166		.062	.000
		Duct	30	.243	1.46	.099	
Cntrl Crawl		Unduct	89	.230		.070	.000
		Duct	45	.301	1.31	.100	
MCS Basement		Unduct	19	.117		.048	.443
		Duct	12	.115	0.98**	.043	
MCS Slab		Unduct	43	.110		.058	.123
		Duct	19	.128	1.16**	.048	
MCS Crawl		Unduct	54	.153		.056	.020
		Duct	24	.188	1.23	.092	

* Ducted/Unducted

** Indicates ratios lack statistical significance

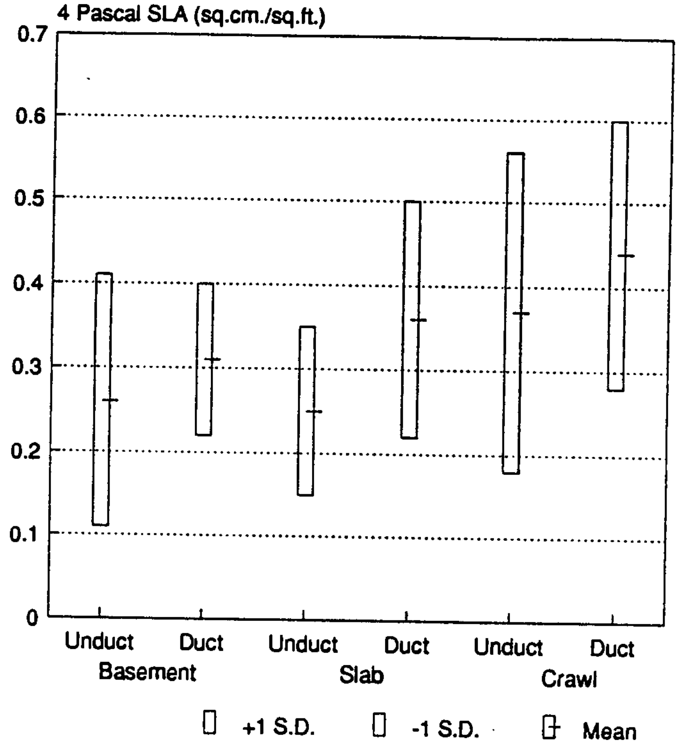

Figure 7. Control group specific leakage area (SLA) by substructure type.

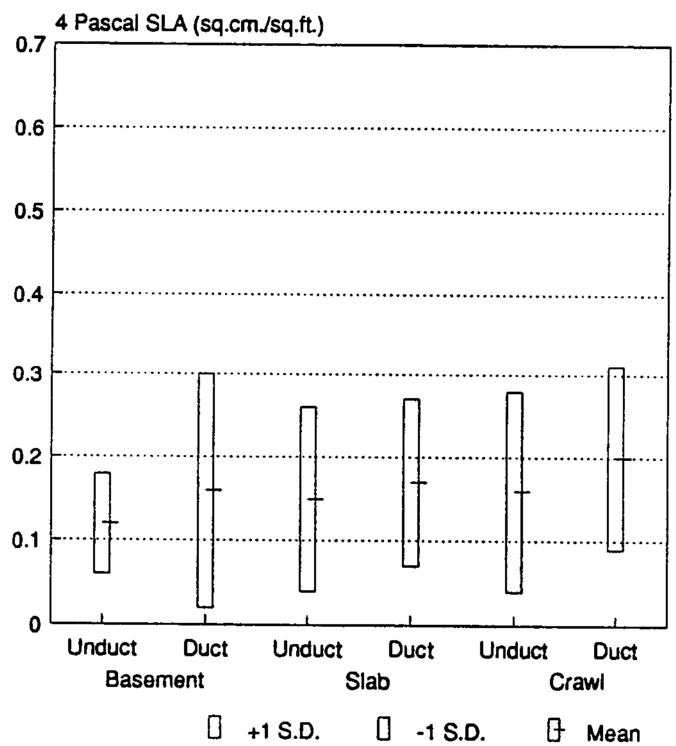

Figure 8. MCS group specific leakage area (SLA) by substructure type.

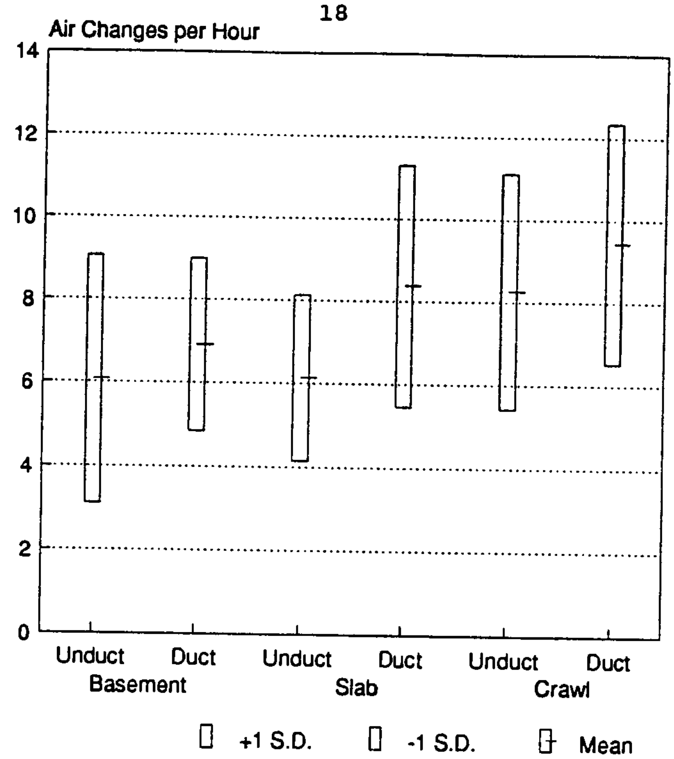

Figure 9. Control group 50 pascal air exchange rate by substructure type.

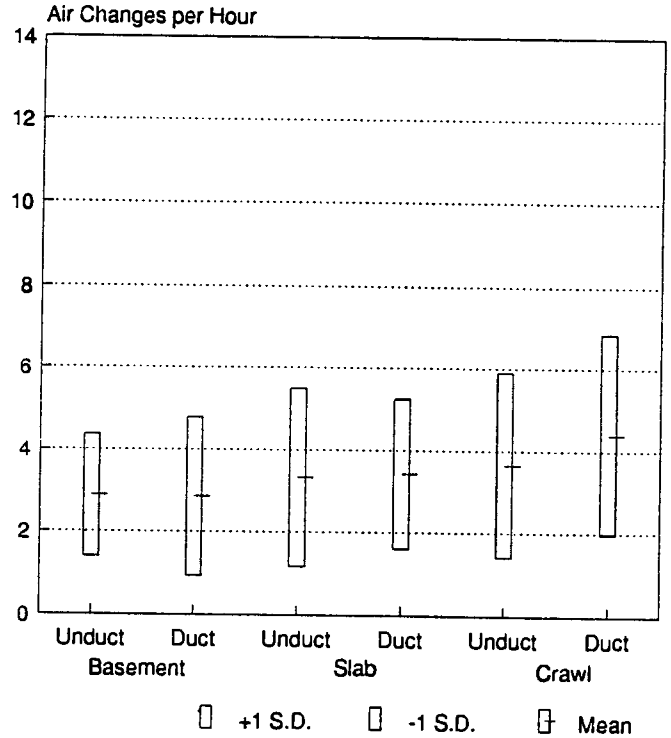

Figure 10. MCS group 50 pascal air exchange rate by substructure type.

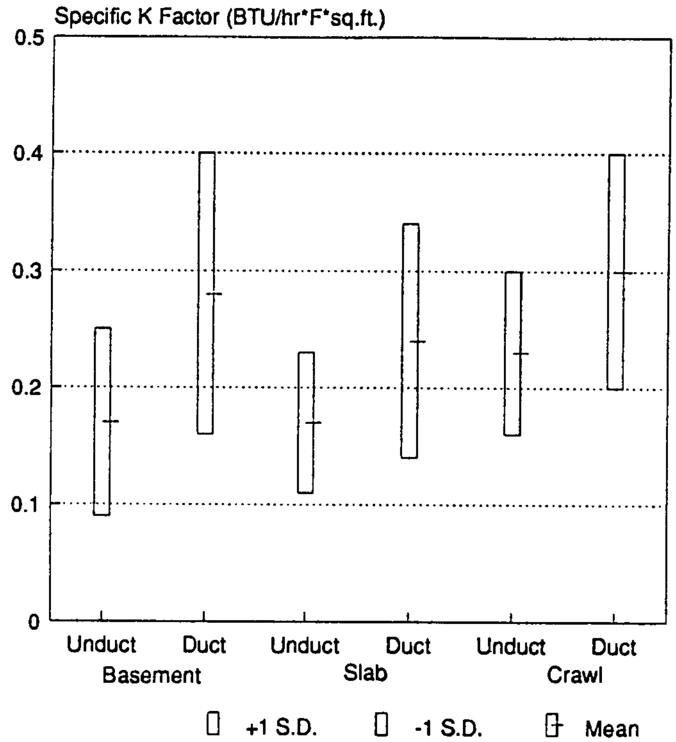

Figure 11. Control group specific K factor by substructure type.

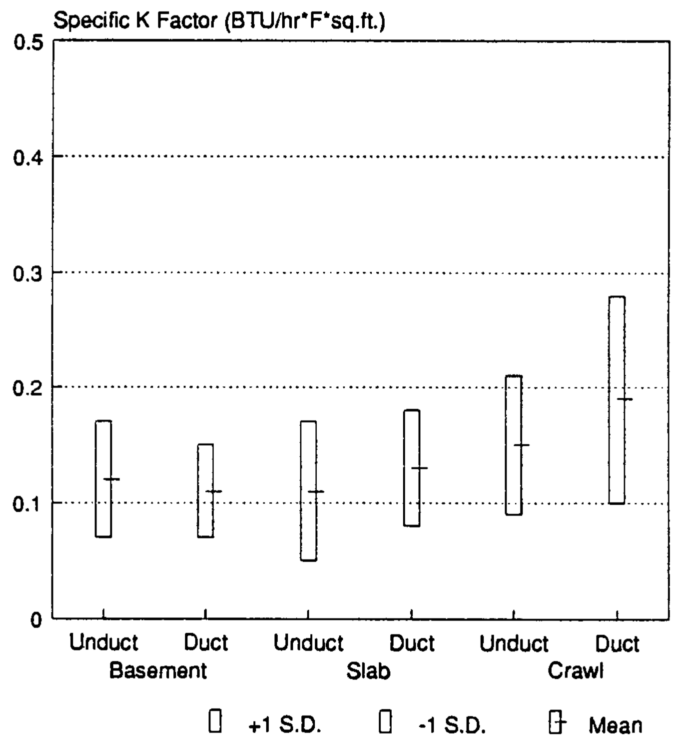

Figure 12. MCS group specific K factor by substructure type.

Comparisons on the basis of substructure type showed some differences which were not intuitively obvious. Comparing the control crawlspace group to the MCS crawlspace group showed that the presence of ducts caused an impact in both groups. The effect of basements was different. In the MCS group, ducted basement cases were leakier, but showed no significant increase in thermal losses. In the control group, ducted basement homes were also leakier. However, basement control homes showed a large elevation in thermal losses for ducted cases. The difference in energy usage was related to the MCS/Control distinction and also a 3-way interaction with the structure, ie. basements affect duct losses more in the control group. Slab homes showed the same general pattern as crawlspace homes. Presence of ducting was associated with greater leakiness and greater thermal losses.

Comparisons of ducted versus unducted cases for one and two story homes also showed ducted homes to be leakier and lossier than unducted homes. Significance levels were generally higher for the control group. The less significant comparisons were associated with small sample sizes. Data for various subsets by number of stories are shown in Appendix B.

The curious effect observed for basement homes, i.e., increase of leakage for ducted homes in both groups, but markedly different effects on thermal losses, prompted three additional statistical analyses. These additional analyses were also used to explore for other potentially relevant trends. Multilinear regressions and analysis of variance (ANOVA) techniques were used. In addition, effect of substructure type (as opposed to ducted versus unducted comparisons) was analyzed using comparison of means. The results of these analyses, discussed in the following four paragraphs, did not provide significant additional insight into the odd effect of basements on thermal losses. Multilinear regression and ANOVA results are shown in Appendix B.

The leakage variables were regressed against dummy variables representing the MCS/Control category, Ducted/Unducted category and substructure type. As expected, the category variables are significant -- MCS homes have less and Ducted homes have more leakage. The results for substructure type are usually not significant. The 50 Pascal Leakage (ACH50) shows the strongest influence. In this case, basements appear to have somewhat less leakage (at the 82% probability level). This effect probably results from the fact that basement surfaces are relatively well sealed, and do not leak as much. In general, the amount of leakiness does not appear to be dependent on basement type.

ANOVA results for substructure type are consistent with multilinear regression results. Substructure type shows an influence, however that influence is primarily due to interactions between duct type and substructure type. Homes with basements tend to have ducted heating systems and the presence of ducts affects leakage.

Comparison of means by category (Table 2) indicated that the slab/finished basement and unfinished basement types are similar categories. For subsequent analysis, these categories were combined leaving just two types -- basement/slab and crawl space. Since there were few slab structures, the first type consists of primarily basement structures. Means for these types were compared using t-tests within categories. ~~Results are shown in Table 3.~~

The results in Table 3 show reasons for caution in interpretation. Even in unducted homes, crawl space structures tend to be more leaky than basement ones. This suggests a construction problem which is unrelated to the heating system. In fact, the MCS homes, which are more carefully constructed, show less influence due to structure type. The presence of ducts clearly affects leakiness and when those ducts are located in a crawl space, leakiness is even worse. Energy usage is more difficult to interpret because the crawl space structures have a larger heat loss coefficient. This suggests that basements tend to serve as tempered buffer spaces reducing heat loss relative to untempered crawl spaces.

2.6 Relationship Between Leakage and Thermal Losses

As previously noted, performing duct leak repairs presume a cause-and-effect relationship between duct leakage and thermal losses. In the context of statistical study results, this is a concern for two reasons. First, the greater leakiness observed in ducted homes can be due to both leaks in the duct themselves, and to duct penetrations of the structure. Thermal consequences of duct leaks are greater than structural leaks. Second, the greater thermal losses observed can be due to duct leakage, duct conduction losses, natural infiltration through duct structural penetrations, and to fan-driven structural leakage.

Unfortunately, the whole-house data from RSDP do not explicitly separate these causes of duct-related leakage and losses. However, if observed losses are primarily due to duct leakage, one would expect leakier home groups to exhibit proportionately greater losses. In the large group comparisons this appears to be the case. Referring back to Figures 5 and 6, control homes show greater duct-related leakage, and greater duct-related losses, than MCS homes.

Examination of the by-substructure comparisons reveals some exceptions. Review of Figures 7 and 11 shows that control basement homes have incremental leakage smaller than either the slab or crawlspace groups. However, control basement homes show the largest incremental losses of the three substructure types. Alternative hypothees are that duct conduction losses or fan-driven envelope leakage account for major portions of the increased losses in control basement homes. High conduction losses from ducts in basements seems unlikely, since basements are typically warmer than either crawlspaces or attics. This leads to the suspicion that fan-

Table 3. Comparison of Substructure Types

Category	Dependent Variable	Basement Type	Number	Mean	S. D.	Significance Level
Cntrl Unducted	SLA	Basement	70	.260	.120	.000
		Crawl Sp	89	.377	.187	
Cntrl Ducted		Basement	50	.345	.127	.001
		Crawl Sp	58	.443	.164	
MCS Unducted		Basement	66	.141	.098	.377
		Crawl Sp	58	.159	.117	
MCS Ducted		Basement	43	.164	.111	.115
		Crawl Sp	35	.204	.110	
Cntrl Unducted	ACH	Basement	70	.469	.204	.020
		Crawl Sp	89	.554	.244	
Cntrl Ducted		Basement	50	.556	.206	.102
		Crawl Sp	58	.635	.283	
MCS Unducted		Basement	66	.254	.170	.588
		Crawl Sp	58	.237	.174	
MCS Ducted		Basement	43	.254	.174	.279
		Crawl Sp	35	.298	.183	
Cntrl Unducted	ACH50	Basement	68	6.213	2.440	.000
		Crawl Sp	89	8.269	2.853	
Cntrl Ducted		Basement	46	7.870	2.723	.007
		Crawl Sp	54	9.435	2.905	
MCS Unducted		Basement	66	3.202	3.657	.235
		Crawl Sp	58	3.657	2.240	
MCS Ducted		Basement	42	3.231	1.822	.018
		Crawl Sp	35	4.405	2.432	
Cntrl Unducted	Sp K	Basement	68	.168	.066	.000
		Crawl Sp	82	.230	.070	
Cntrl Ducted		Basement	47	.256	.108	.000
		Crawl Sp	45	.301	.100	
MCS Unducted		Basement	62	.112	.055	.000
		Crawl Sp	54	.153	.056	
MCS Ducted		Basement	33	.123	.047	.001
		Crawl Sp	24	.188	.092	

driven structural leakage may be a major factor in losses of ducted control homes with basements.

Another exception is evident for basement MCS homes. Reference to Figures 8 and 12 shows that ducted MCS basement homes have incremental leakage similar to slab and crawlspace groups. However, ducted MCS basement homes show no significant incremental losses, while slab and crawlspace groups do show incremental losses. This is the same effect mentioned in section 2.5. MCS requirements include insulation of basement ducts and tight envelopes with continous vapor barrier construction. It may be that both duct conduction losses and fan-driven structural leakage in ducted MCS basement homes are minimal.

While not conclusive, the statistical comparisons show that duct-related leakage and duct-related losses are closely related in most groups. The exceptions for basement groups indicate that duct leakage is not the only cause of duct-related losses. In particular, fan-driven structural leakage appears to be a likely cause of large losses in the basement control homes.

3. FIELD TEST METHODS

3.1 Introduction

The second phase of the duct leakage investigation consisted of field testing of ducted homes, using a before-and-after experimental format. Duct leakage identification and repair was performed between tests. This activity included two components that frequently overlapped -- leak identification, and quantification of leakage effects for impact evaluation purposes. These diagnostics, the underlying theoretical models, and associated precision (or lack thereof), repeatability, and interpretation are discussed in this section.

Significant improvements were made compared to previously reported diagnostics. However, there is still a need for better field test methods and models for interpreting field data. The limited precision and repeatability of these diagnostics prompted extensive reviews, in the context of actual field results (These reviews are presented in Section 4).

Diagnostic methods relating to duct leakage can be divided into two categories based on the type of program wherein they would be applicable. One program type would be production-oriented, that is, directed to repairing a large number of homes in the most cost-effective manner. The other type would be a research-oriented program, investigating the details of leakage and energy interactions.

In a production-oriented retrofit project, simple, reliable, low-cost methods are desirable to:

- Identify homes with significant duct leakage.
- Localize leakage to supply or return ducts.
- Quantify the amount of duct leakage.
- Estimate the energy savings of repairs.
- Pinpoint leak location to guide repair work.

In researching duct leakage, the same objectives apply, but the methodology can include tools which are under development or too costly for production-oriented projects.

Field techniques to localize and quantify duct leakage are described in Sections 3.2 to 3.5. These methods are adaptations or extensions of existing residential test methods. Indicators and diagnostics to identify homes and guide repairs are discussed in Section 4.

3.2. Blower Door Testing

The blower door is a way to measure the air flow versus pressure difference characteristics of a structure. To the extent that the ductwork can be "shut off" or isolated, a sequence of measurements with ducts open and ducts sealed can be made. By subtraction, a rough idea of the flow versus pressure difference characteristics due to the ductwork is obtained. This method implicitly assumes that blocking grills seals all the leakage due to the presence of heating ducts. Penetrations of ductwork through the building envelope are thus lumped together with other structural leaks. Duct related leakage will be underestimated to the extent that such penetrations are leaky.

The blower door testing has other uses as well. It can be used during construction or retrofit weatherizing to identify envelope leaks. Techniques are available for estimating natural infiltration rates using blower door results. Finally, the blower door is useful for producing the pressure differentials needed for other tests and diagnostics.

The procedure for using the blower door calls for installing a large fan in one door of the home. The fan is run at various speeds and the volume of air required to maintain the house at different pressures is measured. There is an empirical relationship:

$$Q = k\,(P)^n \quad \text{where} \qquad [1]$$

Q = volume flow rate
P = pressure difference between house and outside
n = exponent, usually in the range $0.5 < n < 1.0$

Application of the blower door results to determine infiltration often uses methods developed at Lawrence Berkeley Laboratory.[14,15] The Q versus P data are plotted on a log-log plot and extrapolated down to the point where P is equal to 4 Pascals. This pressure is similar in magnitude to the pressures driving natural, or passive, infiltration. At this point, it is assumed that the relationship has the form for inviscid flow through large openings:

$$Q = A\,(2P/p)^{.5} \quad \text{where} \qquad [2]$$

A = Effective Leakage Area (ELA)
p = density of air

The Effective Leak Area (ELA) is then calculated from the extrapolated air flow at 4 pascals.[15] An example of a regression plot is shown in Figure 13. The regression lines are shown extended to the 4 Pa point. As previously discussed, ELA appears to be larger for homes with forced-air systems.

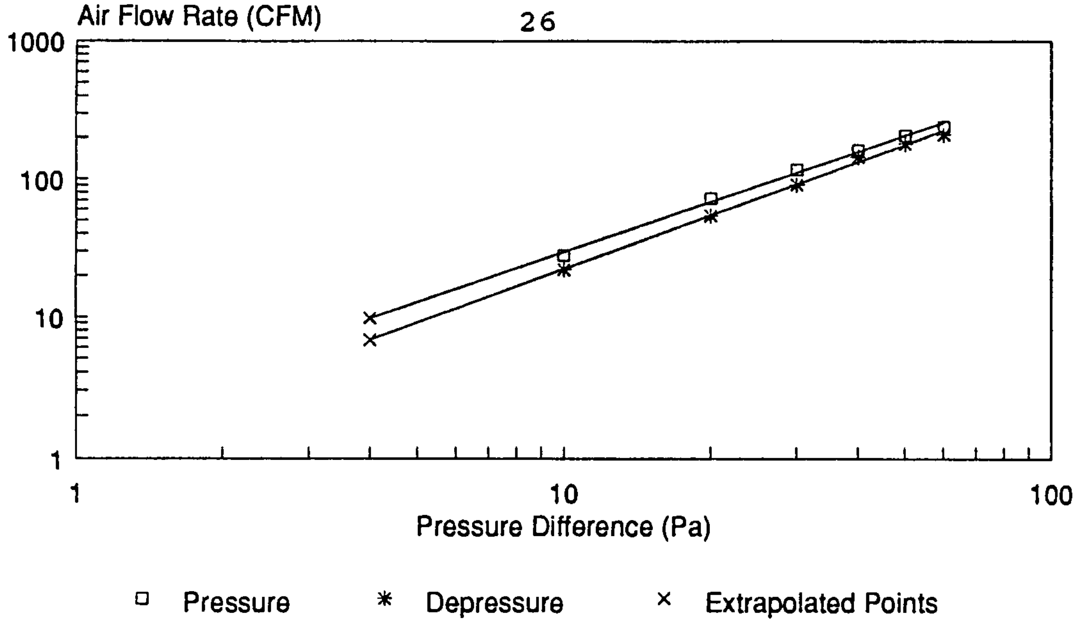

Figure 13. Example of blower door regression - whole house pressurization/ depressurization, site 135.

The four Pascal ELA is one of several measures used to quantify the leakiness of a house. Four Pascals is significantly below the tested pressure differences, which usually range from 10 to 60 Pa. Extrapolation is required to reach the 4 Pa range. Persily has shown that the repeatability of ELA suffers due to this extrapolation.[16] Repeated tests of the same structure yields various exponents for n in Equation [1]. (This exponent is also the regression slope as shown in the Figure 13 example.) Projecting regression lines to 4 Pa with varying exponents produces disproportionally large variations compared to the variations in the underlying air flow and pressure difference data.

An alternative leakiness measure is the volumetric flow rate at 50 Pascals pressure difference (Q50). This may be either the actual test measurement or the regression fit at 50 Pa. This value is inherently more repeatable, being within the tested data range.

When comparing the leakiness of differently sized structures, ELA and Q50 flow rate are often normalized. The ELA normalized (divided by the floor area) is called the Specific Leakage Area (SLA). The Q50 normalized (divided by the house volume) is expressed in units of air changes per hour (ACH) and referred to here as ACH50.

Although blower door testing has the advantage of being a practical field technique, it also has serious limitations. The precision of the 4 Pa ELA estimate is estimated as $\pm$ 10%.[17]

Adapting blower door results to annual energy estimates is problematic. One expects that infiltration during the space heating season will be related to the leakage area. However, local weather will affect infiltration.[18] The geometry and location of the leaks will also have an effect. By assuming typical values for these parameters, a specific infiltration factor can be calculated based on the weather. Seasonal infiltration is then the product of 4 Pa ELA and the specific infiltration factor. These factors have been calculated for a variety of cities.[19]

In summary, the blower door provides a succession of parameters regarding structural leakage characteristics. The most objective and repeatable of these is the empirical flow equation, $Q = k\,(P)^n$. Increasingly subjective and less repeatable parameters such as 4 Pa ELA and annual infiltration can also be obtained. Duct leaks are likely to be masked by structural leakage. Performing before-and-after or ducts open/ducts sealed test sequences are useful but imprecise. As will become apparent in Section 4, the non-repeatability of blower door testing is significant enough that subtractive determinations of duct leakiness can be significantly in error. Such errors can be further amplified through before-and-after comparisons.

3.3. Infiltration Interactions

Infiltration air flows interact in ways that are not obvious. Consider as an example the house shown in Figure 14. Passive infiltration occurs normally as a result of wind and stack effects driving air through the house. However, the passive infiltration can be affected when the furnace fan operates. The fan can induce a net positive or negative pressure in the house. If there are more leaks in the supply ducts, the house will be depressurized. If there are more leaks on the return side, the house will be pressurized. Unbalanced leakage, if it occurs, will affect passive infiltration.

Figure 14 shows a "single zone" conceptual model. Tooley and Cummings have recently shown that actual house pressurization phenomena are often more complex.[20] With central return ducted systems, some conditioned spaces (typically bedrooms) can be highly pressurized, while other spaces (those well-coupled to the central return) are slightly depressurized.

In most cases, the leakage rates appear to be reasonably balanced. In our field investigation, we noticed a few cases where there were seriously unbalanced leaks. Even in these cases, the main house to outside pressure difference due to imbalance was small, up to 0.5 Pa.

The experimenter cannot assume that passive infiltration and fan-induced air exchange will be additive. Modera and coworkers have suggested that the unbalanced portion of the air flow should be added in quadrature with stack and wind induced infiltration.[21] Infiltration would then have the form:

$$\text{Qtotal} = [(\text{Qwind})^2 + (\text{Qstack})^2 + (\text{Qunbalanced})^2]^{.5} + \text{Qbalanced} \qquad [3]$$

where Qbalanced = minimum of supply or return duct leakage rates,
Qunbalanced = difference between supply and return duct leakage rates.

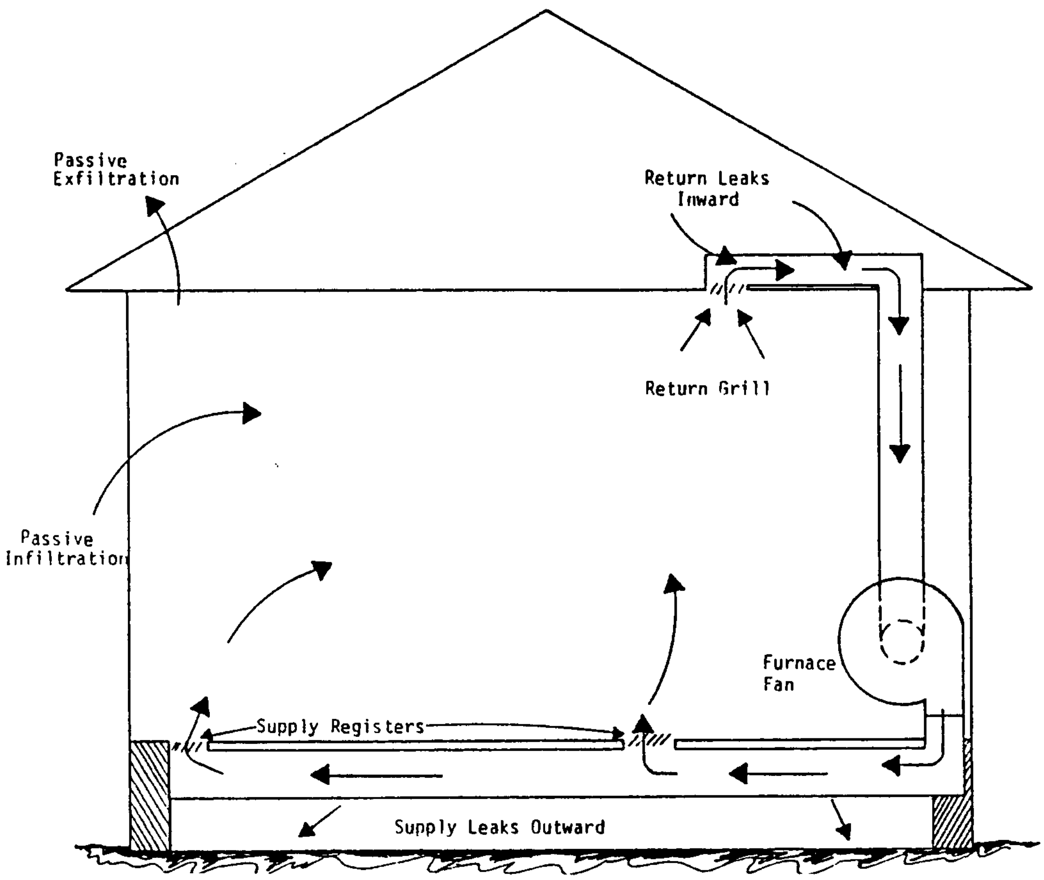

Figure 14. House diagram showing air flows

Alternatives to the quadrature model have been proposed. Kiel and Wilson have suggested that, for large fan-driven exhaust flows, simple linear addition of the flows is a better estimator.[22] The linear model assumes that the unbalanced portion of the flow simply replaces an equivalent volume of passive infiltration. The combined flow is then balanced flow plus either the unbalanced flow or the infiltration, whichever is larger. The addition model applied to this situation would be of the form:

$$Qtotal = |Qbalanced| + Qinfil \quad [4]$$

where $|Q|$ represents the absolute value
Qinfil is the natural infiltration due to stack and wind effects

$$Qinfil = [(Qwind)^2 + (Qstack)^2]^{.5} \quad [5]$$

The models reviewed do not address the kinds of fan-driven infiltration caused by localized pressurization and depressurization reported by Tooley and Cummings. There is a need for improved models to deal with these kinds of phenomena.

3.4. Flow Hood Measurements

In this study, Lambert Engineering improved on a variation of blower door testing which may be a useful field technique. The method used is now under review as part of a draft ASTM standard.[23] The desired information from blower door testing is a plot of log Q versus log P for only the duct leaks. The blower door information for the whole house is of limited utility because the flow quantities are imprecisely determined. Assume as an example, that the flow quantities are known with ± 10% repeatability and that two such quantities (corresponding to ducts sealed and ducts open) are subtracted from each other to estimate the duct leakage air flow quantity. Since the duct leakage is often in the 10% range, it is clear that the experimental noise tends to obscure the information desired.

It is more useful to measure duct leakage flows directly. For this purpose, a low velocity flow hood was used. The supply and return sections of the ducts were isolated from each other by applying a seal at the furnace fan. Then all the registers and grille were sealed except for one supply register and one return grille. The house was pressurized and depressurized with the blower door. This allows air flow into and out of the open grille to be measured directly with a flow hood. Schematic diagrams of the technique are shown in Figures 15a and 15b.

Supply duct characterization concentrated on pressurization tests. Return duct concentrated on depressurization. This is consistent with normal furnace fan operation. It should be noted that ordinary flow hoods are not suitable for the small air flows involved. The flow hood used (Lambert Engineering FH250) was specifically designed for low air flows.

