DNR Contract No. 2030-04-03

FINAL REPORT

Cost Due to Duct Leakage; Return Duct Leakage vs. Supply Duct Leakage; and Sealing Energy Ductwork thereby Reducing Energy Usage in Existing Residential Buildings

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PREPARED FOR

Louisiana Department of Natural Resources (LA DNR)

BY

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2008

Trenchless Technology Center
Louisiana Tech University

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COST DUE TO DUCT LEAKAGE; RETURN DUCT LEAKAGE VS. SUPPLY DUCT LEAKAGE; AND SEALING ENERGY DUCTWORK THEREBY REDUCING ENERGY USAGE IN EXISTING RESIDENTIAL BUILDINGS

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ABSTRACT

An analysis of residential HVAC ductwork has been performed. A new method for determining duct leakage was developed in this project referred to as Generalized Subtraction Correction Algorithm (GSCA). A region-specific empirical model for determining air-tightness of homes was also developed using Multiple Regression technique. A protocol for measuring and estimating return leaks at operating pressure was developed. The weighted average return leakage for the homes sampled was determined to be 115 cfm at operating pressure whereas the weighted average duct leakage was determined to be 348 cfm at 25 Pa. A methodology for determining supply leaks at operating pressure based on the input from the return leaks was also derived. Annual energy savings by sealing duct leaks was determined using both REM/Rate^{TM} and a new protocol developed by combining REM/Rate^{TM} and ASHRAE^{TM} 152. These protocols gave substantially different results and the reasons for using the newly developed protocol are presented. Using the combined protocol, the average annual heating and cooling cost per home due to duct leakage was determined to be $280. Leakage from the return plenums was also measured. We found that on average, return leaks are about 26% of the total duct leakage. Homes were also tested for duct leaks in both pressurization and depressurization mode to determine whether the measurements differed. A statistical test on these differences indicates that there are reservations in using these two modes interchangeably. Additionally, the data was statistically analyzed to determine various correlations between various measured and derived parameters A feasibility study of internally sealing duct leakage was performed. While a promising compound was investigated, and worked well by applying it with a brush, a spraying approach incurred problems in real duct systems. Thus a brush on applicator was designed that should work with various sealing compounds. Further development of that approach is recommended.

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1.0 INTRODUCTION AND RESEARCH OBJECTIVES

1.1 INTRODUCTION

Leakiness of forced-air distribution systems is one of the major causes of high-energy consumption in homes. Our State of Louisiana is no exception to such leaks. According to the Energy Information Administration (EIA) [1], in 2001 the State of Louisiana ranks twenty second in total residential energy consumption and third in total energy consumption per capita. In an earlier study performed by Witriol, Erinjeri et al. [2], the contribution of leakiness via HVAC ducts to this energy use was determined using various existing methods, and a comparison and analysis of these methods were performed.

Figure 1.1 represents the air leakage through the various components in a typical house. It can be seen that majority of the leaks are contributed by the plates (sills and the intersection of walls and ceilings), the HVAC system, and the fireplace. This study, however, mainly focuses on the HVAC part of the air leakage, especially duct leakage. In addition, this study also encompasses other sources of air leakage, with a concentration on energy losses. Leaks through the building envelope also constitute a major source of energy loss in residential buildings.

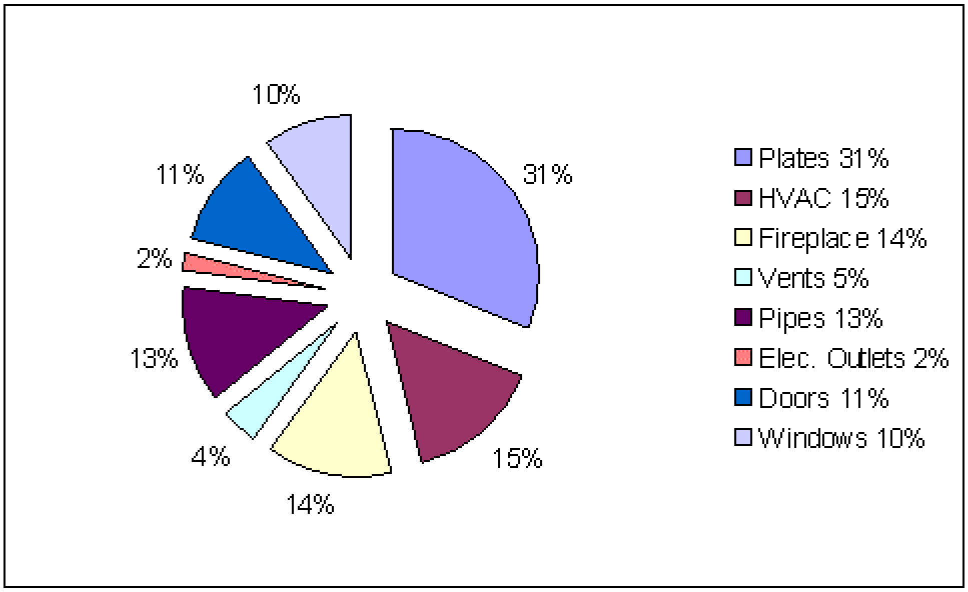


Figure 1-1. Sources of air leakage [3].

In addition, this phase also focused on determining a more effective way of determining duct leakage, resulting in the creation of the Generalized Subtraction Algorithm. The main reasons for this phase of the study were as follows:

1) There was and still is no standard test procedure that can be used to estimate the duct leakage precisely for a given home.
2) New technology has led to the increased replacement of manually collected data methodologies by automated collection methods. Such methods are inherently more accurate because of the reduced error in each datum collected, and the fact that hundreds of times more data are collected for each test. Moreover, such tests actually require less operator time.

