92.105C

Prepared by:
Proctor Engineering Group, Ltd.
San Rafael, CA 94901
(415) 451-2480

Blower Door Guided Weatherization Test Project

Prepared for:
Southern California Edison
Customer Assistance Programs
300 N. Lone Hill Avenue
San Dimas, CA 91773

Final Report
December 19, 1994

Contributors:
Tom Downey
John Proctor, P.E

Creators of CheckMe!®

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

Executive Summary

Southern California Edison (Edison) has been investigating the cost effectiveness of Blower Door Guided Weatherization (BGW). This has involved several steps:

- A comprehensive literature search for previous studies examining cost effectiveness of low income customer Blower Door Guided Weatherization programs.
- The Southern California Blower Door Breakpoint Study.
- The Blower Door Guided Weatherization Field Test.

The primary purpose of the comprehensive literature search was to help define and clarify the primary research questions and to summarize the results of previous Blower Door Guided Weatherization studies.

The Southern California Blower Door Breakpoint Study was conducted to determine the LIRA customer sample selection that the field study would target (Customers that represent a significant portion of the all-electric LIRA customer housing stock with sufficient heating or cooling use to make BGW potentially cost effective). The breakpoint study concluded that approximately 13% of Edison's all electric low income customers have sufficient heating and cooling use to consider BGW[1]. That target population was selected for a field test.

The field test was designed to compare pre-retrofit and post-retrofit energy usage of targeted customers that received BGW with a comparison group of similar LIRA customers. In the first stage of the test careful measurements were completed on twenty homes. These measurements indicated that only 10% of the sample had sufficient air and duct sealing potential to warrant application of blower door guided weatherization. Based on the applicability to such a small population (on the order of 1.3%), the remainder of the field testing was canceled.

Based on field measurements it is concluded:

- The majority of high usage low income customers in this sample did not have excessive cooling or heating energy use due to building shell leakage.

---

[1]Based on an expected savings of 20% from building shell and duct sealing, an expected cost of $500 per home, and a targeted simple payback of 7 years or less. The cost effective ness of Blower Door Guided Weatherization with respect to any other criteria was not assessed.

- There is significant opportunity for energy savings and improved customer comfort in the high use homes tested. The predominate factors in high heating and/or cooling usage appear to be:
  - Ceiling cable heating systems. (25% of the sample)
  - Low operating efficiency (well below design efficiency) in half the air conditioners/heat pumps. (25% of the sample)
  - Duct leakage in half the homes with ducted systems. (20% of the sample)

The factors contributing to high seasonal energy use in these low income customers can be further investigated. Proctor Engineering Group suggests that Southern California Edison consider:

- Performing random blower door shell and duct leakage testing on a random sampling of high SEU Lira customers.
- Studying mitigation techniques applicable to houses with ceiling cable heat.
- A low income weatherization design that targets customers based on their billing data:
  - Screens customers for the presence of equipment potentially capable of causing the high use (ducts, air conditioners, heat pumps),
  - Applies field diagnostics,
  - And where possible applies corrective action.

I Introduction

Beginning in early 1992 Southern California Edison (Edison) committed to a study to determine the cost effectiveness of Blower Door Guided Weatherization (BGW). In Edison's 1991 GRC Decision, the CPUC would not authorize a program utilizing blower door technology to diagnose air leakage and guide repair of excessive air leakage in all-electric homes occupied by Low Income Rate Assistance (LIRA) customers. This decision was based on the fact that no evidence was provided during the rate hearings that showed these techniques were effective in weatherizing LIRA customer homes in Southern California. Edison consequently retained the services of Proctor Engineering Group (PEG) to perform research and analysis of the cost effectiveness of BGW[2]. The purpose was to allow informed program decisions about BGW based on previously completed research and field tests in their service territory.

BACKGROUND

Proctor Engineering Group performed several tasks in the course of examining the cost effectiveness of BGW for Edison. These tasks included:

- A comprehensive literature search for previous studies examining cost effectiveness of low income customer Blower Door Guided Weatherization programs.
- The Southern California Blower Door Breakpoint Study.
- The Blower Door Guided Weatherization Field Test.

The primary purpose of the comprehensive literature search was to help define and clarify the primary research questions and to summarize the results of previous Blower Door Guided Weatherization studies.

The Southern California Blower Door Breakpoint Study was conducted to determine the LIRA customer sample selection that the field study would target. Customers that represented a significant portion of the all-electric LIRA customer housing stock in Edison's territory were selected through this study for targeting. The results of the Southern California Blower Door Breakpoint Study can be

---

[2]Based on an expected savings of 20% from building shell and duct sealing, an expected cost of $500 per home, and a targeted simple payback of 7 years or less. The cost effectiveness of Blower Door Guided Weatherization with respect to any other criteria was not assessed.

found in the report "Southern California Edison Blower Door Breakpoint Study - Target Sample Selection" dated January 18, 1994.

The final phase of the project was the Blower Door Guided Weatherization Field Test. The field test was designed to include pre-/post- BGW retrofit measurement and evaluation of heating and cooling usage through long term monitoring. This report details the results of the field test.

OBJECTIVES

Prior to implementation of a Blower Door Guided Weatherization program Edison needed to know if BGW was a cost effective option for their all-electric LIRA customers. In the process of trying to answer this question several other questions surfaced that also needed to be addressed. The basic questions to be answered were:

- At what point does Blower Door Guided Weatherization become cost effective in Southern California?
- What is the cost of blower door guided weatherization when applied to the appropriate homes in Edison's service territory?
- What is the cooling and heating Seasonal Energy Usage (SEU) reduction from Blower Door Guided Weatherization?
- Do qualified LIRA households in Edison's service territory currently meet the recommended minimum ventilation guidelines as established by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)?
- Can billing data alone be used to predict which customers will realize adequate benefit from Blower Door Guided Weatherization?

II Methodology

The methodology for the Blower Door Guided Weatherization Field Test was developed through discussions with Edison and others over a multi-year process. The Field Test was designed to directly measure the heating and cooling energy savings attainable from properly applied BGW on all-electric high SEU LIRA housing stock in Edison's service territory.

GENERAL APPROACH

The approach designed for this project was the result of several conceptual meetings between Edison and PEG and an extensive research and analysis process completed by PEG. In order to determine the true effect of Blower Door Guided Weatherization, a carefully controlled study that compared pre-retrofit and post-retrofit energy usage of targeted customers that received BGW with a comparison group of similar LIRA customers needed to be implemented.

The approach was:

1) Determine the energy usage that could be effected by use of Blower Door Guided Weatherization in Edison's high SEU LIRA customer base.

2) Perform field testing of the targeted houses to determine the potential for improvement through Blower Door Guided Weatherization.

3) Identify & document the most prevalent problems not related to shell leakage in the targeted customers houses.

4) Execute shell and duct leakage repairs of the targeted houses using blower door guided diagnostics.

5) Monitor pre- and post-retrofit energy usage of the heating and cooling equipment in conjunction with monitored indoor and outdoor temperatures.

6) Utilize a floating control group to determine the energy impact of Blower Door Guided Weatherization.

MONITORING AND SITE WORK PLAN

Sampled houses were to receive a total of seven visits over the sixteen month monitoring period. Each visit was designed to accomplish the tasks listed below:

Initial Visit

Measure the critical parameters that cause high heating and/or cooling use. Houses that passed the initial screening (had adequate heating and cooling savings potential from Blower Door Guided Weatherization and Duct Sealing) and contained central air conditioners had the monitoring devices installed in the initial visit.

Second Visit

Down loading temperature and AC use data and installing monitor on heating equipment. These visits were to take place during November, 1994.

Third Visit

Down loading temperature and heating use data. For Group 1 houses, building shell and duct sealing tasks were to be accomplished. These visits were to take place in January, 1995.

Fourth Visit

Down loading temperature and heating use data, moving monitoring equipment from the heating equipment to the AC equipment. These visits were to take place in April, 1995.

Fifth Visit

Down loading temperature and cooling use data. For Group 2 houses, building shell and duct sealing tasks were to be accomplished. These visits were to take place in July, 1995.

Sixth Visit

Down loading temperature and cooling use data, moving monitoring equipment from the AC equipment to the heating equipment. These visits were to take place in September, 1995.

Seventh Visit

Down loading and removing temperature and heating use monitors. These visits were to take place in January, 1996.

SAMPLE SELECTION

Since the purpose of the study was to determine the break point between where Blower Door Guided Weatherization is sufficiently beneficial and where it is not, the test was limited to a group that could help establish the economics of this form of weatherization. Analysis was performed by Proctor Engineering Group on a sample of Edison's all-electric LIRA customer base to project the breakpoint at which BGW is sufficiently beneficial to Edison's LIRA high Seasonal Energy Use (SEU) customers. See Southern California Edison Blower Door Breakpoint Study - Target Sample Selection.

For this group of customers (N=7,920) the breakpoint was set at $357 (annual space conditioning cost) or roughly 3000 kWh SEU. This breakpoint was set based on the following assumptions:

1) Founded on field testing, the maximum expected savings from BGW on homes with ducted space conditioning systems is 20%.

2) The desired simple payback is 7 years or less.

3) The incremental cost of BGW including duct sealing is $500.

Therefore: ($500 x 7 years + 20% = $357 per year)

Approximately 13% of the sample supplied by Edison paid over $357 for space conditioning, as shown in Figure 2.1.

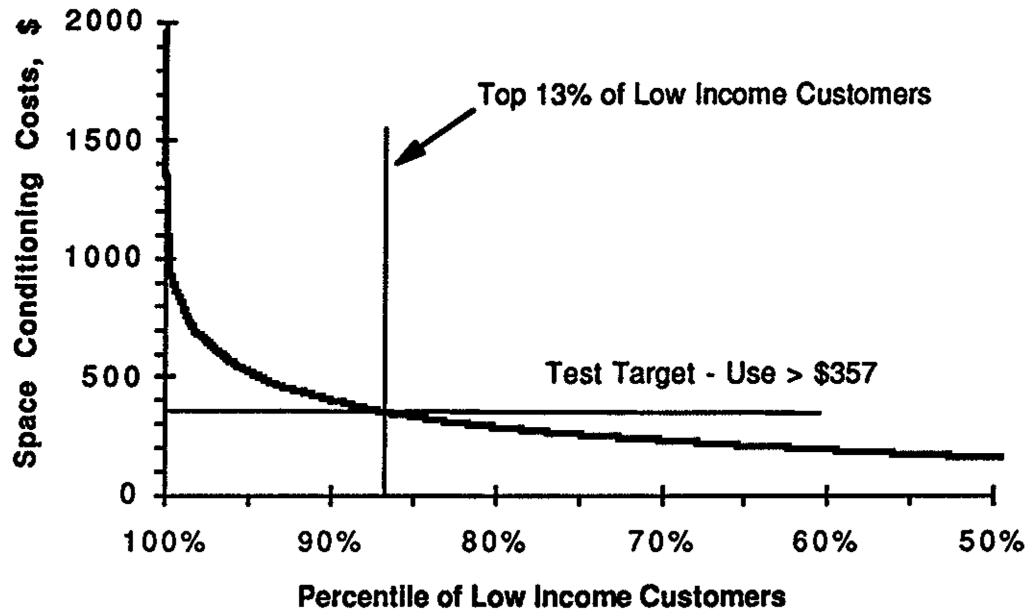


Figure 2.1. Breakpoint Test Target Customers

Through billing analysis and research conducted by Edison staff and Proctor Engineering Group, the "paper" characteristics of the all-electric LIRA target population was determined. The results were:

- Eighty percent of the target customers live in single family residences.
- Very few of the target customers have been weatherized by Edison.
- The largest group of customers live in homes from 1000 to 1500 square feet.
- Over half of the target customers have ducted forced air systems.

With respect to geographic distribution:

- There is a large block of customers in the 29 Palms to Palm Springs area that represent a variety of house sizes (including the smallest homes), and are disproportionately represented in the target group.
- Laguna Hills and the community of Seal Beach represent a large block of both target customers and Edison's low income customers.

A sample group of 24 houses were to be selected for monitoring and retrofit under the test project. Summer temperatures and cooling energy use were to be monitored in the last half of summer 1994. The winter of 1994/1995 would involve pre-retrofit and post-retrofit heating energy use monitoring with the BGW taking place mid winter. Homes would be monitored through the summer of 1995 to determine cooling savings.

