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Pacific Gas & Electric Model Energy Communities Program Air Flow & Duct Leakage Comparative Study

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PG&E

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Creators of CheckMe!®

I. Introduction

The Pacific Gas & Electric (PG&E) Model Energy Communities (MEC) Program commissioned Proctor Engineering Group to complete the Air Flow & Duct Leakage Comparative Study to evaluate the existing technologies available for measuring air flow and duct leakage of residential air conditioning systems.

The MEC program is currently implementing the Residential Air Conditioning Early Replacement (RACER) component of the program. The success of RACER depends on reducing the size of the air conditioner on the home to the smallest practical size and insuring it is operating at its designed efficiency. As a result, PG&E representatives must obtain accurate duct leakage data for use in the sizing calculation. In addition the full capacity and efficiency of the new unit depend on having proper air flow through the indoor coil.

The PG&E Model Energy Communities (MEC) Program desired to accomplish three objectives through this study:

1. Estimate the accuracy of available methods for measuring air flow through the indoor coil
2. Estimate the accuracy of available methods for measuring duct leakage.
3. Compare the time requirements and ease of use for the various methods of measurement.

This study was not designed to provide statistically valid information on the accuracy of the various methods, but rather to give PG&E an indication of which method holds the most promise for ease of use and reliability in field use.

II. Methodology

SAMPLE SELECTION

PG&E selected three houses typical of the housing stock being addressed by the MEC Program. Proctor Engineering together with a representative of PG&E and DMC Services completed site visits to each of the houses selected. Extensive data was gathered during both air flow and duct leakage testing.

Site number one is a single story ranch style home located in Oakley, California. It is equipped with a 30,000 BTU Carrier outdoor condensing unit and a 50,000 BTU Carrier up-flow gas fired furnace. The air handler is located in a hallway closet. All supply ductwork is located in a vented attic space. The return system is comprised of a small platform plenum located directly below the air handler. The ductwork in this home had been addressed by a duct sealing crew from the program.

Site number two is a two story home located in the Discovery Bay region of Byron, California. It is equipped with a 47,000 BTU Heil outdoor condensing unit and a 75,000 BTU Carrier down-flow gas fired furnace. The air handler is located in the garage. The supply ductwork is located in a vented crawl space and between the first and second floor of the home. The return system consists of a small building space plenum located beneath the stairs to the second floor and a rigid duct connecting to the return plenum on the air handler. The ductwork in this home had been addressed by a duct sealing crew from the program.

Site number three is a single story ranch style townhouse located in Antioch, California. It is equipped with a 22,500 BTU Rheem outdoor condensing unit and a 50,000 BTU Rheem up-flow gas fired furnace. The air handler is located in a hallway closet. All supply ductwork is located in a vented attic space. The return system is comprised of a small platform plenum located directly below the air handler. The ductwork in this home had not been addressed by a duct sealing crew from the program.

TEST EQUIPMENT

The equipment used during this study includes both equipment currently in use and equipment under consideration for use in the program. The back pressure compensated flow hood used was the Shortridge Instruments 8400 Series equipped with the Shortridge Instruments ADM-850 Electronic . The Shortridge Instruments ADM-850 Electronic Micro-manometer was used for all static pressure, pitot tube, and Duct Blaster™ flow pressure measurements. The Duct Blaster™ used was a beta test model supplied by The Energy Conservatory. The steady state efficiency testing of the gas furnaces was accomplished with the use of a Universal Enterprises C5A digital oxygen analyzer and a Bacharach Monoxor II digital carbon monoxide analyzer.

Temperature measurements were taken with a Fluke Model 52 digital thermometer equipped with Omega Technologies beaded probe type J thermocouples.

TEST PROCEDURES

A total of seventeen separate air flow and duct leakage tests were run on each residence visited. In addition during each of these tests static pressure readings were taken at various locations throughout the system. A total of twenty sets of pressure readings were taken on each system.