3) There is a continuing debate regarding the best practical method to use and the applicability of these tests to predict duct leakage in an actually running HVAC system.
4) There was a need to determine the differences between the existing methods which led to the development of a new duct leakage methodology, the Generalized Subtraction Correction Algorithm (GSCA).
5) The measurements of estimated duct leakage by employing the Generalized Subtraction Correction Algorithm (GSCA) was compared with the existing method to determine the similarities and differences between them.

Data from 55 homes tested in Northern Louisiana from the report titled "Testing HVAC Duct Leakage in Existing Residential Buildings in North Louisiana" [2] was used to compare the GSCA with the existing Modified Subtraction Algorithm (MSA). An empirical relationship between whole house leakiness and building characteristics was developed from a larger data set, which involved house tests in addition to the 55 homes. Multiple regression techniques were employed to determine this empirical relationship.

Duct leakage can occur in both the supply and the return side of the duct system. Some sources of leaks are readily accessible, while others are much more difficult to access for repair. In particular, the return side of the duct system is more easily accessible than the supply side. The second phase of this study includes development of a new test protocol to measure return leaks. The main focus on this phase of study was the following:

1) To develop a protocol to measure return leaks with resources available to the energy auditor as there is no existing standard method for measuring return leakage.
2) To measure the return as well as the supply leaks at operating pressure.
3) To develop a database of return leakage verses supply leakage.
4) To determine whether or not there are meaningful statistical differences in measurements between the pressurized and the depressurized conditions.

The third phase of the study was the development and testing of a new duct-sealing technology in laboratory conditions. The main reason for this study was that present-day duct sealing technologies can be expensive and time consuming due to the inaccessibility of the locations of these leaks. In addition, some of the duct sealing techniques are found to have health-related problems as they use various biocides along with the sealants. The vapors of such biocides are harmful, if inhaled in excess. The focus on return leaks becomes critical because they are easier to seal than the supply leaks, and are frequently of a similar size. The basic duct sealing technology development concept is to transfer the technology from the well understood and broadly established, piping-industry-standard techniques utilized to internally seal underground pipes to internally sealing HVAC duct systems. This report highlights the feasibility study on a promising duct sealing technology performed in laboratory conditions. This phase also projected the average residential energy savings derived by sealing duct leaks. To obtain the energy savings due to sealing of the duct leaks an energy audit of individual homes was performed. In this study, a sample of 43 homes were tested for duct leaks and audited for energy efficiency.

1.2 OBJECTIVES

The objectives for this study were the following:

1. To determine an empirical relationship between whole-house leakiness and building characteristics.
2. To develop a more effective method of measuring duct leakage, namely the Generalized Subtraction Correction Algorithm (GSCA).
3. To compare the results obtained utilizing GSCA for measuring duct leakage over the existing methods.
4. To develop a test protocol to determine the return leaks at operating pressure and collect sufficient data to generate a database on residential return duct-leakage .
5. To develop a methodology for determining the supply leaks at operating pressure.
6. To statistically determine whether or not there are differences in the measurements of duct leakage between the pressurized and depressurized conditions.
7. To develop and test cost-effective methods to significantly reduce duct-leakage, specifically to:

Perform a feasibility study on a new duct-sealing technology in laboratory conditions.

Measure the actual average effectiveness of the duct-sealing technology in both the supply and the return system of the duct system.

1. To project the average residential energy savings derived from sealing residential duct leaks.
2. To communicate the results of this investigation to energy raters, retrofitting building contractors, and the general public to encourage the adoption of this technology in sealing duct leaks.

1.3 ORGANIZATION

Chapter Two provides the primary literature review performed for this study. In Chapter Three, an empirical relationship between the whole-house leakiness and the building characteristics is presented. Chapter Four describes the development of a new algorithm (GSCA) for determining duct leakage. Chapter Five describes a protocol to test and measure return leaks. Chapter Six provides the data obtained from the actual measurement of duct leakage, taking into account both supply and return leaks. In Chapter Seven, a statistical analysis is presented for determining the differences between pressurized and depressurized conditions on various measurement protocols. Chapter Eight presents a detailed procedure for determining the energy efficiency of a home. This chapter also projects the energy saving in dollars that would result from the sealing of the ducts. Chapter Nine describes a feasibility study on a new duct sealing technology to seal supply and return leaks in laboratory conditions. In Chapter Ten, the conclusions and outlook for future work in this area is presented.

2.0 LITERATURE REVIEW

Existing ductwork has been shown to have substantial leaks in tests performed on existing structures in several states including Arkansas, Washington, and Florida [4, 5, 6]. Reported findings include the following:

1. The leaks are primarily associated with holes or disconnects in the ducts.
2. The main driving force for duct leakage is the HVAC blower.
3. Poor workmanship on the ducts, the wrong materials, and damage by humans and animals are the main causes of the holes in the duct system.
4. Duct leakage results in a significant increase in the summer cooling energy costs of homes due to:
    a) The duct placement outside of conditioned space.
    b) An attic environment, typified by high temperatures and high humidity levels that allows hot, humid air to be added to the cooling load. Duct leakage similarly adds to the winter heating load by allowing additional unconditioned air into the home.

Due to high temperature and humidity in Louisiana and other Southeastern US states, the leakage of unconditioned air into the duct system and/or building envelope can lead to more than a doubling of the heating and cooling energy costs. An estimate of 15 to 30 percent of a home's total heating and cooling energy is lost through leaky ductwork, costing consumers across the nation about five billion dollars per year (value adjusted to 2005) [7].

The RCDP (Residential Construction Demonstration Project) in the Northwest (Idaho, Montana, Oregon, and Washington) funded a project to determine duct leakage in representative homes in their area [8]. They found that the houses had a large range in duct leakiness, from 0 cubic feet per minute at 50 Pascals of pressure (CFM50) to 465 CFM50. In addition, contractors reported duct-sealing costs averaging $355 per house beyond what they normally would spend on installation, with a range from $100 to $900 [8]. Field studies performed in Washington, D.C. and Minnesota revealed that the ducts leaked by about 1300 CFM50 and 2217 CFM50 respectively [9].