The sample consisted of a number of groups to accomplish a variety of objectives. The sample was selected from two geographic areas to obtain a spread of housing types and sizes. Prior to the field test the potential participants were randomly assigned to test and comparison groups. The sample groups, their proposed size, and the associated objectives are shown in Table 2.1.

Table 2.1. Sample Groups

Group	Objectives	Size
Target Population Sample (All other groups are subsets of this sample)	Determine the critical parameters that cause these individual homes to be in the target population	24
Group 1 (a mixture of heating only and heating and cooling homes) This group is weatherized in January 1995	Determine the pre-/post- energy consumption change due to Blower Door Guided Weatherization and duct sealing. Provide a comparison group for Group 2	12
Group 2 (a mixture of heating only and heating and cooling homes) This group is weatherized in July 1995	Determine the pre-/post- energy consumption change due to Blower Door Guided Weatherization and duct sealing. Provide a comparison group for Group 1	12

The original division of sampled houses allocated eight houses in 29 Palms, eight houses in Palm Springs, and eight houses in Laguna Hills. Since substantial attention had been previously paid to the Laguna Hills area, alternative sites in Orange County were selected.

CUSTOMER AND SITE SELECTION

Southern California Edison supplied a pool of high usage LIRA customers to Proctor Engineering Group for sample selection. Seasonal swing analysis was performed on the customer billing data. The use (Daily Base) that is not attributable to air conditioning, heating and other seasonally variable end-uses was estimated from spring and fall data. The Daily Base was calculated as the minimum average daily use from the Spring or Fall. The Daily Base includes average lighting, refrigeration, clothes drying, cooking, water heating, etc. Analysis excluded Spring or Fall months with unreasonably low use (due to vacations, etc.)

The kWh use for the May through October billing periods were summed to total summer use. The kWh use for the November through March billing periods were summed to total Winter use. The Seasonal Energy Cost (SEC) for the customers is based on a marginal LIRA rate of 12¢ per kWh for both the summer and winter billing periods. All customers selected for inclusion in the project needed to have a total SEC of greater than $357, or roughly 3000 kWh of SEU.

The SEU contains all the seasonal electrical use for these households including space conditioning and any change in refrigerator use or other electrical appliances. The relationship between the summer SEU and air conditioner use has been investigated on submetered air conditioners and is detailed in "Pacific Gas and Electric Appliance Doctor Project, Final Report Summer 1991 Activity." For the units in that study, the actual submetered AC use averaged 85% of the SEU.

SCHEDULING

Once the referred customers SEC had been verified to meet the project criteria, a specially trained team of diagnostic technicians were scheduled to visit the house. As expected, an introductory letter from Edison explaining the project and its legitimacy was needed. Many customers were hesitant to allow the crew to visit their house without confirmation from Edison.

In order to achieve a stable customer base for this long term monitoring project, customers were screened to ensure they would be a good candidate for long term monitoring. Additionally in an effort to reduce costs, meet the project's time constraints, and improve the accuracy of the measured results several other criteria were placed on customers in the project. In particular customers were eliminated for the following reasons:

- Renters (Due to potential problems with landlord agreements).
- Customers that have moved in the past twelve months.

- Customers that plan on moving in the next sixteen months.
- Customers that know of any pending occupancy change during the next sixteen months.
- Customers in middle level floors of multifamily buildings (due to the difficulty and uncertainty of measuring external leakage on multi-floor buildings).
- Customers with multiple central or window air conditioning systems (due to cost of additional monitoring equipment).
- Customers with natural gas heating appliances.

SITE TESTING

The initial visit screened the house to ensure that they qualified for inclusion in the project. Specifically the initial visit was designed to measure the critical parameters that cause high heating and/or cooling use. The tests included:

- Building shell leakage
- AC system efficiency
- Duct leakage
- Occupancy effects - set points, etc.
- Calculation of projected savings from BGW

The step by step procedures used in testing each of the houses are presented in Appendices A and B.

Building Shell Leakage

Building shell leakage was measured with the use of the Minneapolis blower door. Single point blower door readings were taken to determine the buildings total shell leakage at a standard house pressure with reference to outside of 50 pascals. Technicians also measured buffer space pressures with a digital micromanometer (which indicates the extent of buffer space communication with the living space).

Building square footage and volume measurements were taken to provide the information necessary to calculate the minimum leakage rate of the building relative to ASHRAE standard 62-1989. Building insulation levels were also recorded as a part of the technicians visit.

Duct Leakage Testing

Duct leakage was measured using the flow hood measurement methodology. This test uses the blower door to pressurize the house to 50 pascals and the flow hood to measure the duct leakage to the exterior of the structure at a return grill. During this test all supply and return registers are sealed (except the largest least restrictive return grill). Any flow measured at the return grill with the flow hood has to be escaping through duct leaks to the exterior of the building or buffer spaces that communicate with the exterior of the building.

As with any duct leakage testing methodology there are advantages and disadvantages associated with this method. The advantages of this method include the speed with which the testing can be accomplished, the accuracy of the flow hood in measuring flow rates, and the fact that it measures only leakage to the exterior of the house. The disadvantages include the fact that there is little control over the uniformity of pressures throughout the duct system during testing. Since the pressure in the duct system during testing is directly controlled by the base pressure in the house, the pressure within the duct system will decrease as leaks are encountered. A more detailed explanation of this duct testing methodology can be found in "Leak Detectors: Experts Explain the Techniques" (Proctor, et. al.) in Appendix C.

Other measurements included, normal system operating static pressures, pressures within the duct system during the duct leakage test and buffer space pressures during the duct leakage test. These parameters were used to adjust the leakage to outside during normal operation of the system. Duct location was also recorded as a part of the technicians' procedures.

AC System Efficiency Testing

Standardized testing procedures developed by Proctor Engineering Group were performed on all central air conditioners and heat pumps. The step by step procedure lead the technician through information gathering and parameter measurement. Technicians gathered information on customers' reported thermostat set points for both summer and winter. They recorded information from the air conditioners outdoor unit to determine the systems rated capacity and EER. Air conditioner measurements included airflow through the indoor coil, cooling capacity and electrical input.

System air flow through the indoor coil was measured with a Shortridge flow hood at the return grill(s). Measured duct leakage on the return system was added to the grill flow to determine the system air flow through the indoor coil. Return system leakage was determined by correcting duct leakage at test pressure to normal operating pressures. The split between supply and return duct leakage was determined through the use of a testing methodology known as "the Half Nelson". The Half Nelson measures pressures in the supply and return systems with all registers covered and the air handler fan on. These pressures are used to estimate the ratio of supply and return system leakage fractions.

The air conditioner capacity was measured after at least fifteen minutes of continual operation. Return and supply dry bulb temperatures were measured. The measured air flow and temperatures were used to calculate the systems capacity. Based on PEG's previous experience in the Coachella Valley and the Los Angeles Basin, the screening procedure was based on sensible capacity. Air conditioning systems in hot dry climates such as these have little latent capacity.

Input wattage for the air conditioner was measured using Edison's revenue kWh meter on each house. Breakers for all other circuits were shut off temporarily while the input was measured. The measured input along with the measured capacity was used to determine the air conditioners instantaneous EER. An air conditioner's EER is dependent on many variables, including the indoor and outdoor temperatures, humidity levels, the air flow across the indoor and outdoor coils and the amount of refrigerant charge.

Potential Savings Screen

The houses were screened against a straightforward calculation of energy savings potential· Potential energy savings was calculated in two stages. First, the Projected Shell Leakage Reduction and Projected Duct Leakage Reductions were calculated. Second, the Projected Energy Savings for heating, cooling, and total were calculated. The screening calculations were:

Projected Shell Leakage Reduction:

1) Leakage from building shell alone is calculated (Total measured CFM50- Duct Leakage CFM50)

2) Minimum Shell Leakage for natural ventilation is estimated (House Volume * .35 air changes per hour * N / 60 minutes per hour)[3]

3) The Total Available Shell Leakage Reduction is calculated (Building Shell Leakage - Minimum Shell Leakage for natural ventilation)

---

[3]N is calculated for each site as detailed in (Sherman, 1987)

4) The Projected Shell Leakage Reduction is calculated as 60% of the Total Available Shell Leakage Reduction (based on field experience)

Projected Duct Leakage Reduction;

1) Projected Duct Leakage Reduction (Duct Leakage CFM50 - 150 CFM50)

Projected Heating Energy Savings (electric resistance);

1) Determine Heating Energy Savings Multiplier

$$M_{res} = [\ (0.24 * 0.075 * 60\ /\ 3412) * DD_{h65} * 24\ /\ N\ ] * 0.6$$

Where

0.24	= Specific Heat of Air (BTU/lb.-°F)
0.075	= Specific Density of Air (lb./cubic feet.)
60	= minutes per hour
3412	= BTU/kWh
DD_{h65}	= Historical Heating Degree Days to base 65°F
24	= hours per day
N	= Leakage /Infiltration Coefficient
0.6	= empirically derived correction to account for a variety of factors that reduce actual energy savings below the savings of the pure model (Energy Conservatory, 1991)

2) Calculate the Projected Heating Energy Savings from Shell (M_{res} * Available Shell Leakage Reduction)

3) Calculate the Projected Heating Energy Savings from Ducts ($4 * M_{res}$ * Projected Duct Leakage Reduction)[4]

Projected Heating Energy Savings (heat pump):

1) Determine Heating Energy Savings Multiplier

$$M_{hp} = M_{res} / 1.6$$

Where

1.6 = Assumed average heat pump COP

2) Calculate the Projected Heating Energy Savings from Shell (M_{hp} * Available Shell Leakage Reduction)

3) Calculate the Projected Heating Energy Savings from Ducts ($4 * M_{res}$ * Projected Duct Leakage Reduction)

[4]Models of duct leakage energy losses are being developed but were not available for this screening process. An energy savings multilplier of four (each CFM50 of duct sealing saves four times what the same CFM50 of shell sealing will save) was used as a reasonable screening tool for this project.

Projected Cooling Energy Savings (air conditioner);

1) Determine Cooling Energy Savings Multiplier

$$Q = [(0.24 * 0.075 * 60 * DD_{c65} * 24 / N] * 0.6 / (EER * 0.8)$$

Where

0.24	= Specific Heat of Air (BTU/lb.-°F)
0.075	= Specific Density of Air (lb./cubic feet.)
60	= minutes per hour
DD_{c65}	= Historical Cooling Degree Days to base 65°F
24	= hours per day
N	= Leakage /Infiltration Coefficient
0.6	= empirically derived correction to account for a variety of factors that reduce actual energy savings below the savings of the pure model
EER	= nominal Energy Efficiency Ratio of the air conditioner (BTU/watt hour) from the Carrier Blue Book
0.8	= assumed actual EER reduction below rated conditions

2) Calculate the Projected Cooling Energy Savings from Shell (Q * Available Shell Leakage Reduction)

3) Calculate the Projected Cooling Energy Savings from Ducts (4 * Q * Projected Duct Leakage Reduction)

Total Projected Energy Savings

1) Calculate Total Projected Energy Savings as the sum of shell and duct savings from both heating and cooling.

III Results

CUSTOMER RECRUITMENT AND SELECTION

Edison supplied a pool of 336 customers for seasonal usage analysis and scheduling. The geographic breakdown of the customers was: 153 were from Orange County , 99 from Yucca Valley, and 84 from the Palm Springs area. The disposition of those 336 leads is shown in Figure 3.1.

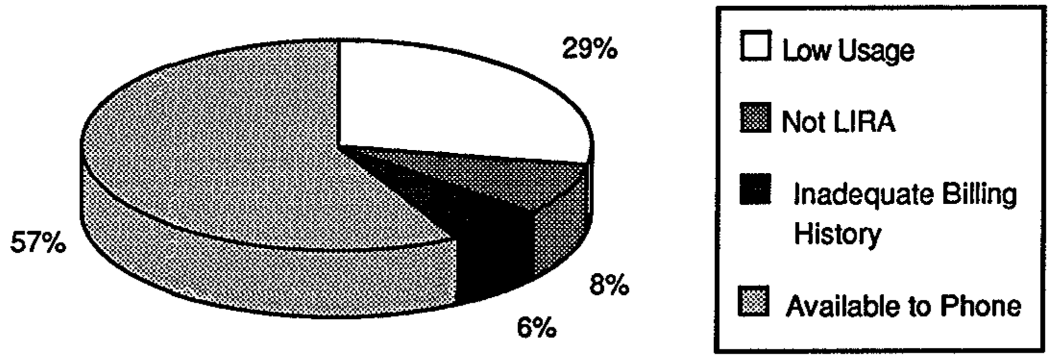


Figure 3.1. Disposition of Initial Leads

Edison initially selected customers by total energy consumption. Seasonal Energy Use is a preferable targeting method since homes with a high base use (refrigerators, lighting, and miscellaneous uses) but low heating and cooling use are captured.