All of the tests run followed a consistent procedure to ensure comparable data. Each pressure measurement was determined by recording the average of three separate time averaged readings. Great care was taken in acquiring all of the pressure measurements to ensure the tests were accurately repeated. All static pressure probes and pitot tube placements were left undisturbed for the duration of all testing.

Table A lists the tests that were performed and the measurements taken on each of the houses visited.

Table A Test Procedures

Test	Test Method	Measurements Taken
Coil Air Flow	Steady State Efficiency Temperature Rise Method	Gas meter flow Supply - Return temperature differential Net flue gas temperature Flue Gas O_2 content Flue Gas CO content
Coil Air Flow	Flow Hood Method	BPC split grill reading Filter in vs. filter out air flow
Coil Air Flow	Duct Blaster™ Method	Supply plenum pressure Fan flow pressure
Whole House Leakage	Blower Door Test	Single point blower door reading
Duct Leakage	Blower Door Subtraction Method	Split system closed supply register single point blower door test Split system closed supply & return registers single point blower door test

Duct Leakage	Flow Hood Method (with blower door)	Split system supply register flow Split system return register flow Total system return register flow
Duct Leakage	Duct Blaster™ Method	Five point supply only flow Single point supply only flow w/ both house & supply at 50 pa Five point return only flow Single point return only flow w/ both house & supply at 50 pa Five point total system flow Single point total system flow w/ both house & supply at 50 pa

The following measurements were performed during each of the tests in Table A. In all, a total of twenty separate pressure reading sets were completed on each house.

- Supply & return plenum pressures
- Air handler blower compartment pressure
- Supply register pressures (At every register)
- Return grill pressures
- Supply system pitot tube readings (Air flow tests only)

III. Discussion

COIL AIR FLOW

The site visits examined three methods of air flow measurement. The three methods tested were:

1. Steady State Temperature Differential
2. Back Pressure Compensated (BPC) Flow Hood
3. Duct Blaster™

In these tests all air flows were measured with a dry indoor coil due to the low outdoor temperature. When measuring air conditioner system air flow during the summertime the system should first operate to condense water on the indoor coil.

Steady State Efficiency Temperature Differential Method

The SSE test method consists of measuring the Btu input of the system airstream and the temperature differential created by the introduction of that energy into the airstream. In order to determine the true cfm air flow with the SSE method it is necessary to for the furnace to reach a nearly constant temperature differential (steady state condition). With electric resistance heat this takes place fairly rapidly. The majority of heating systems in the Model Energy Communities project area however, have gas fired furnaces. With gas fired furnaces reaching the steady state condition can take upwards of 30 minutes which wastes the time of the person performing the test and can cause an inconvenience to the customer.

In addition to time considerations and customer inconvenience this test methodology has numerous potential errors that can be introduced into the calculations. The inaccuracies reflected in these measurements are due mainly to operator error possibilities. There is potential for error in the many measurements required for this testing procedure including: clocking the meter, flue gas O_2 concentration, flue gas temperature, mixed return temperature and mixed supply temperature.

Temperature sensing location is the most critical of all factors with the SSE method. Even with great care it is easy to obtain readings that do not truly reflect the actual delivery temperature of the system. Tests of this type with electric resistance heat (such as those performed on heat pumps) are more reliable than on systems with gas combustion, but still prone to a higher margin of operator error than either the flow hood or Duct Blaster™ methods.

Flow Hood Method

The flow hood method consists of measuring the flow through the return grills and adding in the return system leakage (which can add a significant amount of air to the total flow through the coil). This requires the additional task of measuring the duct leakage and adjusting the result to reflect actual operating (rather than test) pressures. Two methods of obtaining return system leakage were used on these houses, the blower door/flow hood method and the Duct Blaster™ method. These methods are described elsewhere in this report.