According to the Energy Information Administration (EIA) [1], the State of Louisiana ranks third highest among the states in energy consumption by total energy consumption per capita. A study by Witriol et al. of 55 homes in Northern Louisiana has determined average duct leakage in residential homes in the range of 313 CFM25. The same study determined the average duct leakage to be 29% with a projected loss of HVAC efficiency of over 70%. This efficiency loss was determined using the HVAC efficiency tables published by Jeffrey S. Tiller in the book titled *Builders Guide to Energy Efficient Homes in Louisiana* [10]. In Chapter Eight, the problems associated with regards to the application of this table in determining efficiency loss are presented. In addition, a new approach in estimating % energy wastage due to duct leakage is also presented.

In this study, data collected by Witriol et al. in each of the 55 homes tested in North Louisiana were used to develop the GSCA model. In addition, the data were used to compare the GSCA with the Modified Subtraction Algorithm (MSA). A few modifications in duct-leakage calculations were possible due to the contributions made by researchers in this field mainly:

a) In Modified Subtraction, the duct leakage exponent is assumed to be 0.65. This value may have been chosen because it is the apparent average house-leakiness flow exponent of thousands of homes' tested. However, with automated equipment, it is possible to accurately measure any particular home's house-leakiness flow-exponent. Therefore alternative values for this variable can be used.

b) Experimentally measured, mean duct-leakage flow-exponent of 0.60 allows for a renormalization of duct-leakage flows taken at 50 Pa to 25 Pa [2].

c) Using a generalized version of Modified Subtraction as presented in Chapter Four, it is possible to test duct leakage with a Blower Door^{TM} at any duct pressure.

d) Unlike older versions of the Duct Blaster^{TM} manual that required no use of actual measured attic pressure, the latest versions of the manual require testing ducts at the pressure difference between the ducts and the attic.

Typical duct systems lose 25% to 40% of the heating energy or cooling energy put out by a central furnace, heat pump, or air conditioner [11]. Duct repairs made on 25 homes in Florida indicated that 14.0% of the house leaks were in the duct system. Repair of these duct leaks reduced the house ACH50 (hourly air change rate at a pressure difference of 50 Pascals between inside and outside) from 12.30 to 11.13 indicating that 68% of the duct leaks were repaired [12]. They also showed that duct repairs reduced winter peak demand in electrically heated Florida homes by about 1.6 kW per house at about one-sixth the cost of building new electrical generation capacity [12]. Other effects of duct leaks include the following:

e) Increased peak electrical demand–requiring a higher capital cost to the utility (that can be higher than the operating or capital cost to the homeowner) due to the increased demand during the utilities' peak-demand period.

f) Oversizing condenser and air handling systems to compensate for duct leaks–adds to the capital cost to the homeowner and creates humidity problems in the home.

g) Indoor air-quality problems associated with excess or incompletely handled humidity and dirt in the home as well as mechanical ventilation induced air-infiltration–these effects raise the energy bill, decrease comfort, and threaten the health of the residents as well as the longevity of the HVAC equipment.

h) Increased indoor relative humidity with the resulting potential for fungal, mold, and mildew growth, in addition to condensation, on surfaces–threaten human health and building longevity.

i) Possible depressurization of the house, and the possibility of back-drafting of flue gases–threatens occupants' safety with fires or carbon monoxide poisoning.

Diagnosis is the key to successful repair; namely, the leak sites must be found. Ducts leak as the result of failure of duct materials and duct sealants, duct sealant application methods, poor workmanship, inadequately sealed original mechanical joint systems, and damage by humans and animals. Duct repair can also be a very cost-effective means to solve building moisture problems such as mold, mildew, moisture saturation, and material decay. Leaks in return ductwork draw air into the house from crawlspaces, garages and attics, bringing along dust, mold spores, insulation fibers and other contaminants [13]. The repair of 70% of duct leakage in the typical Florida home has been shown, by simulation studies [14, 15] to reduce cooling energy by 21%, and peak demand by 25%, on a peak summer day. Recommended priorities when designing a new home or retrofitting an existing home in Florida include a maximum tested duct-leakage of 25 cfm/1000 sq. ft of conditioned floor area at a 50 Pa test pressure, and all ductwork installed in attics insulated with R-8 or better [16].

There has been a continuous encouragement for the use of high-energy efficient HVAC equipment. However, this impetus does not necessarily result in the returns anticipated over a period of time. It has been shown that a 13 SEER air conditioning unit connected to a duct system with a 30% leakage costs the same to operate as a less expensive 10 SEER unit connected to a tight system. Sealing ductwork would have a considerable impact on summer peak loads by allowing smaller, more efficient cooling equipment to be installed, resulting in an additional reduced expense to the customer. The main areas of concerns researchers found in regards to inefficient duct systems are the use of building cavities as ductwork, excessive use of flex duct and poorly designed duct systems [17].

The return part of the duct system is frequently constructed differently from the supply side, and is believed to cause a significant and frequently larger contribution to duct leakage. Therefore, obtaining a database on the contribution of return vs. supply leakage can be useful in developing cost-effective duct-sealing technology. A previous study by Synertech of Syracuse, New York [9] tested basements in roughly 400 houses. The results showed that roughly 70% of these houses had leaky ducts with return leaks greater than supply leaks in 60% of the houses. Duct-system related studies in Washington, D.C. [9] revealed that for houses in which the supply and the return leaks were differentiated, 55% of the leakage was in the return ducts and a significant fraction of that was to outside, through the attic. Studies performed by North Carolina Alternative Energy Corporation have shown that a deficiency of 20% in indoor airflow reduced the SEER rating by 17% [18]. HVAC systems having a 15% return leak (from a 120° attic) can reduce the effective capacity or, equivalently, Energy Efficiency Ratio (EER) of the system by 50% [10]. A 30% return leak can result in cooling demand that would exceed the capacity of an otherwise properly sized HVAC system. The adverse effects of return leaks are many, including causing, or enhancing major health problems.