The disposition of the customers that passed the targeting criteria is shown in Figure 3.2.

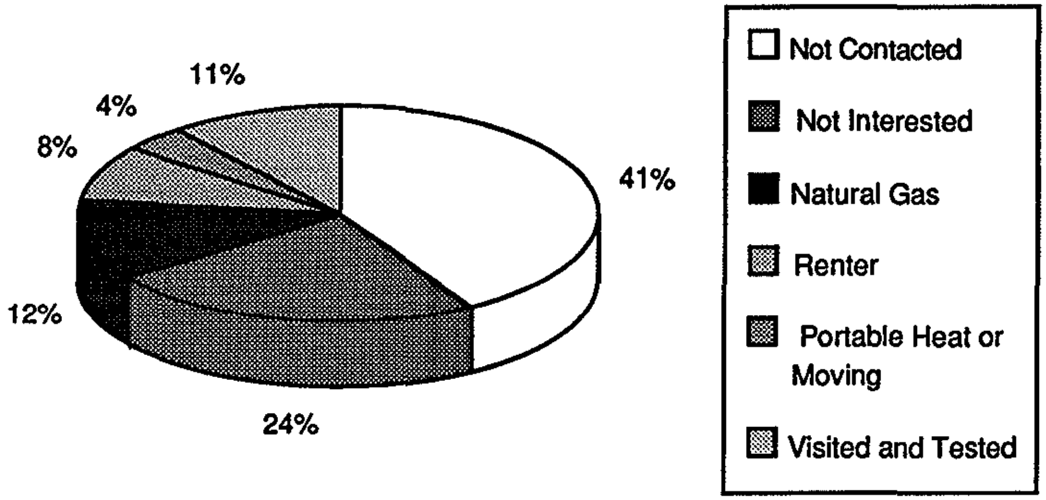


Figure 3.2. Disposition of Targeted Customers

Forty one percent of the customers were not contacted because of disconnected numbers, repeated attempts including evening hours with no response, or decision to terminate the field visits.

Twenty customers passed the targeting and phone screening. These customers were visited and tests were performed on the houses.

CUSTOMER CHARACTERISTICS

Customer Seasonal Energy Usage

The Blower Door Breakpoint - Target Sample Selection Study determined that the top 13% of LIRA customers, in the sampling analyzed, had Seasonal Energy Usage above 2975 kWh. This level of usage was set as the point above which BGW was projected to be cost effective. The high SEU customers analyzed in the Target Sample Selection Study (N=1,011) had a mean winter SEU of 2920 kWh and a mean summer SEU of 1520 kWh.

The average total SEU for the twenty customers in this study was 4862 kWh. Both the winter and summer SEU of those customers are presented in Table 3.1. The BGW Study customers had slightly higher winter and summer Seasonal Energy Use than the target from the Blower Door breakpoint study.

Table 3.1. Seasonal Energy Usage Comparison

		BGW Study N=20	Target Study N=1011
Winter Electric (kWh)	**Mean**	**3142**	**2920**
	Std. Dev.	1784	1562
Summer Electric (kWh)	**Mean**	**1721**	**1520**
	Std. Dev.	1343	1352

Heating usage was the dominant space conditioning electrical consumption in the sample (70% were heating dominated). Of the customers with dominant cooling, the majority were located in the Palm Springs Region, where some groups (i.e. elderly customers) may require cooling due to health problems.

Customer Location and Demographics

The majority of the sampled houses were located in hot, dry climates. Fourteen were located in the Yucca Valley, five were located in the Palm Springs Region and one was located in the Orange County.

Customers that agreed to participate were predominantly elderly. Figure 3.3 shows the breakdown of the sample. The large proportion of elderly may be due to elderly predominating the high Seasonal Energy Use LIRA customers or it may be a artifact of the sampling criteria that was designed to obtain stable customers for metering and the availability and willingness for elderly to accept a home visit.

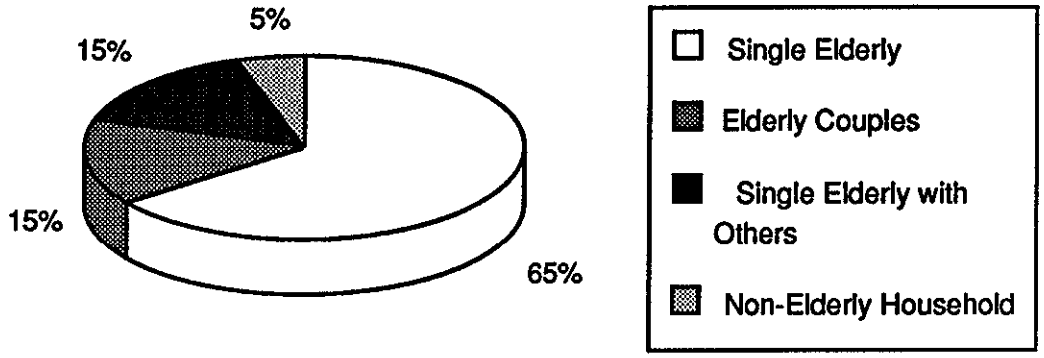


Figure 3.3. Distribution of Sample by Age Group

BUILDING CHARACTERISTICS

The majority of the houses tested were detached single family residences. No effort was made to eliminate any type of housing stock with the exception of units on the middle floor in multi-story apartment buildings[5].

The average square footage of the houses tested was 1102 square feet, ranging from a 319 square foot mobile home to a 1888 square foot house. The average volume of the was 8884 cubic feet.

Insulation levels varied widely. The average attic R-Value in the 18 houses visited that had access to the attic was R-18, with a range of R-40 on one house to no attic insulation at all on another. Eight of the houses visited had less than R-19 insulation in the attic (which is the Edison recommended level of attic insulation). The average wall insulation R-Value of the houses visited was R-8. Five of the houses visited had no wall insulation at all, and the majority of the remaining customers had the standard R-11 wall insulation.

[5]It is extremely unlikely that apartments or condos in the middle of the building have high consumption due to air leakage. Much of the measured leakage for an individual unit in the center of a building is "internal" leakage to/from other units in the building.

Building Shell Leakage, Achievable Reduction, and Potential Energy Savings

Twenty houses were tested with a Minneapolis Model 3 blower door to determine the amount of leakage present in the shell of the home. The average measured shell leakage was 1766 Cubic Feet per Minute at 50 pascals (CFM_{50}). Table 3.2 summarizes the shell leakage characteristics and the kWh savings associated with the achievable shell leakage reduction.

Table 3.2. Shell Leakage and Potential Savings

	Shell Leakage (CFM_{50})	Shell Reduction Available[6]	Heating Shell kWh Savings[6]	Cooling Shell kWh Savings[7]
Average	1766	362	125	109
Std. Dev.	755	307	128	101
Minimum	538	-	-	-
Maximum	3491	1291	529	317

On average, approximately 25% of the seasonal energy use in the winter and 34% of the summer seasonal energy use was attributable to infiltration.

Ventilation

ASHRAE Standard 62-1989 specifies the outdoor air requirements for ventilation in residential facilities in Table 2.3 of the standard (ASHRAE, 1989). That table includes the requirement that outdoor air be supplied to living areas at the rate of "0.35 air changes per hour but not less than 15 CFM per person". To evaluate whether these homes were likely to have an average natural ventilation rate that would comply with the standard, a number of calculations were made. These calculations rely on a simplified application of the LBL infiltration model described in Sherman (1987). None of the 20 houses visited had an estimated ventilation rate of less than 15 CFM per person. The minimum allowable CFM_{50} of the building based on this model was calculated as follows:

---

[6] For the 18 homes that were not already below the minimum ventilation guideline.

[7] For the 9 homes that had air conditioning and were not already below the ventilation guideline.

$$L_{Min} = 0.35 * V * N / 60$$

Where:

L_{Min}	= Calculated Minimum CFM_{50} of the building
0.35	= ASHRAE standard (0.35 ACH)
V	= Volume of the house in cubic feet
N	= Divisor used to estimate natural ACH from CFM_{50} (based on the LBL model)
60	= 60 minutes per hour

The average natural ACH estimated for these houses was 0.59. While the ventilation rate fell short of 0.35 ACH under winter conditions for two homes, few houses had very high ventilation rates as shown in Figure 3.4.

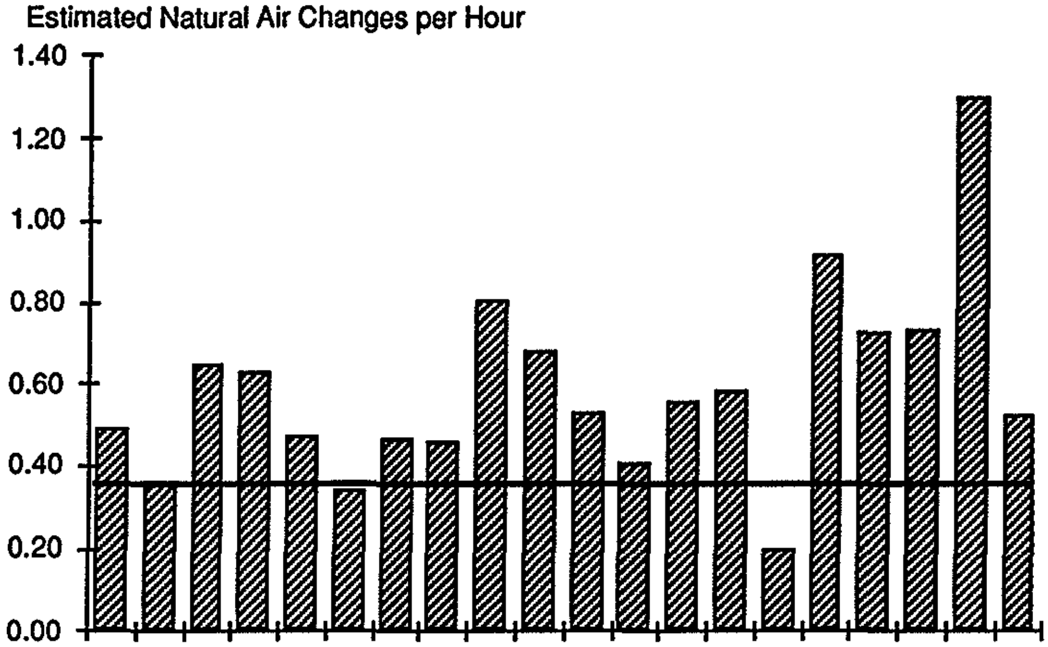


Figure 3.4. Estimated Natural Air Change Rate

Leakage to Attic

Leakage high and low in the building is responsible for the majority of infiltration and energy use due to infiltration. Energy consumption in the cooling mode is particularly effected by leakage between the attic and the house.

Using pressure measurements the amount of leakage into the attic from the house was estimated relative to the leakage from the attic to outside. A house that is well sealed from the attic will show a low house to attic/attic to outside leakage ratio. Figure 3.5 shows these ratios.