At the same time, it was necessary to measure the pressure in the duct. With some experimentation, it appeared that an effective

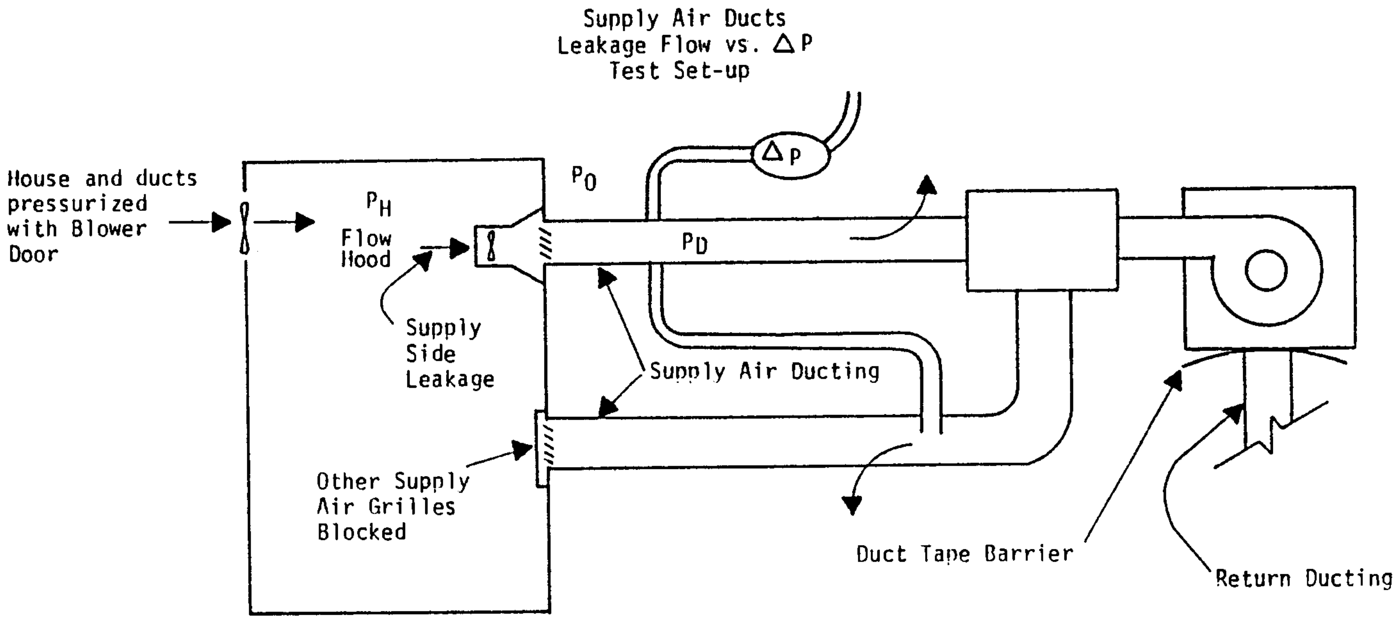

Figure 15a. Flow hood schematic -- supply duct

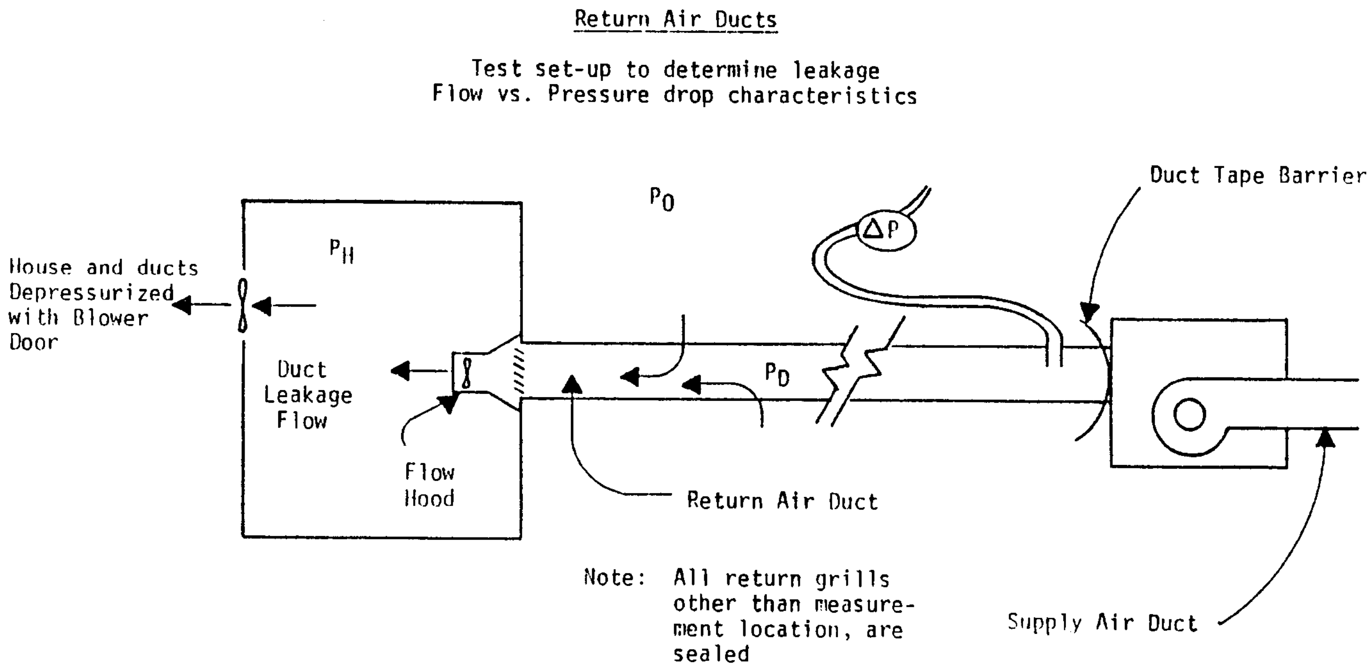

Figure 15b. Flow hood schematic -- return duct

average pressure could be measured which was representative of the entire duct. This is because the velocity in the duct due to leakage was usually small. It was observed that a pressure drop occurred at a small supply register but pressures were fairly uniform inside the ductwork. As would be expected, the return side, with a large grille, tended to be at the house pressure. The supply side with a smaller area entrance, tended to be at an intermediate pressure. Supply duct pressure was measured at a reasonable mid-point near the distribution plenum. The pressure probe was generally inserted into a "stagnant" duct, not the one on which the flow hood was mounted.

With the flow hood technique, it is necessary to accept the fact that there is some uncertainty in the measurement of "effective" duct pressure. This uncertainty in duct pressure does not occur during the conventional blower door test because, with all register and grille areas open, the duct is at the same pressure as that measured for the house.

In summary, the flow hood technique provides much better resolution of duct air flow although there may be some uncertainty in the effective duct pressure. An example of the log Q versus log P regression plot is shown in Figure 16. The chart shows plots for supply and return ducts both before and after retrofit repairs. Change in the plots due to repairs is apparent. Note that the plot also shows "typical" static pressures in the duct as a result of furnace fan operation. Also, note that is possible to obtain values from such a plot for duct leakage flows at either 4 Pa or 50 Pa. This facilitates comparisons with blower door whole-house values of duct leakage in terms of 4 Pa ELA or 50 Pa flowrate.

Another approach for quantifying duct leakage has been suggested.[24] This method uses blower door measurements taken while the fan is operating with a partially blocked return grille. Blocking the grille ensures that a more uniform pressure exists inside the duct. The house is then pressurized to 50 Pa and the difference in air flow from the fan-off point noted. This technique suffers from poor precision for duct measurements since air flow into the whole house is being measured. A log Q versus log P plot is constructed but using only two data points. After some experimentation, we felt that this method was more cumbersome and less reliable than the flow hood technique.

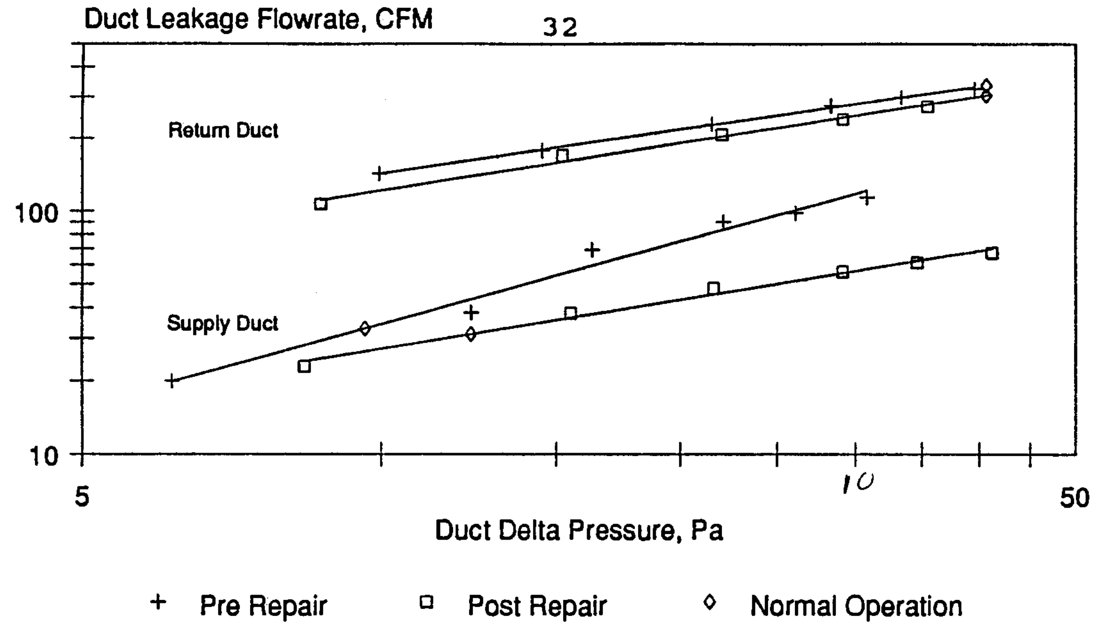

Figure 16. Flow hood regression plot - duct leakage vs. duct pressure difference, site 135.

3.5. Tracer Gas Measurements

Other methods have also been developed for measuring air infiltration using tracer gas. One common method is called Perfluorocarbon Tracer (PFT) testing. Results from PFT tests on some buildings were investigated during the statistical analysis of the RSDP data. A source and absorber pair are placed in a building for some length of time. The amount of PFT absorbed and the amount given off can be determined. The amount absorbed bears an inverse relation to the concentration. Concentration can be calculated and, in turn, the air exchange volume can be computed.

The PFT method has some problems. What is actually measured is the average inverse concentration, from which the average concentration is calculated. However, the average of the inverse is not necessarily the same as the inverse of the average. Houses with large variation in concentration may give misleading results. This would be expected for homes with forced-air systems. Whenever the furnace fan runs, air exchange increases and concentration decreases. Thus forced-air houses with intermittent fan-driven leakage would be expected to show more error in PFT testing than would other homes.

Another tracer technique is conducted over a short time period.[25] In this case, sulfur hexafluoride (SF6) is used for the tracer. The gas is harmless and can be measured precisely in very small concentrations -- at the parts per billion range. With the SF6 method, a small amount of the gas is released and its exponential decay measured over time. The decay rate yields the building's air exchange rate with the outside. This method provides an accurate one-time measure of infiltration.

The SF6 method was used during the field retrofit phase to measure fan-driven air exchange directly. Comparison of the fan-on and fan-off ACH measurements give an indication of the net change in ventilation due to fan operation. Pre- and post-retrofit tests were also run to gauge reductions in fan-driven ACH due to repairs.

3.6. List of Equipment

The following equipment was used during the field test procedures:

Fan Pressurization -- Blower Door.
  Minneapolis Blower Door Company "restriction" type measurement system.
    Accuracy: ± 5% of flow
    Range: 20 to 5000 CFM
    50 Pascal flow capability: >4500 CFM

Air Flow/ Velocity

  Lambert Engineering FH-250 low range flow hood.
    Accuracy: ± 5%
    Range: 25-250 CFM
    Backpressure: <0.01 inches water gauge (3 Pascals) at 250 CFM

  Davis Instrument DI 10102 4" diameter rotating vane anemometer used for estimating system airflow at return grille.
    Accuracy: ± 10% (manual scan mode)
    Range: 30 to 5000 feet/minute

Air Pressure (Static pressure in ducts)
  Setra Pressure Transducer.
    Accuracy: ± 1% Full Scale
    Range: 0 to 1.0 inch water gauge (0 to 249 Pascals)

Temperature
  TM-99 digital thermometer
    Accuracy: ± 0.4 degree F
    Resolution: 0.1 degree F
    Range: 32 degree F to 230 degree F

Gas Chromatograph
  S-Cubed Model 215BGC Laboratory Trace Gas Monitor
    Accuracy: ± 10%
    Range: 10^{-9} to 10^{-12} parts SF_6

4. FIELD TEST RESULTS

The methods of Section 3 were applied to the retrofit group to determine both "as found" characteristics and the effects of repairs. First, each house was tested for as-found duct leakage and fan-driven infiltration, using a blower door, duct hood, and SF_6 decay tests. Leak location and repair was then accomplished. This was followed by repetition of the various tests, including grills-sealed blower door tests.

4.1. Leakage Characteristics of Ducts

The leakage attributed to ducts was measured by several methods:

(1) total house 4 Pa ELA measured with ducts open and ducts sealed and for different leakage sources

(2) ELA measured by extrapolating flow hood data

(3) Q50 air flows measured by difference in blower door tests as well as by interpolating flow hood data

(4) air exchange rate measured by tracer gas

The different measures had consistent results within the precision (or lack of it) of the technique. Whole house blower door testing is not precise. Results agreed with flow hood measurements, but only on the average and with higher variability. Whole house blower door testing was not sufficiently precise to measure small differences in leaks, as for example, in measuring the leakage due to floor penetrations.

4.1.1. Repeatability of Blower Door Testing

Before presenting the results of blower door testing, it is instructive to look at the precision and repeatability of the results. Each house was tested under similar weather conditions at the beginning and end of the site visit. This test was conducted with ducts sealed both times. If test repeatability were perfect, these two tests should yield identical results. The amount the results differ shows non-repeatability. Review of such differences, for many homes, indicates the degree of repeatability. Applying this repeatability criterion to 4 Pa ELA test data for a group of homes requires normalization, since each house had a different ELA. The difference between the two tests was divided by the "control" ELA (the ELA measured with all registers and grilles sealed). The resulting percentage of non-repeatability in ELA is shown in Table 4. On the average, the homes showed results reproducible within 8%. This is about the expected variability due to temperature, weather and other conditions.

The distribution of these differences is shown in Figure 17. There can be considerable difference between two measures of the same house. It is not clear that the difference is merely random "noise". There are differences between fan pressurization and depressurization tests. This has implications for the test results. To minimize the effects of experimental noise, the results of several tests, both pressure and depressure, were averaged whenever possible. However, in most cases, there were not several tests to utilize. Results based on comparisons of one-time tests should be viewed with caution.

Table 4. Change in ELA Between Similar Tests

	Pressure	Depressure	Average P&D
Mean	-0.298%	-1.59%	8.64%
S. D.	3.76	21.03	4.18
n = 20			

50 Pascal Airflow rate (Q50) is an alternative leakiness measure available from blower door data. Like 4 Pa ELA, this measure is obtained from the log Q versus log P plot. The advantage of Q50 is that it is interpolated to a point near field measurements. In contrast, the ELA is based on a point extrapolated to remote extremes from measured data points.

Repeatability of Q50 testing was also examined. The morning and afternoon "ducts sealed" tests should be comparable. Percent change between the two tests is shown in Table 5. Distribution of the fractional change is shown in Figure 18. The Q50 results can be compared to the ELA repeatability in Table 4 and Figure 17. Repeatability is improved somewhat as shown by the tendency for change effect to cluster around zero. However, there is still experimental noise present in the use of the blower door.

Table 5. Change in Q50 Between Similar Tests

	Pressure	Depressure	Average P&D
Mean	-1.73%	-1.63%	-2.19%
S. D.	5.96	9.09	6.89
n = 18			

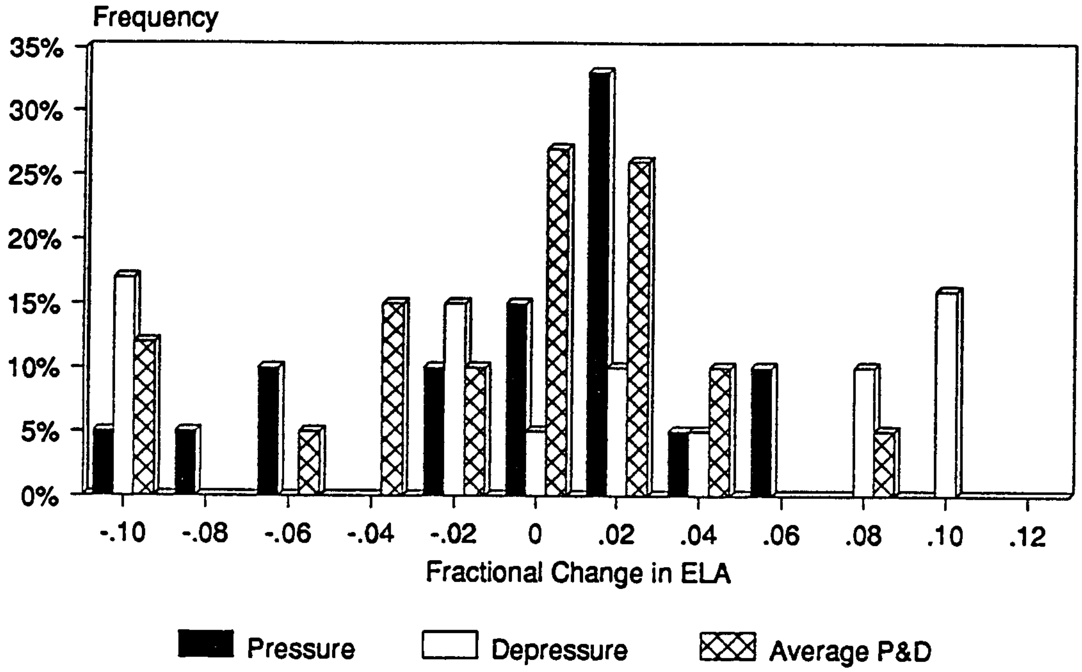

Figure 17. Repeatability of ELA from test to test

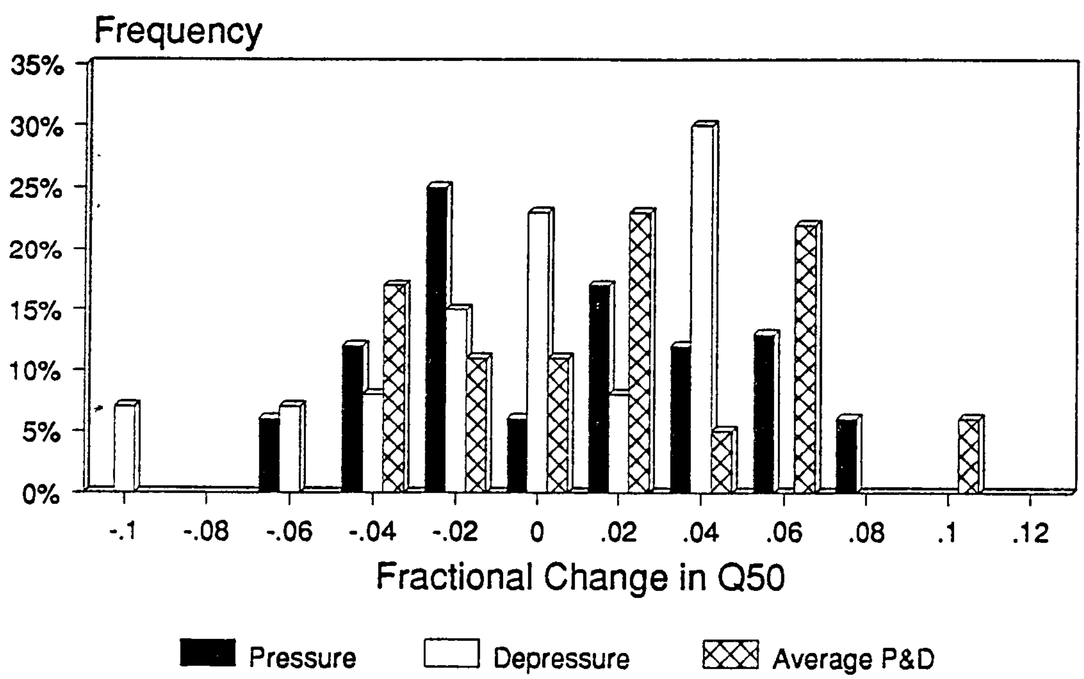

Figure 18. Repeatability of Q50 from test to test

The extent of non-repeatability of blower door results presented a problem for duct leakage determinations, as discussed in Sections 3.2 and 3.4. The flow hood method avoids the errors inherent in subtracting one imprecisely known quantity from another imprecisely known value of similar magnitude.

4.1.2. Whole-house Duct Leakage Results

With the blower door's limited precision in mind, the amount of 4 Pa ELA attributable to duct leakage is listed in Table 6. Results from the flow hood method (discussed below) are also shown. These results are based on the house as found, before any retrofit repairs. Since the repairs affect the amount of leakiness, a stable base case is needed for comparison. The base case is taken to be the "control" amount of leakage, that is, the average ELA measured with all grilles and registers sealed. The additional ELA due to duct leakage is reported as a fraction of the control ELA. This also serves to normalize the different ELA's for variations in house size. Mean duct leakage is about 10%. However, there is considerable distribution of the duct leak fraction as shown in Figures 19 and 20. There are also differences depending on fan pressurization or depressurization tests. [It should also be noted that in this and subsequent tables, the number of cases analyzed may vary. This is because field test data were incomplete for some sites. For comparison of before and after cases, the sites were kept to comparable numbers. That is, comparison tables are limited to those sites with complete data.]

Table 6. ELA Percentage Due to Duct Leakage Before Repair (n = 20)

	Pressure	Depressure	Average P&D
Blower Door Method			
Mean	4.99%	15.30%	9.36%
S. D.	6.31	17.60	7.08
Flow Hood Method			
Mean	6.84%	13.73%	9.49%
S. D.	4.52	10.03	5.43

The first set of measurements are based on blower door testing of the entire house structure. Since the experimental error is similar to the effect under investigation, the precision is poor. Another approach is to measure the duct leakage directly using the flow hood technique as described in Section 3.4. In this case, the duct leakage is extrapolated to the 4 Pa point from the log Q versus log P plots measured for the ducts alone. This allows a better determination of the duct leakage amount. However, the blower door test is still used to provide the amount of "control" leakage used as a base case. A certain amount of experimental

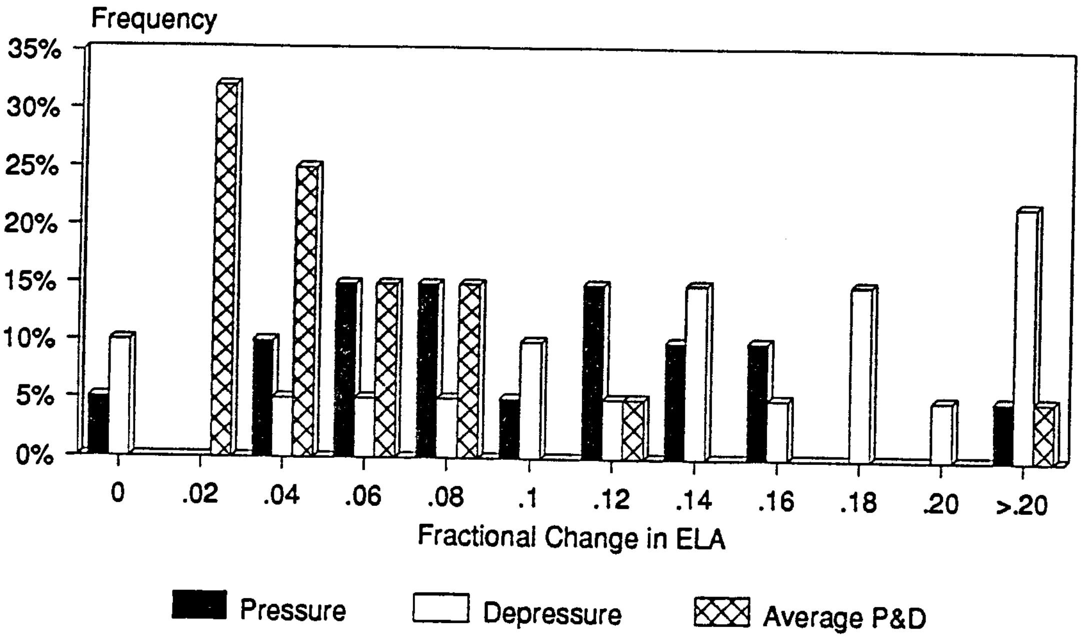

Figure 19. Distribution of duct fraction of ELA, blower door measurement (before repair).

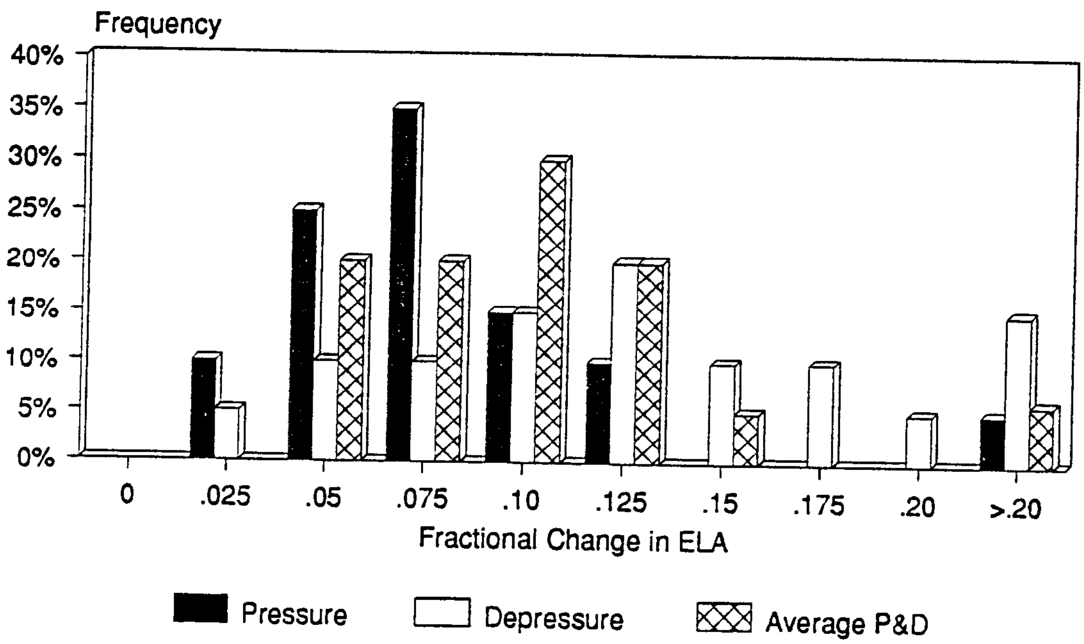

Figure 20. Distribution of duct fraction of ELA, flow hood measurement (before repair).

noise from the blower door technique is inescapable. The fraction of ELA due to duct leakage as determined by the flow hood method is also listed in Table 6. Distribution of the results is shown in Figures 19 and 20. The flow hood method gives similar results to the blower door method, but with some improvement in reducing variability.

Alternative measures of duct leakage, based on 50 Pascal airflow (Q50), can be obtained from both blower door and flow hood measurements. Tabular results of these measures are shown in Table 7. Distribution of values measured with the flow hood are shown in Figure 21. Results are very consistent with the ELA fractions shown in Table 6. Duct leaks account for about 11% of Q50 leakage.

The blower door method of comparing Q50 relies on subtracting the "grilles sealed" flow from the "grilles open" flow. An alternative is to calculate duct leakage. Duct leakage is extrapolated from flow hood measurements. The duct leakage is then divided by the "control" leakage to produce the additional fraction of leakage due to the ducts. Note that incomplete data were present for some sites. The flow hood and blower door comparisons are based on averaged pressure and depressure results.

Both methods produce similar results as shown in Table 7. The flow hood method appears to have less variation. The flow hood method still contains experimental noise since it relies on the blower door test to provide the "control" amount of leakage used as a base case. Q50 results by the two methods are compared in Figure 22. The results do appear to cluster around this correspondence line. The experimental noise shows as the amount of deviation off the one-to-one correspondence line.

Table 7. Duct Portions of Q50 -- Before Retrofit (n=19)

	Flow Hood Method			Blower Door Method
	Q50Depr.	Q50Press.	Q50Ave D&P	
Mean	11.6%	10.8%	11.2%	10.9%
S. D.	5.1	10.4	8.2	11.4

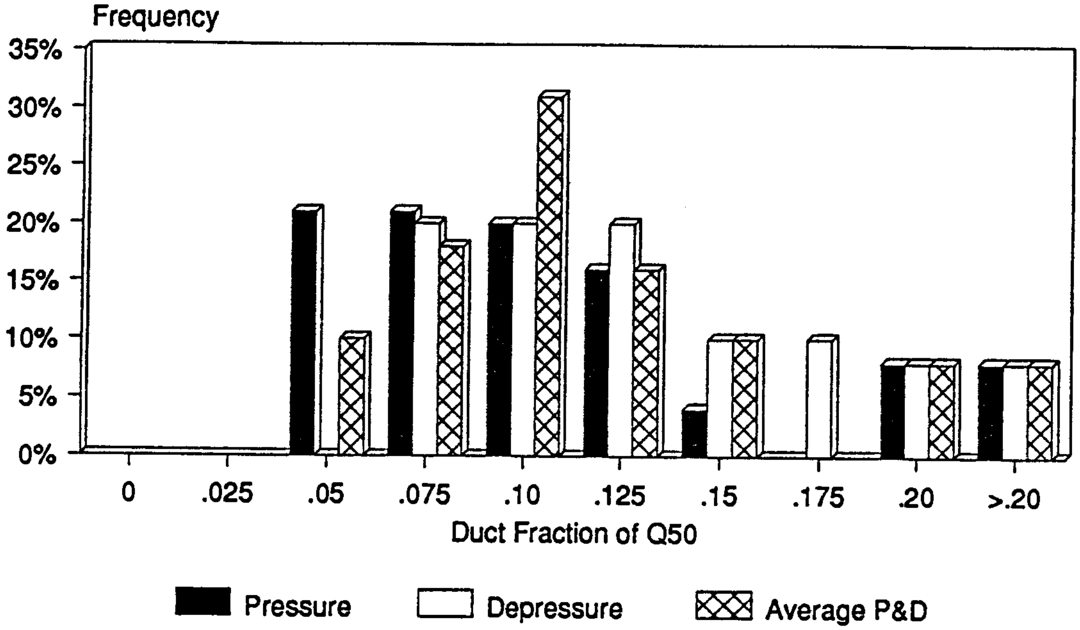

Figure 21. Distribution of duct fraction of 50 pascal airflow (Q50), by flow hood method (before repair)

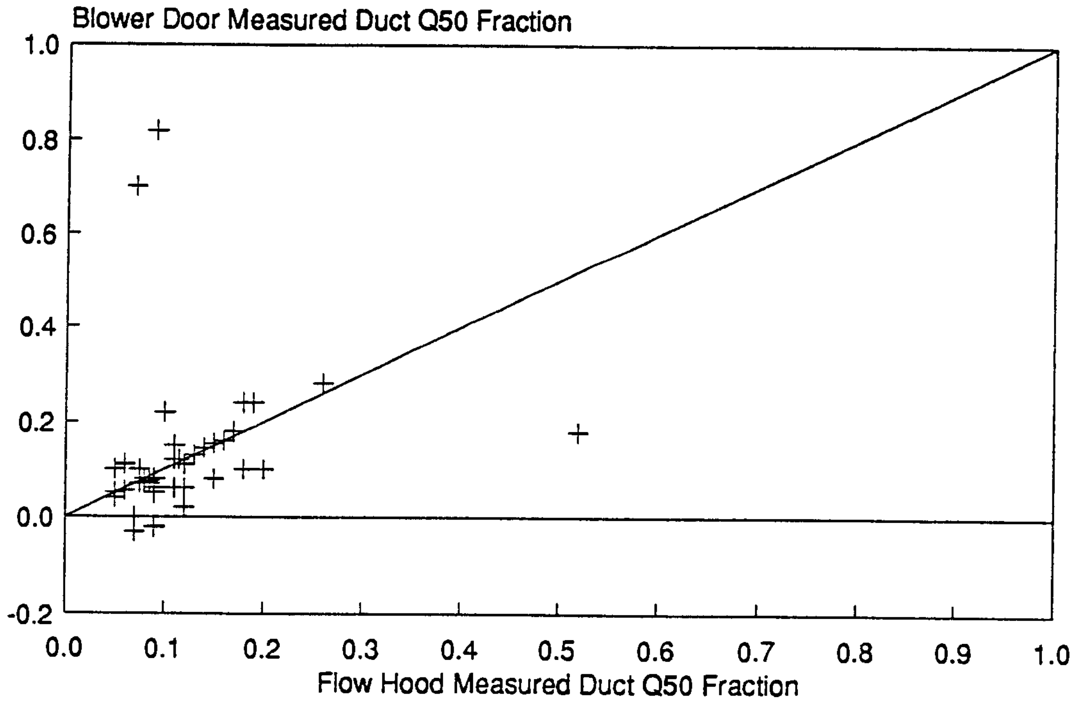

Figure 22. Duct fraction of Q50 - Blower door and flow hood compared

4.2. Identification of Duct Component Leakage

Knowledge of the relative leakiness of various components of ducted systems is important from several standpoints. Thermal impacts of leakage will vary depending on leak location (supply, return, or duct-related structural leaks). Retrofit activities will benefit from knowledge of where leaks typically occur. Also, distribution of leakage between the supply and return side ducting has consequences for fan-driven structural leakage.