With small rips, separations, or cracks in return ducting, air can bypass the filters and the cooling coils. The unconditioned and unfiltered air then enters the supply duct system and is distributed to the entire house. When unfiltered, humid air, consistently reaches the evaporator coil, clogging can result, thus decreasing the efficiency of the cooling system, reducing the airflow through the duct system, lowering the equipment's useful life and threatening the homeowner health with allergic reactions to mold and the possibility of Legionnaire's Disease [71].

During the winter or in colder climates than usually found in Louisiana, dominant return leaks can pressurize a home and force the normally present warm and moist air through exterior walls and ceilings, causing condensation on cold surfaces within the structures [19]. Under these circumstances building material durability is threatened by fungal growth, mildew and rot. If the surface relative humidity exceeds 65% to 70% on a continuous basis, then molds can amplify and create a problem, particularly in the absence of light and airflow [20, 21]. During the summer or in warmer climates common in Louisiana, return leaks frequently cause the HVAC blower to draw air from the attic where the air temperature and humidity level are often higher than ambient outside air. Thus in the summer time a return leak may draw more humid, 150°F air into the duct-system to mix with the 70-80°F conditioned, house air. The higher return air temperature and humidity can overwhelm the system capacity, making it impossible to cool the home. Often HVAC contractors choose to “fix” the problem by installing higher capacity units instead of tightening the duct system; although this overcomes the temperature problem, it simultaneously causes the relative humidity to rise in the home. This “solution” then causes two problems: (1) a lower comfort level at temperatures between 75 to 79°F–which causes the homeowner to lower the thermostat’s set-point and waste energy and (2) poor indoor air quality, which threatens the health of the homeowner and the building’s durability. Thus the adverse effects of return leaks include the following:

- Increased capital cost of oversized air handling systems to compensate for duct leaks.
- Increased capital cost of peak-electricity generation capacity of the local utility.
- Increased energy costs for homeowners.
- Decreased comfort for homeowners.
- Increased health risk to homeowners.
- Increased risk of damage to homes from moisture-related degradation of building materials.
- Increased relative humidity in the summer.
- Potential for mold and mildew growth and condensation on surfaces.
- Increased potential for mold growth on the cooling coil (evaporator) which degrades system efficiency and shortens system life.
- Increased potential harboring and transmission of airborne diseases.
- Increased potential of residents developing allergies from increased exposure to mold.

This study has developed a protocol to measure leaks in the return system. The experimental setup and the process of measurement of return leakage is presented in Chapter Five. The return leakage is also represented as a size of a single hole in square inches, which is the cumulative size of all the holes. This representation lets one visualize the effect of return leaks on energy loss. In addition, this study has developed and demonstrated cost-effective energy-conserving methodologies that can result in substantial benefits to all citizens of the country. Furthermore, duct leakage has the greatest proportional effect on lower-income individuals because they spend a higher percentage of their income on air conditioning.

Measurement of duct leaks as a whole and return leak separately was performed in 43 homes both in the pressurized and the depressurized conditions. The presence of significant differences in measurement between the two conditions is critically important for the research community because the presence of duct leaks is generally measured by pressurizing the house as well as the duct system. However, in normal HVAC operating conditions, the return plenums are depressurized. Thus, the question is whether the measurement made by pressurizing the return plenum accurately measures the pressure in the normally operating HVAC system wherein the return plenum is depressurized. The basic reasoning behind the differences becomes the foremost issue once we determine that the differences are significant. Chapter Seven presents the results of these measurements as well as the statistical analysis of the differences in these measurements.

Two key issues that have recently emerged after World War II in regard to construction of homes are healthy and tight homes. The healthy home refers to buildings that are environmentally friendly, family safe, properly ventilated, and free from indoor pollutants. Tight construction refers to homes that are energy efficient, with an indoor environment well controlled through mechanical ventilation systems [22]. In reality, a compromise must exist between the above two issues for a good home. This report mainly deals with a study regarding the tightness of homes in Northern Louisiana, with the assumption that the homes have an efficient ventilation system.

Air-tightness quantifies the tendency of a home to allow air to flow through its pressure envelope in a range of pressures (typically between 4 and 50 Pascals) against that envelope [22]. Air-tightness of buildings directly reflects air leakage sites. Air leakage sites include exterior doors, windows, foundations, electrical boxes and plumbing fixtures [23]. Building air-tightness measurements are used for a variety of purposes such as [22, 24]:

1. Documenting the construction air-tightness of buildings.
2. Estimating natural air infiltration rates in houses. Air infiltration is nothing but air that leaks into the building through cracks or gaps.
3. Measuring and documenting the effectiveness of air sealing activities.
4. Measuring duct leakage in forced air distribution systems.

There are a number of standardized formats for measuring air-tightness as described in Minneapolis Blower Door^{TM} Operation Manual. However, this study will focus on three commonly used formats namely Cubic Feet per Minute at 50 Pa (CFM50), Effective Leakage Area (ELA) and Equivalent Leakage Area (Eq.LA).

Cubic Feet per Minute at 50 Pascals (CFM50):

CFM50 is the airflow (in cubic feet per minute) through the Blower Door^{TM} fan needed to create a change in building pressure of 50 Pa. It is the most common measure representing air-tightness [22].

Effective Leakage Area (ELA):

ELA was developed by Lawrence Berkeley Laboratory (LBL) and is used in their infiltration model. The Effective Leakage Area is defined as "the area of a special nozzle-shaped hole that would leak the same amount of air as a building does at a pressure of 4 Pa." ELA is most often expressed in square inches (sq. in.) [22].

Equivalent Leakage Area (EqLA):

EqLA is defined by Canadian researchers at the Canadian National Research Council as "the area of a sharp-edged orifice (a sharp round hole cut in a thin plate) that would leak the same amount of air as the building does at a pressure of 10 Pascals" [22].