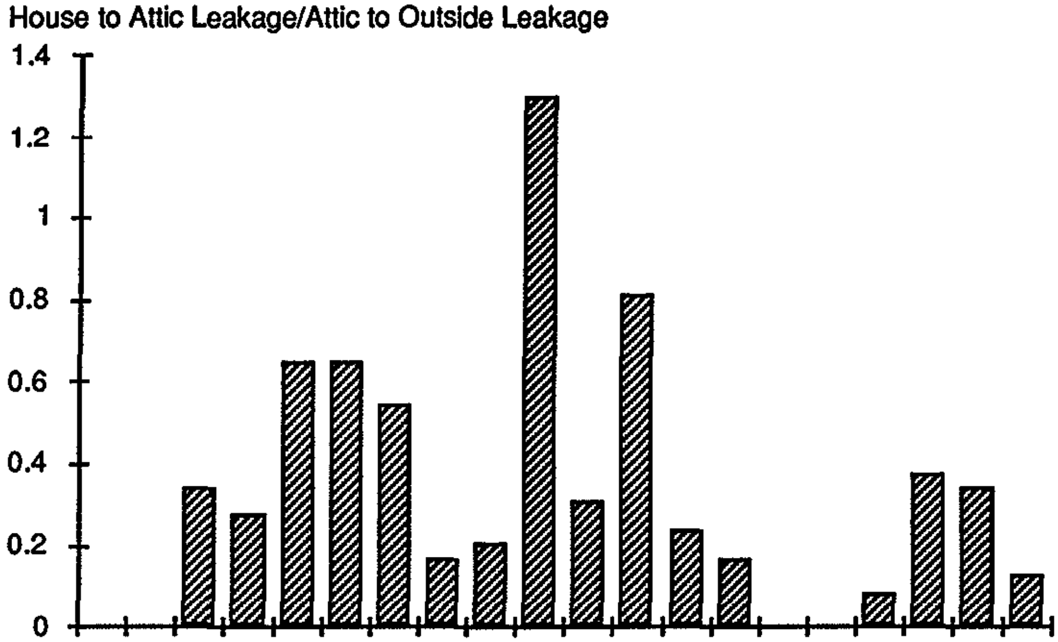


Figure 3.5. House to Attic Leakage

Duct Leakage, Achievable Reduction, and Potential Energy Savings

Duct leakage was measured using a blower door and a flow hood. The average measured duct leakage was 234 Cubic Feet per Minute at 50 pascals (CFM_{50}). Table 3.3 summarizes the duct leakage characteristics and the kWh savings associated with the achievable duct leakage reduction[8].

---

[8] On existing California construction Proctor Engineering Group's testing has shown that duct leakage can be reduced to 150 CFM_{50}. The Pacific Gas and Electric Company's Model Energy Communities Project (MEC) realized an average leakage reduction of 60%. The average remaining leakage on a sample of 2170 houses was 154 CFM_{50}. Homes in the MEC Project were much larger than these homes. Repairing these ducts would require less effort.

Table 3.3. Duct Leakage and Potential Savings

	Duct Leakage (CFM_{50})	Duct Reduction available (CFM_{50})[9]	Percent of Total shell leakage	Duct kWh Savings[6]
Average	234	203	14%	588
Std. Dev.	173	136	11%	304
Minimum	27	97	2%	256
Maximum	579	429	42%	981

The average duct leakage in the 11 houses in this sample was not particularly high. Other studies have found duct leakage to be much higher in houses that have high SEU. Proctor (1991) and Tooley and Moyer (1989) found 419 CFM_{50} and 406 CFM_{50} of duct leakage respectively.

The customer with the largest amount of duct leakage (579 CFM_{50}) also had the highest total SEU (over 8900 kWh).

Duct Leakage Location

The leakage at normal operating pressures separated between supply and return leakage is shown in Table 3.4.

Table 3.4. Duct Leakage by Location

	Supply Duct Leakage	Return Duct Leakage	% of Air Flow Supply/Return
Average	90	111	8%/10%
Std. Dev.	79	120	26%/39%
Minimum	3	15	0.5%/2.3%
Maximum	251	362	16%/23%

[9] For the 5 homes that had duct sealing opportunities

Return system leakage was dominate in the systems tested. This is consistent with the observations of previous studies and is caused by the higher normal operating static pressures measured in the return systems and the construction techniques applied to return systems.

Homes with Sufficient BGW Savings Potential to Justify Monitoring

Twenty houses were visited and tested to determine if the high Seasonal Energy Use was attributable to shell and duct leakage. The on-site measurements assessed shell leakage, duct leakage, operating efficiency of the central air conditioner, and several other parameters.

As shown in Figure 3.6, only 2 houses passed had sufficient potential energy savings from shell and duct sealing to make a combined BGW and duct sealing program cost effective. These two homes had ducted heating and cooling systems (one was a heat pump, the other an air conditioner with an electric furnace).

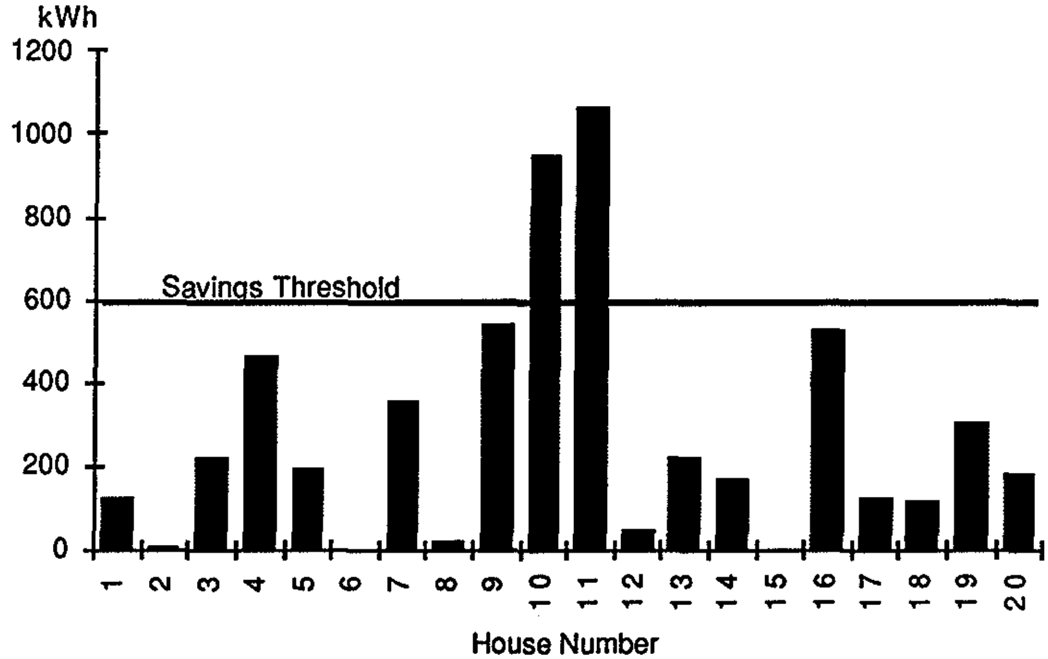


Figure 3.6. Potential Annual Energy Savings from Blower Door Guided Weatherization and Duct Sealing

The lack of available shell savings (including available duct sealing savings) eliminated 90% of the visited units from consideration. The average leakage reduction available for the houses in this group was 309 CFM_{50}. The SEU reduction associated with sealing these houses averaged 153 kWh of combined heating and cooling savings.

Heating Systems

The electric heating systems in these homes varied. When examined by heating system type, the average winter heating consumption is particularly high for customers with ceiling cable heat as shown in Figure 3.7.

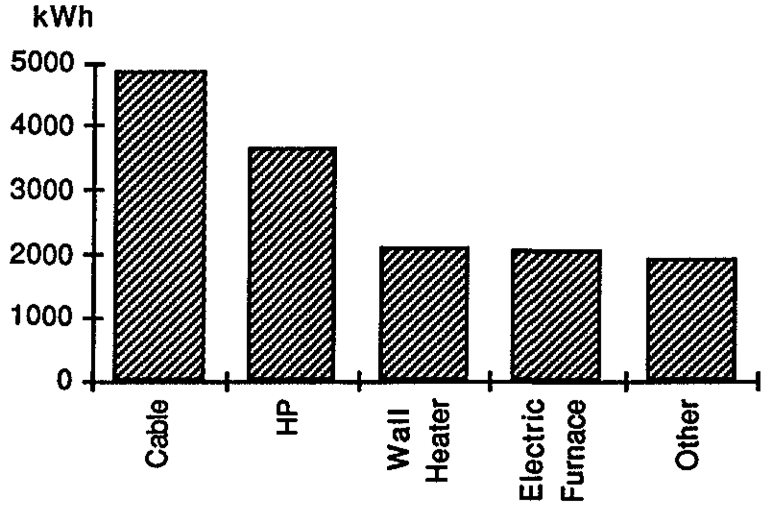


Figure 3.7. Winter Seasonal Energy Use by Heating Type

The level of heating energy consumption is effected by far more than just heating system type. Two of the biggest variables are the size of the heated space and the severity of the heating season. As shown in Figure 3.8, when the heating consumption is normalized by building size and heating degree days, ceiling cable heat and wall heaters both consume more heating energy than the other heating systems in this sample.

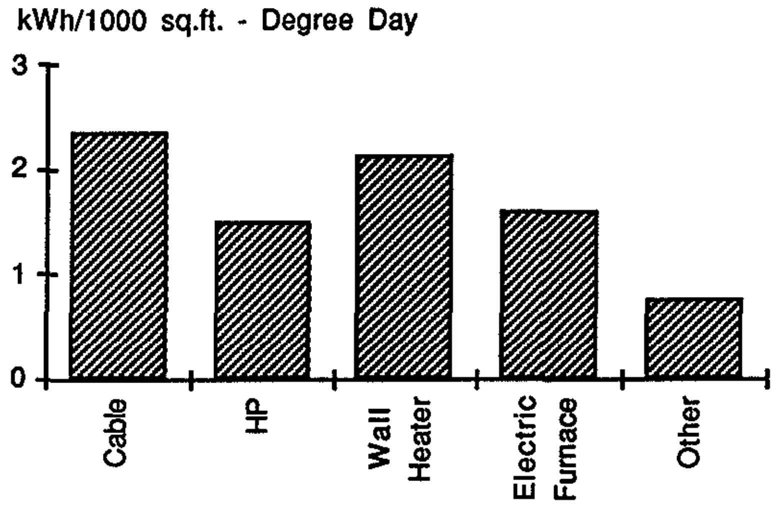


Figure 3.8. Normalized Heating Use by Heating Type

Ceiling cable heated homes were not leaky (they had the lowest average natural air change rate), and they had the highest levels of ceiling insulation.

<u>Air Conditioners and Heat Pumps</u>

Ten of the homes had central air conditioning systems. Five of the refrigerant based systems were heat pumps with electric resistance heat strip back-up, four were central air conditioning systems with electric resistance forced air heating, and one house contained a central air conditioning system with a ceiling cable heating system.

The technicians from CSG performed standardized testing procedures in the cooling mode on all central air conditioners and heat pumps. These tests determine the actual operating sensible capacity and instantaneous energy efficiency ratio (EER) of the systems.

The average manufacturers rated capacity of the air conditioners was 38,250 Btu/hr or 3.2 Tons. The average rated EER of the air conditioners tested was 7.3 with a range of 6.0 to 8.1. The air conditioners were performing poorly (both capacity and efficiency were low). The expected efficiency of these units (based on manufacturers rating adjusted to test conditions) is compared to tested efficiency in Figure 3.9.

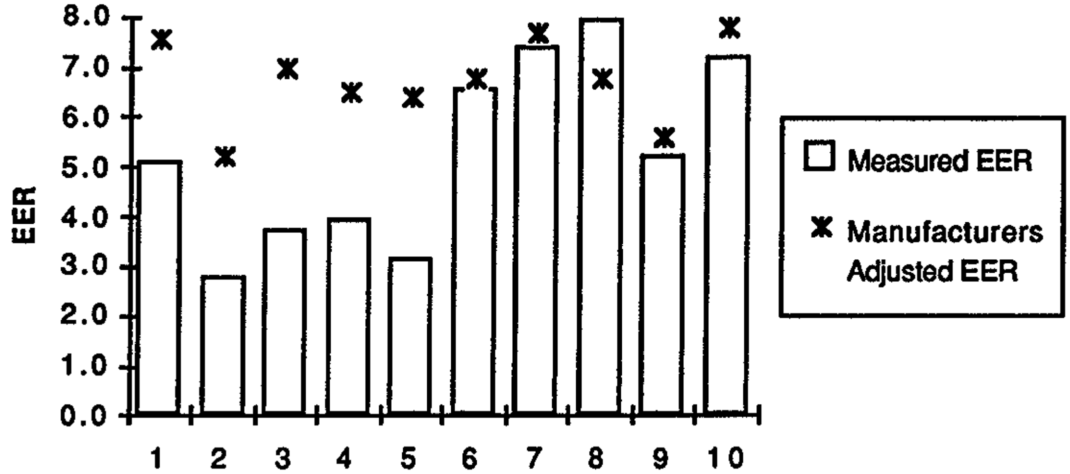


Figure 3.9. Measured vs. Expected Air Conditioner Efficiency

Five of the ten systems had a tested EER well below the expected EER for the test conditions, indicating serious problems.