Attempts to isolate duct leakage by component were not successful using the blower door tests alone. Field procedure called for repairing one part of the duct system. Then the blower door test was conducted to document any improvement in the whole house ELA. The procedure was repeated at several stages during the repair process. The components where improvement identification was attempted were:

(1). After repairs to supply duct leaks allowing loss of heated air
(2). After repairs to furnace filter slots and return duct leaks allowing intake of unconditioned air
(3). After repairs to floor penetrations for grilles and registers.

Supply ducts are the most critical for heating efficiency since they leak heated air. Return duct leaks include the furnace filter slot and other leaks typically located in the garage. The energy impact may not be as large. These leaks draw in "buffered" air as opposed to outside air. It is important to note that leaks located in a garage can affect indoor air quality by drawing in carbon monoxide or other contaminants.[26] The floor penetrations are not directly part of the ductwork. However, they may be responsible for some of the observed difference in ELA between ducted and unducted homes. If so, they will contribute to increased passive infiltration.

This application of blower door testing to identify small incremental improvements was not very successful. In general, the experimental noise far outweighs any change due to the retrofit repair. Results of the post-repair component testing are shown in Table 8. The results show the fractional change in duct related ELA relative to the "control" leakage achieved by each repair step. On some houses, the complete sequence of repairs was not possible. For this reason, the number of homes analyzed varies. The blower door results shown in Table 8 are not meaningful because, with the large variation observed, the results are not statistically significant.

Table 8. Change in Duct-Related ELA After Duct Repairs

	Supply Duct	Return Duct	Floor Penetrations
Mean	4.01%	111.2%	-3.71%
S. D.	157.3	217.7	109.7
n =	18	17	20

The flow hood technique proved more useful for identifying the relative leakiness of the ducting components. In this case, the quantity of air flow was extrapolated from the log Q versus log P plots for the ducts. This quantity was then compared to the flow quantity extrapolated for the entire house ELA. This method does not distinguish floor penetrations. These leaks, if they occur, would show up as supply duct leaks. However, the observation in the field was that floor penetrations were generally tight in the houses examined. This does not imply that penetrations are sealed in more typical housing stock.

Flow Hood results are shown in Table 9. [The same results including both before and after repair cases are displayed graphically in Figures 29 and 30.] On some houses, the complete sequence of repairs was not possible. Thus, these results differ slightly from the results presented in Table 6 for a larger sample. Once again, results are presented as a fraction relative to the "control" leakage for the same house.

Table 9. Component ELAs -- Before Duct Repair

	Supply Duct	Return Duct
Mean	3.31%	8.70%
S. D.	2.52	7.86
n =	17	19

The results confirm field observations. Installers generally try to minimize supply duct leaks but are less careful with return ducts. These results suggest a relatively small additional ELA due to duct leaks. One would expect the increase in passive infiltration is also small. Results are consistent with the observed increase in total ELA of about 11% due to the presence of ducts. These results might seem to be disappointingly small. However, there are larger energy impacts resulting from these small changes. Energy impacts will be discussed in Section 4.5.

4.3. Leakage During Fan Operation

The previous tests were partially aimed at quantifying passive infiltration caused by the increased leakage of forced-air ducts. A different issue is the air exchange during furnace fan operation. The fan-driven leakage is roughly the same order of magnitude as the naturally occurring whole-house passive infiltration that occurs when the fan is off. Interactions between the two flows are not straightforward.

4.3.1. Methods

This fan-driven exchange was investigated using two methods. First, the flow hood measures of duct leakage can be extrapolated to the range of operating pressures caused by the fan. Second, tracer gas tests during furnace fan operation provide a direct measure of air exchange. The flow hood method is discussed in detail below. Tracer gas testing, using SF_6, was performed per ASTM E741-83.

Field measurements were taken of static pressure in the duct during furnace fan operation. Note that the entire process of quantifying duct air flow and pressure needs to be repeated after the retrofit repair. Repairs change cracks and crevices causing leaks. This results in changes to the both log Q versus log P plot and operating point of duct static pressures.

The primary assumption of the flow hood method is that a single static pressure can be considered typical of the entire duct. The single pressure datum is referred to as the effective duct pressure. This pressure is then used to calculate the flow volume of leakage. Some experimentation was conducted on early houses to validate this assumption.

The assumption that a single pressure is representative of the effective duct pressure is reasonable for the return ducts. These ducts are large in diameter with relatively little change in static pressure as the air moves from the grille into the return plenum. The assumption is less reasonable for the supply ducts. These ducts experience a larger change in static pressure between the furnace and the delivery register. Nevertheless, it did appear that static pressures were fairly uniform for much of the duct length. Major drops in static pressure occurred at the distribution plenum and the supply registers. In between, for the long lengths of duct, pressures tended to stay at a plateau.

There is no reason to expect that the distribution of leaks and cracks is uniform in the ducts. Some major installation errors, such as ripped seams, are more likely to occur on large ducts near the furnace. Unfortunately this is the area where static pressure is high. In general, however, the field inspections tended to support the conclusion that a mid-range measure of static pressure could be taken as the effective pressure in the entire supply duct. For this purpose, field measures were taken of fan static pressure at a duct near the supply plenum.

4.3.2. Results

Results of fan-driven air exchange are shown in Table 10. This table lists both estimated air exchange derived from the Flow Hood measurements and actual exchange derived from tracer gas measurements. The estimates are considered reasonably accurate because the fan static pressures usually fall within the range of measured blower door data points. That is, the flows do not have to be extrapolated to an extreme point. The only question is whether the choice of "effective" duct pressure, particularly on the supply ducts, is reasonable. Flows are listed in cubic feet per minute (CFM) for both supply and return.

Notice the distinction between balanced and unbalanced air flows. To facilitate comparison, these flows and the tracer-measured air exchange rates are listed in terms of the number of house volumes that would be exchanged per hour (ACH). The ACH represents the air flow for one hour divided by the house volume.

Comparison with the tracer measured air exchange shows that not all the fan-driven air losses result in exchange of household volume. The difference due to fan operation is at least as large as the balanced flow. However, the unbalanced flow does not contribute one-for-one to household air exchange due to interactions with the infiltration flow.

Although the flow hood method provides reasonable estimates of the fan-driven air exchange, it does not provide a complete picture. The tracer gas testing provides a more direct measure of the actual air exchange. This procedure calls for conducting one tracer gas test while the furnace fan is running. Then the fan is shut off and another test conducted to find the passive rate under similar weather and temperature conditions. Subtracting the second air exchange rate from the first gives a measure of the net additional air exchange due to the fan operation. In a few cases, this procedure was not successful. It appears that gusty wind conditions can interfere with identifying a comparable passive infiltration rate.

4.3.3 Comparison of Results to Model Predictions

At this point, it is necessary to examine the predictive models for air flow interactions. The LBL model suggests that unbalanced air flow should be added in quadrature to stack and wind driven infiltration. The linear model suggests that balanced flow should add linearly.

First, the unbalanced flow is examined. As already mentioned, unbalanced leakage will result in net pressurizing (or depressurizing) of the house. When there are more leaks on the return side, pressurization results. Flows are estimated from the flow hood method as shown in Table 10. The distribution of unbalanced flow is shown in Figure 23. This value represents return minus supply leakage. Thus, a positive value means that the house will be pressurized. Positive pressure occurred in most of the houses examined. The effect of pressurization will be to reduce passive infiltration (as distinct from passive exfiltration) while the fan operates.

Investigation of the quadrature model is complicated because wind- and stack-driven air flows must also be estimated. In Kiel and Wilson's case, the test building had been calibrated. That is, sufficient infiltration data were available to establish linear regression coefficients for the square of infiltration versus temperature difference and wind pressure. In this case, only a few one-time measures were available on each building. The LBL infiltration model was used to estimate the stack- and wind-driven flows. Accordingly, the current investigation is better described as a general check of the LBL model. Figures 24 and 25 show the distribution of the tracer measured air exchange rates versus that predicted from the LBL model using quadrature. Although the general trends are similar, the quadrature model overpredicts infiltration; agreement is poor.

Table 10. Fan-Driven Air Exchange

Flow Hood Method -- Estimated Gross Air Flows (n = 20)

	Qsupply	Qreturn	Qbalanced	Qunbalanced
Before Repair				
Mean	86.2 CFM	178.1 CFM	.415 ACH	.441 ACH
S. D.	46.4	97.3	.249	.273
After Repair				
Mean	66.4 CFM	154.7 CFM	.324 ACH	.398 ACH
S. D.	35.0	101.2	.150	.363

Tracer Gas Method -- Measured Net Air Flows (n = 20)

	Fan On	Fan Off	Difference
Before Repair			
Mean	.817 ACH	.275 ACH	.542 ACH
S. D.	.447	.124	
After Repair			
Mean	.682 ACH	.316 ACH	.366 ACH
S. D.	.279	.150	

Figure 26 shows a direct comparison between the LBL Model and the tracer measurements. Figure 27 shows the same comparison applied only to those points where the furnace fan was not operating. The poor agreement seems to be a result of limitations in the LBL model. There does not appear to be any difference between houses experiencing only stack-driven or a combination of stack and wind-driven infiltration. The LBL model appears to predict larger infiltration rates than were actually measured with tracer tests. This is consistent with infiltration estimates observed during the RSDP program. Seasonal infiltration estimated using the LBL model was larger than that measured using PFT tests.[27] Both methods used for RSDP estimates were so ambiguous that no clear conclusions were possible.

A similar comparison is made for the linear addition model in Figure 28. This model appears to provide somewhat better agreement between predicted and observed results.

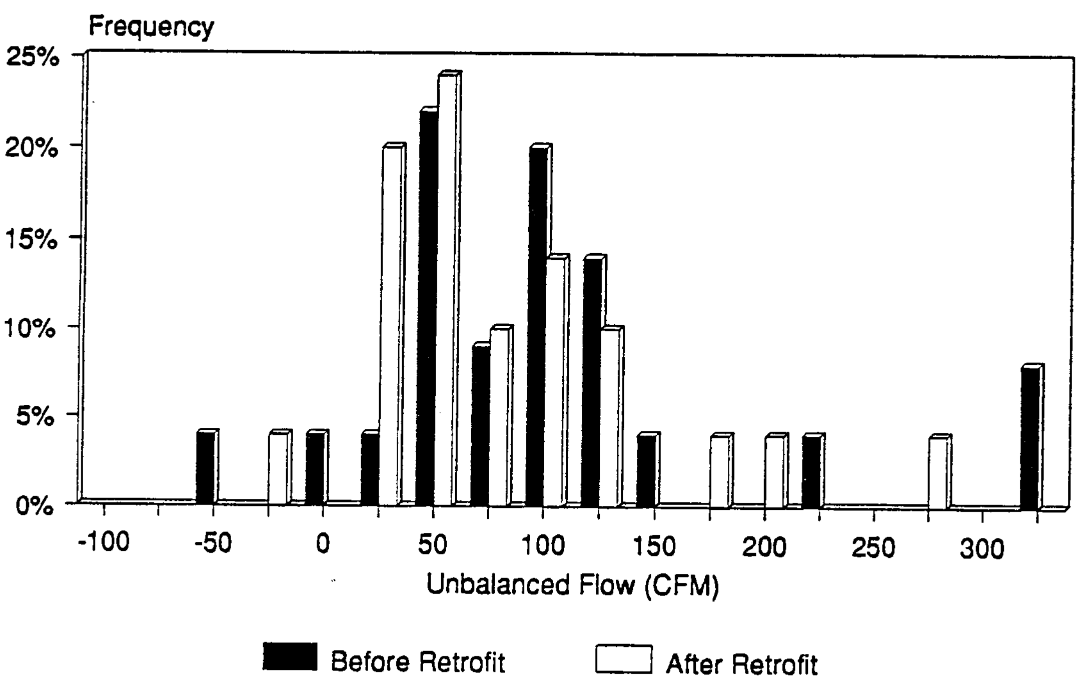

Figure 23. Distribution of unbalanced flows due to furnace fan operation

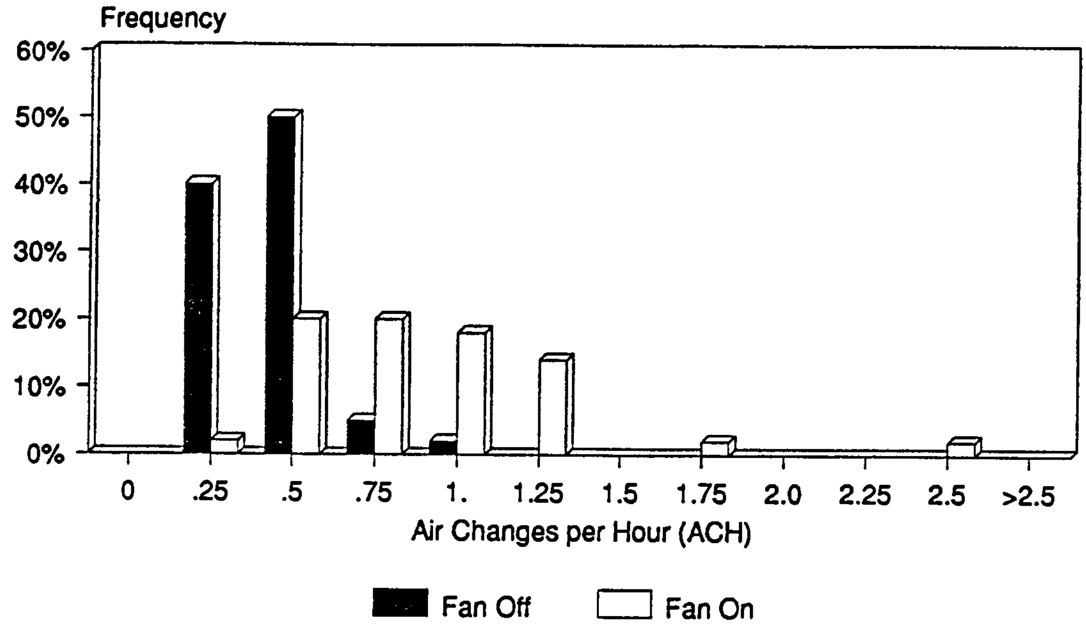

Figure 24. Distribution of air exchange rates as measured with tracer gas

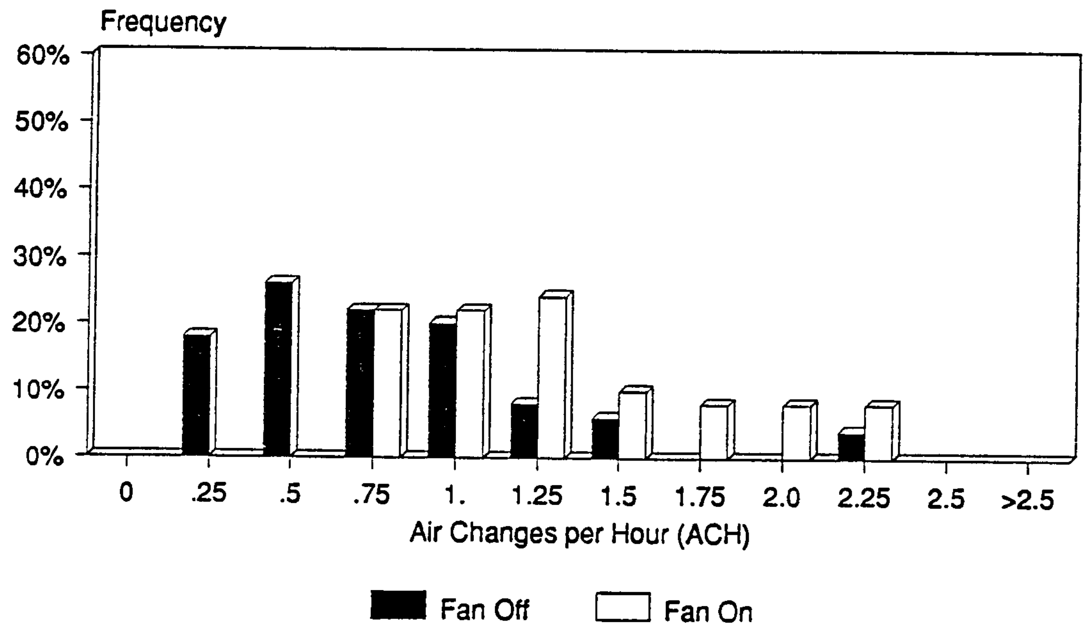

Figure 25. Distribution of air exchange rate as predicted by LBL quadrature model

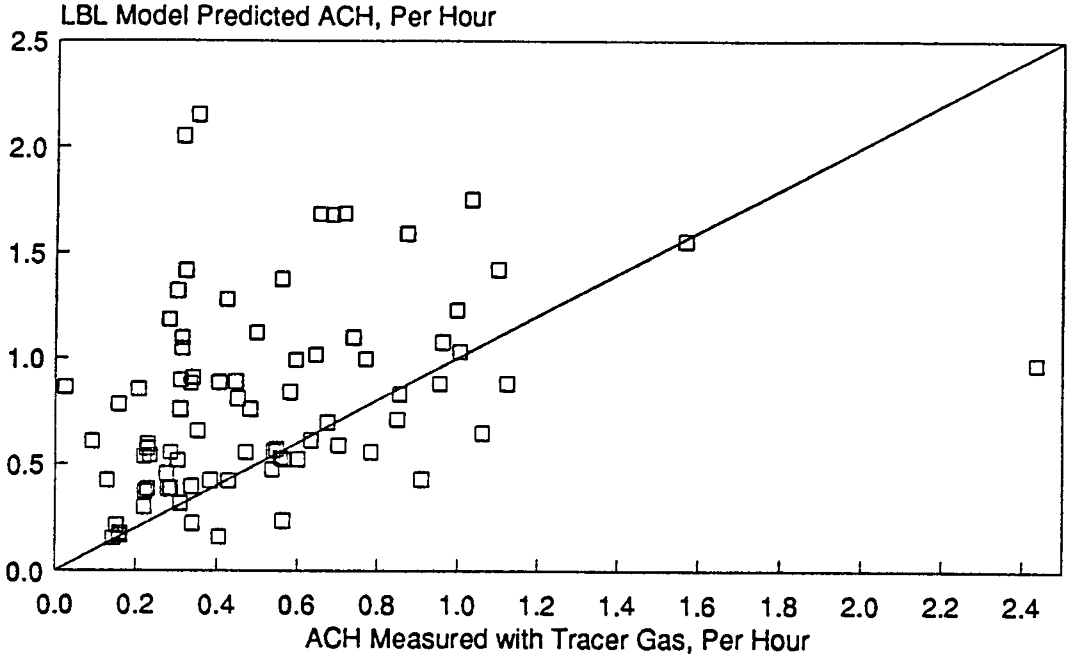

Figure 26. Predicted vs. actual air exchange rates; LBL quadrature infiltration model vs SF6

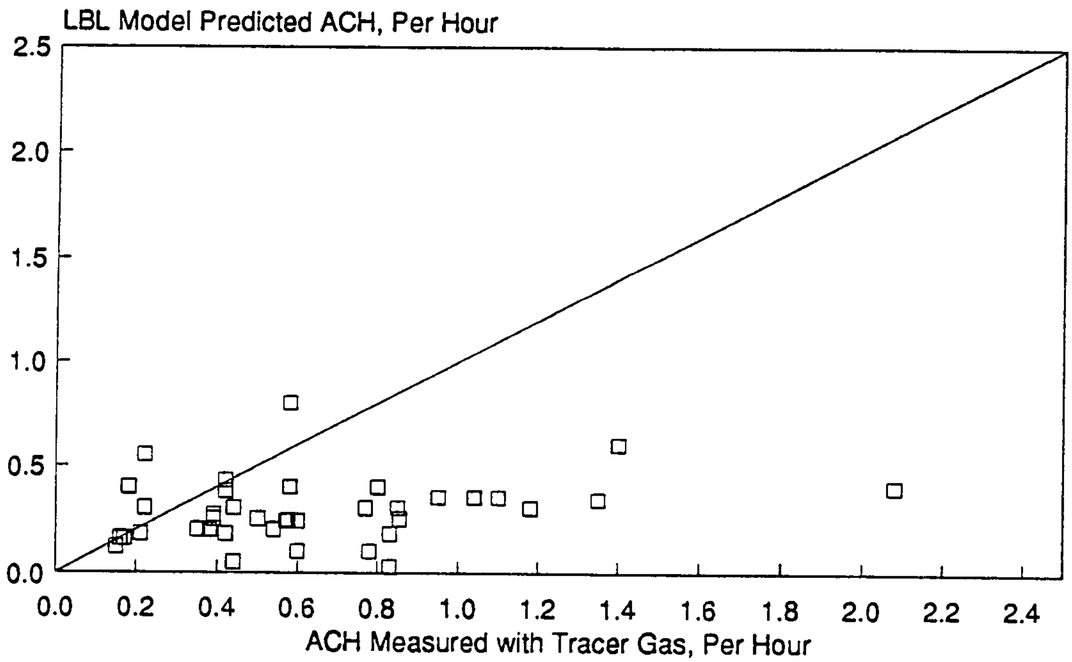

Figure 27. Predicted vs. actual air exchange rate (fan off); LBL quadrature infiltration model vs SF6

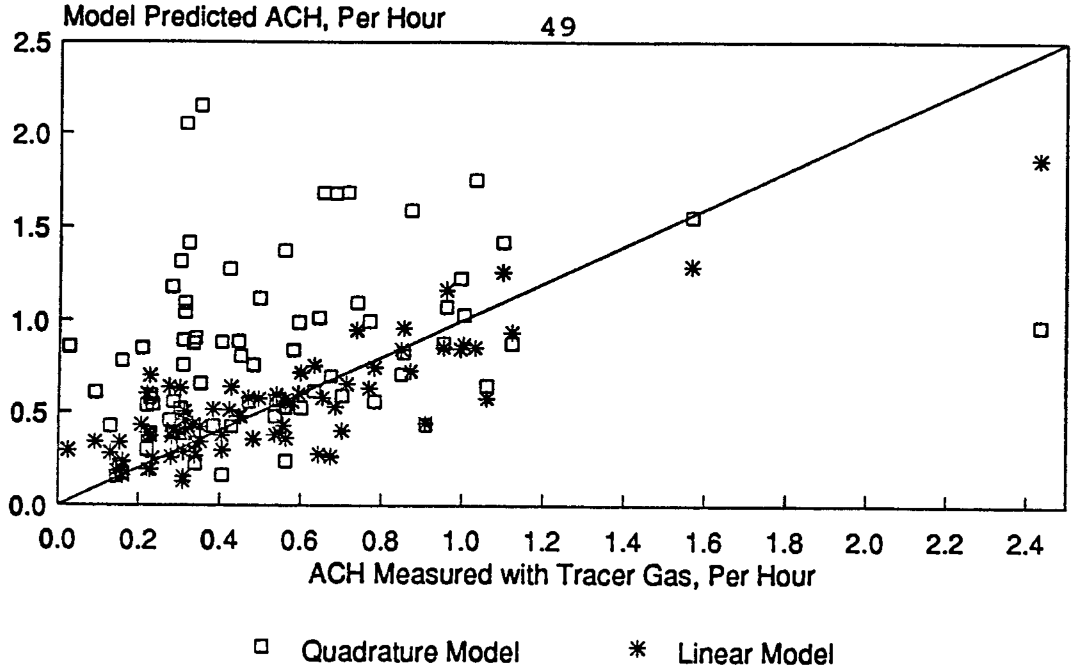

Figure 28. Quadrature and linear models compared with SF6 tracer gas

Comparison of the various models is shown in Table 11. The Flow Hood Estimate is the gross amount (sum of supply and return leakage) of losses. Obviously, this overestimates air exchange rates greatly. The LBL Quadrature Model also overestimates exchange rates. This discrepancy may be due to assumptions regarding stack and wind components and not necessarily to the quadrature assumption. The Linear Model shows the best agreement with the tracer gas tests. The tracer results are subject to some uncertainty due to wind during some of the tests. Use of the total leakage measured with the flow hood is probably unrealistic. If the sum of balanced and unbalanced flows is used instead, the resulting flow hood estimates are .856 (before repair) and .772 (post repair).

Table 11. Residential Air Exchange Rates

	Flow Hood Estimate	LBL Quad. Model	Linear Model	Tracer Measured
Before Repair (n = 20)				
Mean	1.270 ACH	1.185 ACH	0.690 ACH	0.817 ACH
S. D.	0.568	0.404	0.282	0.447
After Repair (n = 20)				
Mean	1.046 ACH	1.144 ACH	0.640 ACH	0.682 ACH
S. D.	0.486	0.511	0.263	0.279

4.4. Repairability of Leaks -- Results, Strategies and Diagnostics

4.4.1. Results

The best information on repairability comes from the flow hood method. Plots of log Q versus log P were gathered both before and after repair. Static pressure during fan operation also changes as a result of repairs. The duct losses must be recomputed based on the post-repair data. Comparison of the before and after component leakage percentages is shown in Table 12. These results are listed as the fraction of the "control" ELA for the entire house.

Table 12. Component Percentages of 4 Pa ELA

	Before Repair		After Repair	
	Supply	Return	Supply	Return
Mean	3.31%	8.70%	2.67%	6.93%
S. D.	2.52	7.86	1.89	4.97
n =	17	19	17	19

Comparison of before-repair to the after-repair cases is instructive. The variability decreases showing that dramatic repairs occur on a few extremely leaky houses. On the average, the repairs reduce the duct portion of 4 Pa ELA by about 20%. Distribution of the leakage fractions both before and after repairs are shown in Figures 29 and 30. Note that supply leakage is based on pressure data plots and return leakage on depressure data plots.

The amounts of 4 Pa ELA attributable to duct leakage repairs are deceptively small. A better measure of their impact is the energy estimates described in Section 4.5. The estimated reduction of energy losses is shown in Table 13. One important measure is the estimated heating efficiency loss caused by the duct leaks. This measure is not simply the volumetric loss. It includes some estimate for the increased run time caused by the duct leaks. It does not include conductive energy losses in the duct. Distribution of before and after losses are shown in Figure 31. The fractional amount of this loss reduced by the repair is referred to as the repair fraction. Distribution of the repair fraction is shown in Figure 32.

Table 13. Repairability of Duct Leaks

	Duct Efficiency Loss		Fraction Leakage	Annual
	Before Repair	After Repair	Repaired	Savings
Mean	12.2%	9.72%	0.236	$18.78
S. D.	6.30	6.06	0.231	30.20
n =	19	19	19	19

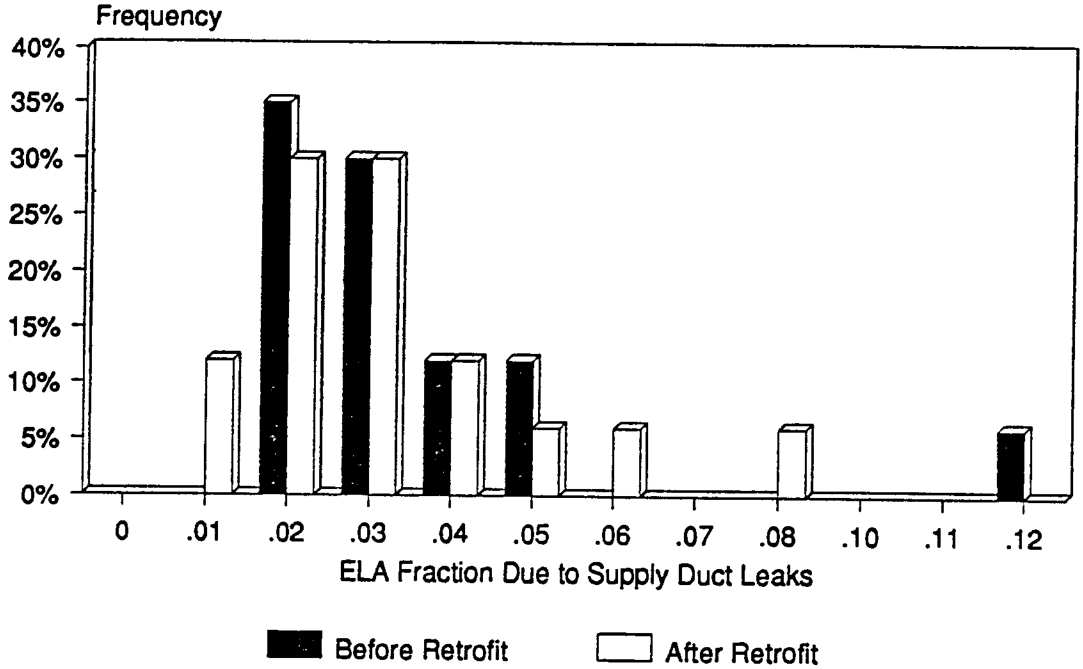

Figure 29. Distribution of supply duct leakage fraction

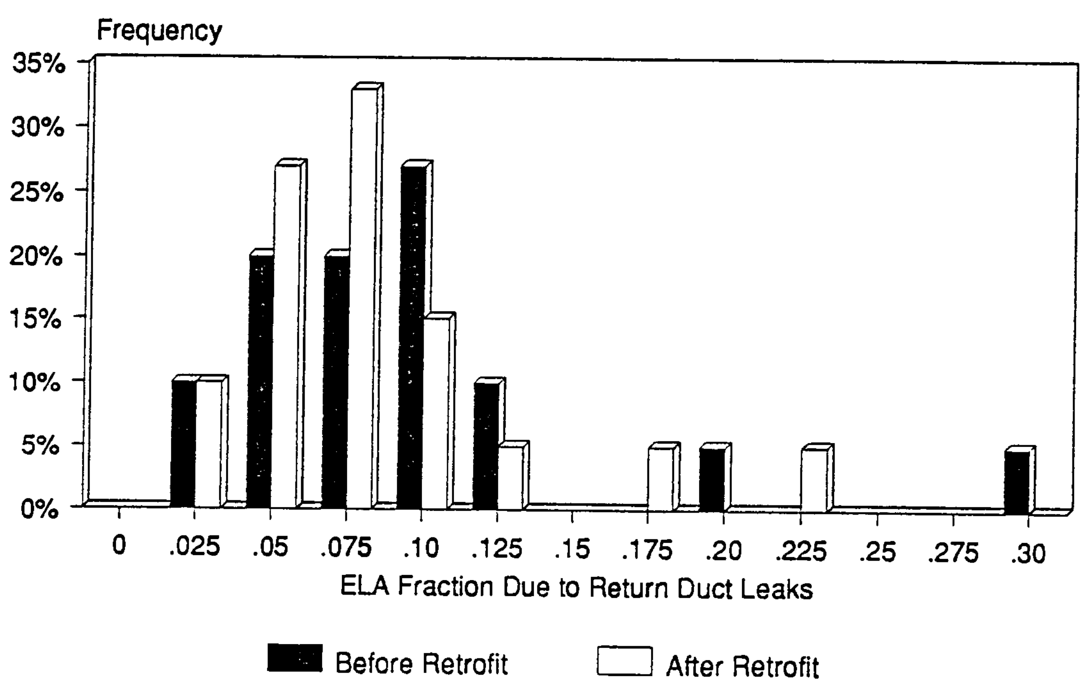

Figure 30. Distribution of return duct leakage fraction

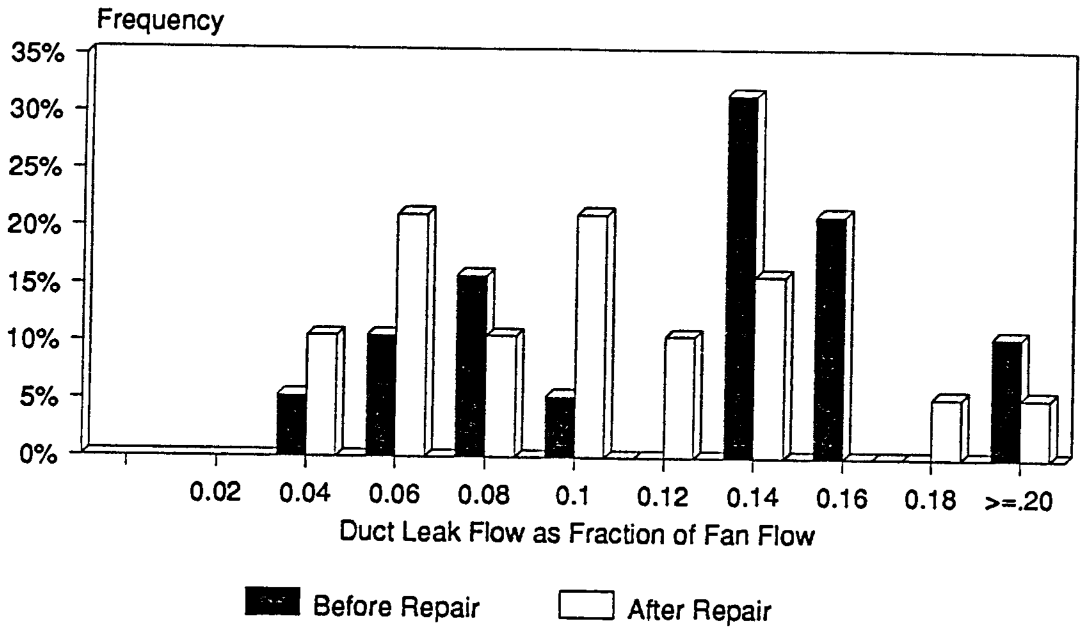

Figure 31. Distribution of duct volumetric losses before and after repair

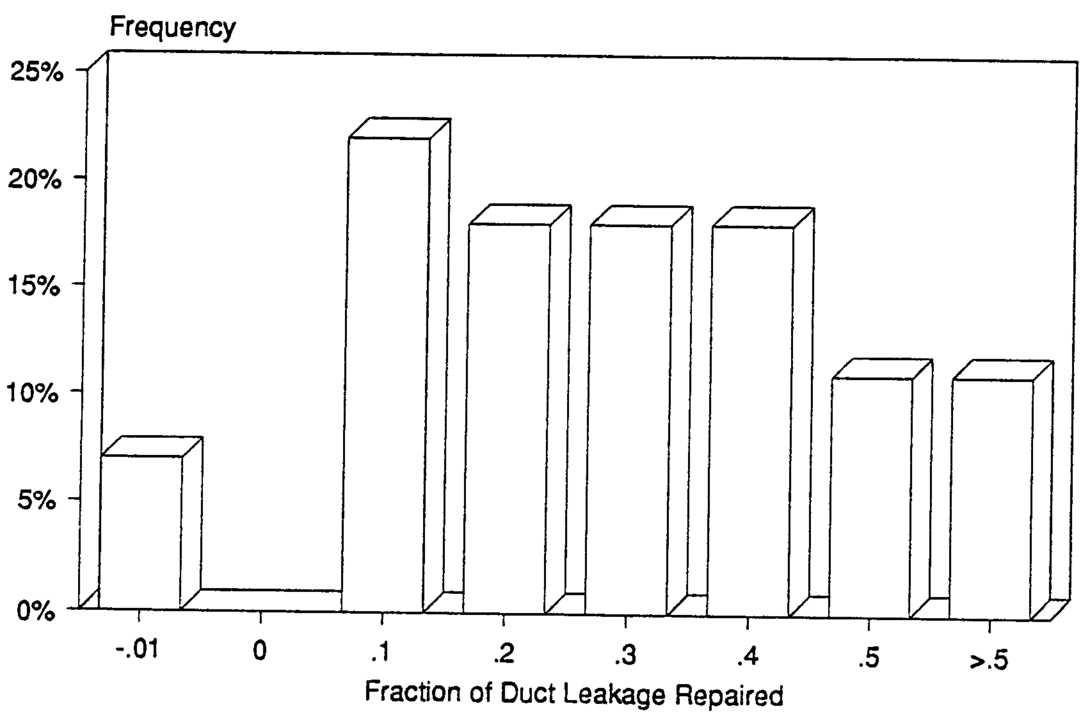

Figure 32. Distribution of duct leakage repaired based on estimated energy loss

4.4.2. Discussion of Repair Strategies

Based on these results, some comments can be made regarding repair strategies. It must be noted that the homes studied were not necessarily representative of existing housing stock. These homes were probably less leaky than the norm.