For air leakage to occur there must be both a hole or crack and a driving force (pressure difference) to push the air through the hole. The five most common driving forces, which operate in buildings, are [22]:

1. Stack Effect: Stack effect is the tendency of warm buoyant air to rise out the top of a building and be replaced by colder outside air entering the bottom.
2. Wind Pressure: Wind blowing on a building will cause outside air to enter on the windward side of the building and leave on the leeward side.

3. Point Source Exhaust or Supply Devices: Chimneys for combustion appliances and exhaust fans push air out of the building when they are operating.
4. Duct Leakage to the outside: Leaks in forced air duct systems that cause air leakage to outside the building envelope.
5. Door Closure coupled with forced air duct systems: Research has shown (Minneapolis Blower DoorTM) that in buildings with forced duct systems, imbalances between supply and return ducts can dramatically increase air leakage.

Any of the above factors will lead to a pressure gradient between the inside of the home and the outside. This pressure gradient (the driving force) along with the presence of a hole or crack propagates the air leakage. However, it is very difficult to quantify all of the above driving forces at the same time, and obtain a fixed consistent air-tightness value. Specialized devices are used to measure the air-tightness of homes, but these measurements are subject to change when the magnitude and direction of driving forces change.

In regard to the air-tightness, this study involves developing an empirical model to estimate the air-tightness of residential buildings without actually performing a Blower Door^{TM} test. The Minneapolis Blower Door^{TM}, manufactured by the Energy Conservatory is an example of a specialized tool used to measure air-tightness in residential buildings [22]. The Blower Door^{TM} fan blows air into or out of the building to create a pressure gradient between the inside and the outside of the building. This pressure gradient is used to measure the air-tightness in terms of volumetric units. Avoiding the use of Blower Door^{TM} to obtain air-tightness will be very beneficial to those who want a quick and reasonable estimate. This model will estimate the air-tightness of a given house based on the physical information such as the year of construction, conditioned area, conditioned volume, the number of stories and the number of bedrooms. The estimate of the air-tightness obtained from the tested houses will be compared with houses of known air-tightness to check for its effectiveness. It is important to note that such a model will be applicable to Northern Louisiana only, because we assume that the houses in this region have similar kind of building and environmental characteristics. We have not found such air-tightness models applied by any industry in a particular region. This region-wise specific model is the first approach in this direction. There are some building diagnostic software programs in the market to determine the air-tightness values such as TECTITE^{TM} and ZipTest Pro^{TM} [24]. These software programs are used at homes while performing air-tightness tests. In addition, these programs require various user inputs such as CFM50, leakage flow exponent, the weather factor, floor area, building volume, building height, and occupant count. However, this study seeks to limit the user input by considering a given region in the US rather than stretching the estimations to the whole of US. The usefulness of the model developed lies in the fact that it is less time consuming to reasonably estimate air-tightness. In this study, we have grouped the homes with air infiltration based on area and age. The advantage of this model is that based on the physical information of the house, the air-tightness can be determined without even visiting the house. However, the disadvantage is that individual houses are unique, and the deviation from the mean may be very large. Thus in some instances, with certain categories (age, location, etc.), the model may be more efficient in determining which houses should be tested, rather than be used to give specific values for an home.

The third phase of the study involves sealing of duct leaks. Sealing duct leaks is very important as it helps in:

1. Reducing the amount of heated or cooled air the supply fan must run to deliver the same amount of air to the conditioned space.
2. Saving energy and also save homeowners money.
3. Improving indoor air quality.
4. Enhancing human comfort.

The most commonly used sealant methods are duct tape, foil tape and fiberglass tape, which in actuality do not adequately seal joints between ducts and have short lives. Researchers at Department of Energy's Lawrence Berkeley National Laboratory have developed aerosol spray sealants [25] capable of sealing cracks of 1/4 inch or less in diameter. The sealant is a fine mist of vinyl plastic monomer injected into the duct system by a computer-controlled machine which forces sealant-laden air out of cracks and leaks. As the air leaves the ducts, sticky particles are deposited where leaks occur and seal the leaks. The technology is effective in sealing supply leaks effectively and costs (1998) between \$450 and \$600, depending on what needs to be done; roughly the same as the cost of hand sealing, though less labor intensive [26, 27]. Measurements have demonstrated that aerosol duct sealing systems can only reduce duct leakage rates to between 2% and 3% in commercial buildings. However, aerosol duct sealing is a labor-intensive service that costs on the order of \$0.40/ft^2 (of floor space), with light commercial buildings costing slightly less and large commercial buildings costing slightly more (due to system complexity). Because the average commercial building spends approximately \$0.60/ft^2 each year on HVAC energy consumption, aerosol duct sealing will pay itself back in about ten years [27]. It is important to note that this estimate does not include any impact on peak electricity demand which, due to the strong correlation between air-conditioning loads and peak electricity demand, would tend to improve the economics of duct sealing. The authors of the article titled "Improved Duct Sealing" states that cost reduction opportunities exist for the aerosol sealing technology [27]. Therefore, inexpensive, more stable and permanent materials need to be researched.