The proper operation of an air conditioner depends on correct air flow through the indoor coil. Most major manufacturers recommend that air conditioners have an air flow of 400 CFM/Ton (+/- 50 CFM/Ton) for each nominal ton of rated capacity. Sixty percent of the systems tested had air flows less than 350 CFM/Ton. This is similar to the findings of other studies Proctor (1991) and Neal (1990). Table 3.5 displays the air flow test results.

Table 3.5. Air Conditioner Air Flow

	Measured CFM/Ton	Percent of Deficient Air Flow
Average	338	16%
Std. Dev.	58	15%
Minimum	263	- 2%
Maximum	409	34%

Only four systems has correct air flow. Of those, three are performing near the manufacturers specified EER (lowest was 92% of rating) while the other system appears to have a serious charge problem (EER only 50% of expected).

While no attempt was undertaken to determine if the air conditioners were properly sized, it was noted that one house had one ton of cooling for every 128 square foot of living space.

Thermostat Settings

The thermostat settings used by the customers was examined through the use of a questionnaire. Survey results of this survey are presented in Table 3.6.

Table 3.6 Customer Reported Thermostat Settings

	Winter Day	Winter Night	Summer Day	Summer Night
Average	74	71	76	77
Minimum	68	64	70	72
Maximum	80	80	80	85

AVAILABLE POPULATION FOR TARGETED BLOWER DOOR GUIDED WEATHERIZATION

The field tests on this twenty household sample of customers show that ten percent have sufficient energy savings to make blower door guided weatherization with duct sealing cost effective based on a simple payback of less than 7 years[10]. This sample was selected from Edison low income customers that have heating and cooling seasonal energy consumption high enough to warrant consideration of BGW. The previous study of Edison low income customers "The Southern California Blower Door Breakpoint Study" established that 13% of the Edison all electric low income customers fell into this high consumption class. As a result it is estimated that the percentage of Edison all electric LIRA customers that would benefit sufficiently from BGW to result in less than a 7 year payback is on the order of 1.3%. These is illustrated in Figure 3.10.

[10]The cost effectiveness of Blower Door Guided Weatherization with respect to any other criteria was not assessed.

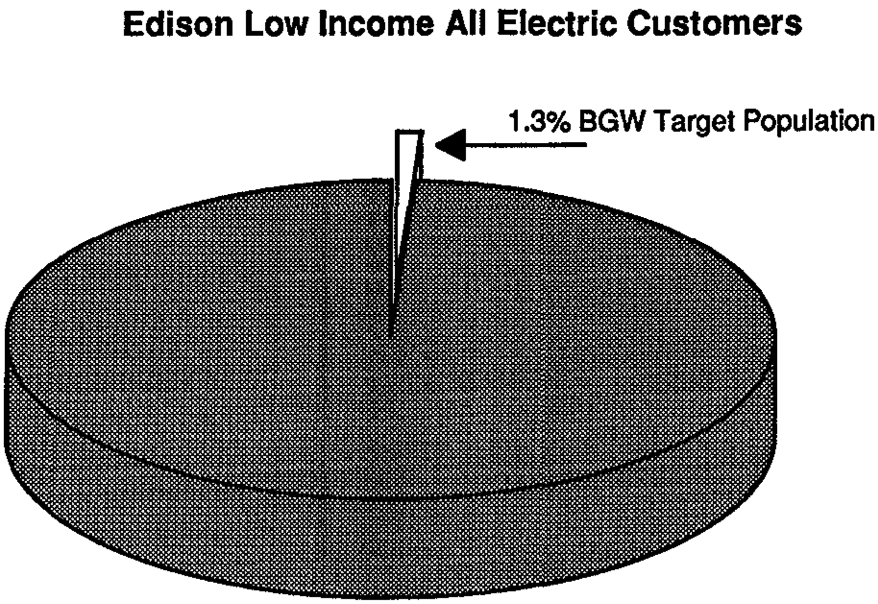


Figure 3.10. Targeted Edison All Electric LIRA Customers for Blower Door Guided Weatherization

The sample used in this field test was drawn to ensure adequate data from monitoring houses for over a year. It is possible that this sample is in some way biased compared to the Edison population of high space conditioning energy use, all electric, low income customers. Determining whether such a bias exists could be tested by diagnostic visits to a random sample of high SEU LIRA homes.

IV Conclusions and Recommendations

In this field study on Southern California Edison low income all electric customers a number of field tests were run to determine the probable targets for blower door guided weatherization combined with duct sealing. Ten percent of this sample would be likely targets if a simple payback of 7 years or less is expected. The majority of high usage LIRA customers in this sample did not have excessive cooling or heating energy use due to building shell leakage.

There is significant opportunity for energy savings and improved customer comfort in the high use homes tested. The predominate factors in high heating and/or cooling usage appear to be:

- Ceiling cable heating systems. (25% of the sample)
- Low operating efficiency (well below design efficiency) in half the air conditioners/heat pumps. (25% of the sample)
- Duct leakage in half the homes with ducted systems. (20% of the sample)

The factors contributing to high seasonal energy use in these low income customers can be further investigated. Proctor Engineering Group suggests that Southern California Edison consider:

- Performing random blower door shell and duct leakage testing on a random sampling of high SEU Lira customers.
- Study mitigation techniques applicable to houses with ceiling cable heat.
- Exploring heat pump and air conditioner repair to bring the equipment to proper efficiency.
- Exploring duct repair alone as a potentially cost effective measure for high use customers with ducted systems.
- A low income weatherization design that targets customers based on their billing data, screens customers for the presence of equipment potentially capable of causing the high use, applies field diagnostics, and where possible applies corrective action.

BIBLIOGRAPHY AND REFERENCES

ASHRAE 19891 "Ventilation for Acceptable Indoor Air Quality" ASHRAE Standard 62-1989, American Society of Heating Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Cummings, J., J. Tooley Jr., N. Moyer and R. Dunsmore. 1990. "Impact of Duct Leakage on Infiltration Rates and Pressure Differences in Florida Homes." Proceedings from the ACEEE 1990 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Washington, D.C.

Energy Conservatory, 1991. Minneapolis Blower Door Operation Manual, Model 3, page 37.

Jacobson, R., J. Proctor and A. Polak. 1992. "PG&E Appliance Doctor Pre-Production Test." Proceedings from the ACEEE 1992 Summer Study on Energy Efficiency in Buildings, American Council for an Energy Efficient Economy, Washington, D.C.

Neal, L. 1990. "Field Experiences with Central Air Conditioners and Heat Pumps", AEC North Carolina Alternative Energy Corporation.

Proctor, J., B. Davids, F. Jablonski, and G. Peterson. 1990. "Pacific Gas and Electric Heat Pump Efficiency and Super Weatherization Pilot Project: Field Technical Report". Pacific Gas and Electric Company, San Francisco, CA.

Proctor, J. 1991. "Pacific Gas and Electric Appliance Doctor Pilot Project: Final Report." Pacific Gas and Electric Company, San Francisco, CA.

Proctor, J. and R. Pernick. 1992. "Getting it Right the Second Time: Measured Savings and Peak Reduction from Duct and Appliance Repair." Proceedings from the ACEEE 1992 Summer Study on Energy Efficiency in Buildings American Council for an Energy Efficient Economy, Washington, D.C.

Proctor, J. 1993. "Estimating Peak Reduction from Submetered Data." 1993 International Energy Program Evaluation Conference, Chicago, IL.

Proctor, J., M. Blasnik, B. Davis, T. Downey, M. Modera, G. Nelson and J. Tooley. 1993. "Diagnosing Ducts: Finding the Energy Culprits". Sept./Oct. 1993 *Home Energy* pp 26-31.

Sherman, M. 1987, "Estimation of Infiltration from Leakage and Climate Indicators" *Energy and Buildings* Number 10 (1987), pp 81-86.

Tooley, J. Jr. and N. Moyer. 1989. "Mechanical Air Distribution and Interacting Relationships". Proceedings from Symposium on Improving Building Systems in Hot and Humid Climates, pp. A24-31. Texas A&M University, College Station, TX.

APPENDIX A: SCREENING PROCEDURE FORM 1

TECHNICIAN 1

SCE BLOWER DOOR PROJECT SCREENING PROCEDURE

Customer Name ______________________________ Phone ____________

Address ______________________________ City ____________

Technician 1 ____________ Technician 2 ____________ Date ____________

1.	Use the first portion of the attached customer certification sheet to complete the initial customer interview.
2. **Heating System Type** ____________ **# of Thermostats** ________	Record the type of heating system present in the house. (i.e.. electric furnace, heat pump, radiant ceiling panels, electric baseboard, gas furnace, etc...) If the house has radiant ceiling panels or electric baseboards record the number of thermostats .
3. SUMMER SETTINGS ______ Now ______ Daytime ______ Night ______ Unoccupied.	Ask the customer about their "normal" summer weekday thermostat settings during the daytime, at night when they go to bed, and when the house is unoccupied (i.e. when everyone is at work or school). Also ask about 3, 5, and 6 PM. ______ 3 PM ______ 5 PM ______ 6 PM
4. WINTER SETTINGS ______ Now ______ Daytime ______ Night ______ Unoccupied.	Ask the customer about their "normal" winter weekday thermostat settings during the daytime, at night when they go to bed, and when the house is unoccupied (i.e. when everyone is at work or school). Also ask about 3, 5, and 6 PM. ______ 3 PM ______ 5 PM ______ 6 PM
5. **Dueling Managers** Yes No	If this is a heat pump ask the customer if there are any people in the house that do not agree on the thermostat setting in the winter time. (i.e. one person turns the thermostat down and another person keeps turning it up).
6. ______ ° F Cool Off Heat	Record the current thermostat control switch setting and temperature setting.
7. Manual Control Setback Clock Programmable	Record the type of thermostat presently installed in the home.
8.	With the customer present, turn on the air conditioner in the cooling mode and set it at the coolest setting. Check to ensure both the indoor and outdoor components work (START YOUR WATCH TO MEASURE TIME). If the system does not work inform the customer that their house can not be included in the project. If the house does not have central AC skip to step # 23.

TECHNICIAN 1

9.	**Have the homeowner assist you in finding each register in all rooms of the house.** Start at the front door and move to the right (clockwise). Open as many windows and doors as necessary to keep the inside temperature as close to 80°F as possible. OPEN ALL SUPPLY REGISTERS NOW.
10.	**INFORM CUSTOMER THAT YOU WILL BE SHUTTING OFF ALL OF THE POWER TO THE HOUSE.**
11. ____________	Locate the circuit breaker panel and record its location.
12.	Shut off all breakers except the main service disconnect, the air handler and outdoor unit breakers to determine correct breakers for the air handler and outdoor unit. Once the correct breakers have been determined, MARK THEM. If the air handler or the outdoor unit were accidentally shut off wait five minutes before restoring power and reset your stop watch when the outdoor unit turns on. **TURN ALL BREAKERS BACK ON.**
13. ________ Manf. ________ Mod.	Record the manufacturer and model number from the outside unit nameplate.
14. **CAPACITY** Blue Book Model # ____________ Cap ____________ EER	Look up the rated cooling capacity and EER for the air conditioner in the Carrier Blue Book. If the model number can not be found in the Blue Book, the capacity equals the model number nominal capacity rating. If using the model number nominal capacity or the Blue Book year is after 1984 the EER equals: Fan FLA ________ + Comp. RLA. ________ + 2.3 = Amps ________ Amps ______ X Volts _______ X .95 = Input ___________ Capacity _________ / Input _________ = EER ________
15. ________ Tons	Convert the cooling capacity to tons. Capacity / 12,000 = Tonnage
16.	Place a thermocouple at the outdoor unit to read temperature of air **entering the outdoor coil.** (Locate 1/2 up on coil & 3" from coil).
17.	Prepare thermocouples to measure temperatures in both the supply and return plenums.
18. _________ Grille #1 _________ Grille #2 _________ Grille #3 _________ Grille #4 _________ Total (B)	With the filters in and **after at least ten minutes,** measure every return grille flow with the flow hood and record the results. **DIVIDE THE GRILLES AND TAKE AT LEAST TWO READINGS AT EACH GRILLE. ADD THE SUM OF THE READINGS FOR EACH GRILLE.**