The Shortridge flow hood utilizes a sixteen point pressure sensing grid to sense both total pressure and static pressure. These pressures are spaced across a known area in the flow hood. The sensed pressures are averaged to a single velocity pressure, which is transmitted to the meter for conversion to an air flow readout. This instrument has a specified accuracy of ±5% of the reading ±5 cfm. (Shortridge, 1988) Since the addition of a flow grid and a restricted (known) area will result in some reduction in air flow, this piece of equipment has a back pressure compensation feature to estimate the flow without the flow hood in place. In theory, this should produce an accurate flow measurement of air through the return grilles.

There has been substantial discussion of the applicability of the back pressure algorithm to residential return systems. Based on a November 1992 personal communication with Ernest Shortridge, these tests utilized the back pressure compensation feature while measuring half of the return grille at a time. The total flow was estimated to be the sum of these two measurements. In a study for the Salt River Project, Cynthia Kuenki (Kuenzi and Wood, 1987) concluded that the back pressure compensation feature resulted in significant overcompensation by 10% to 30% of the air flow for residential supply systems.

In addition to potential back pressure compensation problems, the flow hood requires an adequate seal between the hood and the grille, a requirement that is sometimes difficult to accomplish. If this seal is compromised, the back pressure compensation is certainly invalid.

Besides a possible bias towards high air flow readings the main draw back of the flow hood in measuring coil air flow is the need to obtain true operating system return leakage in order to determine the correct air flow.

Duct Blaster™ Method

The Duct Blaster™ consists of a combined flow inducing device (fan) and a flow measuring device, not unlike a blower door. The Duct Blaster™ method of measuring coil flow consists of first measuring the supply plenum pressure downstream of the coil under actual operating conditions. The return system is then blocked off at the air handler blower compartment to force all of the air passing over the indoor coil to come through the Duct Blaster™. The Duct Blaster™ is attached to the air handler blower compartment opening and both the air handler and the Duct Blaster™ are turned on. The Duct Blaster™ fan speed is adjusted to bring the static pressure in the supply plenum to the pressure normally experienced by the system. This system is using the supply system restriction (which is unchanged at the same flow) to bring the flow through the flow measuring device to the same value as normal coil air flow.

The Minneapolis Duct Blaster™ utilizes the pressure drop created by air flowing across the precision fan opening to determine the air flow. They use the ASTM method for calibration which results in a specified accuracy of ±3% with an accurate digital pressure guage. The calibration independent on fan rpm. In theory, this device should produce an accurate flow measurement of the air through the blaster into the air handler cabinet.

The basic measurement method has been examined through the course of blower door development and is widely accepted. The primary sources of error in this measurement come from operator errors in sealing the air handler cabinet from the return system, the measurement and duplication of supply plenum pressure, and the measurement of the flow pressure. With time averaging of pressures and care in isolating the cabinet from the return system, this method should be accurate for systems with inside coils. The greatest advantage of this method is that it eliminates the uncertainty associated with estimating the return system leakage.

The primary question is whether or not this method actually duplicates the undisturbed system flow. To investigate that question we compared pressure readings at all the supply registers (5 to 11 locations) with the system in normal operation, and when the Duct Blaster™ duplicated the supply plenum pressure. A single pitot tube reading in a supply run was also compared for two of the locations. The results are shown in Figure 1. Figure 1 also shows the same measurements for the systems with the filter removed