The third part of this study is the development, testing and education of the public regarding innovations in duct-sealing technology. This study has attempted to develop a cost-effective technique to find and seal duct-leaks effectively, thereby reducing air conditioning-related energy consumption in existing construction. The basic development concept is to transfer the technology from the well understood and broadly established, piping-industry-standard techniques utilized to internally seal underground pipes to internally sealing HVAC duct systems. As underground pipe systems (e.g., water lines) age, they frequently have similar leak problems to those found in duct systems. To avoid having to dig up the pipes, an otherwise very expensive operation, methodologies (Trenchless Technology) have been devised to fix/seal these flaws from the inside. Namely, they use robotic or pull-through cameras [28] to access the condition of the system, and location and severity of any leaks found. One of two means is then employed to seal leaks. The first method employs a robotic or pull-through observation and spray-sealing system. It is passed through the pipes and an epoxy sealer is sprayed on the walls of the pipes to seal the leaks from the inside. The second method inserts a folded inflatable lining through the damaged pipe system. The lining is then expanded like a balloon, expands, and is sealed to the walls of the pipe. Holes are then cut for laterals. Since underground systems are designed to operate under higher pressures than duct-systems, they are usually heavier, structurally robust and can support significant weight; therefore, the equipment used to seal them is similarly heavy. Ductwork is less robust than pipelines and may not be able to support heavy equipment. On the other hand, the conditions within a duct system are probably cleaner and more suitable for imaging than underground systems. However, because the problems for sealing leaks in pipes/ducts transporting fluid (water/air) are similar, it is expected that a similar solution can be employed. In researching the application to ducts, we found that the liners were comparatively expensive, and there is a need to develop thinner liners that would be cheaper. There are two specific applications where this may be appropriate: (1) holes which are too difficult to access or too large to be sealed by the spray technology and (2) where ducts may be too flexible or flimsy to support the spray equipment. The first case includes return chases to attic HVAC units, which typically may have very large holes to the attic. The second case is typical of flex-duct systems wherein the expanding liners after curing would make the ducts rigid, and, therefore more robust and durable–significantly increasing their longevity. It is widely believed that the first of these two problems can be more economically repaired with simpler technology. But the marketplace for flex ducts may be greater than a simple fix for duct leakage, because there is a large difference in longevity between the more expensive metal duct-systems and flex ducts. Thus the same technology originally conceived for duct leakage repair could become a cost-effective original installation option for new construction. However, for most cases, the spray technology would be cheaper and simpler to use. This research has focused on developing the spray technology and demonstrating its cost-effectiveness on sealing duct-systems. This dissertation presents a feasibility study performed in the laboratory for sealing ducts. Various critical zones of a duct system where duct leak occurs were sealed with a special sealing compound. This compound was tested for its sealing capabilities in laboratory conditions with the goal of developing a spray technology to seal ducts. In particular, the compound was initially tested by applying the compound with brush on metal ducts as well as wooden structures. The study on return leaks becomes vital, as it is easier to detect and seal return leaks than supply leaks. If return leaks dominate in a home, then it is more practical to seal the return than the supply leaks.

In Chapter Eight, we discuss the issues relating to the HVAC efficiency tables published by Jeffrey S. Tiller's book titled *Builders Guide to Energy Efficient Homes in Louisiana* [10]. We have addressed the ASHRAE^{TM} 152 standard and employed it in conjunction with REM/Rate^{TM} to study the potential average energy savings that sealing duct leaks would have for Louisiana homeowners. In addition, we have compared these results with the most widely used auditing software-REM/Rate^{TM}. The information on energy savings will then be used to estimate the total cost of duct leakage to Louisiana citizens. This study comprised of testing the 43 homes to determine the difference in average annual utility costs incurred by an individual homeowner with and without duct leaks.

In response to market pressures, we expect that many retrofitting and new building contractors will consider these methodologies. In a market already sensitized to the economic, global-political and environmental needs for conservation and to the very common desire to capture the potential cost savings and improved environmental health aspects, many contractors will be looking to new construction and repair methods. This research's target audiences are building contractors and architects. The work on this project will highlight the importance of the constructing of leak-proof return systems. It will also enable home energy raters to more reliably determine the source of duct leaks in a home. The information provided by this study can be also extended to small commercial buildings because the principles behind the construction and functionality of HVAC systems, as well as the equipment, are often identical.

3.0 EMPIRICAL AIR-TIGHTNESS MODEL OF RESIDENTIAL HOMES IN NORTH LOUISIANA

Two key issues have recently emerged after World War II in regard to construction of homes-healthy homes and tight homes. The healthy home refers to buildings that are environmentally friendly, family safe, properly ventilated, and free from indoor pollutants. Tight construction refers to homes that are energy efficient, with an indoor environment well controlled through mechanical ventilation systems [22]. In reality, there must be a compromise between the above two features for a good home. This chapter deals mainly with a study regarding the tightness of homes in Northern Louisiana, assuming that homes have an efficient ventilation system. The purpose of this study is to develop an empirical model to estimate the air-tightness in residential houses in Northern Louisiana without actually measuring the air leakage rates.

3.1 OVERVIEW

Air-tightness quantifies the tendency of a home to allow air to flow through its pressure envelope in a range of pressures (4-50 Pa) against that envelope [2]. Air-tightness of buildings directly reflects air leakage sites. Air leakage sites include exterior doors, windows, foundations, electrical boxes and plumbing fixtures [29].

There are a number of standardized formats for measuring air-tightness as described in Minneapolis Blower Door^{TM} Operation Manual [22]. However, this study will focus on three of the commonly used formats namely Cubic Feet per Minute at 50 Pa (CFM50), Effective Leakage Area (ELA) and Equivalent Leakage Area (EqLA). The definitions of these three formats were described in Chapter Two.

The Minneapolis Blower Door^{TM}, manufactured by the Energy Conservatory, is a specialized tool used to measure air-tightness in residential buildings [22]. The Blower Door^{TM} fan blows air into or out of the building to create a pressure gradient between the inside and the outside. This pressure gradient is used to measure the air-tightness in terms of volumetric units. Avoiding the use of the Blower Door^{TM} to obtain air-tightness will be very beneficial to those who want a quick and reasonable estimate. This study involves developing an empirical model to estimate the air-tightness of residential buildings without actually performing a Blower Door^{TM} test. This model will estimate the air-tightness of a given house based on the physical information such as the year of construction, conditioned area, the number of stories and the number of bedrooms. The estimate of the air-tightness obtained from the developed model is compared with houses of known air-tightness to check for its effectiveness. It is important to note that such a model will only be applicable to Northern Louisiana, because we assume that the houses in this region have similar building and environmental characteristics. We have not found such air-tightness models applied by any industry in a particular region to the best of our knowledge. This region-specific model is the first approach in this direction. The usefulness of the model developed lies in the fact that it is less time consuming to reasonably estimate air-tightness. The advantage of this model is that, based on the physical information of the house, the air-tightness can be determined without even visiting the house. In addition, we have attempted to categorize the homes as needing or not needing to be fixed for whole house leakiness, without actually inspecting or testing the home.