TECHNICIAN 1

19. **B** _____ Sup DB. **C** _____ Ret DB.	**At 15 minutes** record the supply and return plenum dry bulb temperatures.
20. **D** _____ Meter Kh **E** _____ # of rev **F** _____ Seconds	**INFORM CUSTOMER THAT YOU WILL BE SHUTTING OFF ALL OF THE POWER TO THE HOUSE.** Turn off ALL breakers except those to the air conditioner and the air handler. Measure the watts from the house meter by counting the number of revolutions of the disc. Clock for at least 90 seconds. **WHEN DONE WITH TEST TURN ALL BREAKERS BACK ON.**
21. _______°F.	Record the outdoor air temperature from the outside thermometer.
22.	Set the thermostat to the off position.
23.	Prepare for blower door and duct leakage tests by closing all exterior windows and doors and opening all interior doors.
24. **SHELL LEAKAGE** ________ House Pressure ________ Fan Pressure ________ True Fan Flow ________ Corr. Fan Flow Open A B Flow Ring	As soon as the blower door gauges are zeroed, T 2 will pressurize the house to 50 pascals. Record the house pressure, fan pressure, fan flow and flow ring configuration. If you are not able to pressurize the house to 50 pa. use the correction factors on the blower door fan control to determine the corrected fan flow. **SHUT THE BLOWER DOOR OFF.**
25.	With T 2s assistance cover all supply registers with paper and/or masking tape. Also cover all return grilles except the largest least restrictive return grille.
26. **DUCT LEAKAGE** ________ House Pressure ________ Ret. Grille Flow ________ Corrected Flow	Pressurize the house to 50 pa (WRT outside) with the blower door. As soon as the house is at 50 pa (WRT outside), <u>check every register seal to ensure an air tight seal</u>. Measure the flow at the return grille with the flow hood and record the results. **DIVIDE THE GRILLE AND TAKE AT LEAST TWO READINGS. ADD THE SUM OF THE READINGS FOR THE GRILLE TO GET THE DUCT LEAKAGE.** If the house can not be pressurized to 50 pa (WRT outside), adjust to highest house pressure possible. Use the correction factors table on the blower door fan control to determine the corrected flow.

TECHNICIAN 1

27. **DUCT PRESSURES** _______ S. Plenum Pres _______ R. Plenum Pres _______ S. Register Pres _______ R. Grille Pres	With the house still pressurized to 50 pa. measure the pressure in the supply and return plenums WRT outside and the pressure in the return grille and one supply register WRT outside. The supply register selected should be the one located the furthest from the air handler. The return grille should be the one used for the flow hood duct leakage reading.
28. **BUFFER PRESSURES** _______ Attic _______ Between Floors _______ Crawlspace	With the house still pressurized to 50 pa. measure and record the pressure in any zone that ducts are located. **The reference for this measurement should be the house.** Once all measurements have been made turn off the blower door.
29. ______ Sup. Pressure ______ Ret. Pressure	Record the pressures that T 2 measured as the normal system operating pressures.
30. **HALF NELSON** ______ S. Pressure ______ R. Pressure	Once the duct leakage tests are completed seal the opening of the return grille that was used for the duct leakage flow hood measurement. Perform the Half Nelson by turning on the fan switch at the thermostat. Record the return and supply plenum pressures. <u>Do not leave the fan on any longer than necessary.</u> Once test is completed turn off fan at the thermostat and uncover all supply registers and return grilles.
31. _______ **B**	Using the Half Nelson pressures measured in step # 30 divide the supply pressure by the return pressure to obtain **B**. Supply Pressure _____ / Return Pressure _____ = **B** _______
32. **Average Ret. Pres.** _______	Using the return system pressures from step # 27, calculate the average return system pressure during the duct leakage test. Return system average pressure equals: (_____ Ret. Plenum Pressure + ______ Ret. Grille Pressure) / 2
33. ______ **G**	Using the attached lookup table find the correct multiplier (**G**) by finding the number that corresponds to **B** on the vertical axis and the number that corresponds to the average return system pressure recorded in step # 32 on the horizontal axis. The correct multiplier (**G**) is determined by the point at which the row for **B** and the column for the average return pressure intersect.
34. ______ **H**	Using the attached lookup table find the correct multiplier (**H**) by finding the number that corresponds to the return system static pressure recorded in step # 29. If the number in **H** is not an exact match interpolate to determine the correct multiplier.

TECHNICIAN 1

35. **RETURN LEAKAGE** ________ CFM	Calculate the return system leakage by multiplying the total duct leakage measured in step # 26 times G times H. Return Leakage = Duct leakage ________ X G ______ X H ______
36. Total Flow __________ CFM / Ton __________	Using the information from steps # 18 and 35 calculate total system air flow. Total system air flow equals: ________ Return leakage + __________ Total grille flow = ________ Total flow Calculate Air Flow per Ton ________ Flow across coil ÷ ________Tons = ________ CFM/Ton

37.

TOTAL CAPACITY (H_T)

(C) _______ Ret dry bulb - (B) _______ Sup dry bulb = _______ Temp. Split

(A) _______ CFM X _______ Temp. Split X 1.08 = (H_T) _______ Btu/hr.

38.

ACTUAL INPUT

(D) (___ Kh X (E) ____ # of Revs. X 3600) ÷ (F) ____ seconds = ______ INPUT (Watts)

39.

ENERGY EFFICIENCY RATIO

(H_T)__________ CAPACITY ÷ _______ INPUT = _______ EER

40.	Use the attached EER chart to determine if the measured EER is adequate to justify allowing the house to participate in the project. **If the measured EER is below the corresponding line for the manufacturers rated EER inform the customer that their house can not be included in the project.** If the EER is too low discontinue the procedure at this point.
41. **INFILTRATION** _______ House Volume _______ N Factor _______ Min. CFM_{50}	Use the building volume and N factor information gathered by T 2 and the shell leakage information from step # 24 to determine if the house has adequate natural ventilation to allow air sealing. Minimum CFM shell leakage for natural infiltration is: 0.35 X (house volume) X N / 60
42. **TOO TIGHT** Yes No	Is the CFM_{50} measured in step # 24 below the minimum needed for the house? If yes, inform the customer that their house can not be included in the project.

TECHNICIAN 1

43. **Projected Shell Leak** _______ CFM_{50} Shell Reduction	Using the information from steps #24 and 41 calculate the projected CFM_{50} of the house if the shell leakage repair was completed. _______ Shell CFM_{50} - (______ Min CFM_{50} + ____ Duct CFM_{50}) X .6 = _______ CFM_{50} Shell Reduction
44. **Projected Duct Leak** _______ Duct CFM_{50}	Using the information from step # 26 calculate the projected CFM_{50} of the house if the duct leakage repair was completed. Projected CFM_{50} equals: ________ Duct CFM_{50} - 150 = ______ Duct CFM_{50} Reduction
45.	ICalculate the projected % of savings possible from sealing the house and ducts. Projected % of savings possible equals: If the house screens as being a good candidate for the continue. If not, discontinue testing at this point.
46. **FIREPLACE ZONE** ______ ΔP Zone 1 ______ ΔP Zone 2 ______ ΔP Zone 3 **PRESSURE RELIEF NEEDED?** Yes No	If a fireplace or wood stove is present, open the damper for the fireplace or wood stove and close all bedroom doors. If there is more than one fireplace or wood stove they must be tested individually (only open one damper at a time). Measure the pressure in the room containing the fireplace or wood stove (WRT outside). The ΔP must be -3 pa or less for fireplaces and -10 pa or less for wood stoves. If the ΔP is greater (more negative) than the limits above, the customer must sign the fireplace/wood stove zone pressure relief agreement form or they can not participate in the project.
47.	Open all interior room doors and close all fireplace and/or wood stove dampers.
48.	Return the thermostat to its original setting recorded in step # 6.
49.	While T 2 performs the combustion safety tests meet with the customer to report the results of the tests completed. Use the second portion of the attached customer certification sheet to complete the customer interview. If the customer gives permission for their home to be part of the project, get their signiture on the customer agreement form.

TECHNICIAN 1

50.	Once you have the customer agreement form signed, install the monitoring systems in the house. Install the Pacific Science & Technology CT Logger on the common wire of the compressor at the outdoor unit of the air conditioner. Ensure that: • The Logger has been reset (by pushing the reset button) • The AC current clamp is completely closed and the common wire of the compressor is being monitored. • The CT Logger is in the wiring junction box of the air conditioner or somewhere that it will not be exposed to the weather. • The CT logger display indicates the system is on when the air conditioner is turned on at the thermostat and indicates the air conditioner is off when turned off at the thermostat.
51.	Once the CT logger has been installed and checked install the ACR Temperature Logger inside the return duct, near the return grille. Ensure that: • The ACR Logger has had the correct time set on it and is set to read temperature in ° F. • The ACR Logger has been securely fastened in place so that its positioning will not change over the course of the next 16 months. • The remote temperature bulb for the ACR Logger has been securely fastened near the outdoor unit of the air conditioner and that it is reading the true temperature of the air entering the outdoor unit (no radiant gain). • The ACR logger indicates the correct temperature for both the return location and the outdoor location.
52.	Once the CT and ACR Loggers have been installed and their operation checked, spend some time trying to determine why this customer has high usage. Through visual observation of the house and asking questions of the customer, try to determine the reason for the customers high kWh usage. Record all pertinent information in the comments section of this form.

TECHNICIAN 1

COMMENTS

APPENDIX B: SCREENING PROCEDURE FORM 2

TECHNICIAN 2

SCE BLOWER DOOR PROJECT SCREENING PROCEDURE

Name ______________________________ Address ________________________________

1. REPAIRS NEEDED Yes No	While T 1 is talking with the customer, examine the house for major structural repairs that need to be made. If there are repairs needed that will affect the amount of cfm reduction we will be able to get, the house can not be included in the project.
2. ADEQUATE ACCESS Yes No	Check to make sure that there is access to both the attic and the duct system. If there is a problem with access to either of these and in your opinion you will not be able to get access (and therefore can't complete the sealing needed), then the house can not be included in the project.
3. NATURAL GAS Yes No	Check to make sure that the house is not supplied with natural gas. If there is natural gas supplied to the home for heating, the house can not be included in the project.
4. WINDOW AC Yes No	Check for the presence of multiple window air conditioners. If the house has multiple window air conditioners and has high summer cooling usage then the house can not be included in the project.
5. Clean Dirty Clogged	Check and record the condition of the HVAC system air filter. If the filter is clogged clean or replace it with a new filter.
6.	Unload all tools needed to complete testing on the house. This includes the Duct Blaster™, blower door, drop cloths, masking gun and tape, etc...
7.	Set up the flow hood in the configuration that best fits the return grille sizes and locations.
8. ______ Sup. Pressure ______ Ret. Pressure	Make holes in the supply and return plenums to measure temperatures and pressures. **THE SUPPLY PLENUM HOLE SHOULD BE LOCATED IN THE MIDDLE OF THE PLENUM. IT MUST BE DISTANT FROM THE COIL AS WELL AS WHERE THE AIR IS MIXED AND HAS GOOD VELOCITY.** Measure and record the normal system operating pressures in both plenums.
9. ____________ Door	Set up the blower door in a doorway that will not interfere with the air flow into the return grille. (Attach the 50′ green tube to the tube coming off the top blower door gauge).