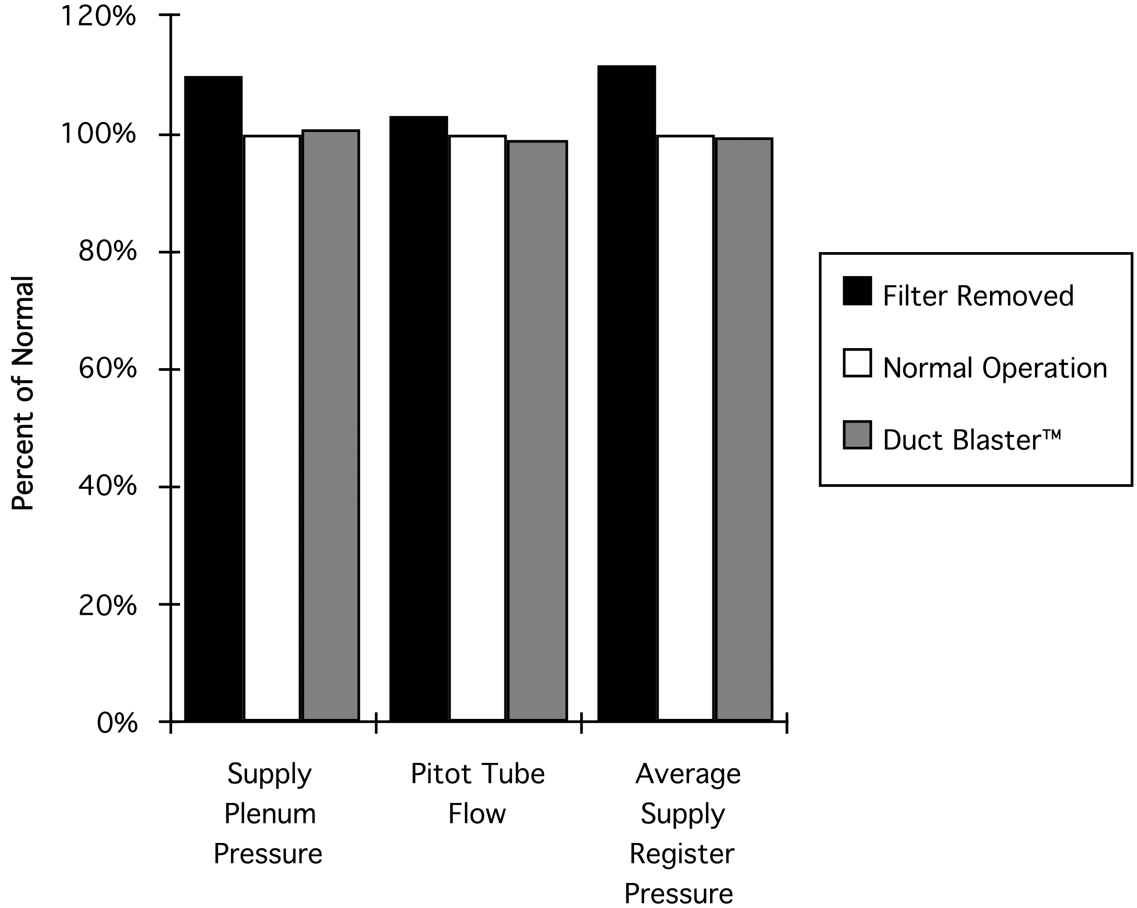

Figure 1 Pressure and Flow Duplication - Normal Operation vs. Duct Blaster™

The static pressure and pitot tube readings confirmed that the Minneapolis Duct Blaster™ was correctly duplicating normal operating conditions.

The supply plenum pressure should be equal in the normal operation and Duct Blaster™ operation. The small difference in measurements during testing represents the ability of the operator to duplicate the same reading. The time averaged readings indicate an average error of 1%.

Effect of Removing Air Filter

As shown in Figure 1, removing the filter from the system increases the airflow through the system. The average increase in airflow due to filter removal on these houses was 80 cfm. All three houses were tested with clean filters. If the system filter is dirty or clogged and removed for air flow testing the size of the induced error would be larger.

Coil Air Flow Test Comparison

The air flow through the air handler was compared for the three air flow measurement methods tested on each house. The measured air flows are recorded in Table B.

Table B - Air Flow Test Method Comparison

	Duct Blaster™ Airflow	SSE Method Airflow	Flow Hood Airflow w/ Leakage
House # 1	1069 CFM	1005 CFM	1242 CFM
House # 2	1154 CFM	1272 CFM	1174 CFM
House # 3	731 CFM	850 CFM	772 CFM

Based on the error analysis above, the Duct Blaster™ air flow is assumed to be the most accurate. In order to compare the other methods to the Duct Blaster™ method table C was prepared. It lists each method as a percentage of the Duct Blaster™ measurement.