Part of the leakage problem lies in poor standards for installers. The building code does not require specific tightening measures. The general contractor does not always check on the subcontractor's quality. Therefore, the first requirement is for at least a visual inspection of the installation. All of the serious errors observed, (10% of the sample) were direct and obvious. Any inspection of the crawl space would have noticed these errors.

Visual inspection is facilitated by noting that installation errors tend to occur with specific components. Right angle elbows can fall apart. Seams at Y-joints may be ripped. Obvious dirt on fiberglass insulation is a sign that air is being sucked in. This is particularly noticeable for furnace leaks in the garage. Operation of the fan will cause the insulation over large supply leaks to bulge. Alternatively, the warm air can be used to track down leaks.

Special attention should also be paid to the furnace filter slot and other openings in the garage. The danger of infiltrating carbon monoxide is not known but should not be ignored.

Flexible duct is widely used for the return duct. This type of duct may be easy to install, but it is more difficult to seal tightly at the ends. Installers should pay careful attention to sealing details.

The common sealant is duct tape. This tape may be adequate when wrapped tightly several times. However, the tape tends to lose adhesion and becomes brittle with time. It is not clear what improvement should be considered.

The tape is inadequate for sealing finger joints where a round duct is butted into a square distribution plenum. A commercial sealant product (Airlock, Rectorseal Corporation, 2830 Produce Row, Houston TX 77023-5822) appeared much superior. The sealant is a latex-based caulk or putty. The sealant cures to a strong, flexible, fire-retardant material. The only disadvantage is that application is slower and messier than tape. For this reason, its adoption by installers is doubtful despite its superior qualities.

Floor penetrations for heating registers were generally adequate. However, most homes had at least one penetration that was sloppy.

Identification of duct leaks with simple diagnostics tools may be difficult. In this study, diagnostics evaluated included a return air temperature test (RAT), check for unbalanced pressure and visual inspection. The RAT assumed that leakage in the return duct would reduce the return air temperature significantly. Of course, this test could only be attempted during cold weather. RAT results are not very useful. It appears that conduction loss and thermal capacitance in the duct interferes with this test.

The unbalanced pressure test is conducted by comparing the difference in static pressure inside versus outside the house when the furnace fan is on to the difference when the fan is off. However, a very large unbalanced leak is required to cause a noticeable change in the pressure difference. This is usually due to some serious installer error. In this case, visual inspection is just as useful in identifying the problem.

Other diagnostics from the RSDP project were investigated. In many instances, smoke stick tracing showed excessive air loss into ducts during blower door testing. Large smoke intake into ducts usually was not a reliable indicator, as other, similarly leaky ducts did not exhibit smoke intake. The mean leakiness was compared for houses where smoke losses were noted and houses where no such notation was made. Both showed a similar likelihood of leakiness.

The specific K factor is larger in the aggregate for homes with duct problems. However, variability in the housing stock is large. The normal range of "bad" and "acceptable" leakiness overlaps such that it is difficult to make a determination for a single individual house.

4.4.3. Recommendations

In summary, recommended preventative and repair strategies are just common sense. Our recommendations are:

(1). In new construction, ducts, if used at all, should be installed inside the conditioned space. One possible exception would be combustion appliances. The possibility of backdrafting may be a good reason to install a combustion furnace outside the house.

(2). Inspect installations for obvious errors. This requires a visual check under the crawl space and in the attic. Look for dirty insulation as an indicator of leaks.

(3). Use sealant on duct joints. Duct tape is the minimum requirement. Latex sealant is recommended for finger joints.

(4). Installers should pay special attention to sealing flexible duct ends and to sheet-metal elbows and Y-joints.

(5). Floor penetrations for heating registers should be sealed with caulk.

4.5. Energy Impact Estimates and Cost-Effectiveness

4.5.1. Cost-Benefit Analysis

Finally, there is the question of the overall energy impact. Preliminary calculations have been conducted on the field test data using the methodology described in Appendix A to estimate annual energy savings. The results are shown in Table 14. The simple payback is the number of years for the repair to pay for itself with savings. The benefit cost ratio is the present value of savings over the cost. Present value, in this case, is computed on the basis of consumer economics (5 cents/KWh, 10% fuel inflation) generalized to national norms. The levelized cost based on 3% discount rate (2.39% effective rate) has been used for other Northwest regional studies. The 6% (6.06% effective) discount rate is used to represent the consumer perspective. A conservative 10 year lifetime is assumed. It is not clear how durable the repairs will be for any longer time period. There is little difference between the two discount rates.

Economic measures are computed for the program as a whole. That is, the measures are computed based on average costs and savings for the study. Averaging individual calculations gives variable results since the cost-effectiveness varies greatly between individual homes. The program costs are also computed with "dry hole" costs included. "Dry hole" homes are those where duct-related ELA was found to be so small, at the initial test, that repair attempts were considered unwarranted. There were six such homes, where no repairs were possible but nevertheless costs were incurred in a site visit. Even with these "dry hole" costs included, the program appears to be very cost-effective, resulting in savings costing about 1 cent per KWh. Distribution of the economic measures are shown in Figures 33 through 35.

Table 14. Energy Savings Estimates

	Annual KWh Saved (Kwh/yr)	Retro Cost ($)	Simple Payback (Years)	Benefit Cost Ratio	3% Level Cost ($/KWh)	6% Level Cost ($/KWh)
Mean	375.57	67.24	3.58	5.08	0.009	0.010
S. D.	603.96	19.71				
n = 19						
Including "dry hole" costs						
n = 25		80.92	4.31	4.22	0.010	0.013

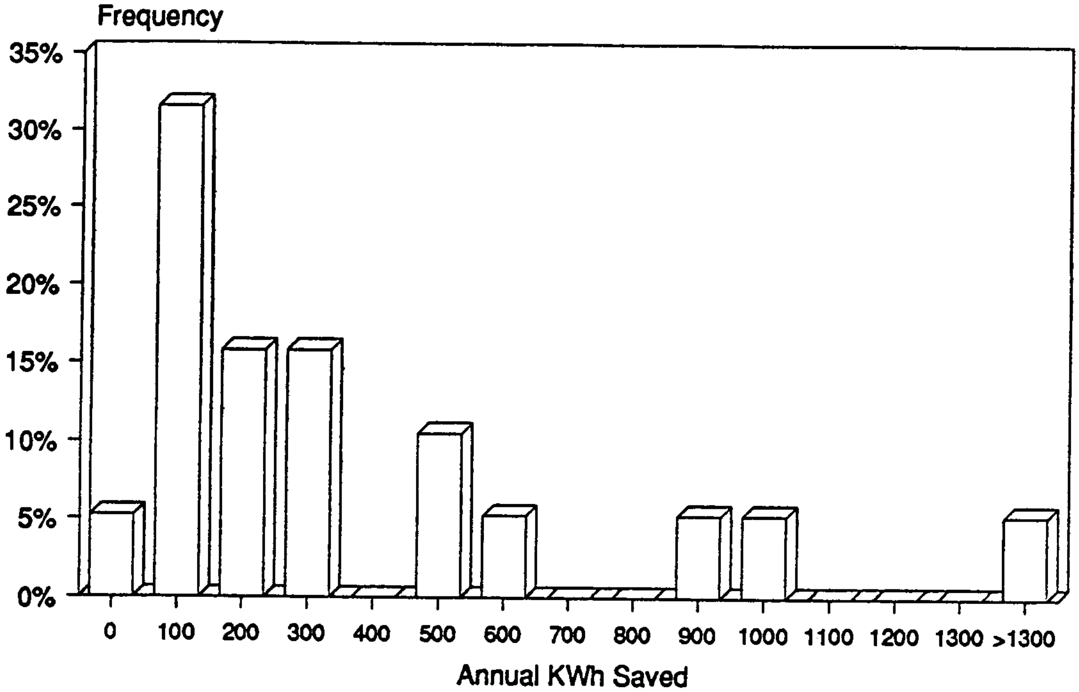

Figure 33. Distribution of estimated annual energy savings

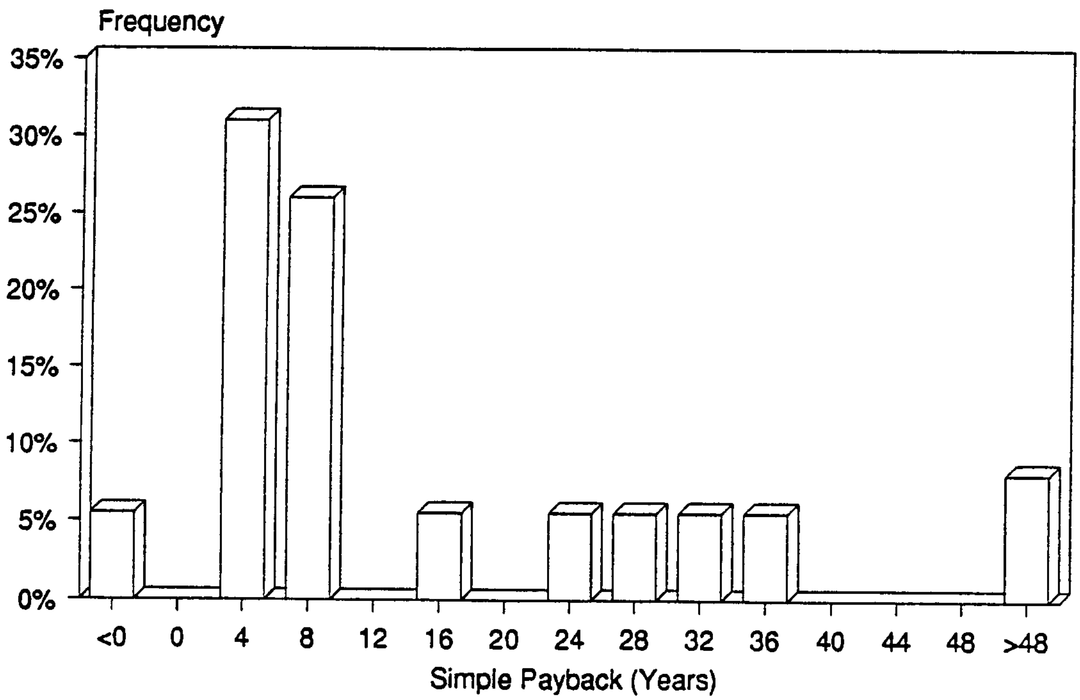

Figure 34. Distribution of simple payback

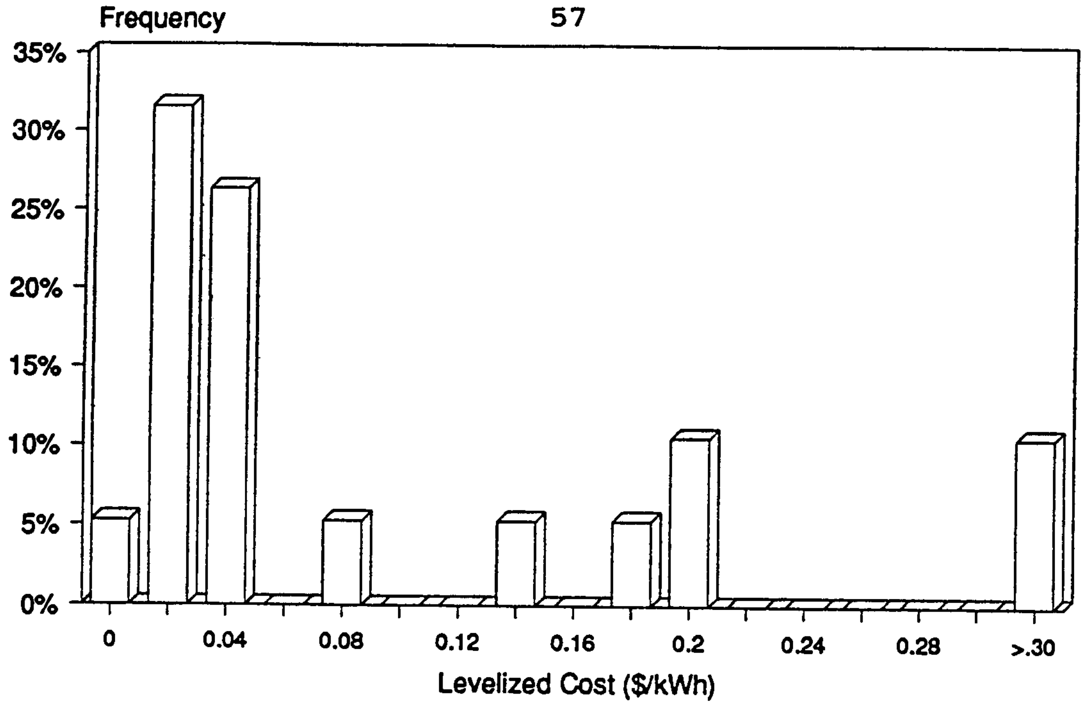

Figure 35. Distribution of levelized cost - societal discount rate (3%)

4.5.2. Conclusions Regarding Savings

The duct leakage investigation was intended to be a research study. Costs for the retrofit repair were separated, on the assumption that a utility might consider a duct repair component as part of retrofit weatherization. The costs were generally minimal. The retrofit repairs took an average of 2-3 hours and required less than $20 of materials.

Energy savings estimates are highly variable. Simple payback estimates average about 3 years. The benefit to cost ratio (BCR) assumes a 10% discount rate and 10 year lifetime. It averages over four, indicating a good return on investment.

To calculate total cost, an assessment of travel time and cost was included. These costs averaged $40. Travel costs may not be applicable if duct repair were added to an existing weatherization program. In this case, the cost effectiveness would be even better.

5. ENERGY USE MONITORING RESULTS

Monitoring data were collected during the periods before and after the retrofit repair. As expected, there is considerable experimental "noise" in the monitoring results. It is difficult to demonstrate that savings are clearly present for the retrofitted homes. This is because the "noise" tends to be larger than any experimental effect. This becomes even more apparent when comparing the observed to predicted savings.

5.1. Analysis Method

5.1.1. Regression K Factor

The method of K factor regression has been discussed previously (see Section 2.2). Monitored space heating energy is regressed against the monitored indoor-outdoor temperature difference. The resulting slope or "K factor" describes the sensitivity of the home to climate. The procedure is very similar to PRISM analysis with the difference that actual monitored information is available for the indoor temperature and submetered space heat. The advantage of the method lies in its ability to provide a normalized regression coefficient for periods of varying climatic conditions. Monitoring for the pre-retrofit period has already taken place. Monitoring for the post-retrofit period was done for one year after the retrofit. The retrofit repair is expected to improve the heating system efficiency and, to a lesser extent, improve the thermal integrity of the home. This improvement should be apparent as a decrease in the regression slope corresponding to reduced energy usage. A savings estimate procedure has been developed to predict the improvement.

5.1.2. Estimated Change Due to Field Tested Repairs

As discussed earlier, the field tests were an attempt to quantify the improvement in heating efficiency as a result of retrofit repairs. The data collected included (1) the whole house infiltration rate measured by blower door (2) the relative amount of infiltration caused by the presence of heating ducts (3) air leakage in supply and return ducts as a result of furnace fan operation. The leakage quantities were measured using blower door techniques, flow hood testing of the ducts and tracer gas testing of the house with and without furnace fan operation. Measurements were taken both before and after repairs. The field test data are used in combination with monitoring data. The monitoring data are analyzed to estimate annual space heating usage, duty cycle and other parameters.

A procedure to estimate the difference caused by the retrofit repair was prepared. The estimation procedure calculates the expected change in the regression slope as a result of the improved furnace duct efficiency. The calculation procedure attempts to take into account changes in furnace duty cycle and delivery efficiency of forced air flows. The calculation procedure is listed with a worksheet in Appendix A. Energy savings estimates prepared with this procedure have been discussed previously. For this report, we will consider the predicted change in regression slope.

5.1.3. Discussion of Results

To identify the experimentally induced change, post-repair monitored data were regressed and the regression coefficient compared both to the previous and the predicted new coefficient. Statistical significance is determined by a t-test based on the pooled standard deviations. Post-repair results, together with preretrofit and predicted K factors, are listed in Table 15. An example comparing before and after results is shown in Figure 36. Similar figures for all sites are included as Appendix D.

The first question is whether a measurable savings has occurred. Those savings are expected to be apparent in retrofit sites but not in control sites. Of twelve retrofit sites, six showed savings but only three were statistically significant. Six sites showed negative savings, however only one proved to be statistically significant. Two additional sites were not useful because homeowners supplied poor or inconsistent data. Thus, it would be more correct to say that of the twelve sites, eight showed no savings, three showed significant positive savings and one showed significant negative savings. Of seven control sites, four showed no savings, two showed significant positive savings and one showed significant negative savings. These results demonstrate problems with experimental "noise" in the monitoring data. Of the three control sites with significant changes, two can be explained by structural changes in the home.

The second question is whether the savings agree with those predicted. The experimental "noise" interferes with drawing firm conclusions. Of the twelve experimental sites, two showed savings larger than expected. All the others showed savings which were not significantly different from those predicted. It must be pointed out that the savings expected from the retrofit repair are small. In fact, when the expected savings are compared to the dispersion of monitoring data, it appears that only one site would be expected to have a statistically significant observable result. This is consistent with observed results. The expected change in energy usage was expected to average about 5%. This small change would not be observed considering the variation in monitored usage. The observed average of about 8% change cannot be distinguished from experimental noise. Table 16 shows the expected changes expressed as a percentage change in energy usage.

Table 15. Monitoring Results -- Verification of Savings

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

Comparison With Prediction

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

NOTE: ns = not significant
AAX = air-to-air heat exchanger
Tb = balance point temperature

Table 16. Monitoring Results -- Percentage of Savings

Site No.	Observed t-test Significance	Observed Savings Percentage	Expected Savings Percentage	
Control Sites				
134C	0.15	30.6	0	
705C	ns	23.7	0	
723C	ns	5.4	0	
770C	ns	5.6	0	
Average		16.4	0	
Control Sites with Structural Changes				
183C	ns	61.5	0	
217C	0.06	74.5	0	
170C	0.15	-0.31	0	
Experimental Sites				
610	ns	28.2	3.9	
613	ns	-2.4	0.6	
625	ns	-7.9	0.7	
655	ns	15.6	25.0	few data
664	ns	-9.9	1.9	
677	ns	-13.2	5.8	
695	0.05	27.6	3.0	fix break
710	ns	3.7	6.3	
735	ns	-10.0	-1.2	
745	ns	-3.7	0.1	
754	0.0	25.4	3.4	wood use?
135	ns	14.8	1.6	
Average		7.7	4.8	

NOTE: ns = not significant

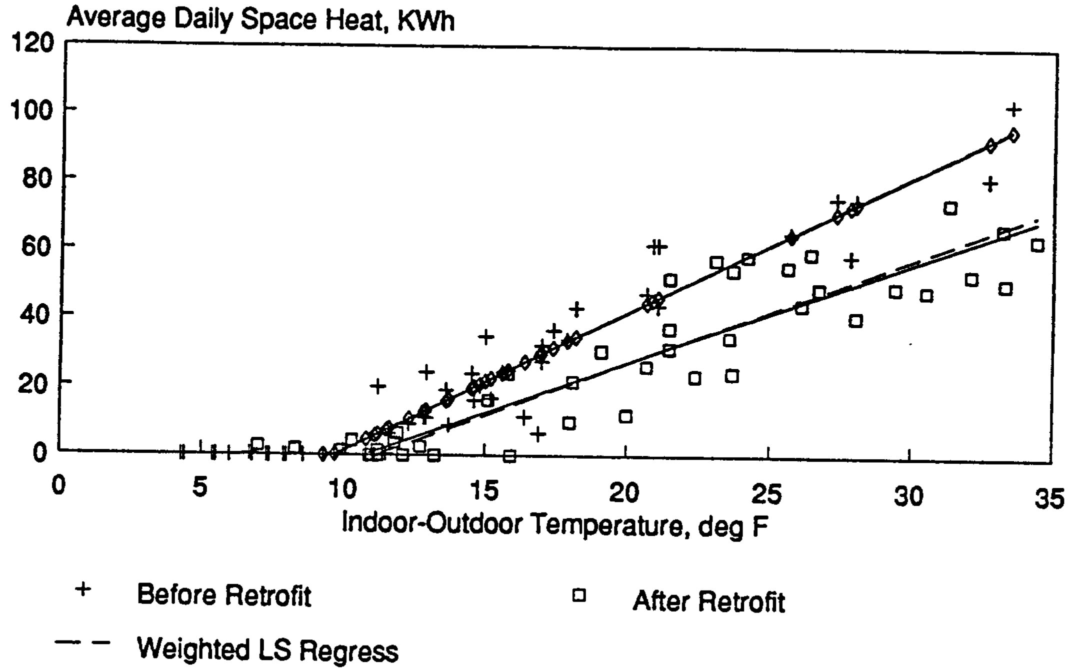

Figure 36. Before-and-after K factor regression example - site 695

Review of the field reports suggests several reasons for the observed differences. Sites 183C and 217C are control sites where the owner changed air supply details to remove the air-to-air heat exchanger. This probably accounts for the changes in energy usage. Site 170C installed a finished basement which apparently resulted in increased energy usage.

Of the experimental sites, the field reports also suggest explanations for some of the observations. Site 613 is occupied by an elderly lady who apparently changed her pattern of other energy use. A major change occurred in the balanced point temperature although the regression slope does not appear to have been affected. Site 655 received a major repair and should have demonstrated a sizable change. However, it suffered from few data points and correspondingly poor resolution. Site 695 was one of the most successful. At this site, a major break was discovered and repaired. This apparently resulted in even greater savings than expected. The occupants of site 754 may have used a wood stove -- their data appears suspect due to high variability. Site 711 was not used because the data showed extreme dispersion. This particular site was constructed using an interior joist space as the return air plenum. That structure type appears to be overly sensitive to wind-induced air infiltration. Consequently, the data from Site 711 were highly scattered.

5.1.4. Conclusions

In summary, the monitored results, while "noisy", are not inconsistent with expectations. All the sites, even the control sites, tended to show some improvement. With one exception, the change in the control sites was either small and not significant or explained by structural changes at the site. The experimental sites also tended to show some improvement. However, in most cases it was not sufficient to be statistically significant. A few sites showed negative savings, but with one exception, this change was not significant. In at least one of these cases, the negative savings were associated with a change in heating operation due to reducing the balance point temperature. Of the sites which experienced positive savings, one was questionable due to possible wood stove use. Two others were associated with major duct repairs. The other sites showed small changes which lacked significance.

Table 16 shows that the improvements tended to agree with predictions. That is, for those sites where only a small improvement was expected, any change was hidden in the "noise". In most cases, the sites which experienced a large improvement were either expected to do so or showed the possible wood stove use. Overall, the average change observed and that expected appear consistent. Nevertheless, the small sample size and variation in the data prevent drawing any statistically valid conclusions.

6. SUMMARY AND CONCLUSIONS

6.1. Assessing Impact of Duct Losses

Estimating effects of ducting on residential energy use is desirable in two contexts. In conservation research, ducting may affect predicted or experimentally observed energy savings. In production-oriented retrofit programs, ducting may affect retrofit cost-effectiveness expectations. In either case, methods to evaluate effects of duct-related thermal losses are needed. In research applications, fairly extensive evaluation of duct effects may be justified. In production retrofit programs, simple low cost diagnostics or "rule-of-thumb" methods are more appropriate.

Ideally, a simple low cost test or set of audit observations to accurately define duct effects on individual homes is needed. No such test or observation set has been identified. Available tests are either costly and complex, or lack precision, or both. Known tests, with proven value in quantifying duct loss effects are suitable only for research level applications. Work in this project has resulted in audit-type guidelines which provide approximate characterizations applicable to groups of homes. However, the project results indicate that these guidelines are unlikely to be reliable or precise when applied to individual homes. The state-of-the-art in testing and auditing for duct effects is still in a developmental phase.

6.2. Duct Loss Testing

Work in this project has provided additional tests relevant to duct losses. It is also worthwhile to briefly note other tests of possible use in identifying duct losses. Duct-related thermal loss mechanisms fall in several categories:

- Natural infiltration through duct leaks and duct-related leakage paths.
- Fan-driven leakage through duct leaks.
- Fan-driven infiltration through structural leaks, induced by unbalanced duct leakage resulting in structure pressurization.
- Conduction losses through duct surfaces located in unconditioned spaces.
- Fan-driven infiltration through structural leaks, induced by fan-driven local pressure variations within the structure that are not caused by duct leakage.

Of these loss mechanisms, the last is the least demonstrated and the least understood.

Work on this project has resulted in testing improvements relating to measurement of fan-driven leakage through duct leaks, and quantifying unbalanced duct leakage. Use of whole-house pressurization in combination with flow hood measurements enables direct measurement of duct leakage flows. In conjunction with duct effective pressure measurement, this permits better characterization of fan-driven leakage flowrates than previously available. When applied to isolated supply or return ducts, the technique provides a substantially improved measurement of unbalanced duct leakage, which has previously been difficult to quantify.

The statistical comparisons of ducted and unducted homes suggest (but do not prove) that leak paths associated with presence of ducting (as contrasted to leaks <u>through</u> ducting) may be significant. Such leak paths are only demonstrable in a test-reference situation. The implication is that previously available tests, such as whole-house fan pressurization or tracer gas tests, should be considered in matched pair tests of ducted versus unducted homes.

Diagnostic tests attempted without success in the field testing phase included the "return air temperature drop test," and testing for whole-house pressurization by the furnace fan. The return air temperature drop test is based on the hypothesis that severe conduction or leakage losses of return ducts in unconditioned spaces will result in measurable depression of return air temperature (below average house inside temperature) at the furnace return. The field tests performed did not show such measurable depressions. The negative result is attributed in part to transient responses of temperature sensors used, and of the ducting itself. Also, such testing would work best under extreme cold ambient conditions, which did not occur during field trials. While the negative result is not conclusive, it does suggest that fast response, high accuracy temperature sensors and extreme cold weather would be prerequisites for further attempts of such testing.

The test for whole-house pressurization by the furnace fan was hampered by minor wind-induced fluctuations in house-to-ambient pressures. Any change in house-to-ambient pressure would result from either unbalanced duct leakage or zonal pressure variations within the house. Such changes would tend to be minor, if present, and would likely be masked by even minor wind effects. We believe we may have observed a pressure change of about 1 or 2 Pascals at one house. This observation was at the threshold of sensitivity of the pressure transducer used, and of doubtful reliability. The negative result indicates such testing is of marginal value unless high sensitivity can be combined with a method to average out wind effects. Similar testing for fan-induced pressure differences between zones within test homes was not attempted. Such testing might be worth consideration.

Other tests, not used in this project, are possible. Such tests may be useful in further work. They include:

- Co-heating combined with thermal heating system efficiency testing.

- Infrared thermography, contrasting fan-on and fan-off conditions.

The concept of electric co-heating tests has been described.[28] A variation of this technique, for measurement of residential heating system efficiency, is described by Frey and McKinstry.[29] Another variation, consisting of repeated alternations between electric heating with in-room heaters and the forced air system, is also possible. Previously used for other purposes, these methods should be applicable to evaluation of forced air heating system efficiency versus duct loss parameters. Although complex and expensive, they may represent the only test methods which directly address the thermal consequences of all the listed duct loss mechanisms.

Infrared thermography may be useful in investigating interactions between structural leaks and furnace fan-driven pressure variations within the house. We have heard anecdotes concerning observed differences in heat loss patterns between fan-on and fan-off conditions, using thermography. Thermography could be a useful tool in locating supply duct leakage.

6.3. Field Estimation Techniques

Methods to account for duct effects at the energy audit level previously have been virtually non-existent. Our field work did not reveal any visually observable features which correlate closely with tested fan-induced infiltration rates. The statistical study demonstrates correlations that were significant for groups of homes. These correlations reflect the overall thermal consequences of presence of ducting, in terms of effective average heating system "distribution efficiency." These factors are to be applied to the estimated useful heat to be delivered to the space. Baseboard or other in-room electric heat represents a distribution efficiency of 1.0. Estimated energy input to forced air systems would be:

$$\text{Predicted Space Heating Energy} = \frac{\text{Useful Heat Required}}{(\text{Combustion Efficiency})*(\text{Distribution Efficiency})}$$

The combustion efficiency will be applicable to fuel-fired equipment only. Rated AFUE for combustion equipment, or a similarly based value derated for equipment age or condition is probably appropriate. The statistical correlations obtained in our data set were obtained for electric resistance heat. They are also recommended for fuel-fired equipment, for lack of correlations specific to combustion equipment. Distribution efficiencies for ducted forced air house types, based on our statistical results, are:

- Category I Houses - substantially above code envelope insulation, continuous vapor barrier, recent (post-1980) vintage, well insulated ducts -

- unfinished basement	1.00
- slab	0.86
- crawlspace	0.81

- Category II Houses - standard construction, near code envelope insulation levels, no continuous vapor barrier, recent (post-1980) vintage, uninsulated basement ducts -

- unfinished basement	0.61
- slab	0.68
- crawlspace	0.76

- Category III Houses - older (pre-1980) vintage, envelope insulation significantly less than 1980 code, uninsulated basement or other ducts - use appropriate category II (or lower) values.