TECHNICIAN 2

<table>
<tr><td>10. ________ Square Feet
________ Cubic Feet
________ N Factor</td><td colspan="5">Measure and record the square footage of the house. Use the average ceiling height to determine the volume of the house. Also determine the N factor of the building using the table below:</td></tr>
<tr><td rowspan="4"></td><td># of stories</td><td>1</td><td>1.5</td><td>2</td><td>3</td></tr>
<tr><td>Well Shielded</td><td>29.4</td><td>26.5</td><td>23.5</td><td>20.6</td></tr>
<tr><td>Normal</td><td>24.5</td><td>22.1</td><td>19.6</td><td>17.2</td></tr>
<tr><td>Exposed</td><td>22.1</td><td>19.8</td><td>17.6</td><td>15.4</td></tr>
<tr><td>11.</td><td colspan="5">Once T 1 is done with the air conditioner testing
<u>REMOVE ALL HVAC SYSTEM AIR FILTERS.</u></td></tr>
<tr><td>12.</td><td colspan="5">Remove the thermocouples from the plenums. Install and secure the static pressure probes in the supply and return plenums (with tubing into house) for pressure measurements.</td></tr>
<tr><td>13.</td><td colspan="5">Install tubing through attic access opening to measure pressures. Also install tubing between floors and into crawlspace if ducts run through those spaces.</td></tr>
<tr><td>14.</td><td colspan="5">As soon as T 1 has the house closed up for testing, zero the blower door gauges (with fan cover in place).</td></tr>
<tr><td>15.</td><td colspan="5">Pressurize the house to 50 pa. and report the pressure and flow readings to T 1.</td></tr>
<tr><td>16.</td><td colspan="5">Assist T 1 with covering all of the supply registers. Once all of the registers have been covered, assist T 1 in performing the duct leakage test by maintaining the blower door at 50 pascals.</td></tr>
<tr><td>17. Insulation Levels
______ Attic R-Value
______ Wall R-Value
______ Floor R-Value</td><td colspan="5">While T 1 completes the calculations and the fireplace/wood stove zone test, check and record the R-value of the attic, wall and floor insulation.</td></tr>
</table>

TECHNICIAN 2

18.	Record the duct location by percentage of total supply or return duct system.			
Duct Location by %	Supply Ducts	Insulated?	Return Ducts	Insulated?
Attic Space		Yes No		Yes No
Crawl Space		Yes No		Yes No
In Walls or Between Floors		Yes No		Yes No
Garage		Yes No		Yes No
Hall Platform		Yes No		Yes No
Garage Platform		Yes No		Yes No
19.	Once T 1 has completed the fireplace/wood stove zone test, perform the combustion safety tests if there are any combustion appliances in the house. Use the correct combustion safety test procedure to complete the testing.			
20.	Once the combustion safety test procedure has been completed assist T 1 with finishing the installation of the monitoring equipment and performing a detailed energy audit to find out the reason for the customers high energy usage.			

COMMENTS

APPENDIX C: "LEAK DETECTORS: EXPERTS EXPLAIN THE TECHNIQUES"

APPENDIX C: "Leak Detectors: Experts Explain the Techniques"

DUCT LEAKAGE DIAGNOSTICS

by John Proctor, Michael Blasnik, Bruce Davis, Tom Downey, Mark Modera, Gary Nelson, and John Tooley

If you have attended a national conference in the last two years you have been bombarded by a variety of duct leakage diagnostic techniques. Every year this field explodes with new ideas and methods. Individuals entering the field are overwhelmed by the wide variety of options available to enable effective duct sealing.

Each of the authors has invented a method of diagnosis for distribution duct leakage. This article is an effort to bring together the ideas of these innovators. It focuses primarily on PRODUCTION technology, that is, diagnostic tools that can be used in production distribution duct sealing programs designed to seal tens to thousands of systems per year. Other, more time consuming measurements exist for research purposes. The measurements from research tools, along with other factors, are used to predict energy use due to duct leakage.

Working on duct systems will often change the pressure distribution in a home, sometimes dramatically. These changes can effect combustion appliance drafting, Radon migration, moisture, ventilation, and indoor air quality. The diagnostic tools described should be used only by individuals testing for combustion safety, schooled in potential harmful effects, and practicing the precautions necessary.

Each of the diagnostic methods can be viewed as a new tool for our toolbox. Some of the tools will be used in special cases, while others will become the tool we reach for most often. These diagnostic methods can be classified as quantitative or qualitative.

QUANTITATIVE MEASUREMENTS

Under specified test conditions, these quantitative measurements provide numerical measurements of duct leakage (in cfm). They estimate neither the actual leakage from the ducts when the system is operating, nor the leakage across the leakage sites when all sites are at the same pressure. The purpose of a PRODUCTION quantitative measurement is to obtain quality work that will reliably impact energy use.

A good quantitative diagnostic tool has the following features:

- Repeatable results - so inspections will result in nearly identical readings.

- Accurate information - so work resulting in high energy savings is easily and immediately distinguished from work that has little or no effect. Technicians must be able to immediately distinguish effective work from ineffective work.

- Quick - so technician time is maximized and devoted to proper installation or repair of the distribution system.

With the wide variety of diagnostic tools available, investigators have noted substantial differences in the measured duct leakage between test methods. Variations between test methods are the result of differing pressures across the leakage sites (shown in Table C-1) and different tests measuring different leakage locations (leakage to inside, leakage to outside, or total leakage). These locations are illustrated in Figure 1.

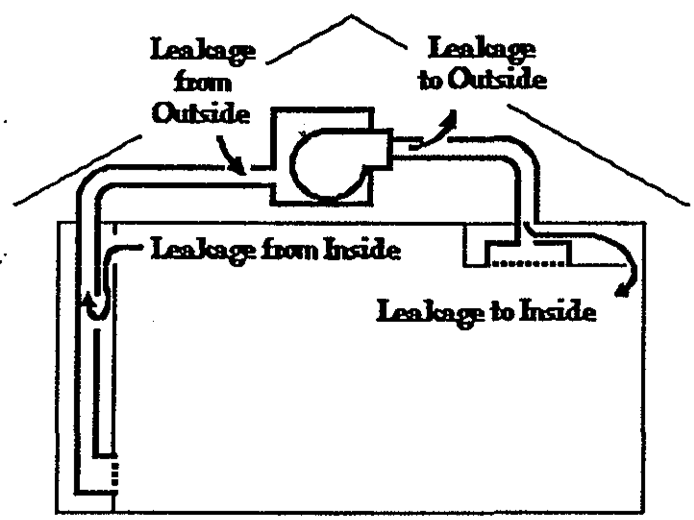


Figure 1. Duct Leakage Location Categories

Test Conditions

The more closely the test conditions match the normal operating conditions of the ducts, the more likely the test method will produce answers that reflect the energy effects of the duct sealing. Ideally both flow and pressure would be duplicated in the test procedure.

If duct leaks are evenly distributed throughout the system, the pressures in the system are distributed in a manner similar to Figure 2. Leakage location and location of the filter substantially influence the actual pressure distribution. The highest pressures occur at the supply and return plenums. The return system is under negative pressure while the supply system is positive. Reference pressure for the test must be specified as well.

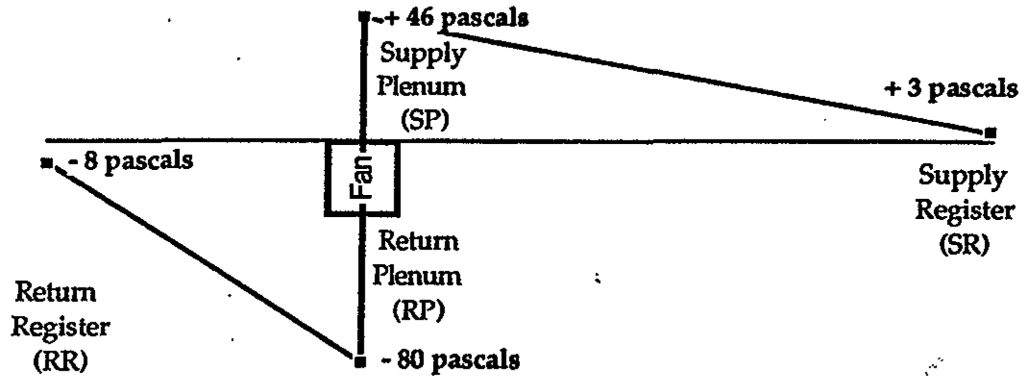


Figure 2. Idealized Duct Pressure Distribution in Normal Operation

Since the early testing was an expansion of blower door testing, the first test pressures were 50 pascals. There is now a trend toward more accurate pressure measurement (multiple duct locations with a digital manometer) and lower test pressures such as 25 pascals (.10" water column).

Measured operating pressures are helpful in interpreting the results of the quantitative duct leakage tests.

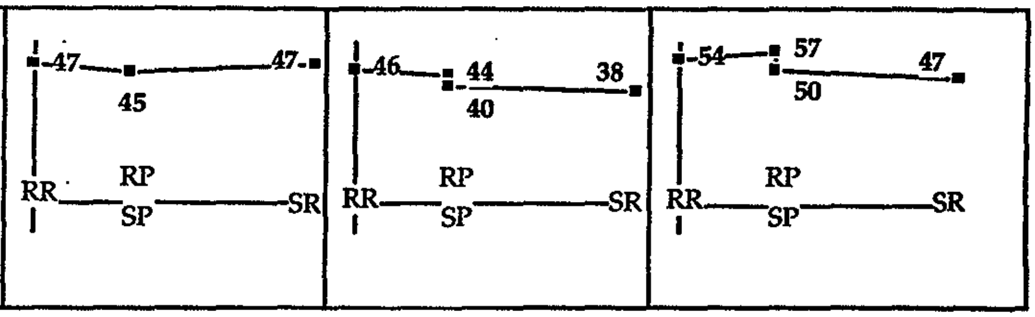
Primary Quantitative Methods

The three primary quantitative methods used to measure flow through leaks (at a test pressure) are: Blower Door Subtraction, Blower Door and Flow Hood, and Duct Blaster™. Their features of these are listed in Table 1. Other quantitative methods are used primarily for research, these include: Tracer Gas, Tracer Temperature, and combined STEM™ / FAST™ testing. Tracer Gas measures leakage and both Tracer Temperature and the STEM™/FAST™ combination measure the energy effect of duct leakage and duct conduction.

Table 1. Quantitative Duct Leakage Tests

Test	Subtraction	Flow Hood	Duct Blaster™
Equipment	Blower Door	Blower Door and Flow Hood	Combined Duct Pressurization and Flow Device
Advantages	• Inexpensive - only one piece of equipment required • Good control over duct pressure • Measures only leakage to outside	• High certainty on flow rate • Measures only leakage to outside	• Inexpensive - only one piece of equipment required • Duct pressures well controlled and pressure distribution closest to normal operating mode (except return is pressurized) • Measures low flows accurately • Measures total duct leakage • Can be used on houses before drywall is installed
Common Disadvantage	Does not duplicate operating pressure distribution or flow, resulting in under/over estimation of leakage at various points in the system		
Dis-advantages	• Low repeatability under windy conditions or on leaky homes • Inaccurate for low flows • Large piece of equipment • Cannot test ducts before drywall is installed • Overemphasizes leaks near the registers	• Less control over duct pressure • Requires two pieces of equipment • Cannot test ducts before drywall is installed • Overemphasizes leaks near return registers	• Requires a blower door to measure leakage to outside • Overemphasizes leaks near registers to a lesser degree than the other two tests

Idealized Test Pressure Distribution



<u>Blower Door Subtraction Method</u>

The blower door subtraction method estimates flow through duct leaks to outside with the house at 50 pascals. Either pressurization or depressurization tests are roughly equivalent (see Modera article in this issue). These will both be referred to as "pressurization". This method uses two blower door flow readings to determine the amount of duct leakage. The house is pressurized with a blower door to obtain the total leakage of the structure including the duct leaks. All duct openings are then covered and another blower door reading is taken. Both tests are done with the house to outside pressure differential of 50 pascals. The total leakage of the second test is subtracted from the total leakage of the first test yielding the duct system leakage.

Two significant errors are introduced using this method. First, the blower door is measuring relatively large flows (whole house leakage with and without ducts at 50 pascals). Small percentage errors in these readings become large percentage errors when applied to the duct leakage (typically 10% to 20% of total house leakage) Second, the method assumes that all of the leakage from the ducts to outside is eliminated when the registers are sealed. If there is any leakage at the registers, or any other leakage from the house to the duct system, this assumption is incorrect.

The first flaw is the critical one. An error of 5% in only one of the blower door readings (due to operator error or wind effects) becomes a 50% error in duct leakage for a system with 10% of the house leakage in the ducts. For example, if the initial test shows a leakage of 3000 CFM50 (which is 150 CFM low), and the second test shows 2700 CFM50 with no error, the estimated duct leakage is 300 CFM. The true difference however, is 450 CFM (150% of the estimate).

The second flaw can be overcome. Using the method developed by Michael Blasnik of GRASP (Blasnik and Fitzgerald, 1992), the error due to leakage from the house to the ducts can be estimated. This method is explained under Leakage Ratio Tests.

Flow Hood Method

The flow hood method estimates flow through duct leaks to outside with the house at 50 pascals. One variation of this method is to bring the ducts near the return grille to 50 pascals relative to outside.