Table C - Air Flow as Percentage of Duct Blaster™ Measured Air Flow

	Duct Blaster™ Airflow	SSE Method Airflow	Flow Hood Airflow w/ Leakage
House # 1	100 %	94 %	116 %
House # 2	100 %	110 %	102 %
House # 3	100 %	116 %	106 %

The steady state efficiency method is both too time consuming and has too many sources of error to be considered for general use. In comparing the flow hood with the Duct Blaster™, it is clear that either the flow hood measurements are biased high, or the Duct Blaster™ is biased low. (Some of each bias is also possible.) This bias is evident even before the operating return system duct leakage is added to flow hood measured flow at the return grill. Based on previous work and the analysis above, we believe that most of the bias is probably in the flow hood measurement. If any bias is introduced by the Duct Blaster™ it is probably a calibration error which can be corrected.

DUCT LEAKAGE

The site visits examined three methods of duct leakage measurement. The three methods tested are:

1. Blower Door Subtraction
2. Blower Door and Flow Hood
3. Duct Blaster™

During all duct leakage testing, the air filters were removed and the registers were blocked with masking paper and tape.

It has been a concern to investigators that the duct leakage numbers varied significantly from test method to test method. Based on theoretical considerations, Proctor Engineering Group suspected that much of that variation was due to different pressures generated across the leakage sites. With the flow and pressure information gathered during these tests, we were able to confirm that suspicion.

Blower Door Subtraction Method

The blower door subtraction method estimates flow through duct leaks to outside with the house at 50 pascals. This method uses two blower door flow readings to determine the amount of duct leakage. In this test the house is pressurized with a blower door to obtain the total leakage of the structure. All duct openings are then covered and another blower door reading is taken. Both tests are done with a 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. The blower door subtraction method was used for both whole system duct leakage and split system duct leakage (with a divider installed between the return and supply) on all three houses tested.

The blower door subtraction method does a good job of pressurizing the majority of the duct system to near 50 pascals with all of the registers open.

The blower door subtraction method introduces two significant errors. First, the blower door is measuring relatively large flows (whole house leakage ± 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 there is any other leakage from the house to the duct system, this assumption is incorrect.

The first flaw is the fatal 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. Two of the houses measured in this study had no change in blower door fan flow and one house had increased flow through the blower door fan when the duct openings were covered. Great care was taken to get correct readings with the blower door. However, these tests were run on windy days which are typical of the Sacramento Delta area.

The second flaw can be overcome. With the data gathered, Proctor Engineering examined an approach for determining duct leakage to outside developed by Michael Blasnik of GRASP (Blasnick and Fitzgerald)

Relating Duct Leakage to Inside with Duct Leakage to Outside

Even though the blower door subtraction method provided inaccurate duct leakage measurements on all three houses, these tests did indicate that use of the blower door (or the Duct Blaster™ in a window) with the registers covered and an additional pressure test is valuable for determining the proportion of duct leakage to outside versus inside. Based on Blasnick (ibid), the following test and calculation is performed. With the registers sealed and the house pressurized a pressure reading is taken in the duct system. The following equation estimates the relationship between leakage area to outside and leakage area to inside.

$$(P_2 / P_1)^{.65} = A_1 / A_2$$

Where:

P_1 = Pressure of duct relative to house

P_2 = Pressure of duct relative to outside

A_1 = Leakage area house to duct

A_2 = Leakage area duct to outside

There are numerous assumptions in this calculation. Accuracy of this estimation depends largely on determining a pressure that represents the average test pressure across the duct leaks.

If the total duct leakage has been measured (by a method such as the Duct Blaster™), the following calculation estimates the leakage to outside:

$$Q_4 = Q_3 * P_1^{.65} / (P_2^{.65} + P_1^{.65})$$

Where:

Q_3 = Measured total duct leakage (cfm)

Q_4 = Duct leakage to outside

Flow Hood Method

This method has been used for testing duct system leakage on all houses tested throughout the duration of the Model Energy Communities Program. This method estimates flow through duct leaks to outside with the house at 50 pascals.