The category III recommendations are made in the absence of test data for older homes, on which to base more specific recommendations. Recommendation of correlation-based (rather than model-based) distribution efficiencies reflects what we believe is an incomplete understanding of duct-related loss mechanisms and their relative importance. Using correlations based on thermal performance data appears relatively safe, since such data should include all duct effects, whether well understood or otherwise. It is noted that the recommended correlation factors are based on data for homes in the Pacific Northwest, for relatively new construction. To the extent that construction or ducting practices vary geographically, by climate zone, or by house vintage, better correlation factors may be obtainable through further investigation.

The above efficiency penalties apply when comparing heating systems. Caution should be used when attempting to estimate heating usage directly from calculated UA values. For example, the widely used Degree-Day method multiplies the building UA times degree-days times an experimentally derived "C" factor. The "C" factor is necessary to correct for consumer behavior, solar gains and other factors. The method we are proposing would not replace use of the appropriate "C" factor. It should, however, correctly predict energy usage of comparable homes differing only by the type of heating system.

6.4. Conclusions

(1). Duct leakage repair or avoidance constitutes an easy energy efficiency improvement. This affects current Northwest programs in the following ways:

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

(2). More research is needed to quantify the impact and extent of duct leakage in current housing stock. The homes in this study are probably better constructed than the norm. In particular, there was been no study of natural gas-heated homes. This oversight is of particular concern because the health impacts of combustion appliances may be significant.

Models to understand the complexities of interacting air flows in buildings are not adequate. Further research could provide very beneficial insight into low cost-opportunities for energy conservation.

(3). The precision of blower door testing to measure infiltration resulting from duct leakage is questionable. Further testing of whole-house air flow is not recommended as a technique to quantify the small air flows involved in duct leakage. The Flow Hood technique initiated in this study shows potential as a more accurate method for quantifying duct leakage.

(4). One-time tests demonstrated measurable improvements in duct leakage and reductions in fan-driven infiltration. However, long term monitoring was not sufficiently precise to show statistically significant space heat energy savings. This was a result of small expected savings, experimental "noise", and small sample size.

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APPENDIX A

Energy Estimate Savings Worksheet

ENERGY SAVINGS CALCULATION

Site No. ____________

1) From RSDP audit:

W= ________ KW   Seasonal ACH= ________   V= _______ ft^3

From RSDP monitoring:

K= ________ KW/day° Seasonal SH= _______ KW/yr G= ________ KW/day

Heating Days= __________   Ave in/out temp diff ______ °

2) From duct study:

Initial ELA= ________ cm^2 Final ELA= __________ cm^2

Before Retrofit

Air Flow= ________ CFM Supply Q= ______ CFM Return Q= _______ CFM

After Retrofit:

Air Flow= ________ CFM Supply Q= ______ CFM Return Q= _______ CFM

3) Calculate

Duty hrs= Seasonal SH/W	Duty hrs= ______
$Infil_1$= ACH*V*24*.018/3413	Infil1= ________
Q_t= AF + Q_R	Qt1 = __________
Q_t1, Q_t2	Qt2 = __________
Average Qt's	Qt = __________
Furnace dT=W*3413/Q_t*60*.018	dTF1= __________
dT_F1, dT_F2	dTF2= __________
$Loss_1$=[(Q_S*dT_F)+(Q_R*.5*dTave)]*60*.018*duty/3413	Loss1= ______
Infil ratio= (ELA2/ELA1)	Infratio= ________
Efficiency ratio= (Q_T1-Q_S1)/(Q_T2-Q_S2)	Effratio= ________
$Loss_2$=[(Q_S2*dT_F2)+(Q_R2*.5*dTave)]*60*.018*duty*in ratio*eff ratio /3413	Loss2 = __________
Energy savings= Loss1-Loss2	Save= __________
%Duct leaks repaired= Savings/Loss1	%rep= __________
K_2= [1- (Loss1-Loss2)/SeasonSH]*K	K2 = ___________

APPENDIX B
Statistical Study Results

APPENDIX B
Tabular Details
of
Statistical Comparisons

Contents

Appendix B Page No.

Statistical comparisons of the RSDP houses is described in this appendix. First, the means of selected variables are compared. Ducted houses tend to be larger in house volume, requiring that results be normalized. There are some differences by states. These differences may represent differences in the level of construction expertise or at least attention to energy details. However, differences by states were not investigated in this study.

Ducted versus unducted results are compared for MCS and Control group homes using t-test. Since the presence of ducts is expected to increase test variables, a one-tailed treatment of significance is appropriate. This means the two-tailed probabilities listed in the following tables should be divided by 2, adjusting for the fact that the difference occurs in the direction of interest. An alternative comparison was also conducted using one-way analysis of variance. This is a different procedure which attempts to partition the observed variation into that caused by the treatment and that caused by random effects.

Results for the MCS group are listed on pages B-12 to B-19. Results for the Control group are on pages B-20 to B-27. Definitions of the terms and variables used in this report are:

Model Conservation Standards (MCS) Group, group of homes built to high energy-efficiency standards.

Control or "Current Practice" Group, group of homes which are not MCS but instead more typical of current construction practices.

Natural Infiltration, calculated from blower door results, normalized to house volume, units: air changes per hour (ACH).

House volume, units: cubic feet.

Effective Leak Area (ELA), from blower door results, units: sq. cm.

Specific Leak Area (SLA), ELA normalized to floor area, units: sq. cm./sq. ft.

K Factor, regression slope of space heat energy versus indoor-outdoor temperature difference, units: Btu/hour degree F.

Specific K Factor, K factor normalized to floor area, units: Btu/hour degree F. sq. ft.

PFT measured air change rate (PFT), units: air changes per hour (ACH).

Basement Type -- Structure type representing: Slab/Finished Basement, Unfinished Basement, Crawl Space.

No. Stories -- Structure type representing: Single Story, Split Level, Double or More Stories.

Summaries of Estimated Seasonal Air Change Rate (ACH)
By levels of DUCT
MCS
STATE

Variable	Label	Mean	Std Dev	Case
For Entire Population		.4239	.2602	51
Unducted		.3942	.2464	30
Control		.5143	.2301	16
State	ID	.3802	.1340	1
State	MT	.5063	.2445	4
State	OR	.6713	.1965	3
State	WA	.4728	.2191	7
MCS		.2428	.1719	13
State	ID	.1517	.1163	1
State	MT	.2344	.1487	2
State	OR	.3625	.2242	2
State	WA	.2169	.1460	6
Ducted		.4668	.2739	21
Control		.6046	.2472	12
State	ID	.4564	.1899	1
State	MT	.7698	.3377	
State	OR	.8222	.2802	2
State	WA	.5395	.1827	8
MCS		.2721	.1738	8
State	ID	.2491	.1628	1
State	MT	.2543	.1459	
State	OR	.4032	.1717	2
State	WA	.2280	.1569	5

Total Cases = 522
Missing Cases = 9 OR 1.7 PCT.

Summaries of House Volume
By levels of DUCT
MCS
State

Variable		Label	Mean	Std Dev	Case
For Entire Population			14801.2101	5490.4807	51
Unducted			13596.1151	4765.9991	30
Control			12385.1361	4176.5659	16
State	ID		15670.9444	5070.8895	1
State	MT		13883.8500	4111.1966	4
State	OR		9940.5676	2352.7849	3
State	WA		11998.0541	3914.4419	7
MCS			15112.0815	5032.6859	13
State	ID		15577.7500	3348.4068	1
State	MT		15216.3333	4494.1149	2
State	OR		14906.3846	6288.9059	2
State	WA		15101.3188	5069.1984	6
Ducted			16545.7286	5990.9913	21
Control			14897.3984	4934.4216	12
State	ID		16457.1000	5057.8097	1
State	MT		15099.7500	6248.8544	
State	OR		13541.8571	5412.2392	2
State	WA		15163.4321	4677.8409	8
MCS			18876.1264	6580.6609	8
State	ID		17319.0909	5806.6694	1
State	MT		16461.7500	5490.1510	
State	OR		19513.6500	6125.4175	2
State	WA		19146.0192	7031.9212	5

Total Cases = 522
Missing Cases = 8 OR 1.5 PCT.

Summaries of Effective Leak Area (ELA) (sq. cm.)

By levels of DUCT
MCS
State

Variable	Label	Mean	Std Dev	Case
For Entire Population		466.0634	284.8400	513
Unducted		379.5218	225.4260	303
Control		467.2592	209.4186	169
State	ID	510.2111	216.2242	18
State	MT	364.1800	170.5020	40
State	OR	539.4486	191.8400	37
State	WA	476.4351	217.6179	74
MCS		268.8679	194.6115	134
State	ID	211.1583	156.5861	12
State	MT	169.4000	85.6357	27
State	OR	431.0615	280.6196	26
State	WA	256.9676	154.8492	68
Ducted		590.9305	314.3327	210
Control		716.9618	282.4110	123
State	ID	662.2200	412.0182	10
State	MT	552.3250	303.2054	4
State	OR	895.7286	269.0070	28
State	WA	670.0543	243.9601	81
MCS		412.7483	268.5913	87
State	ID	372.4818	221.5105	11
State	MT	252.7750	200.6985	4
State	OR	634.6500	269.3675	20
State	WA	348.2250	238.1516	52

Total Cases = 522
Missing Cases = 9 OR 1.7 PCT.

Summaries of Specific Leak Area (SLA) (sq. cm./ sq. ft.)

By levels of DUCT
MCS
State

Variable		Label	Mean	Std Dev	Case
For Entire Population			.2733	.1761	51
Unducted			.2454	.1679	30
Control			.3222	.1679	16
State	ID		.2637	.1032	1
State	MT		.2226	.1265	4
State	OR		.4435	.1463	3
State	WA		.3296	.1717	7
MCS			.1485	.1069	13
State	ID		.1064	.0688	1
State	MT		.0948	.0525	2
State	OR		.2397	.1482	2
State	WA		.1423	.0889	6
Ducted			.3136	.1802	21
Control			.4072	.1610	12
State	ID		.3187	.1302	1
State	MT		.3091	.1324	
State	OR		.5686	.1784	2
State	WA		.3672	.1184	8
MCS			.1813	.1092	8
State	ID		.1829	.1105	1
State	MT		.1164	.0686	
State	OR		.2672	.1018	2
State	WA		.1529	.0976	5

Total Cases = 522
Missing Cases = 9 OR 1.7 PCT.

Summaries of K Factor (Btu/ hour degree F)

By levels of Ducted or Unducted
MCS or Control Groups
STATE

Variable	Value	Label	Mean	Std Dev	Case
For Entire Population			332.4974	182.3510	45
Unducted			273.5722	140.8500	28
Control Group			304.5039	153.3301	15
STATE	ID		256.6720	108.2348	1
STATE	MT		239.6253	78.0027	3
STATE	OR		282.1821	113.5052	3
STATE	WA		366.1448	189.3274	6
MCS Group			234.5394	112.2678	12
STATE	ID		188.1116	100.8442	1
STATE	MT		169.3364	65.3715	2
STATE	OR		218.9796	113.3336	2
STATE	WA		274.4258	114.0295	6
Ducted			430.1350	200.8664	17
Control Group			492.9890	196.9558	10
STATE	ID		344.8876	239.8458	
STATE	MT		306.1134	129.7353	
STATE	OR		522.1105	186.6077	2
STATE	WA		506.2262	192.4011	7
MCS Group			329.1878	163.3753	6
STATE	ID		181.6565	60.7639	
STATE	MT		173.0624	60.1576	
STATE	OR		354.3747	189.7671	1
STATE	WA		348.7123	156.1938	4

Total Cases = 457

Summaries of Specific K Factor (Btu/ hour degree F sq. ft.)

By levels of Ducted or Unducted
MCS or Control Groups
STATE

Variable	Value	Label	Mean	Std Dev	Case
For Entire Population			.1929	.0978	45
Unducted			.1701	.0757	28
Control Group			.2005	.0732	15
STATE	ID		.1342	.0393	1
STATE	MT		.1454	.0494	3
STATE	OR		.2322	.0698	3
STATE	WA		.2332	.0625	6
MCS Group			.1315	.0596	12
STATE	ID		.1005	.0520	1
STATE	MT		.0952	.0365	2
STATE	OR		.1276	.0685	2
STATE	WA		.1526	.0558	6
Ducted			.2308	.1172	17
Control Group			.2805	.1101	10
STATE	ID		.1842	.1297	
STATE	MT		.1913	.1377	
STATE	OR		.3265	.1051	2
STATE	WA		.2788	.1022	7
MCS Group			.1484	.0747	6
STATE	ID		.0971	.0571	
STATE	MT		.0830	.0110	
STATE	OR		.1630	.1195	1
STATE	WA		.1549	.0613	4

Total Cases = 457
Missing Cases = 4 OR .9 PCT.

Summaries of 50 Pascal Air Flow (Q50) units: Cubic Feet per Minute (CFM)

By levels of Ducted or Unducted
MCS or Control Groups
STATE

Variable	Value	Label	Mean	Std Dev	Case
For Entire Population			1350.8862	735.4401	50
Unducted			1153.7143	601.4168	30
Control Group			1428.4551	525.8390	16
STATE	ID		1476.4706	620.6783	1
STATE	MT		1221.4103	454.4605	3
STATE	OR		1528.4595	491.4563	3
STATE	WA		1476.5405	535.5923	7
MCS Group			811.3134	507.7967	13
STATE	ID		651.8333	415.5944	1
STATE	MT		579.2963	261.5968	2
STATE	OR		1274.9615	692.8929	2
STATE	WA		754.8971	406.0630	6
Ducted			1647.6300	816.3288	20
Control Group			2029.2281	700.3007	11
STATE	ID		1609.7778	670.3241	
STATE	MT		1451.3333	447.2766	
STATE	OR		2417.2400	737.4050	2
STATE	WA		1974.7922	646.8045	7
MCS Group			1141.7907	673.7875	8
STATE	ID		1130.1818	670.9398	1
STATE	MT		841.5000	577.1635	
STATE	OR		1659.0526	653.6183	1
STATE	WA		978.3462	603.3127	5

Total Cases = 522
Missing Cases = 21 OR 4.0 PCT.

Summaries of 50 Pascal Air Flow Volume (ACH50) units: Air Changes per Hou

By levels of Ducted or Unducted
MCS or Control Groups
STATE

Variable	Value	Label	Mean	Std Dev	Case
For Entire Population			6.0312	3.4434	50
Unducted			5.5923	3.2079	30
Control Group			7.3596	2.8190	16
STATE	ID		5.9312	2.1313	1
STATE	MT		5.6027	2.4451	3
STATE	OR		9.3448	2.3882	3
STATE	WA		7.6210	2.6379	7
MCS Group			3.3898	2.1177	13
STATE	ID		2.4804	1.3756	1
STATE	MT		2.4552	1.2673	2
STATE	OR		5.3551	2.6423	2
STATE	WA		3.1667	1.8202	6
Ducted			6.6916	3.6807	20
Control Group			8.8822	3.0312	11
STATE	ID		6.6010	2.7355	
STATE	MT		7.8664	4.0157	
STATE	OR		11.7343	3.2993	2
STATE	WA		8.2623	2.3000	7
MCS Group			3.7879	2.1299	8
STATE	ID		4.2464	2.7873	1
STATE	MT		2.9569	1.5127	
STATE	OR		5.2715	1.7745	1
STATE	WA		3.2128	1.8800	5

Total Cases = 522
Missing Cases = 21 OR 4.0 PCT.

Summaries of PFT - Measured Air Exchange Rate units: Air Changes per Hour

By levels of Ducted or Unducted
MCS or Control Groups

Variable	Mean	Std Dev	Cases
For Entire Population	.328811	.274378	244
Unducted	.315194	.322513	144
Control	.314372	.376455	86
MCS	.316414	.222740	58
Ducted	.348420	.184076	100
Control	.394920	.181782	50
MCS	.301920	.176074	50

Total Cases = 264
Missing Cases = 20 OR 7.6 PCT.

Note: Pages 12 through 19 refer to the <u>MCS Group Sample</u>

t-test for: Blower Door Measured Air Exchange Rate (ACH)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	134	.2428	.172	.015
Ducted	87	.2721	.174	.019

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.02	.900	-1.23	219	.218	-1.23	182.37	.220

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	.0454	.0454	1.5235	.218
Within Groups	219	6.5246	.0298		
Total	220	6.5700			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	134	.2428	.1719	.0148	.2134	To	.
Ducted	87	.2721	.1738	.0186	.2351	To	.
Total	221	.2543	.1728	.0116	.2314	To	.

Group	Minimum	Maximum
Unducted	.0203	1.1349
Ducted	.0008	.7381
Total	.0008	1.1349

t-test for: PFT - Measured Air Exchange Rate units: Air Changes per Hour

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	58	.3164	.223	.029
Ducted	50	.3019	.176	.025

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.60	.094	.37	106	.711	.38	105.25	.707

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	.0056	.0056	.1375	.711
Within Groups	106	4.3470	.0410		
Total	107	4.3527			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	58	.3164	.2227	.0292	.2578	To	.
Ducted	50	.3019	.1761	.0249	.2519	To	.
Total	108	.3097	.2017	.0194	.2712	To	.

Group	Minimum	Maximum
Unducted	.0420	.9500
Ducted	.0550	1.0020
Total	.0420	1.0020

t-test for: Effective Leak Area (ELA) (sq. cm.)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	134	268.8679	194.612	16.812
Ducted	87	412.7483	268.591	28.796

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.90	.001	-4.61	219	.000	-4.31	143.81	.000

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	1092030.684	1092030.684	21.2746	.000
Within Groups	219	11241345.53	51330.3449		
Total	220	12333376.21			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	134	268.8679	194.6115	16.8119	235.6147	To	302.
Ducted	87	412.7483	268.5913	28.7960	355.5037	To	469.
Total	221	325.5086	236.7716	15.9270	294.1196	To	356.

Group	Minimum	Maximum
Unducted	24.5000	1269.1000
Ducted	.9000	1312.4000
Total	.9000	1312.4000

t-test for: Specific Leak Area (SLA) (sq. cm./ sq. ft.)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	134	.1485	.107	.009
Ducted	87	.1813	.109	.012

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.04	.819	-2.21	219	.028	-2.20	181.04	.029

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	.0567	.0567	4.8808	.028
Within Groups	219	2.5456	.0116		
Total	220	2.6024			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	134	.1485	.1069	.0092	.1302	To	.
Ducted	87	.1813	.1092	.0117	.1580	To	.
Total	221	.1614	.1088	.0073	.1470	To	.

Group	Minimum	Maximum
Unducted	.0167	.7870
Ducted	.0006	.5072
Total	.0006	.7870

t-test for: K Factor (Btu/ hour degree F)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	126	234.5394	112.268	10.002
Ducted	66	329.1878	163.375	20.110

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
2.12	.000	-4.72	190	.000	-4.21	98.01	.000

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	388007.6538	388007.6538	22.2693	.000
Within Groups	190	3310452.265	17423.4330		
Total	191	3698459.919			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	126	234.5394	112.2678	10.0016	214.7449	To	254.
Ducted	66	329.1878	163.3753	20.1101	289.0252	To	369.
Total	192	267.0748	139.1534	10.0425	247.2663	To	286.

Group	Minimum	Maximum
Unducted	37.0878	797.2180
Ducted	63.0408	872.8300
Total	37.0878	872.8300

t-test for: Specific K Factor (Btu/ hour degree F sq. ft.)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	125	.1315	.060	.005
Ducted	64	.1484	.075	.009

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.57	.033	-1.69	187	.093	-1.57	105.08	.120

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	.0120	.0120	2.8424	.093
Within Groups	187	.7922	.0042		
Total	188	.8042			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	125	.1315	.0596	.0053	.1210	To	.
Ducted	64	.1484	.0747	.0093	.1297	To	.
Total	189	.1373	.0654	.0048	.1279	To	.

Group	Minimum	Maximum
Unducted	.0265	.2765
Ducted	.0423	.4710
Total	.0265	.4710

t-test for: 50 Pascal Air Flow Rate (Q50) (CFM)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	167	1428.4551	525.839	40.691
Ducted	114	2029.2281	700.301	65.589

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.77	.001	-8.21	279	.000	-7.78	196.87	.000

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	24453204.89	24453204.89	67.3372	.000
Within Groups	279	101317673.5	363145.7831		
Total	280	125770878.4			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	167	1428.4551	525.8390	40.6906	1348.1172	To	1508.
Ducted	114	2029.2281	700.3007	65.5892	1899.2841	To	2159.
Total	281	1672.1851	670.2102	39.9814	1593.4828	To	1750.

Group	Minimum	Maximum
Unducted	330.0000	3088.0000
Ducted	496.0000	4071.0000
Total	330.0000	4071.0000

t-test for: 50 Pascal Air Flow Volume (ACH50) (ACH)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	134	3.3898	2.118	.183
Ducted	86	3.7879	2.130	.230

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.01	.942	-1.36	218	.176	-1.36	180.61	.177

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	8.3009	8.3009	1.8427	.176
Within Groups	218	982.0542	4.5048		
Total	219	990.3551			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	134	3.3898	2.1177	.1829	3.0280	To	3.
Ducted	86	3.7879	2.1299	.2297	3.3313	To	4.
Total	220	3.5454	2.1265	.1434	3.2629	To	3.

Group	Minimum	Maximum
Unducted	.7416	14.4930
Ducted	.1860	8.9647
Total	.1860	14.4930

Note: pages 20 to 27 refer to the Control Group Sample.

t-test for: Blower Door Measured Air Exchange Rate (ACH)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	169	.5143	.230	.018
Ducted	123	.6046	.247	.022

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.15	.390	-3.21	290	.001	-3.17	251.73	.002

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	.5801	.5801	10.2883	.001
Within Groups	290	16.3519	.0564		
Total	291	16.9320			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	169	.5143	.2301	.0177	.4793	To	.
Ducted	123	.6046	.2472	.0223	.5604	To	.
Total	292	.5523	.2412	.0141	.5245	To	.

Group	Minimum	Maximum
Unducted	.1015	1.3777
Ducted	.0630	1.7541
Total	.0630	1.7541

t-test for: PFT - Measured Air Exchange Rate units: Air Changes per Hour

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	86	.3144	.376	.041
Ducted	50	.3949	.182	.026

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
4.29	.000	-1.42	134	.158	-1.68	130.45	.096

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	.2051	.2051	2.0115	.158
Within Groups	134	13.6652	.1020		
Total	135	13.8703			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	86	.3144	.3765	.0406	.2337	To	.
Ducted	50	.3949	.1818	.0257	.3433	To	.
Total	136	.3440	.3205	.0275	.2896	To	.

Group	Minimum	Maximum
Unducted	.0590	3.5190
Ducted	.0810	.9340
Total	.0590	3.5190

t-test for: Effective Leak Area (ELA) (sq. cm.)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	169	467.2592	209.419	16.109
Ducted	123	716.9618	282.411	25.464

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.82	.000	-8.68	290	.000	-8.29	214.27	.000

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	4438693.453	4438693.453	75.2846	.000
Within Groups	290	17098058.06	58958.8209		
Total	291	21536751.51			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	169	467.2592	209.4186	16.1091	435.4568	To	499.
Ducted	123	716.9618	282.4110	25.4641	666.5530	To	767.
Total	292	572.4421	272.0468	15.9203	541.1085	To	603.

Group	Minimum	Maximum
Unducted	84.4000	1523.4000
Ducted	124.0000	1641.7000
Total	84.4000	1641.7000

t-test for: Specific Leak Area (SLA) (sq. cm./ sq. ft.)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	169	.3222	.168	.013
Ducted	123	.4072	.161	.015

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.09	.627	-4.35	290	.000	-4.38	269.11	.000

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	.5151	.5151	18.9179	.000
Within Groups	290	7.8963	.0272		
Total	291	8.4114			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	169	.3222	.1679	.0129	.2967	To	.
Ducted	123	.4072	.1610	.0145	.3785	To	.
Total	292	.3580	.1700	.0099	.3384	To	.

Group	Minimum	Maximum
Unducted	.0776	1.3541
Ducted	.0464	.9855
Total	.0464	1.3541

t-test for: K Factor (Btu/ hour degree F)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	159	304.5039	153.330	12.160
Ducted	106	492.9890	196.956	19.130

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.65	.004	-8.74	263	.000	-8.32	186.73	.000

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	2259493.301	2259493.301	76.3057	.000
Within Groups	263	7787715.396	29611.0852		
Total	264	10047208.70			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	159	304.5039	153.3301	12.1599	280.4871	To	328.
Ducted	106	492.9890	196.9558	19.1300	455.0576	To	530.
Total	265	379.8979	195.0836	11.9839	356.3018	To	403.

Group	Minimum	Maximum
Unducted	74.9436	1302.8244
Ducted	88.3538	1130.0417
Total	74.9436	1302.8244

t-test for: Specific K Factor (Btu/ hour degree F sq. ft.)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	158	.2005	.073	.006
Ducted	106	.2805	.110	.011

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
2.26	.000	-7.09	262	.000	-6.57	166.77	.000

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	.4058	.4058	50.2765	.000
Within Groups	262	2.1149	.0081		
Total	263	2.5207			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	158	.2005	.0732	.0058	.1890	To	.
Ducted	106	.2805	.1101	.0107	.2593	To	.
Total	264	.2327	.0979	.0060	.2208	To	.

Group	Minimum	Maximum
Unducted	.0390	.4057
Ducted	.0384	.6509
Total	.0384	.6509

t-test for: 50 Pascal Air Flow Rate (Q50) (CFM)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	167	1428.4551	525.839	40.691
Ducted	114	2029.2281	700.301	65.589

F Value	2-Tail Prob.	Pooled Variance Estimate: t Value	Degrees of Freedom	2-Tail Prob.	Separate Variance Estimate: t Value	Degrees of Freedom	2-Tail Prob.
1.77	.001	-8.21	279	.000	-7.78	196.87	.000

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob
Between Groups	1	24453204.89	24453204.89	67.3372	.000
Within Groups	279	101317673.5	363145.7831		
Total	280	125770878.4			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for		
Unducted	167	1428.4551	525.8390	40.6906	1348.1172	To	1508.
Ducted	114	2029.2281	700.3007	65.5892	1899.2841	To	2159.
Total	281	1672.1851	670.2102	39.9814	1593.4828	To	1750.

Group	Minimum	Maximum
Unducted	330.0000	3088.0000
Ducted	496.0000	4071.0000
Total	330.0000	4071.0000

t-test for: 50 Pascal Air Flow Volume (ACH50) (ACH)

	Number of Cases	Mean	Standard Deviation	Standard Error
Unducted	167	7.3596	2.819	.218
Ducted	114	8.8822	3.031	.284

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.16	.393	-4.31	279	.000	-4.25	231.00	.000

Analysis of Variance

Source	D.F.	Sum of Squares	Mean Squares	F Ratio	F Prob.
Between Groups	1	157.0703	157.0703	18.5895	.0000
Within Groups	279	2357.3913	8.4494		
Total	280	2514.4616			

Group	Count	Mean	Standard Deviation	Standard Error	95 Pct Conf Int for Mean		
Unducted	167	7.3596	2.8190	.2181	6.9289	To	7.7902
Ducted	114	8.8822	3.0312	.2839	8.3197	To	9.4446
Total	281	7.9773	2.9967	.1788	7.6254	To	8.3292

Group	Minimum	Maximum
Unducted	2.2759	18.6733
Ducted	1.3907	18.7892
Total	1.3907	18.7892

*** * * * M U L T I P L E   R E G R E S S I O N * * * ***

Dependent Variable.. SLA

Multiple R	.60812
R Square	.36981
Adjusted R Square	.36284
Standard Error	.13604

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	5	4.90894	.98179
Residual	452	8.36527	.01851

F = 53.04887 Signif F = 0.0

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
DUCT	.04754	.01307	.13597	3.636	.0003
SLAB	-.04130	.07945	-.11365	-.520	.6035
MCS	-.18382	.01288	-.53583	-14.276	.0000
BASE	-.06688	.08032	-.14135	-.833	.4055
CRAWL	.02177	.07921	.06392	.275	.7835
(Constant)	.34168	.07950		4.298	.0000

*** * * * M U L T I P L E   R E G R E S S I O N * * * ***

Dependent Variable.. ACH

Multiple R	.58015
R Square	.33658
Adjusted R Square	.32924
Standard Error	.20280

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	5	9.43115	1.88623
Residual	452	18.58979	.04113

F = 45.86262 Signif F = 0.0

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
DUCT	.03860	.01949	.07600	1.981	.0482
SLAB	-.02890	.11844	-.05473	-.244	.8074
MCS	-.27936	.01919	-.56047	-14.554	.0000
BASE	-.04083	.11974	-.05939	-.341	.7333
CRAWL	.01112	.11808	.02247	.094	.9250
(Constant)	.53077	.11851		4.479	.0000

*** * * * M U L T I P L E R E G R E S S I O N * * * ***

Dependent Variable.. ACH50

Multiple R	.68199
R Square	.46511
Adjusted R Square	.45920
Standard Error	2.50060

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	5	2457.65779	491.53156
Residual	452	2826.34807	6.25298

F = 78.60754 Signif F = 0.0

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
DUCT	.92985	.24031	.13330	3.869	.0001
SLAB	-1.36724	1.46035	-.18858	-.936	.3497
MCS	-4.23456	.23668	-.61867	-17.892	.0000
BASE	-1.97510	1.47643	-.20924	-1.338	.1816
CRAWL	-.18156	1.45599	-.02671	-.125	.9008
(Constant)	8.32900	1.46128		5.700	.0000

* * * A N A L Y S I S   O F   V A R I A N C E * * *

SLA
BY MCS/Control
Ducted/Unducted
Basement Type

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	4.904	4	1.226	67.092	0.0
MCS	3.767	1	3.767	206.171	.000
DUCT	.249	1	.249	13.601	.000
BMT	.599	2	.300	16.391	.000
2-way Interactions	.193	5	.039	2.111	.063
MCS DUCT	.032	1	.032	1.752	.186
MCS BMT	.154	2	.077	4.210	.015
DUCT BMT	.011	2	.005	.288	.750
3-way Interactions	.028	2	.014	.755	.471
MCS DUCT BMT	.028	2	.014	.755	.471
Explained	5.124	11	.466	25.494	0.0
Residual	8.150	446	.018		
Total	13.274	457	.029		

522 Cases were processed.
64 CASES (12.3 PCT) were missing.

* * * A N A L Y S I S   O F   V A R I A N C E * * *

ACH
BY MCS/Control
Ducted/Unducted
Basement Type

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	9.429	4	2.357	57.225	0.0
MCS	8.710	1	8.710	211.463	.000
DUCT	.164	1	.164	3.972	.047
BMT	.221	2	.111	2.685	.069
2-way Interactions	.131	5	.026	.634	.674
MCS DUCT	.023	1	.023	.551	.458
MCS BMT	.094	2	.047	1.137	.322
DUCT BMT	.014	2	.007	.175	.840
3-way Interactions	.090	2	.045	1.097	.335
MCS DUCT BMT	.090	2	.045	1.097	.335
Explained	9.650	11	.877	21.297	0.0
Residual	18.371	446	.041		
Total	28.021	457	.061		

522 Cases were processed.
64 CASES (12.3 PCT) were missing.

* * * A N A L Y S I S O F V A R I A N C E * * *

ACH50
BY MCS/Control
Ducted/Unducted
Basement Type

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	2452.177	4	613.044	99.420	0.0
MCS	1997.395	1	1997.395	323.927	.000
DUCT	95.969	1	95.969	15.564	.000
BMT	229.135	2	114.568	18.580	0.0
2-way Interactions	67.506	5	13.501	2.190	.054
MCS DUCT	28.603	1	28.603	4.639	.032
MCS BMT	34.985	2	17.493	2.837	.060
DUCT BMT	5.447	2	2.724	.442	.643
3-way Interactions	14.204	2	7.102	1.152	.317
MCS DUCT BMT	14.204	2	7.102	1.152	.317
Explained	2533.887	11	230.353	37.358	0.0
Residual	2750.119	446	6.166		
Total	5284.006	457	11.562		

522 Cases were processed.
64 CASES (12.3 PCT) were missing.

* * * A N A L Y S I S   O F   V A R I A N C E * * *

SLA
BY Ducted/Unducted
MCS/Control

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	2.971	2	1.486	59.799	.000
DUCT	.114	1	.114	4.575	.034
MCS	2.822	1	2.822	113.584	.000
2-way Interactions	.007	1	.007	.275	.601
DUCT MCS	.007	1	.007	.275	.601
Explained	2.978	3	.993	39.957	0.0
Residual	5.540	223	.025		
Total	8.518	226	.038		