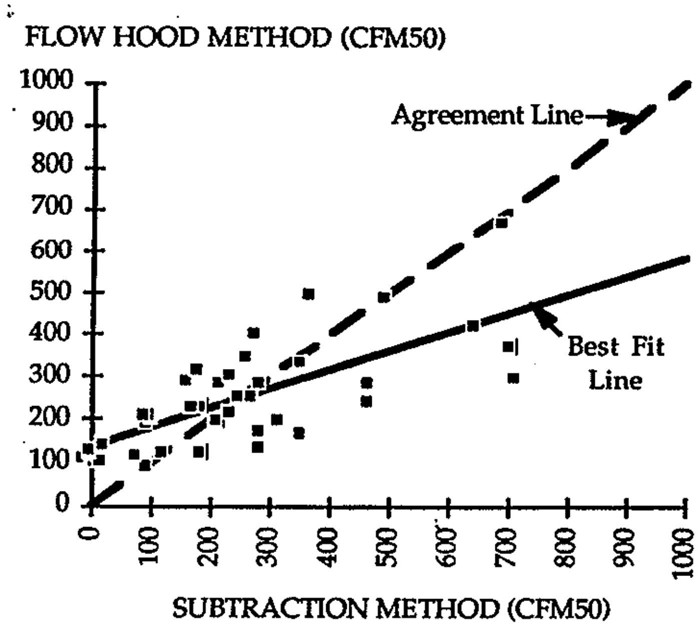
During the test all registers except the largest, least restricted location are blocked. The house is pressurized (or depressurized) to 50 pascals relative to outside and the flow hood is used to measure the amount of air flowing through the open grille. Any flow through the flow hood into the grille must be duct leakage to outside.

A number of potential errors are introduced using the flow hood method. First, the pressures at the leakage sites are more variable than with the subtraction method. Second, not all the leakage from the ducts flows through the flow hood. Some of the leakage to outside flows through gaps around the registers and other communication locations between duct and house. This effect is the same as was noted in the subtraction method. However the effect is much smaller since the open grille provides a preferred (lower resistance) flow path. This will result in lower leakage measurements than actually occur during the test.

The flow hood directly measures the flow through the open grille during these tests, rather than inferring it from two larger measurements as in the subtraction method. Pressures applied to the duct system with this testing method are usually lower than those applied by using the blower door subtraction or the Duct Blaster™ methods. The flow hood method measures flow more accurately but due to restrictions within the duct system and duct leakage a higher uncertainty about pressures is introduced. Traveling from the open grille, pressure is lost as restrictions or duct leakage are encountered.

The ability of this method to estimate leakage flow at uniform test pressure is largely determined by how well the average pressure across leaks is estimated. If based on a series of pressure measurements, such as at a number of blocked grilles as well as at the plenums, the accuracy will improve. Once a determination of the leakage and pressure is made, the leakage at any other pressure can be estimated as shown in the sidebar.

The subtraction method and the flow hood method measure leakage at different pressures, therefore the results are not directly comparable. Figure 3 shows the relationship between the two tests when no corrections are made for leakage from the house to the ducts or for different pressures. The flow hood measurement measures higher leakage than the subtraction method on tight systems and lower leakage on loose systems. This data is from tests conducted by Proctor Engineering Group on 42 houses.



Flow Hood CFM50 = 134 + .45 x Subtraction CFM50

Figure 3. Subtraction Method Results vs. Flow Hood Results

Duct Blaster™ Method

The Duct Blaster™ measures the flow through the ducts to leaks both inside and outside the house (total duct leakage). Measurements are taken with the Duct Blaster™ attached at the blower compartment of the air handler or attached to the return grille. During these tests all registers are covered and the Duct Blaster™ flow is adjusted to create a reference pressure (usually 25 pa.) in the supply plenum or the nearest connected supply grille.

Potential errors using this method are more limited than the other two methods. One source of error continues to be the variability of pressures across the leakage sites. Other errors are operator error, location of the reference pressure probe, and variations in how the seals at the register perform pressurized and not pressurized.

Pressure variations increase due to restrictions such as a coil, blower, or small duct work. Pressure variations are also effected by large leakage sites. When the Duct Blaster™ is installed at the blower compartment, the pressure variations across the leakage sites are less than with the flow hood because of any restriction in the return system. The blower compartment door is preferred because it reduces the possibility of restrictions or leaks in the return system from influencing the leakage readings. As with the flow hood, a series of pressure measurements at different locations in the duct system reduce the effect of pressure variation errors.

Operator error can be reduced by digital time averaged measurements (of five seconds or longer), proper training and quality assurance, as well as step by step procedures.

The Duct Blaster™ measures the total duct leakage (leakage to inside plus leakage to outside). In order to determine the leakage from the ducts to outside the house a house pressurization test has to be performed. The most common method of measuring the leakage to outside (Blaster/Blower Door) is to first bring the house to a specified pressure with the blower door. Then, by adjusting Duct Blaster™ flow, the reference location in the ducts is brought to zero pressure differential with respect to the house. If the pressure in the ducts is uniform, all the flow through the Duct Blaster™ is leakage to outside. Another method known as the Blasnik method, described in Leakage Ratio Tests, can also be used.

In a small series of tests, the Blasnik method and the Blaster/Blower Door methods of estimating leakage to outside gave similar results. This continues to be investigated.

LEAKAGE RATIO TESTS

Leakage ratio tests provide technicians with a rapid method of estimating what portion of the leakage can be assigned to different areas. While initially this may sound simple, it is quite complex. Between floors for example is not necessarily "inside" the actual building pressure envelope. When tested with a blower door, basements may be more inside or more outside the pressure envelope. The effect of duct leakage in these spaces is only now under investigation. As these effects are further characterized knowing what portion of the leakage occurs there will become more important.

The features of a good leakage ratio tool are the same as a good quantitative tool and the tool should be faster than measuring both of the leakages that make up the ratio.

Primary Leakage Ratio Tests

The two primary ratio test methods are the Blasnik and the "Half Nelson". The first quantifies the relationship between the leakage to inside and the leakage to outside. The second estimates the ratio of supply leakage areas to return leakage areas. Table 2 lists the characteristics of these two tests.

Table 2. Leakage Ratio Tests

Test	Blasnik	"Half Nelson"
Estimates	Ratio: duct leakage area to house / duct leakage area to outside	Ratio: supply duct leakage area / return duct leakage area
Equipment	Blower Door and Micro-manometer	Micromanometer
Advantages	• Fast once the registers are sealed and blower door installed • Can be used to convert total leakage to leakage to inside and leakage to outside	• Inexpensive - only one piece of equipment required • Fast once the registers are sealed • Can be used to convert system leakage to supply and return leakages (which have differing energy effects)
Common Disadvantage	• Is based on assumption that flow exponent is .65 and duct test pressures are uniformly distributed	
Disadvantages		• Should not be used on duct board systems since they are held together with tape and high pressures will damage them

Using the Blasnik Method: Inside/Outside Split

The Blasnik method is a valuable way of determining the proportion of duct leakage to outside versus inside. With a blower door pressurizing the house to 50 pascals, two pressure readings are taken: pressure of the duct relative to the house ($P_{D\text{-}H}$) and pressure of the duct relative to outside ($P_{D\text{-}O}$). The ratio of the leakage between the duct and the house ($Q_{D\text{-}H}$) and the leakage between the duct and the outside ($Q_{D\text{-}O}$) when the duct is under pressure is computed as shown in the sidebar.

This procedure is part of a method of estimating leakage flows without the use of a flow hood or Duct Blaster™. The method adds a hole of known size to the duct system and by calculation estimates leakage. This tool is further described in Blasnik and Fitzgerald.

Using the Half Nelson: Supply/Return Split

The effect of supply leakage and return leakage on energy use is different. It is advantageous in estimating the energy effect of duct leakage to know how much of the leakage is in the supply and how much is in the return. The "Half Nelson" is a fast method which estimates the ratio between the total supply leakage area and the total return leakage.

With all the registers sealed the air handler is turned on and the pressures in the supply (P_S) and return (P_R) plenums are measured. The ratio of the total supply leakage area (A_S) to the total return leakage area (A_R) is estimated as shown in the sidebar.

There are risks with this method. The test starves the blower motor for cooling air and should not be continued over a long period of time. It cannot be used immediately after repairs since the high pressures generated will "blow out" uncured mastic. In addition John Tooley warns that duct board systems can be damaged under these high pressures.

This procedure is part of a method of estimating leakage flows without the use of a flow hood, Duct Blaster™, or blower door. The method (the "Full Nelson"), like the Blasnik method, adds a hole of known size to the duct system and calculates a leakage estimate.

Supply/return split can also be measured by conducting separate tests on both sections of the system with a blockage placed at the blower.

QUALITATIVE MEASUREMENTS

Qualitative measurements provide technicians with a method of rapidly assessing the areas of largest leakage and quickly checking on progress.

The features of a good qualitative assessment tool are:

- The tool provides clear and unambiguous direction for the technician.

- The tool consumes as little time as possible to maximize technician time devoted to proper installation or repair of the distribution system.

Primary Qualitative Methods

The three primary qualitative methods are: Smoke Stick, Pressure Pan, and Register Pressure. The features of these methods are listed in Table 3. Other qualitative methods include: Tactile Flow Test, Visual Observation, and Blocked Return Test.

Table 3. Qualitative Duct Leakage Tests

Test	Smoke Stick	Pressure Pan	Blocked Register Pressure
Equipment	Smoke Stick and Blower Door	Pressure Pan and Blower Door	Duct Blaster™
Advantages	• Fast once the Blower Door is set up	• Fast once the Blower Door is set up • Gives a numeric reading that relates to proximity and size of leak • Can be completed without taping registers • This method can be a quick stand in for measured CFM	• Fast once the Duct Blaster™ is set up and registers taped • Gives a numeric reading that relates to proximity and size of leak • Can be completed without removing tape from registers
Disadvantages	• Requires more judgment (is more ambiguous) than the other two methods	• Once the registers are taped, it requires removing the tape	• Requires that the registers be taped • Less descriptive than the Pressure Pan

Smoke Stick Method

Like the subtraction method, the smoke stick is an extension of blower door technology. With the blower door pressurizing the house by 10 to 15 pascals, smoke released near a register will be more aggressively pulled into a register that has a major leak in that branch than a register that is distant from the larger leaks. Careful observation will often pinpoint leaks at sheet rock to boot, etc.

Pressure Pan

The pressure pan is a shallow pan (like a rectangular cake pan) that will cover and seal the supply or return register. The pan has a pressure tap that senses the pressure at the register when it is blocked off. Natural Florida Retrofit produces a prebuilt pressure pan and flow estimation device.

With the house pressurized to 50 pascals by the blower door, the pressure drop across the pressure pan when it blocks the register, is recorded. If the pressure drop is less than half a pascal, any duct leaks are distant to that location. A larger pressure drop at one register (2 to 5 pascals) indicates that a large leakage site is near the location.

The pressure pan method is beneficial in prioritizing the attack on duct leakage sites, it can "see" leakage sites that are hidden in walls and under floors, and it provides a rapid check on progress.

The pressure pan method is described in more detail in the March/April 1992 issue of Home Energy (page 17).

Blocked Register Pressure

The blocked register test is an extension of the pressure pan technique, usable while the registers are taped shut. With the ducts pressurized by the Duct Blaster™, the pressure drop across each taped register is measured by inserting a small probe. The register with the lowest pressure drop is near a large leakage site. If a few registers show low pressures relative to the remaining ones, it is likely that a significant leak exists near the branch of ducts.

This method is less descriptive than the pressure pan.

CONCLUSION

The duct technician's "tool box" should contain a wide variety of diagnostic procedures to be used as conditions dictate.

Quantitative leakage measurement is best conducted with the Duct Blaster™ (and a blower door, if leakage to outside is required). The authors, with one exception, also see the blower door and flow hood as a useful method.

The ratio methods are helpful since they estimate the leakage to particular areas.

To check the integrity of the duct system if a blower door is in place, the pressure pan method is suggested.

The blower door subtraction method is generally not suggested. It has the highest variability of the three quantitative methods described and provides weak feedback to the technicians sealing the duct system. The crew could be very successful at sealing the duct system but would not see it indicated.

REFERENCES:

Blasnik, M. and J. Fitzgerald. "In Search of the Missing Link". *Home Energy* , November/December 1992

Modera, M., "Residential Duct System Leakage: Magnitude, Impacts, and Potential for Reduction". ASHRAE *Transactions* , V.95, Part 2.

Davis, B. "Pressure Pan Takes the Cake" *Home Energy* , March/April 1992.