During the test all registers except the largest least restricted location are blocked. The house is pressurized 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. The flow hood method was used for both whole system duct leakage and split system duct leakage (with a divider installed between the return and supply) on all three houses tested.

The flow hood method introduces a number of potential errors. First, the pressures at the leakage site is more variable than with the subtraction method. Second, the method assumes that all of the leakage from the ducts to outside flows through the open register. If there is any leakage at the registers, or there is any other leakage from the house to the duct system, this assumption is incorrect.

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 introduces a higher uncertainty about pressures. This is due to restrictions within the duct system and duct leakage. Traveling from the open grille, pressure is lost as either restrictions or duct leakage are encountered.

The accuracy of this method is largely determined by how well the average pressure across leaks is estimated. If based on a series of pressure measurements (such as at number of blocked grilles as well as at the plenums, the accuracy will improve. The leakage at a reference pressure (such as 50 pascals) can be computed from the measured leakage and estimated test pressure with the following:

$$Q_r = Q_t * (P_r / P_t)^{.65}$$

Where:

P_r = Reference pressure for duct leakage

P_t = Average test pressure

Q_t = Measured duct leakage (cfm) at average test pressure

Q_r = Duct leakage (cfm) at reference pressure

This calculation can also be used to estimate leakage at normal operating pressures from leakage at a test pressure.

Not all the leakage from the ducts to outside flows through the open grille. Some of the leakage to outside flows through leakage 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 open grille provides a preferred (lower resistance) flow path. This effect will result in lower leakage measurements than actually occur.

When the average duct test pressure is measured while the flow hood is in place, there is no need to use the back pressure compensation feature on the flow hood. This eliminates a potential source of error.

Duct Blaster™ Method

The Duct Blaster™ was used to measure the system duct leakage at all three houses. This method measures the flow through the ducts to leaks both to inside and outside the house (total duct leakage). In these tests measurements were taken with the Duct Blaster™ attached at the blower compartment of the air handler and attached to the return grill. During these tests all registers were covered and the duct blaster flow was adjusted to create a reference pressure in the blower compartment. This method was used for both whole system duct leakage and split system duct leakage (with a divider installed between the return and supply) on all three houses tested.

In order to obtain the leakage to outside the distribution systems were also tested with the average duct pressure at 50 pascals and the house at 50 pascals. If the pressure in the ducts was uniform, all the flow through the Duct Blaster™ is leakage to outside.

Both single point (50pa.) and five point testing was performed (with test pressures selected evenly across a logarithmic scale). This allowed estimation of the flow exponent for each supply, return, and total system.

The 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, others are operator error and variations in how the seals at the register perform pressurized and not pressurized.

Due to restrictions within the duct system and duct leakage the pressures across leakage sites varied from site to site. 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. As with the flow hood, a series of pressure measurements at different locations in the duct system will reduce the effect of this error.

Operator error can be reduced for all methods by digital time averaging measurement devices, proper training and quality assurance, as well as step by step procedures.

In the tests the seals at the register were sometimes disturbed by the pressure in the ducts. If the Duct Blaster™ is used in a depressurization mode, this effect would be reduced.

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, either a house pressurization or depressurization test has to be performed. The first method is to use the Blasnick method described in "Relating Duct Leakage to Inside with Duct Leakage to Outside" section of this report. The second method is to bring the ducts to a specified average pressure with the Duct Blaster™ and then duplicate that pressure in the house with the blower door. This takes a series of adjustments since they interact.