227 Cases were processed.
0 CASES (.0 PCT) were missing.

* * * A N A L Y S I S   O F   V A R I A N C E * * *

Specific K Factor
BY Ducted/Unducted
MCS/Control

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	.487	2	.244	32.433	0.0
DUCT	.077	1	.077	10.235	.002
MCS	.400	1	.400	53.207	.000
2-way Interactions	.008	1	.008	1.040	.309
DUCT MCS	.008	1	.008	1.040	.309
Explained	.495	3	.165	21.968	0.0
Residual	1.674	223	.008		
Total	2.169	226	.010		

* * * A N A L Y S I S O F V A R I A N C E * * *

SLA
BY Ducted/Unducted
MCS/Control
Basement/Crawl

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	3.867	3	1.289	58.020	0.0
DUCT	.138	1	.138	6.191	.013
MCS	3.230	1	3.230	145.369	.000
CRAWL	.344	1	.344	15.470	.000
2-way Interactions	.075	3	.025	1.131	.337
DUCT MCS	.006	1	.006	.268	.605
DUCT CRAWL	.001	1	.001	.060	.807
MCS CRAWL	.070	1	.070	3.170	.076
3-way Interactions	.001	1	.001	.047	.829
DUCT MCS CRAWL	.001	1	.001	.047	.829
Explained	3.944	7	.563	25.357	0.0
Residual	6.532	294	.022		
Total	10.476	301	.035		

303 Cases were processed.
1 CASES (.3 PCT) were missing.

* * * A N A L Y S I S   O F   V A R I A N C E * * *

Specific K Factor
BY Ducted/Unducted
MCS/Control
Basement/Crawl

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	.794	3	.265	36.068	0.0
DUCT	.129	1	.129	17.540	.000
MCS	.564	1	.564	76.784	.000
CRAWL	.075	1	.075	10.253	.002
2-way Interactions	.039	3	.013	1.772	.153
DUCT MCS	.034	1	.034	4.656	.032
DUCT CRAWL	.006	1	.006	.801	.372
MCS CRAWL	.000	1	.000	.034	.855
3-way Interactions	.018	1	.018	2.429	.120
DUCT MCS CRAWL	.018	1	.018	2.429	.120
Explained	.851	7	.122	16.564	0.0
Residual	2.158	294	.007		
Total	3.009	301	.010		

303 Cases were processed.
1 CASES (.3 PCT) were missing.

*** ANALYSIS OF VARIANCE ***

SLA
BY Ducted/Unducted
MCS/Control
Basement/Slab

Source of Variation			Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects			1.421	3	.474	36.495	0.0
DUCT			.149	1	.149	11.475	.001
MCS			1.230	1	1.230	94.784	.000
SLAB			.006	1	.006	.461	.498
2-way Interactions			.069	3	.023	1.768	.154
DUCT	MCS		.056	1	.056	4.346	.038
DUCT	SLAB		.009	1	.009	.672	.413
MCS	SLAB		.001	1	.001	.089	.765
3-way Interactions			.026	1	.026	1.971	.162
DUCT	MCS	SLAB	.026	1	.026	1.971	.162
Explained			1.516	7	.217	16.680	0.0
Residual			2.778	214	.013		
Total			4.294	221	.019		

226 Cases were processed.
4 CASES (1.8 PCT) were missing.

* * * A N A L Y S I S   O F   V A R I A N C E * * *

Specific K Factor
BY Ducted/Unducted
MCS/Control
Basement/Slab

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	.548	3	.183	32.709	0.0
DUCT	.140	1	.140	25.091	.000
MCS	.381	1	.381	68.249	.000
SLAB	.003	1	.003	.469	.494
2-way Interactions	.060	3	.020	3.562	.015
DUCT MCS	.056	1	.056	9.993	.002
DUCT SLAB	.000	1	.000	.090	.765
MCS SLAB	.002	1	.002	.281	.597
3-way Interactions	.008	1	.008	1.349	.247
DUCT MCS SLAB	.008	1	.008	1.349	.247
Explained	.615	7	.088	15.737	0.0
Residual	1.195	214	.006		
Total	1.810	221	.008		

226 Cases were processed.
4 CASES (1.8 PCT) were missing.

* * * ANALYSIS OF VARIANCE * * *

SLA
BY Ducted/Unducted
MCS/Control
Crawl/Slab

Source of Variation	Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects	4.428	3	1.476	73.746	0.0
DUCT	.230	1	.230	11.487	.001
MCS	3.498	1	3.498	174.778	.000
CRAWL	.423	1	.423	21.153	.000
2-way Interactions	.205	3	.068	3.414	.018
DUCT MCS	.060	1	.060	2.981	.085
DUCT CRAWL	.006	1	.006	.285	.593
MCS CRAWL	.146	1	.146	7.296	.007
3-way Interactions	.027	1	.027	1.325	.250
DUCT MCS CRAWL	.027	1	.027	1.325	.250
Explained	4.660	7	.666	33.258	0.0
Residual	7.386	369	.020		
Total	12.045	376	.032		

380 Cases were processed.
3 CASES (.8 PCT) were missing.

* * * A N A L Y S I S   O F   V A R I A N C E * * *

Specific K Factor
BY Ducted/Unducted
MCS/Control
Slab/Crawl

Source of Variation			Sum of Squares	DF	Mean Square	F	Signif of F
Main Effects			1.048	3	.349	53.793	0.0
DUCT			.159	1	.159	24.466	.000
MCS			.628	1	.628	96.764	.000
CRAWL			.183	1	.183	28.154	.000
2-way Interactions			.028	3	.009	1.452	.227
DUCT	MCS		.025	1	.025	3.790	.052
DUCT	CRAWL		.004	1	.004	.586	.444
MCS	CRAWL		.001	1	.001	.225	.635
3-way Interactions			.002	1	.002	.379	.539
DUCT	MCS	CRAWL	.002	1	.002	.379	.539
Explained			1.078	7	.154	23.730	0.0
Residual			2.396	369	.006		
Total			3.474	376	.009		

380 Cases were processed.
3 CASES (.8 PCT) were missing.

Summaries of SLA
By levels of MCS/Control
Ducted/Unducted
Basement Type

Variable	Label	Mean	Std Dev	Cases
For Entire Population		.2716	.1742	469
Control Group		.3545	.1681	267
Unducted		.3253	.1707	159
Slab/Finished		.2587	.1039	48
Unfinished Basement		.2632	.1509	22
Crawl Space		.3765	.1874	89
Ducted		.3976	.1551	108
Slab/Finished		.3609	.1409	32
Unfinished Basement		.3162	.0942	18
Crawl Space		.4431	.1635	58
MCS Group		.1620	.1098	202
Unducted		.1495	.1072	124
Slab/Finished		.1493	.1078	47
Unfinished Basement		.1222	.0641	19
Crawl Space		.1586	.1173	58
Ducted		.1819	.1117	78
Slab/Finished		.1674	.0966	29
Unfinished Basement		.1568	.1392	14
Crawl Space		.2040	.1104	35

Total Cases = 522
Missing Cases = 53 OR 10.2 PCT.

Summaries of ACH
By levels of MCS/Control
Ducted/Unducted
Basement Type

Variable Label	Mean	Std Dev	Cases
For Entire Population	.4234	.2600	469
Control Group	.5496	.2425	267
Unducted	.5164	.2306	159
Slab/Finished	.4703	.1930	48
Unfinished Basement	.4654	.2305	22
Crawl Space	.5538	.2442	89
Ducted	.5985	.2523	108
Slab/Finished	.5530	.1987	32
Unfinished Basement	.5605	.2252	18
Crawl Space	.6354	.2827	58
MCS Group	.2566	.1744	202
Unducted	.2458	.1715	124
Slab/Finished	.2498	.1716	47
Unfinished Basement	.2632	.1698	19
Crawl Space	.2369	.1743	58
Ducted	.2738	.1787	78
Slab/Finished	.2593	.1621	29
Unfinished Basement	.2427	.2036	14
Crawl Space	.2982	.1833	35

Total Cases = 522
Missing Cases = 53 OR 10.2 PCT.

Summaries of ACH50
By levels of MCS/Control
Ducted/Unducted
Basement Type

Variable	Label	Mean	Std Dev	Cases
For Entire Population		5.9897	3.4003	458
Control Group		7.8987	2.9507	257
Unducted		7.3787	2.8622	157
Slab/Finished		6.2777	2.1753	46
Unfinished Basement		6.0779	2.9711	22
Crawl Space		8.2694	2.8526	89
Ducted		8.7152	2.9161	100
Slab/Finished		8.3784	2.9181	30
Unfinished Basement		6.9171	2.0736	16
Crawl Space		9.4350	2.9052	54
MCS Group		3.5488	2.1458	201
Unducted		3.4149	2.1176	124
Slab/Finished		3.3329	2.1685	47
Unfinished Basement		2.8794	1.4945	19
Crawl Space		3.6568	2.2396	58
Ducted		3.7645	2.1870	77
Slab/Finished		3.3983	1.7830	29
Unfinished Basement		2.8566	1.9257	13
Crawl Space		4.4052	2.4316	35

Total Cases = 522
Missing Cases = 64 OR 12.3 PCT.

Summaries of SLA
By levels of MCS/Control
Ducted/Unducted
No. of Stories

Variable	Label	Mean	Std Dev	Cases
For Entire Population		.2693	.1732	490
Control Group		.3528	.1668	278
Unducted		.3228	.1693	164
Single Story		.3273	.1600	106
Split Level		.2559	.1172	23
Double Story		.3529	.2130	35
Ducted		.3960	.1538	114
Single Story		.4087	.1386	45
Split Level		.3793	.1512	28
Double Story		.3934	.1729	41
MCS Group		.1598	.1086	212
Unducted		.1467	.1059	129
Single Story		.1353	.0872	43
Split Level		.1405	.0892	34
Double Story		.1602	.1282	52
Ducted		.1801	.1102	83
Single Story		.1649	.0975	40
Split Level		.2046	.0811	8
Double Story		.1918	.1283	35

Total Cases = 522
Missing Cases = 32 OR 6.1 PCT.

Summaries of ACH
By levels of MCS/Control
Ducted/Unducted
No. of Stories

Variable	Label	Mean	Std Dev	Cases
For Entire Population		.4201	.2596	490
Control Group		.5480	.2415	278
Unducted		.5146	.2315	164
Single Story		.5153	.2413	106
Split Level		.4723	.1939	23
Double Story		.5405	.2254	35
Ducted		.5961	.2485	114
Single Story		.5516	.2096	45
Split Level		.6212	.2715	28
Double Story		.6279	.2696	41
MCS Group		.2524	.1727	212
Unducted		.2412	.1701	129
Single Story		.2085	.1501	43
Split Level		.2511	.1553	34
Double Story		.2616	.1925	52
Ducted		.2699	.1762	83
Single Story		.2377	.1533	40
Split Level		.2917	.1308	8
Double Story		.3016	.2051	35

Total Cases = 522
Missing Cases = 32 OR 6.1 PCT.

Summaries of ACH50
By levels of MCS/Control
Ducted/Unducted
No. of Stories

Variable Label	Mean	Std Dev	Cases
For Entire Population	5.9445	3.3845	478
Control Group	7.8679	2.9314	267
Unducted	7.3526	2.8437	162
Single Story	7.5288	2.7834	104
Split Level	5.9624	2.5381	23
Double Story	7.7425	3.0159	35
Ducted	8.6629	2.8998	105
Single Story	8.9874	3.0080	43
Split Level	8.2529	1.9687	26
Double Story	8.5715	3.3312	36
MCS Group	3.5107	2.1163	211
Unducted	3.3520	2.0883	129
Single Story	3.1829	1.8035	43
Split Level	3.2898	1.7202	34
Double Story	3.5325	2.5085	52
Ducted	3.7605	2.1486	82
Single Story	3.5783	2.0259	40
Split Level	3.8673	1.4506	8
Double Story	3.9497	2.4403	34

Total Cases = 522
Missing Cases = 44 OR 8.4 PCT.

Summaries of Specific K Factor
By levels of MCS/Control
Ducted/Unducted
No. of Stories .

Variable	Label	Mean	Std Dev	Cases
For Entire Population		.1908	.0948	433
Control Group		.2291	.0944	252
Unducted		.2011	.0736	155
Single Story		.1992	.0712	100
Split Level		.1711	.0723	22
Double Story		.2270	.0751	33
Ducted		.2739	.1064	97
Single Story		.2733	.0887	40
Split Level		.2416	.1036	23
Double Story		.2965	.1235	34
MCS Group		.1374	.0648	181
Unducted		.1300	.0576	121
Single Story		.1441	.0563	39
Split Level		.1232	.0425	32
Double Story		.1234	.0655	50
Ducted		.1524	.0755	60
Single Story		.1554	.0897	27
Split Level		.1360	.0375	6
Double Story		.1531	.0674	27

Total Cases = 457
Missing Cases = 24 OR 5.3 PCT.

Control Unducted
t-test for: SLA

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	70	.2601	.120	.014
Crawl Space	89	.3765	.187	.020

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
2.46	.000	-4.52	157	.000	-4.76	151.06	.000

t-test for: ACH

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	70	.4688	.204	.024
Crawl Space	89	.5538	.244	.026

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.44	.118	-2.34	157	.020	-2.39	156.43	.018

t-test for: ACH50

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	68	6.2131	2.440	.296
Crawl Space	89	8.2694	2.853	.302

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.37	.182	-4.76	155	.000	-4.86	152.98	.000

Control Ducted

t-test for: SLA

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	50	.3448	.127	.018
Crawl Space	58	.4431	.164	.021

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.66	.071	-3.45	106	.001	-3.51	104.91	.001

t-test for: ACH

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	50	.5557	.206	.029
Crawl Space	58	.6354	.283	.037

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.88	.026	-1.65	106	.102	-1.69	103.32	.094

t-test for: ACH50

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	46	7.8701	2.723	.402
Crawl Space	54	9.4350	2.905	.395

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.14	.660	-2.76	98	.007	-2.78	97.08	.007

Control Unducted
t-test for: NK

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	68	.1682	.066	.008
Crawl Space	82	.2295	.070	.008

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.15	.567	-5.48	148	.000	-5.51	145.88	.000

Control Ducted
t-test for: NK

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	47	.2564	.108	.016
Crawl Space	45	.3009	.100	.015

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.15	.634	-2.05	90	.043	-2.05	89.93	.043

MCS Unducted

t-test for: SLA

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	66	.1415	.098	.012
Crawl Space	58	.1586	.117	.015

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.45	.149	-.89	122	.377	-.88	111.26	.383

t-test for: ACH

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	66	.2537	.170	.021
Crawl Space	58	.2369	.174	.023

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.05	.837	.54	122	.588	.54	119.10	.589

t-test for: ACH50

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	66	3.2023	1.997	.246
Crawl Space	58	3.6568	2.240	.294

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.26	.370	-1.19	122	.235	-1.19	115.18	.238

MCS Ducted

t-test for: SLA

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	43	.1639	.111	.017
Crawl Space	35	.2040	.110	.019

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.00	.999	-1.59	76	.115	-1.59	72.88	.115

t-test for: ACH

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	43	.2539	.174	.027
Crawl Space	35	.2982	.183	.031

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.11	.752	-1.09	76	.279	-1.08	71.24	.282

t-test for: ACH50

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	42	3.2306	1.822	.281
Crawl Space	35	4.4052	2.432	.411

		Pooled Variance Estimate			Separate Variance Estimate		
F Value	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.	t Value	Degrees of Freedom	2-Tail Prob.
1.78	.078	-2.42	75	.018	-2.36	62.01	.022

MCS Unducted
t-test for: NK

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	62	.1120	.055	.007
Crawl Space	54	.1525	.056	.008

F Value	2-Tail Prob.	Pooled Variance Estimate: t Value	Pooled Variance Estimate: Degrees of Freedom	Pooled Variance Estimate: 2-Tail Prob.	Separate Variance Estimate: t Value	Separate Variance Estimate: Degrees of Freedom	Separate Variance Estimate: 2-Tail Prob.
1.01	.962	-3.93	114	.000	-3.93	111.65	.000

MCS Ducted
t-test for: NK

	Number of Cases	Mean	Standard Deviation	Standard Error
Basement	33	.1229	.047	.008
Crawl Space	24	.1879	.092	.019

F Value	2-Tail Prob.	Pooled Variance Estimate: t Value	Pooled Variance Estimate: Degrees of Freedom	Pooled Variance Estimate: 2-Tail Prob.	Separate Variance Estimate: t Value	Separate Variance Estimate: Degrees of Freedom	Separate Variance Estimate: 2-Tail Prob.
3.86	.001	-3.48	55	.001	-3.16	31.68	.003

APPENDIX C
Monitoring Analysis Method

The methodology calls for comparing the slopes of two regressions using a t-test to examine significance. The method assumes homogeneous variance. (Reference: Kleinbaum, D. G. and Kupper, L. L., Applied Regression Analysis and Other Multivariable Methods, Duxbury Press, University of North Carolina, 1978, pp. 100-105.) For the two regressions, indicated as (1) and (2), the pooled estimate of residual mean standard error is:

$$s^2 P\ Y/X = \frac{SSE(1) + SSE(2)}{N1 + N2}$$

where SSE(1) = standard error of the estimate (1)
SSE(2) = standard error of the estimate (2)
N1 = number of observations (1)
N2 = number of observations (2)

The estimate of the standard deviation of the estimated difference between slopes is:

$$s^2 \text{ pooled} = s^2 P\ Y/X \quad \frac{1}{(N1-1)*s1^2} + \frac{1}{(N2-1)*s2^2}$$

where s1 = standard error of the regression slope B(1)
s2 = standard error of the regression slope B(2)

The t-test is then calculated from the pool estimate for the standard deviation of the estimated difference in slopes:

$$t = \frac{B(1) - B(2)}{s \text{ pooled}}$$

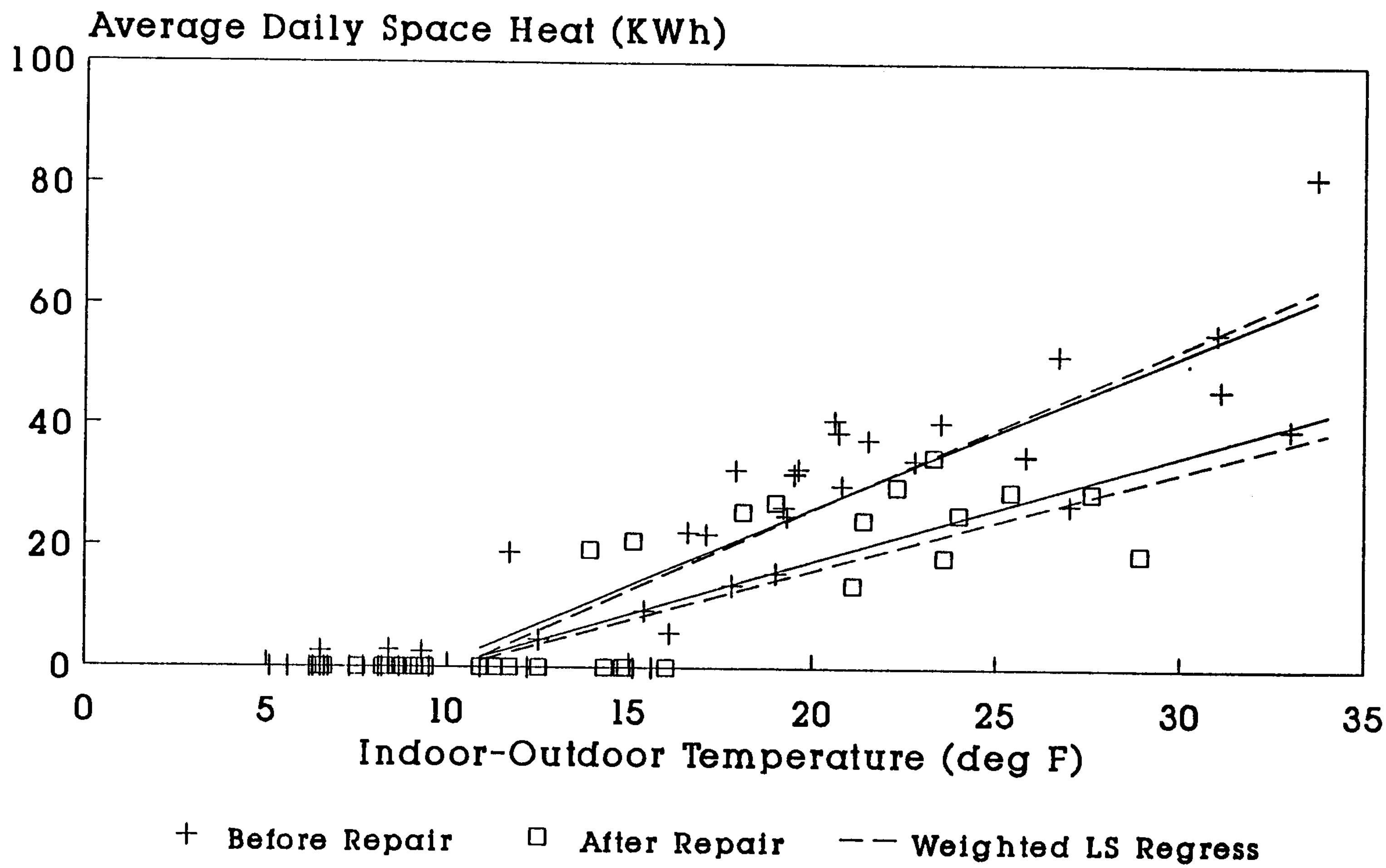
The t value is tested against the critical value of t for (N1 + N2 - 4) at the (1-a/2) significance level for a one-tailed test. This is the case where savings are expected. For the control sites, where savings are not expected, the critical value is simply the 1-a level.

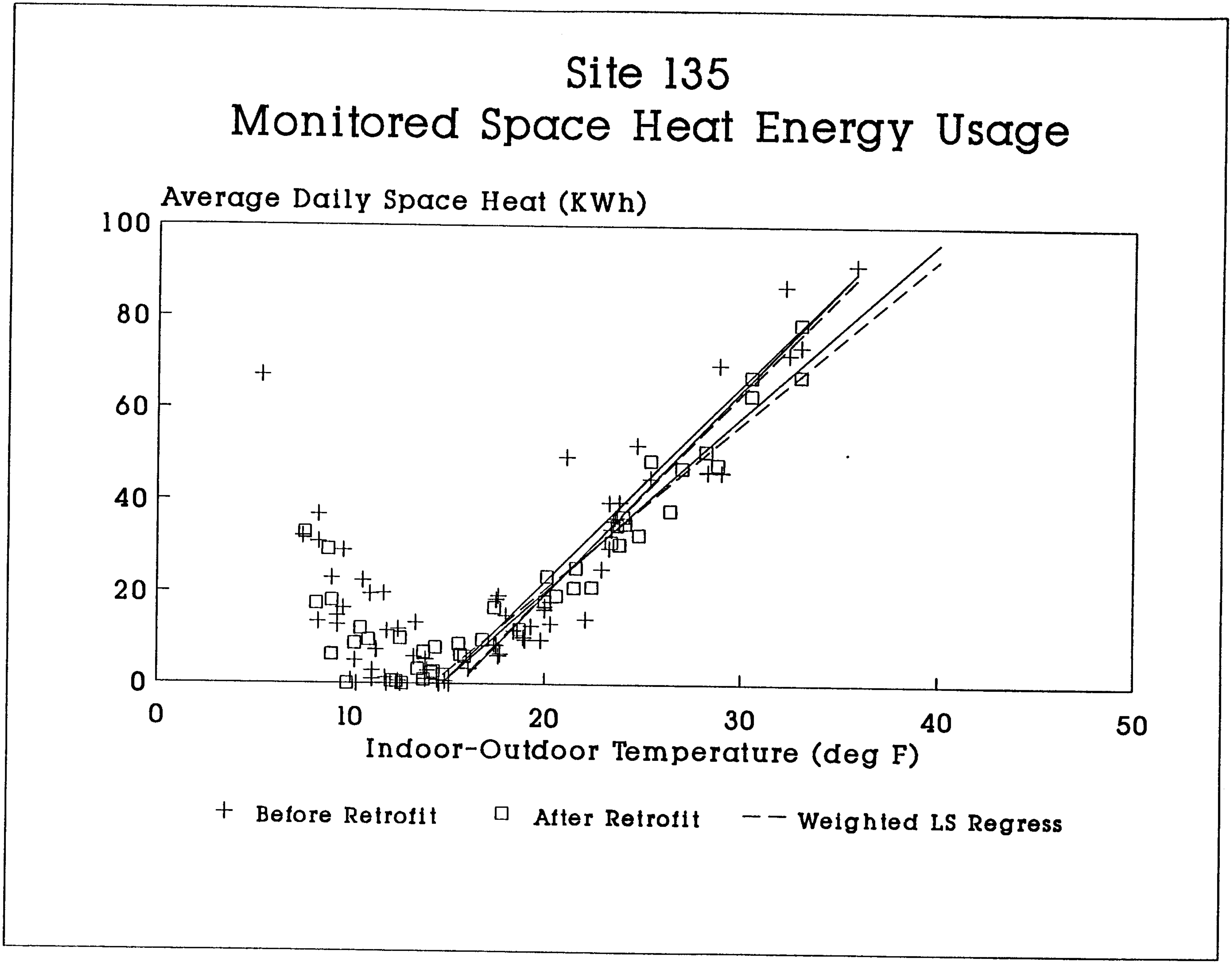
Ordinary Least Squares

site	Before retro n	slope	sesl	After retro n	slope	sesl	Slope s2p,y/x	s2 pool	Null tes t sl
Experimental Sites									
610	21	1.79765	0.05765	30	1.29004	0.08586	0.108218	2.134267	0.347460
613	80	5.40652	0.10399	45	5.53477	0.12089	0.092476	0.252060	-0.25544
625	37	4.29288	0.23011	25	4.63244	0.24262	0.180532	0.222495	-0.71987
655	29	4.98713	0.1837	5	4.20933	0.62896	0.340007	0.574715	1.025985
664	37	5.25008	0.26727	28	5.76792	0.301	0.265008	0.211385	-1.12631
677	36	2.25083	0.12869	25	2.54738	0.14345	0.163418	0.612826	-0.37881
695	38	4.00357	0.21887	41	2.90042	0.24055	0.236387	0.235497	2.273218
710	50	4.8552	0.19971	35	4.6736	0.19517	0.190042	0.243980	0.367652
711	11	0.0696	0.20539	23	0.04753	0.09358	0.237396	1.794960	0.016473
735	56	2.36583	0.13853	19	2.60043	0.15178	0.139844	0.469736	-0.34229
745	40	4.14637	0.15571	21	4.30044	0.17576	0.182879	0.489407	-0.22023
754	21	5.83778	0.81367	19	4.35698	0.48185	0.662296	0.208491	3.243040
135	37	4.45934	0.25183	28	3.80066	0.16707	0.191660	0.338263	1.132522
Control Sites									
134C	32	2.54943	0.26548	21	1.76833	0.34557	0.347148	0.304237	1.416121
183C	12	2.38898	0.50035	5	0.91961	0.45895	0.743237	1.152028	1.368987
217C	55	2.20938	0.12023	25	0.56297	0.08553	0.098799	0.689309	1.983036
705C	30	0.38704	0.03153	33	0.29507	0.02158	0.016608	1.690615	0.070733
723C	31	2.97868	0.1738	3	2.81765	1.76946	0.792968	1.001686	0.160894
770C	35	4.38033	0.17198	23	4.13432	0.30375	0.194779	0.289650	0.457104
170C	26	2.71256	0.20974	15	3.88301	0.43514	0.343290	0.441648	-1.76122

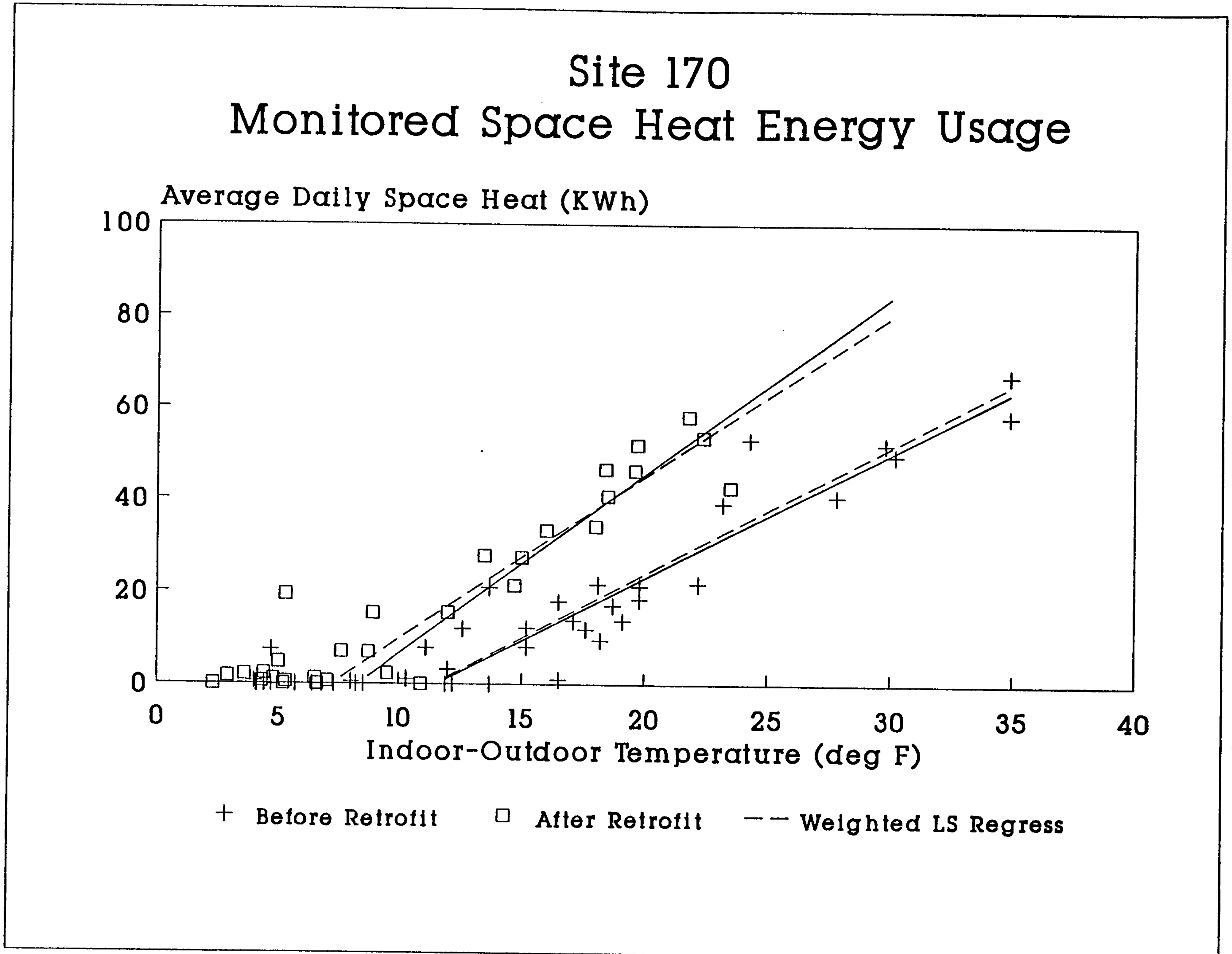
APPENDIX D
Pre- and Post-retrofit Regression Plots