It is important to note that environmental-related problems such as poor indoor air quality (IAQ) could have a significant negative impact on a building's value. Lower market value or a lease rent reduction are two likely scenarios that can occur once an unresolved IAQ problem becomes known or a building is tagged with "sick building syndrome" [30]. Presently, in the US energy experts can review the house plans and can conduct a Home Energy Rating to assess the energy efficiency of a home. The Home Energy Rating System [31] has now become a nationally recognized system used to evaluate all the features of a house. These features include structure and foundation type, insulation levels, heating and cooling systems, air-tightness, windows, water heating equipment, and appliances. Building Tightness Limits (BTL) have been developed in some states in the US. BTL are guidelines based on estimates of the minimum air exchange rate of a building necessary to provide enough fresh air to maintain satisfactory health of the occupants and durability of the structure [32]. BTL usually specify a building's minimum air leakage rate in CFM50 for comparison with the measured value of CFM50. Various building tightness calculation procedures have been developed for ensuring acceptable IAQ. One of these methods is based on the American Society of Heating, Refrigerating and Air-Conditioning Engineers Standard 62-1999, Ventilation for Acceptable Indoor Air Quality. This method referred to as the BTL method is clearly explained in an article by Tsongas in Home Energy magazine [33]. For an acceptable IAQ, this standard requires 15 cfm per person (assuming a minimum of five people) or 0.35 Air Changes per Hour (ACH), whichever is greater, that must be supplied by natural air leakage and/or continuously operating ventilation. We have not developed a model with ACH in this report but recommend it as a part of a future study.

Blower doors^{TM} measure building tightness, and the natural infiltration rate of a house based on a number of parameters. A single BTL does not incorporate factors like climate, a building's wind exposure, building size, or the number of occupants. Air exchange rates can vary widely depending on such factors. Max Sherman of the Lawrence Berkeley Laboratory has developed tables for each of the four climate zones in the United States [33, 34]. The tables include a U.S. map, divided into four climate zones. The tables account for the number of occupants, the number of stories of the building, and its wind shielding characteristics. Weatherization personnel can use the map to find their particular zone and then select the appropriate table with the correct CFM50 minimum values. However, the simple model presented in this report does not take into consideration all of the factors discussed for determining air-tightness. The main objective of this empirical study is to give reasonable estimates of air-tightness with minimum inputs. The easily obtainable characteristics of a residential building are taken as the independent variables. The model developed is based on the assumption that the houses in a particular region have similar kinds of building and environmental characteristics. This assumption is basically considered to suppress the influence of climatic factors and other related factors attributed to a particular region–in this case North Louisiana. Also, the variables considered in the model are obtainable without even visiting a home; the purpose being quick and inexpensive. However, if precise and accurate measurements are required, then this model may not be the suited one. The details regarding the variables considered in this model is presented in Section 3.4.

3.2 SAMPLING AND DATA COLLECTION

The primary data were collected performing additional Blower Door^{TM} tests in 66 homes in and around Ruston, Lincoln Parish, in North Louisiana. The locations of the 66 houses tested in North Louisiana are presented in Figure 3.1. From Figure 3.1, we observe that the majority of the houses sampled are from Ruston (87%) followed by Dubach (5%), Choudrant (2%), Monroe

(2%) and Simsboro (2%). The data of 66 houses were split into two parts to perform cross-validation. Cross validation is a validation technique wherein the data set is split into model building and prediction sets [35]. The first part comprising of 46 homes formed the model building set or the estimation sample where as the remaining 20 homes comprised of the prediction set or the validation sample. The complete set of data is presented in Table A1. The detail of the validation process is described in Section 3.7.

The data for this study were collected by performing Blower Door^{TM} tests in sixty-six homes in the Northern part of Louisiana. The details of the testing procedure using Blower Door^{TM} are as follows:

Step 1: Calculate the floor area and the volume of the home.

Step 2: Set control on pilot for all combustion appliances.

Step 3: Turn off the air handler of the HVAC unit and remove the filter. Turn off attic fans, dryer and other exhaust fans.

Step 4: Attach the Blower Door ^{TM} to an exterior doorframe-selecting one, which provides a clear airflow path to outside.

Step 5: Prepare the Automated Performance Testing System (APT) measuring equipment for testing in depressurized mode.

Step 6: Launch the TECTITE^{TM} software and run the process.

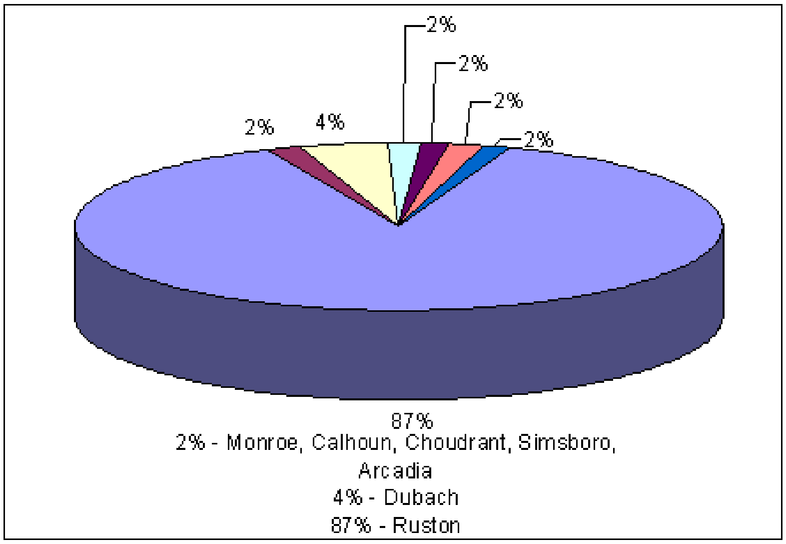


Figure 3-1. % Location of residential houses sampled.