In these tests the Blasnick method and the blaster plus blower door methods of estimating leakage to outside gave nearly identical results. This is shown in Table D

Table D - Leakage to Outside

	Site #1 Return	Site #2 Return	Site #3 Return	Site #1 Supply	Site #2 Supply	Site #3 Supply
Blasnick (Duct Blaster™, Blower Door)	**9**	56	**69**	test error	**172**	**47**
Duct Blaster™ plus Blower Door	**7**	test error	**71**	**50**	**169**	**41**
Flow hood plus Blower Door	22	43	125	**51**	129	75

Bold numbers indicate tests in close agreement.

The Duct Blaster™ was tested at both the blower compartment door and at the return grille. The blower compartment door is the preferred location because it reduces the possibility of restrictions or leaks in the return system from influencing the leakage readings in the supply system.

OPERATING DUCT LEAKAGE

If the purpose of the duct testing is to estimate the effect of those leaks on energy use, capacity, or efficiency, it is necessary to estimate the leakage to outside under normal operation. Converting the leakage figures in the test to leakage under air handler operation involves a number of assumptions. Normally it is assumed that the pressure in the system is at a maximum at the plenum and that it drops linearly along the length of the duct run. The other assumption is that duct leaks are randomly and evenly distributed throughout the system. With these two assumptions an estimate of the true leakage can be obtained in two ways. In both cases, the average duct pressures have to be estimated (based on a number of measurements in the system). In the first option, the duct test is then run with an average test pressure matching the estimated average duct pressure. The second option is to use a standard pressure for all duct leakage then correct the results to the estimated average running pressure. The formula for that calculation is:

$$Q_a = Q_t * (P_a / P_t)^{.65}$$

Where:

P_a = Average operating duct pressure

P_t = Average test pressure

Q_a = Duct leakage (cfm) at average operating pressure

Q_t = Measured duct leakage (cfm) at average test pressure

SUPPLY/RETURN LEAKAGE SPLIT

The effect of supply leakage and return leakage on energy use is different. It is very helpful 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. This information can be obtained in two ways. These field tests divided the supply system from the return system at the blower and measured leakage in each system. This method is accurate, but it is also time consuming. Since the time of this study another method (known as the half-Nelson) has been tested by the authors on another project. That method is now judged as preferable to the split system test.

IV. Conclusions and Recommendations

Coil Air Flow Measurement

The data gathered on the three houses visited indicate that the Minneapolis Duct Blaster™ is likely to be the most reliable technique of measuring air flow through the indoor coil on most residential air conditioning systems. The Duct Blaster™ duplicated very closely the system operating pressures throughout the entire duct system. It also is less time consuming than using either the SSE or flow hood method.

The Duct Blaster™ method includes all return system leakage in the flow measured making it the easiest of the three methods for determining true system air flow through the indoor coil. The Duct Blaster™ will with the aid of air handler blower can easily duplicate the operating system static pressure on most residential systems.

The Duct Blaster™ is judged to be the more accurate coil flow measurement method of those tested. Proctor Engineering Group recommends that the air flow through the coil be measured with the Duct Blaster™ technique.

Duct Leakage Measurement

The blower door subtraction method is not suggested as a way of testing duct system leakage for the Model Energy Communities Program. Besides being the least accurate of the three methods tested it also provides too weak of a feedback mechanism to the technicians sealing the duct system. The crew could be very successful at sealing the duct system but still not see it indicated in the blower door subtraction method results.

The flow hood method now used at MEC has significant potential for error. Switching to the Duct Blaster™ should reduce those errors and improve the estimation of the energy and capacity effect of duct leakage.

Proctor Engineering Group recommends that the supply and return leakage to outside be measured with the Duct Blaster™ in the following manner:

1) Run the system and determine the average supply and return system operating pressures.
2) Cover all registers and use the Duct Blaster™ to pressurize the house. Measure the pressure drop between the house and the ducts, and the pressure drop from the ducts to outside. Calculate the relationship between inside and outside leaks using the Blasnick method.
3) Run the air handler and using the half-Nelson method determine the relationship between the supply leakage and the return leakage.

4) Measure the total duct leakage with the Duct Blaster™ and calculate leakage to outside for both the supply and return systems under operating pressure.