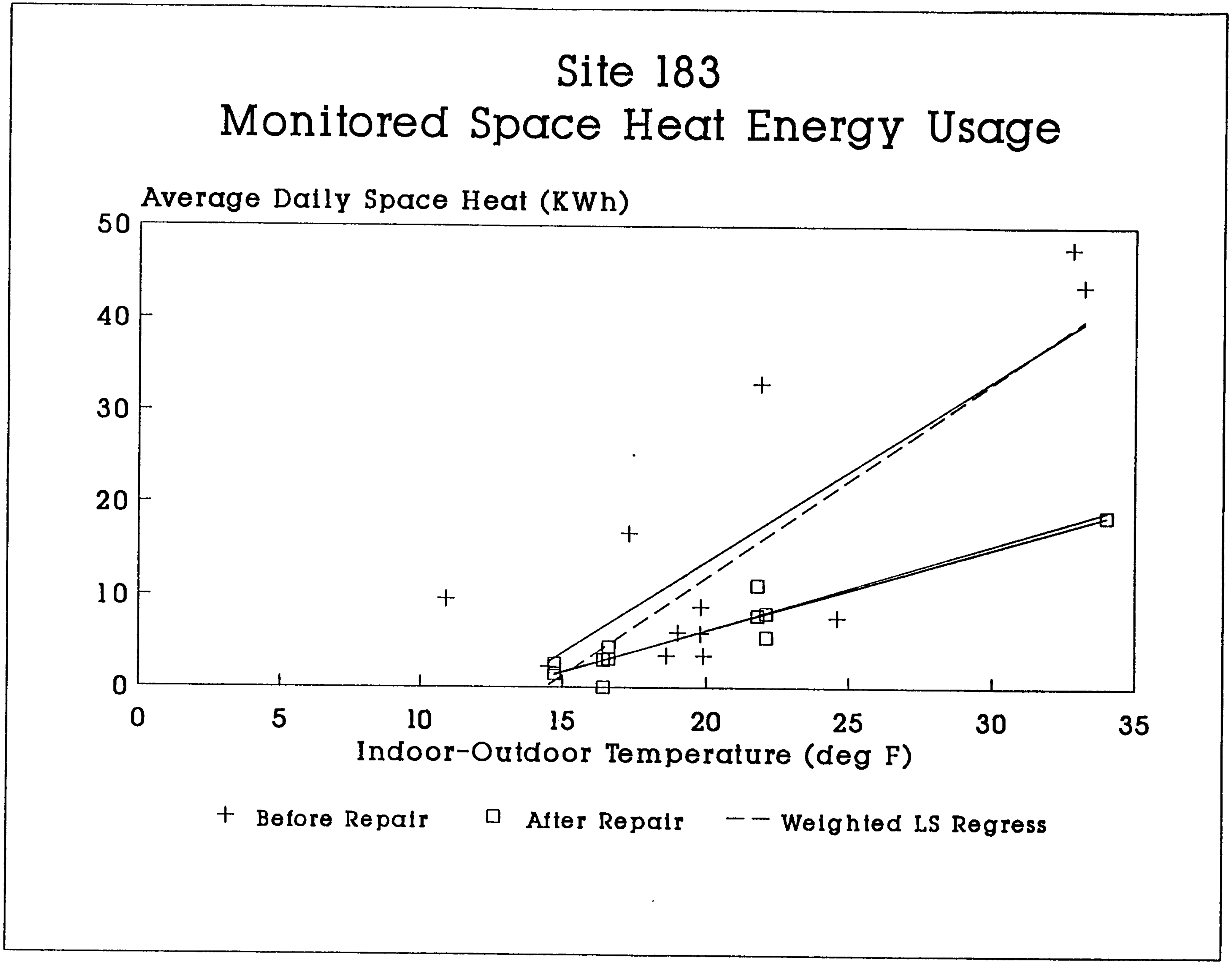
Site 134
Monitored Space Heat Energy Usage





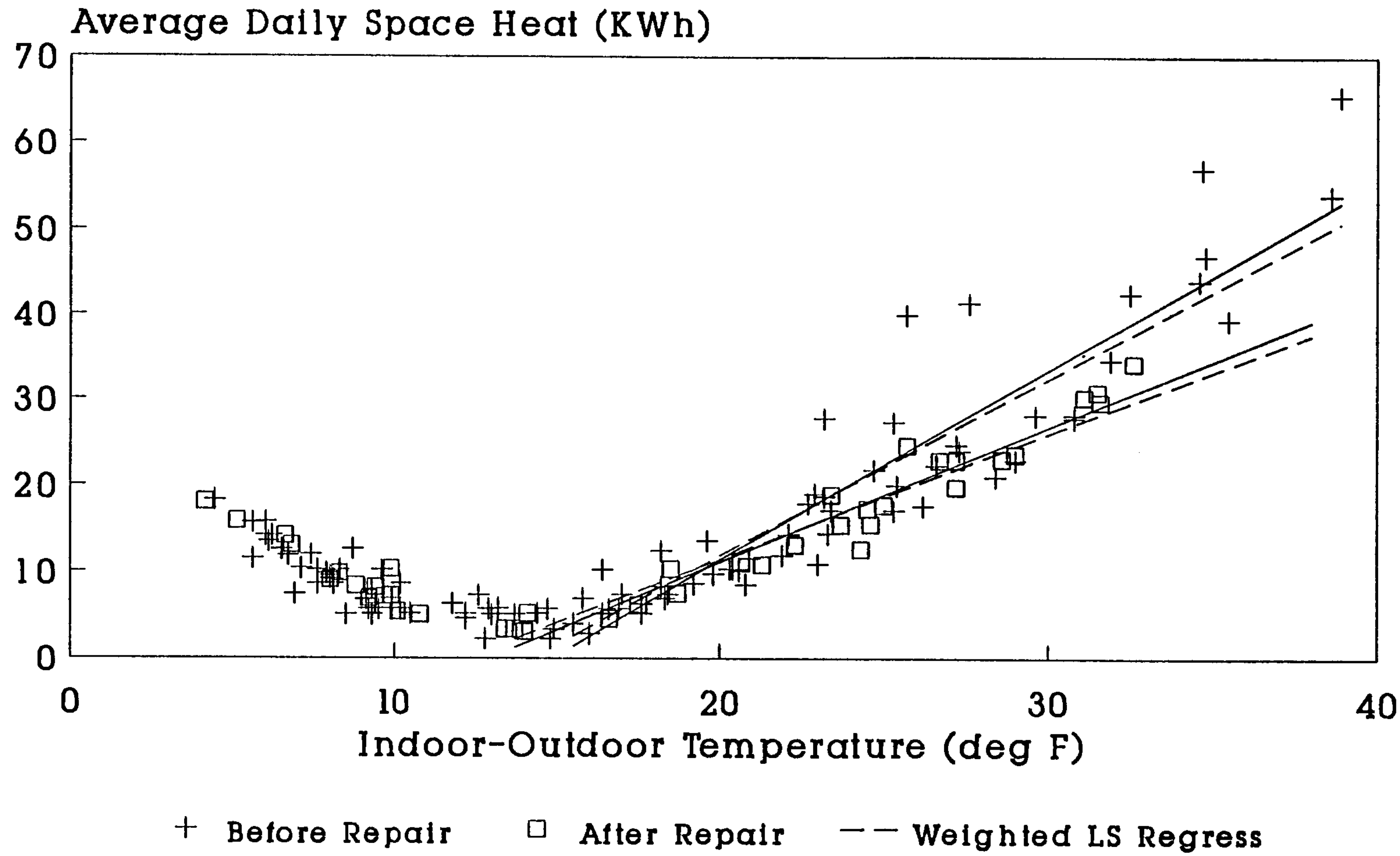
Site 135
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
100
80
60
40
20
0
0
10
20
30
40
50
Indoor-Outdoor Temperature (deg F)
Before Retrofit
After Retrofit
Weighted LS Regress

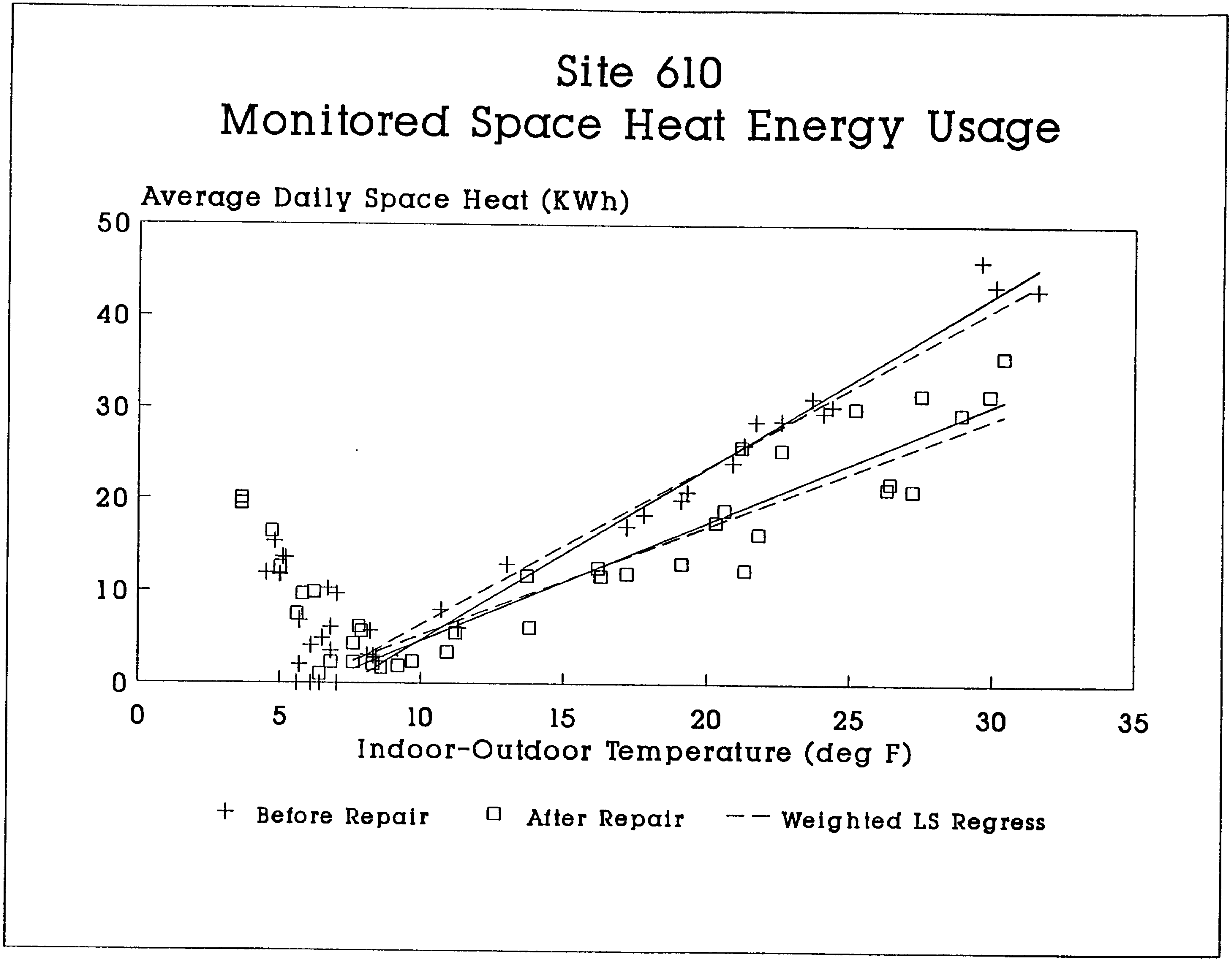

Site 170
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
100
80
60
40
20
0
0
5
10
15
20
25
30
35
40
Indoor-Outdoor Temperature (deg F)
Before Retrofit
After Retrofit
Weighted LS Regress

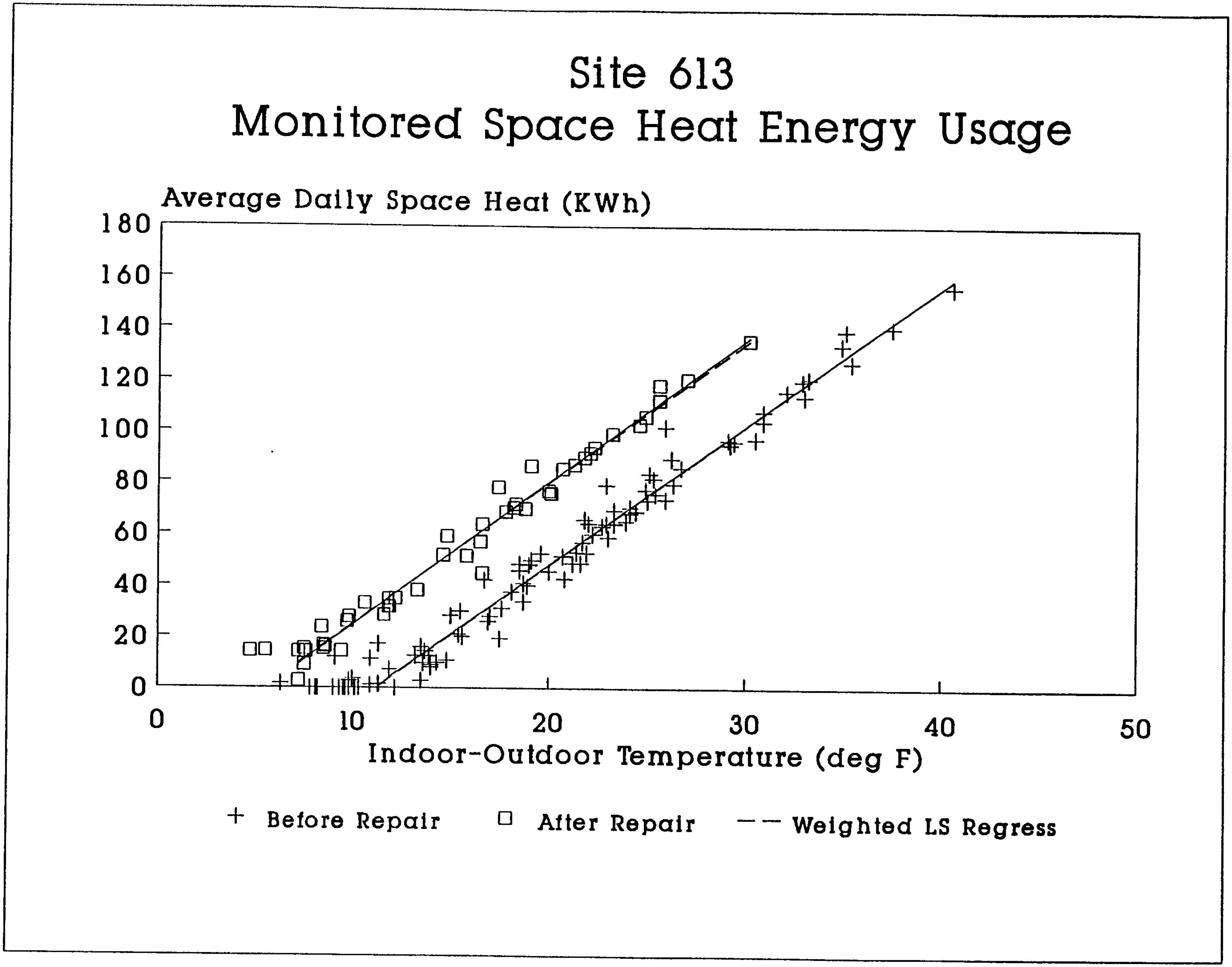


Site 183
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
50
40
30
20
10
0
0
5
10
15
20
25
30
35
Indoor-Outdoor Temperature (deg F)
+ Before Repair
□ After Repair
— — Weighted LS Regress

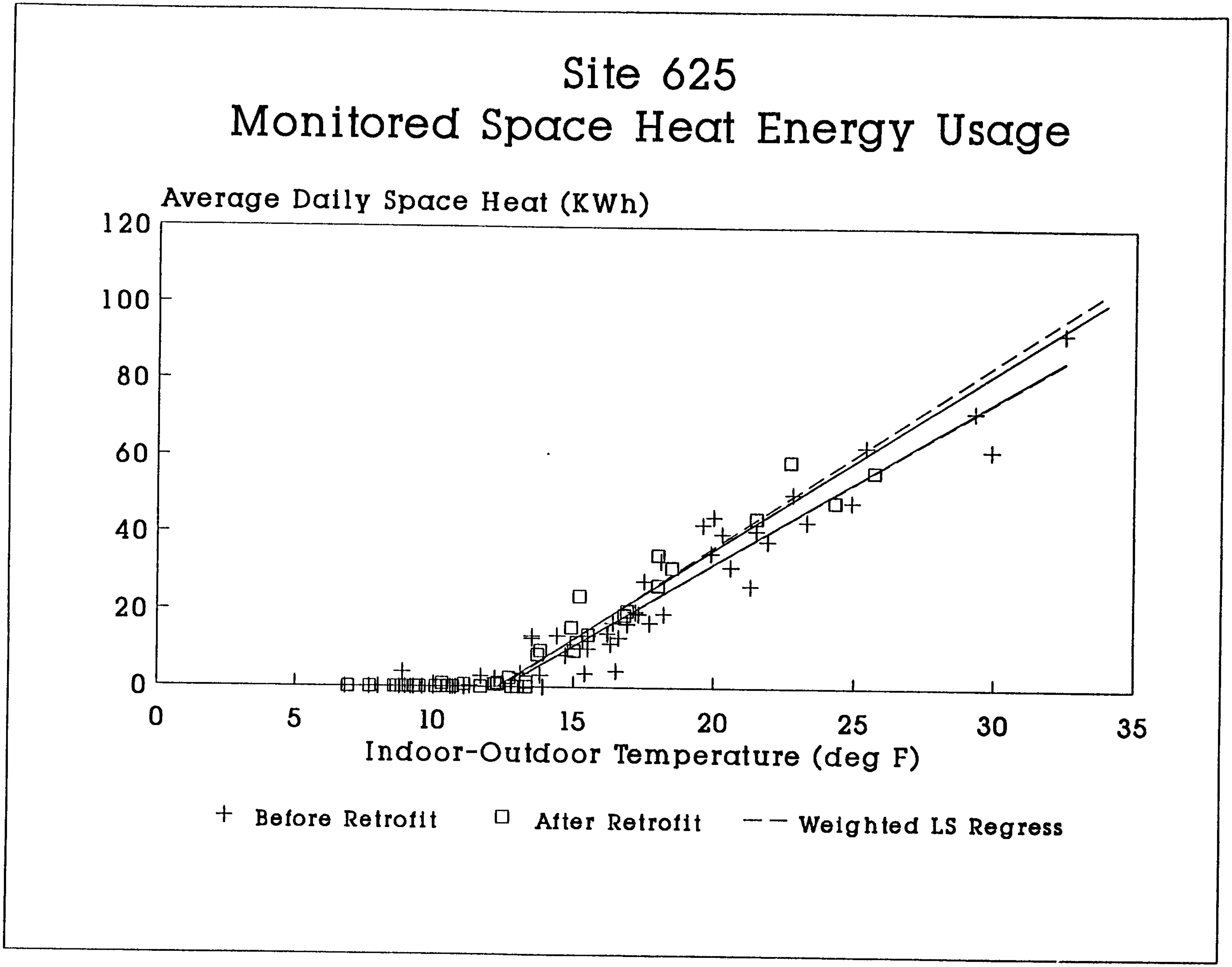
Site 217
Monitored Space Heat Energy Usage



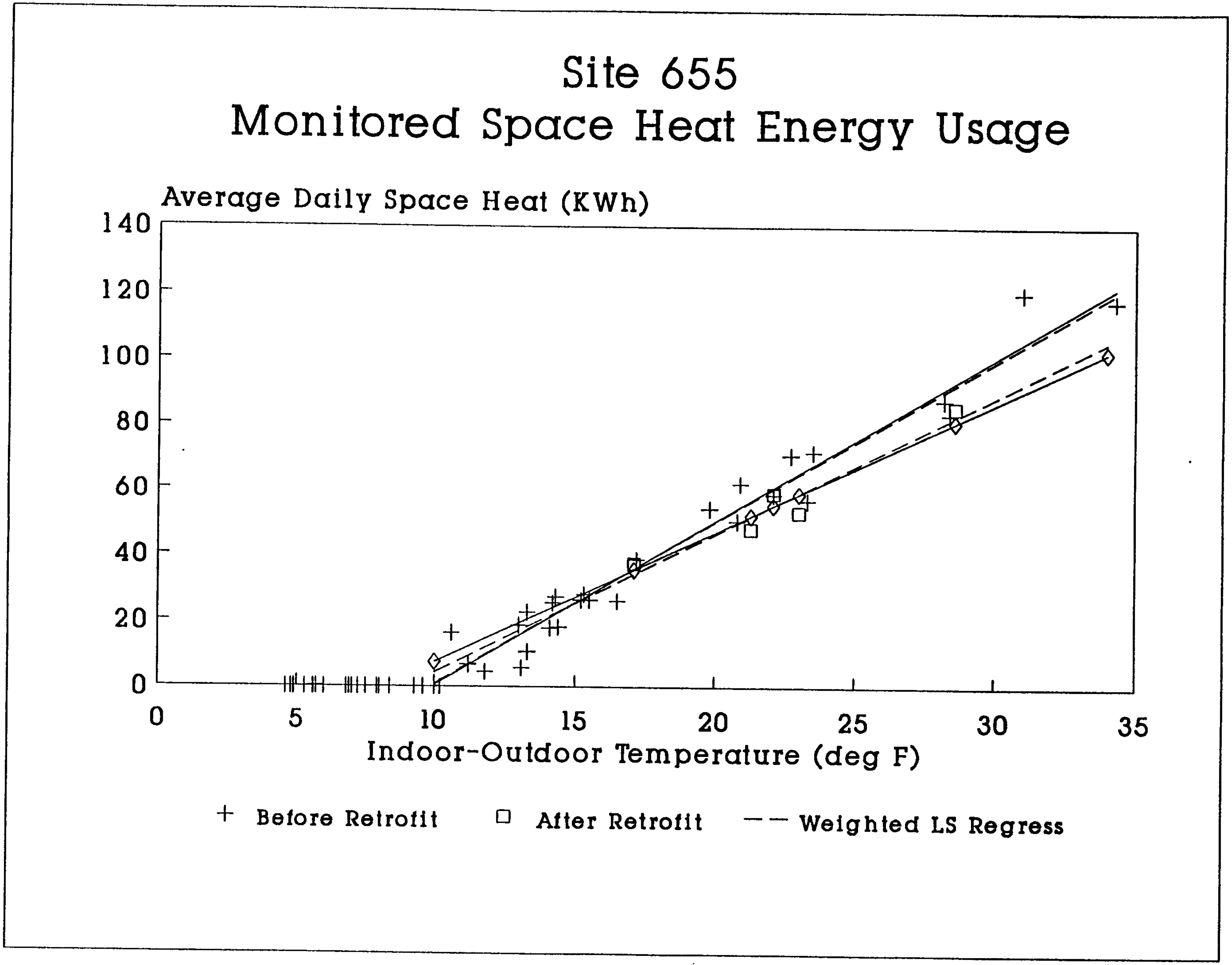

Site 610
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
50
40
30
20
10
0
0
5
10
15
20
25
30
35
Indoor-Outdoor Temperature (deg F)
+ Before Repair
□ After Repair
— — Weighted LS Regress



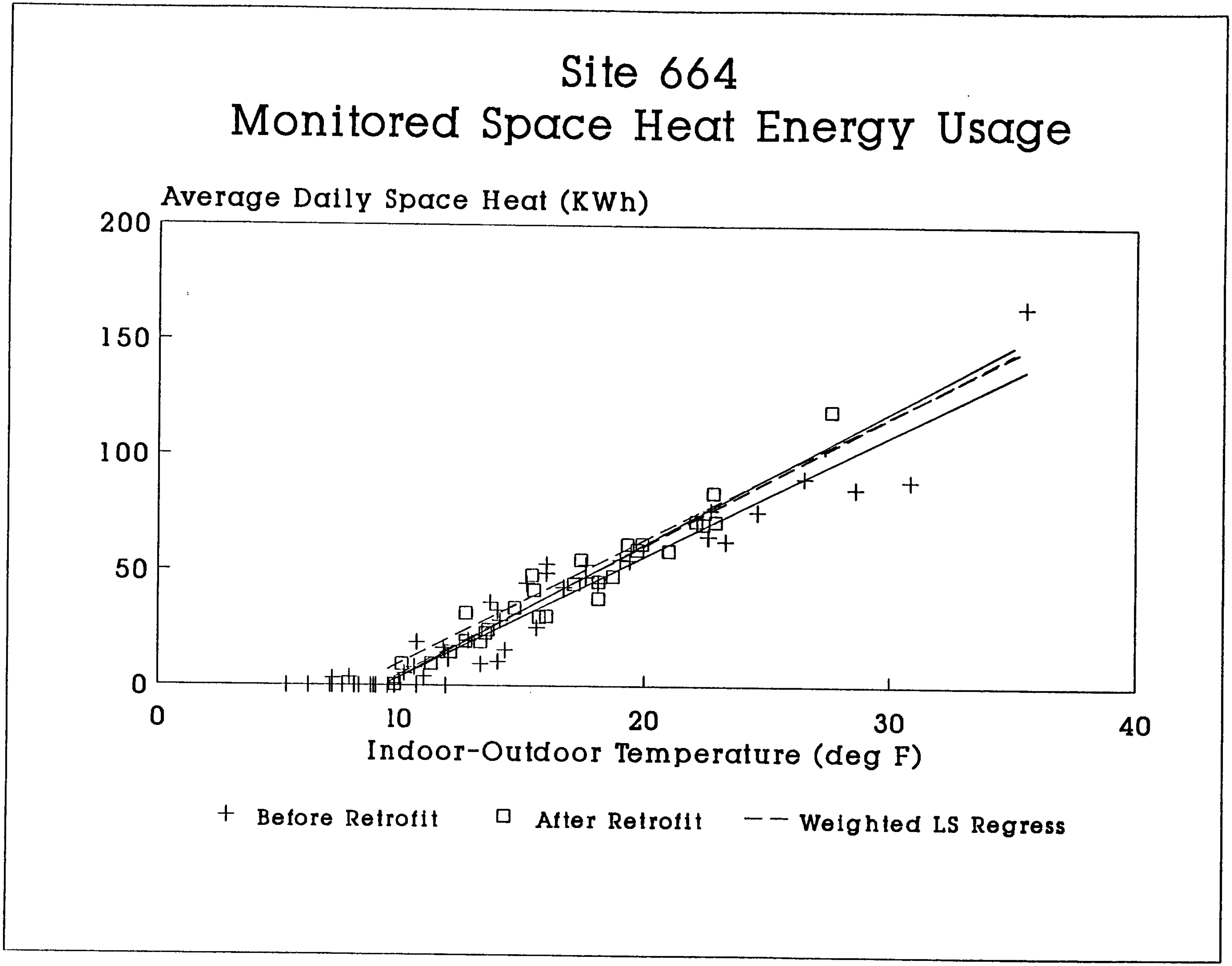
Site 613
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
180
160
140
120
100
80
60
40
20
0
0
10
20
30
40
50
Indoor-Outdoor Temperature (deg F)
Before Repair
After Repair
Weighted LS Regress



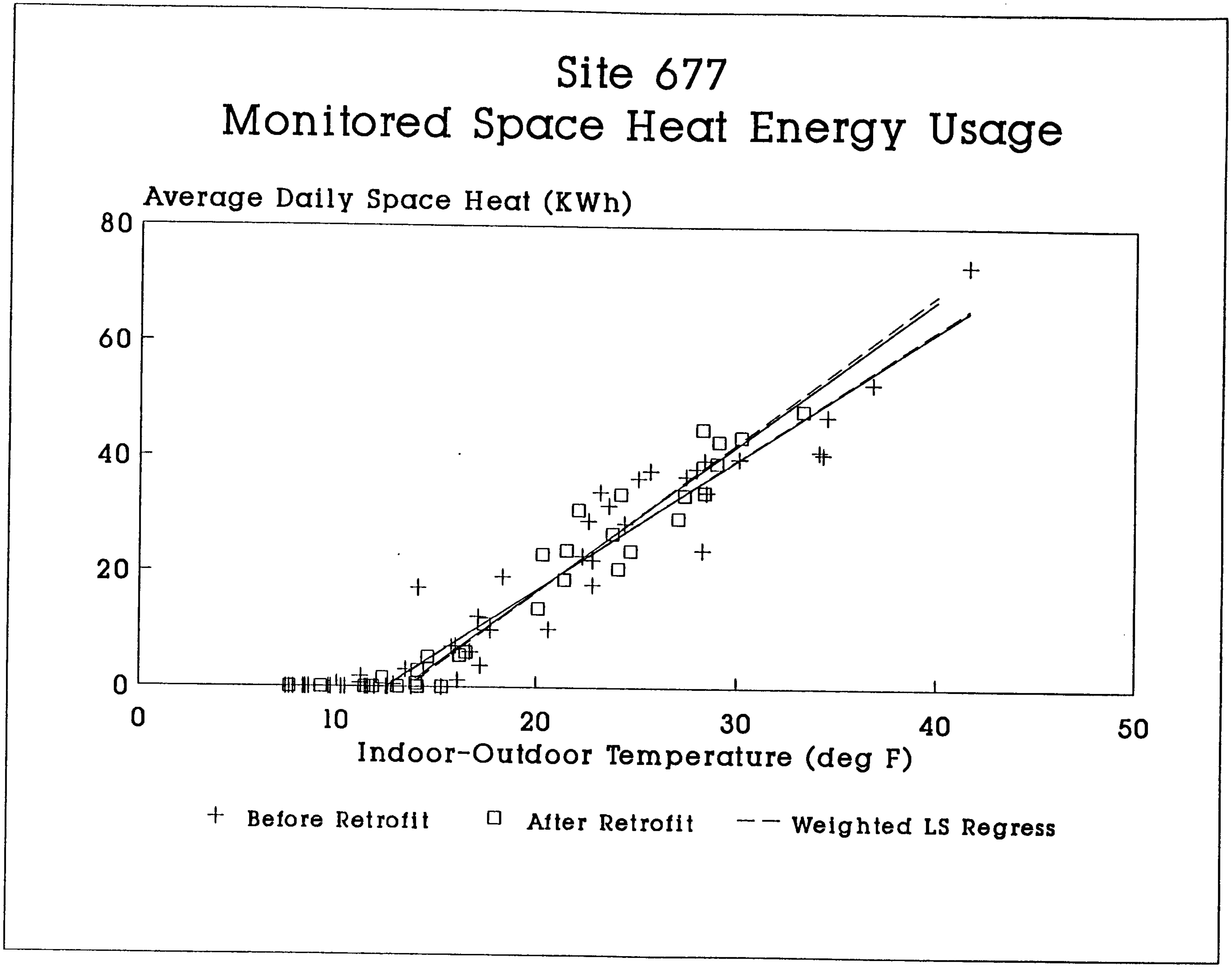
Site 625
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
Indoor-Outdoor Temperature (deg F)
Before Retrofit
After Retrofit
Weighted LS Regress

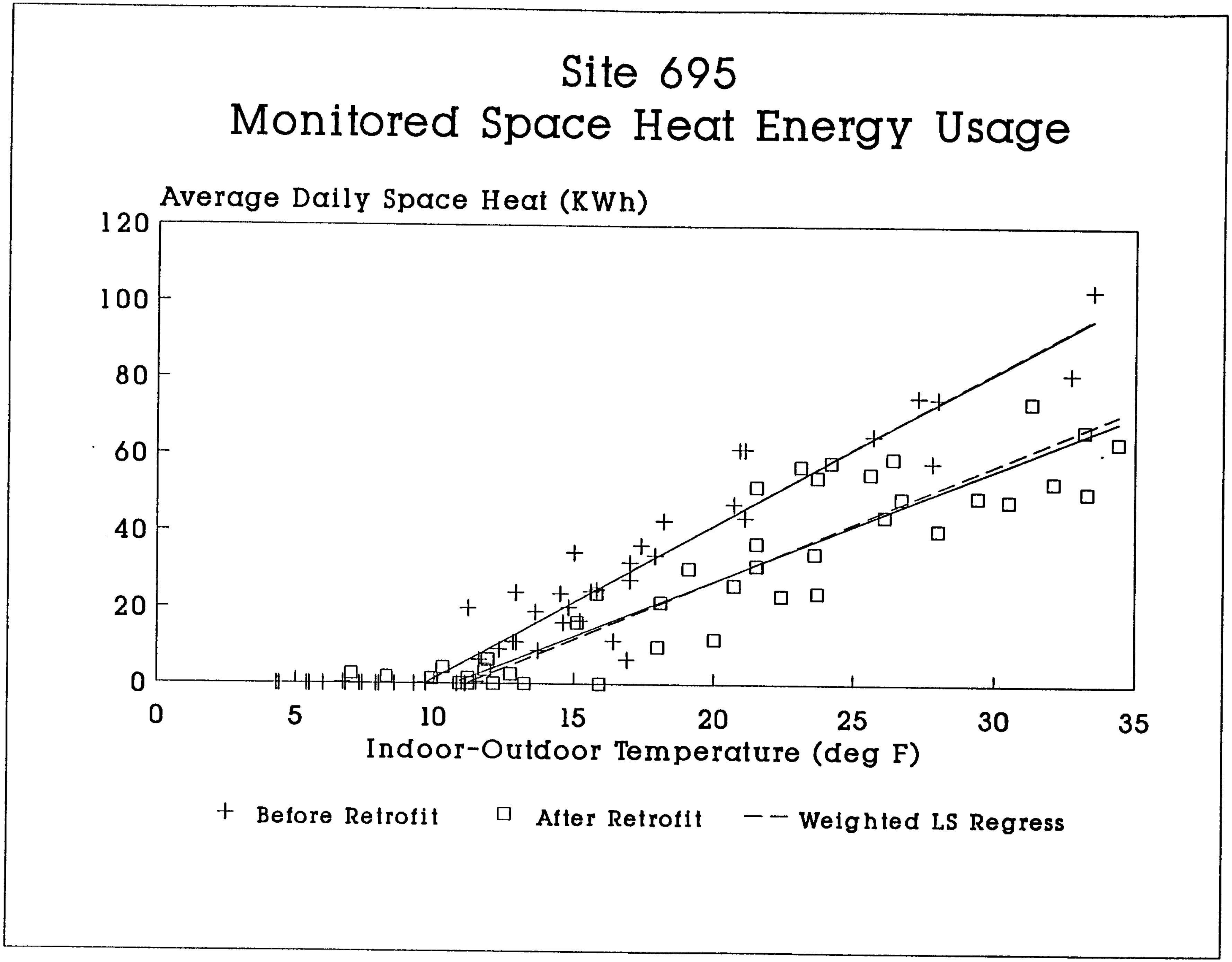


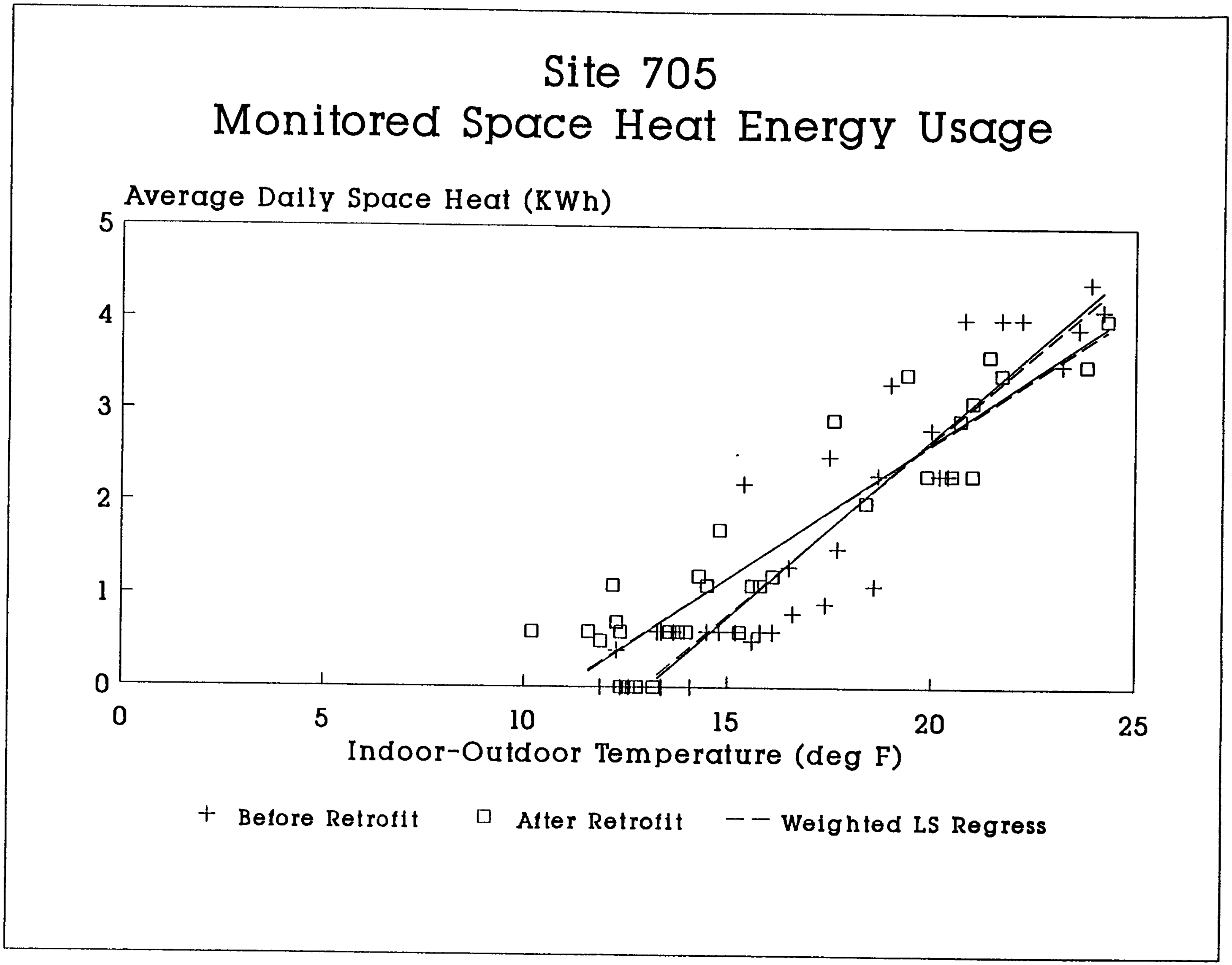
Site 655
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
Indoor-Outdoor Temperature (deg F)
Before Retrofit
After Retrofit
Weighted LS Regress



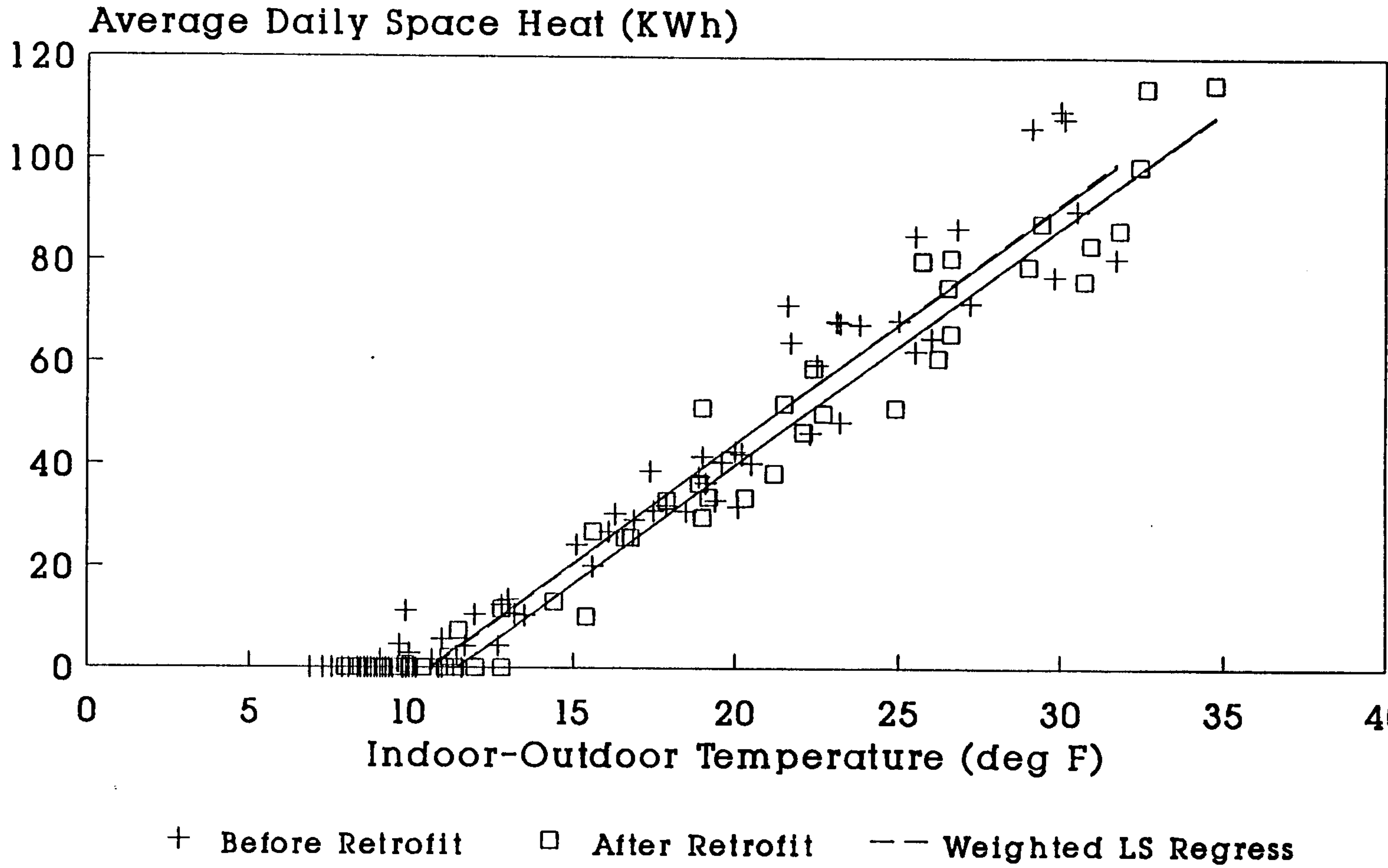
Site 664
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
200
150
100
50
0
0
10
20
30
40
Indoor-Outdoor Temperature (deg F)
Before Retrofit
After Retrofit
Weighted LS Regress

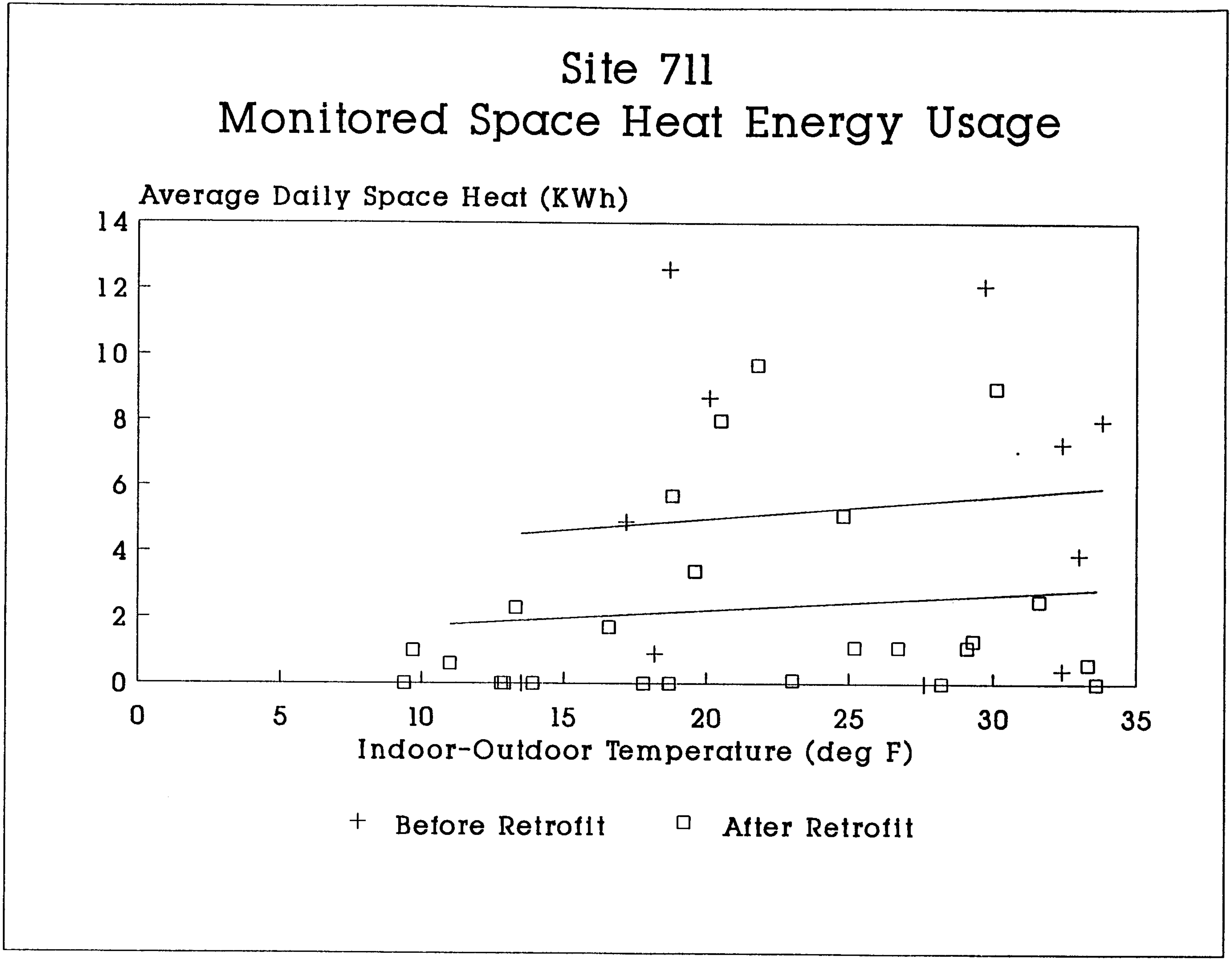

Site 677
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
80
60
40
20
0
0
10
20
30
40
50
Indoor-Outdoor Temperature (deg F)
Before Retrofit
After Retrofit
Weighted LS Regress

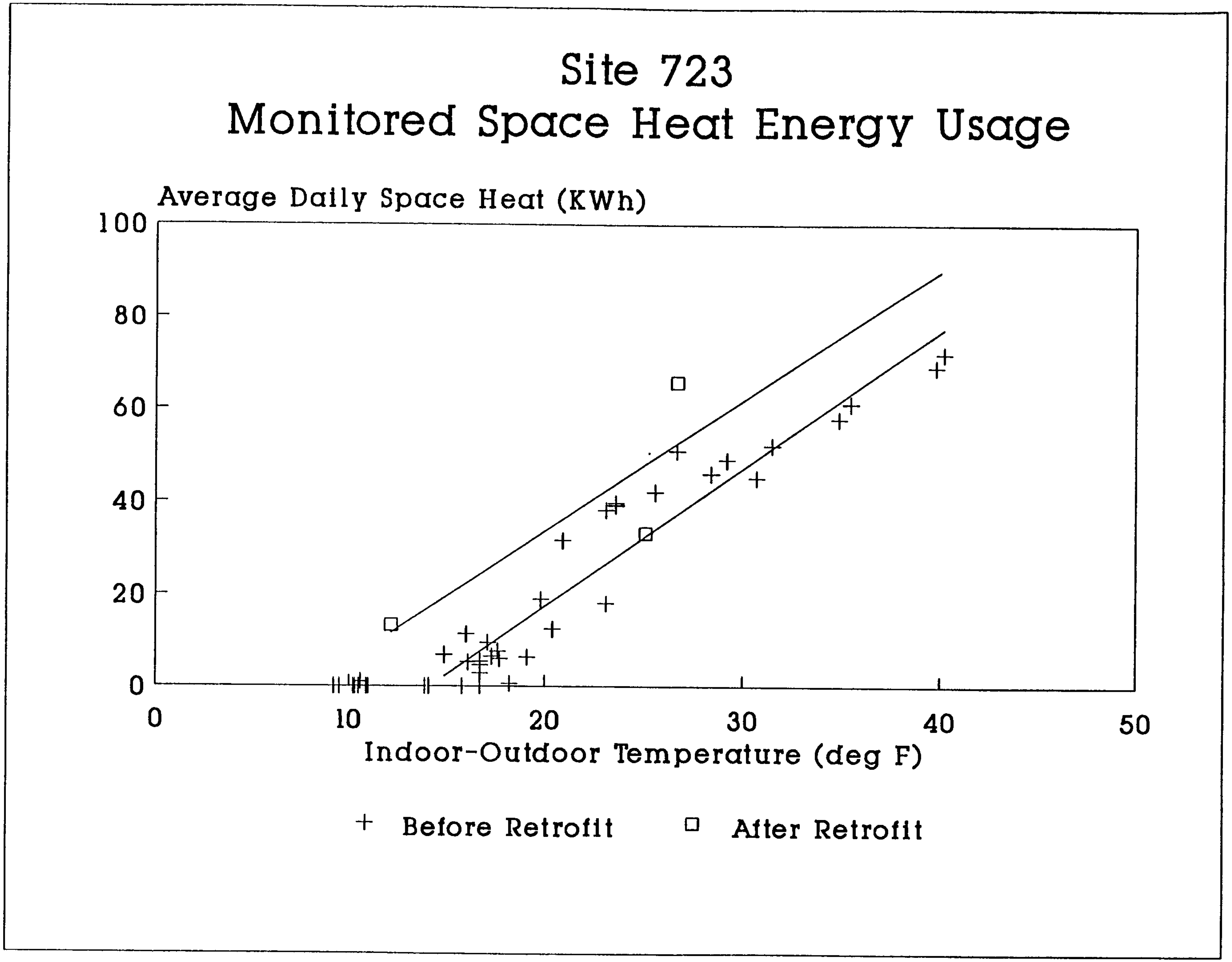

Site 695
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
120
100
80
60
40
20
0
0
5
10
15
20
25
30
35
Indoor-Outdoor Temperature (deg F)
+ Before Retrofit
□ After Retrofit
— — Weighted LS Regress

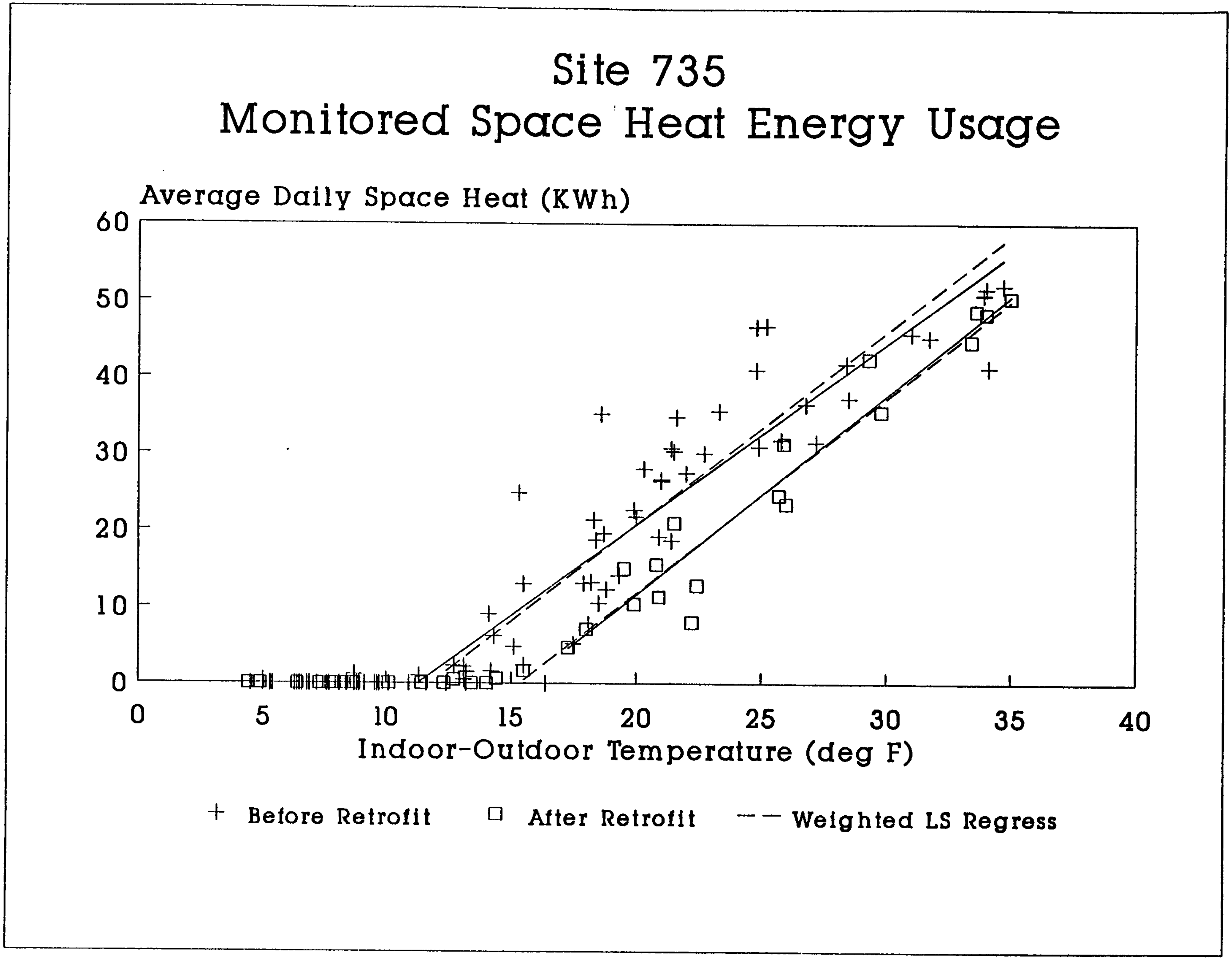

Site 705
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
0
1
2
3
4
5
0
5
10
15
20
25
Indoor-Outdoor Temperature (deg F)
Before Retrofit
After Retrofit
Weighted LS Regress

Site 710
Monitored Space Heating Usage

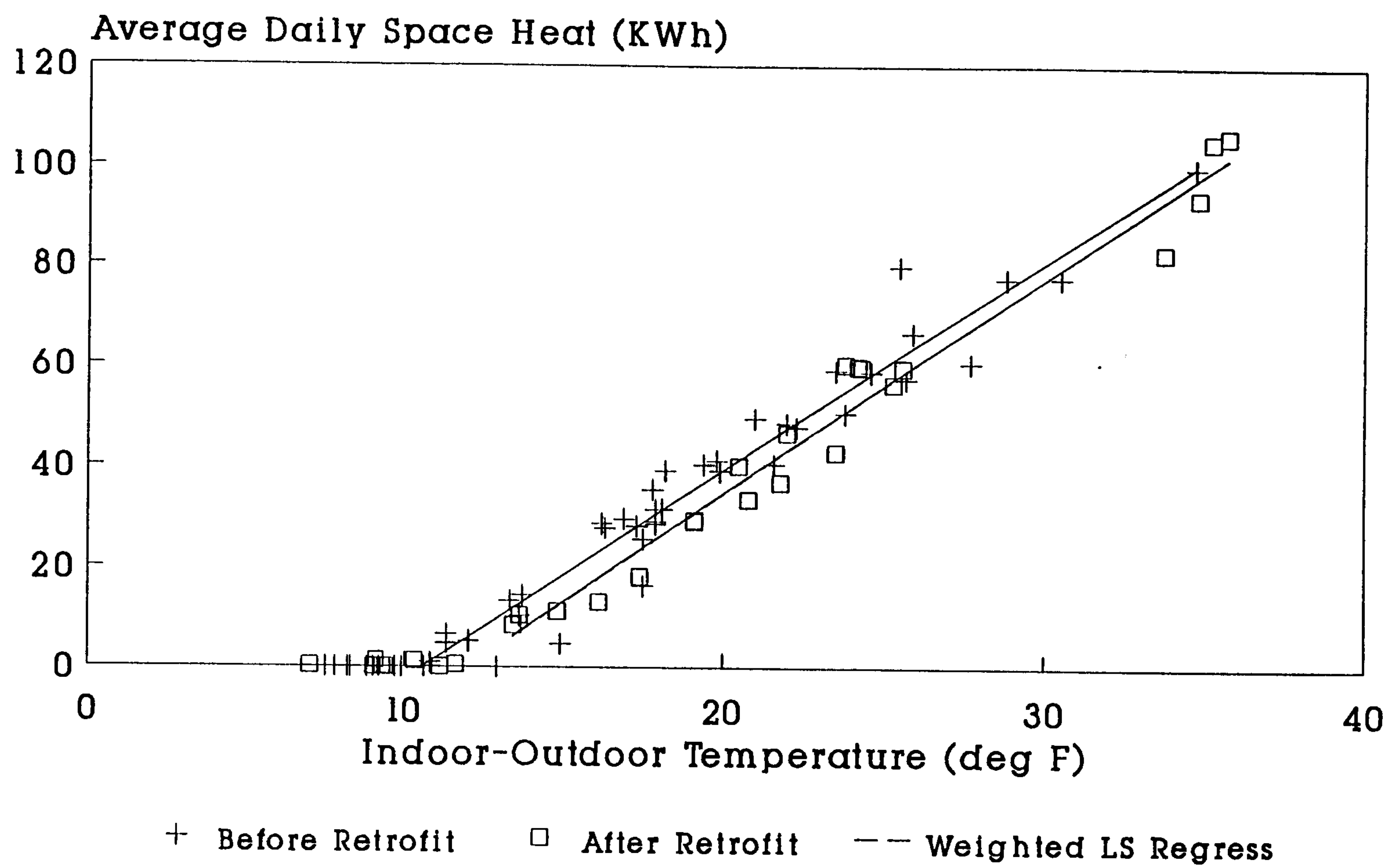


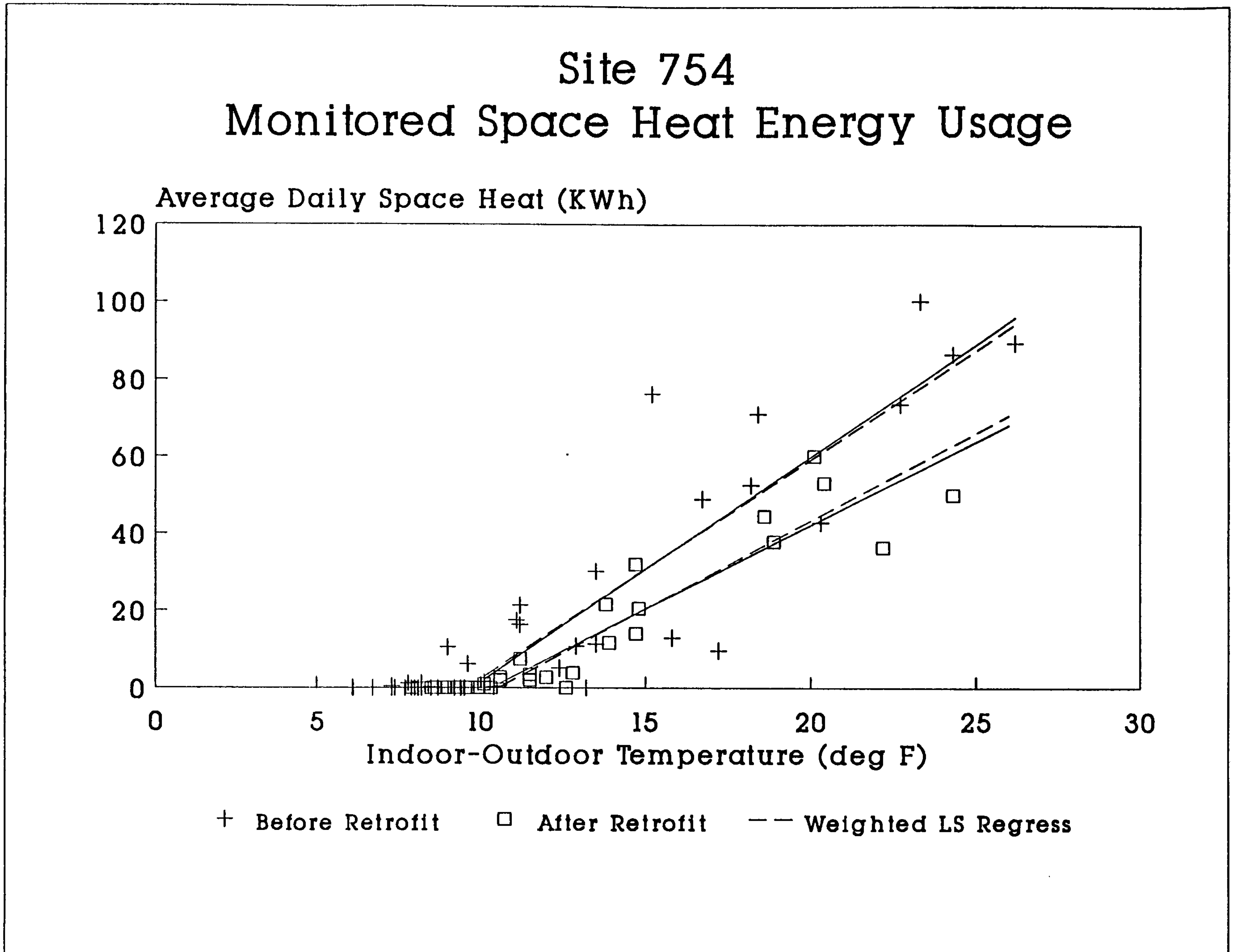

Site 711
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
0
2
4
6
8
10
12
14
0
5
10
15
20
25
30
35
Indoor-Outdoor Temperature (deg F)
+ Before Retrofit
□ After Retrofit


Site 723
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
100
80
60
40
20
0
0
10
20
30
40
50
Indoor-Outdoor Temperature (deg F)
Before Retrofit
After Retrofit

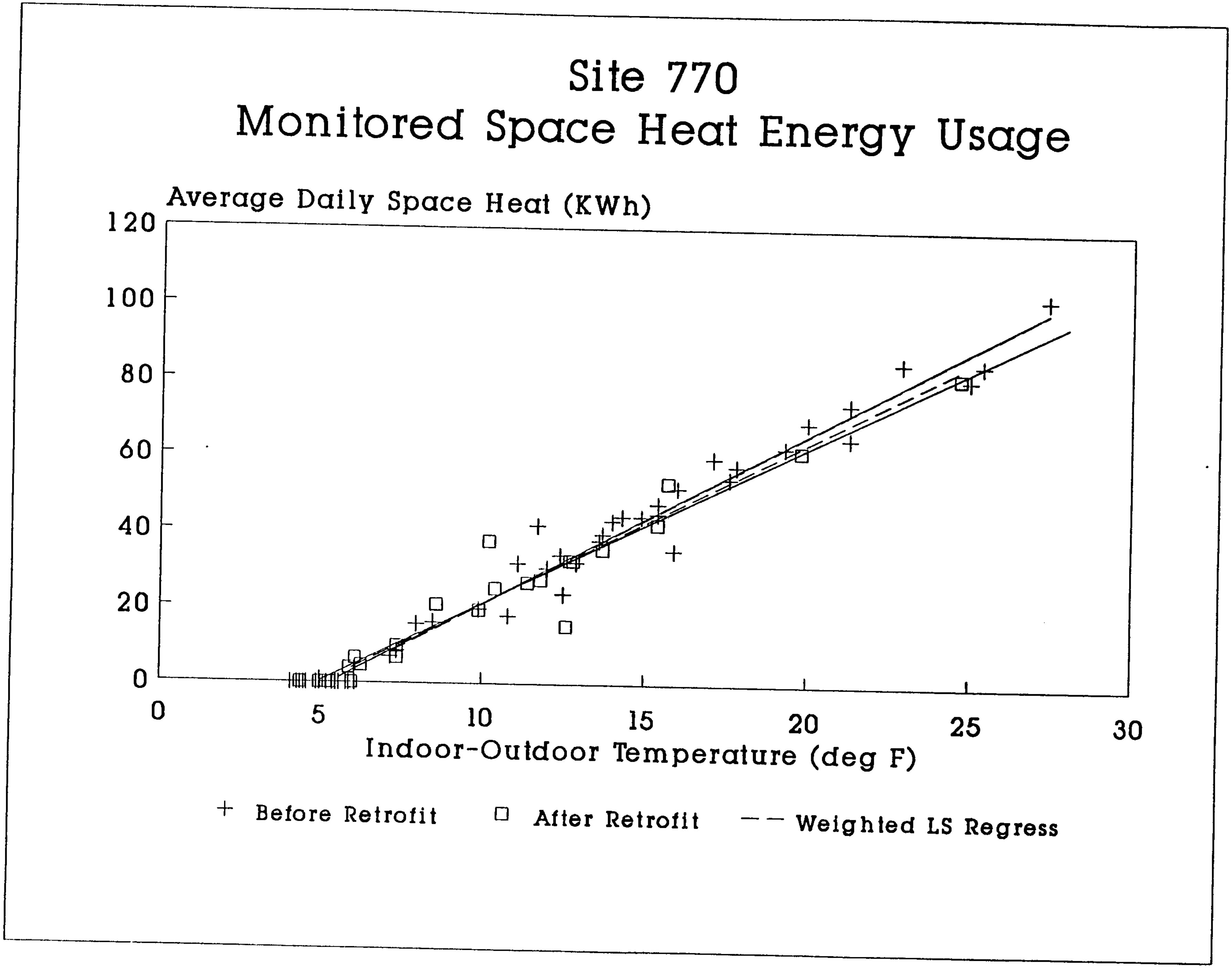

Site 735
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
Indoor-Outdoor Temperature (deg F)
Before Retrofit
After Retrofit
Weighted LS Regress

Site 745
Monitored Space Heat Energy Usage





Site 754
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Indoor-Outdoor Temperature (deg F)
Before Retrofit
After Retrofit
Weighted LS Regress



Site 770
Monitored Space Heat Energy Usage
Average Daily Space Heat (KWh)
120
100
80
60
40
20
0
0
5
10
15
20
25
30
Indoor-Outdoor Temperature (deg F)
+ Before Retrofit
□ After Retrofit
— — Weighted LS Regress