In default mode of the TECTITE^{TM} software, 100 data are collected at the beginning and end of the test for each set pressure difference between the home and outside (50, 45, 40, 35, 30, 25, 20 and 15 Pa). The output of this entire process gives air-tightness measures such as CFM50, ACH50, Effective Leakage Area (ELA), and Equivalent Leakage Area (EqLA). It is important to note that this study has only considered the three most common measures of air-tightness-CFM50, ELA and EqLA. The definitions of all these measures were described in Chapter Two.

3.3 RESPONSE VARIABLES-CFM50, ELA AND EQLA

The three response variables or the dependent variables–CFM50, ELA and EqLA measured using Blower Door^{TM} were compared against each other and the plots between these two variables are shown in Figures 3.2, 3.3 and 3.4. From Figure 3.2, we can see that as ELA increases CFM50 also increases. However, the relationship between ELA and CFM50 widens beyond the 250 sq. in. and 4000 CFM mark. Considering the line of equality, a 45° line from the origin, we can see a few points lie away from the line of equality.

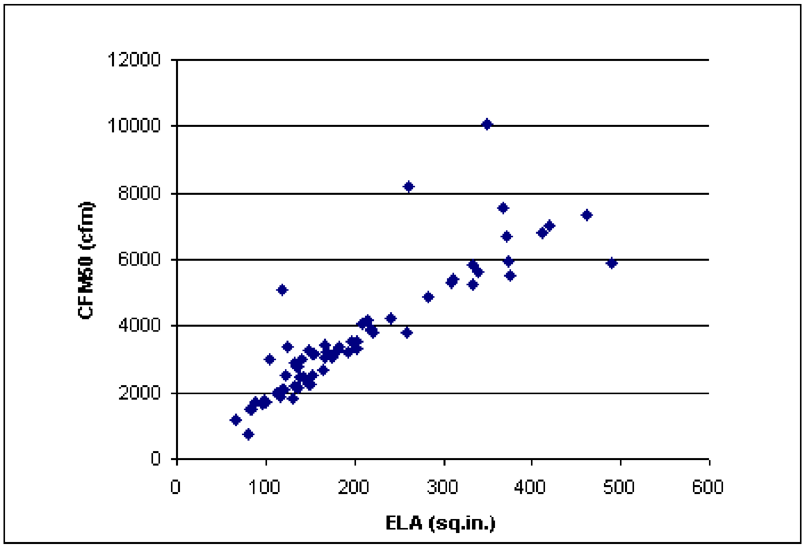


Figure 3-2. Plot of CFM50 vs. ELA.

The correlation coefficient between CFM50 and ELA was determined to be 0.88, which indicates a high correlation. However, this value of correlation does not indicate the agreement between them but measures only the strength of the relationship [36].

The relationship between ELA and CFM50 [13]: is given by:

$$\text{ELA} = 0.055 \times \text{CFM50} \quad (3.1)$$

Equation 3.1 is an empirical relationship and the value of 0.055 is questionable. The data obtained by our study were compared against this model by calculating the ratio of ELA to CFM50. However, we obtained a mean of 0.056217 with a standard deviation of 0.011389 for the complete sample of 66 houses. Therefore, this suggests that there is a kind of relationship between CFM50 and ELA but it is to be noted that these values vary from home to home.

The plot of EqLA vs. ELA is presented in Figure 3.3. From the plot of EqLA vs. ELA we can see a linear relationship between these two variables with a high correlation of 0.98. The average of ratio of EqLA to ELA was determined to be 1.895521 with a standard deviation of 0.167797. The obtained ratio is in accordance with the Blower Door^{TM} Manual [22], which states that the calculated EqLA will typically be about two times as large as the ELA.

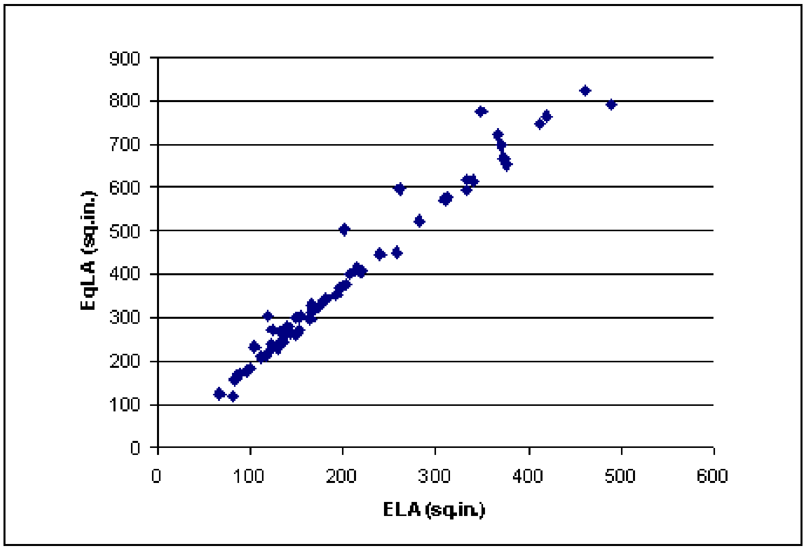


Figure 3-3. Plot of EqLA vs. ELA.

Figure 3.4 shows the plot of EqLA vs. CFM50 and we can see that as EqLA increases CFM50 also increases. However, the relationship between ELA and CFM50 widens beyond the 450 sq. in. and 4000 cfm mark. Considering the line of equality, we can see that there are a few points, which lie away from the line of equality.

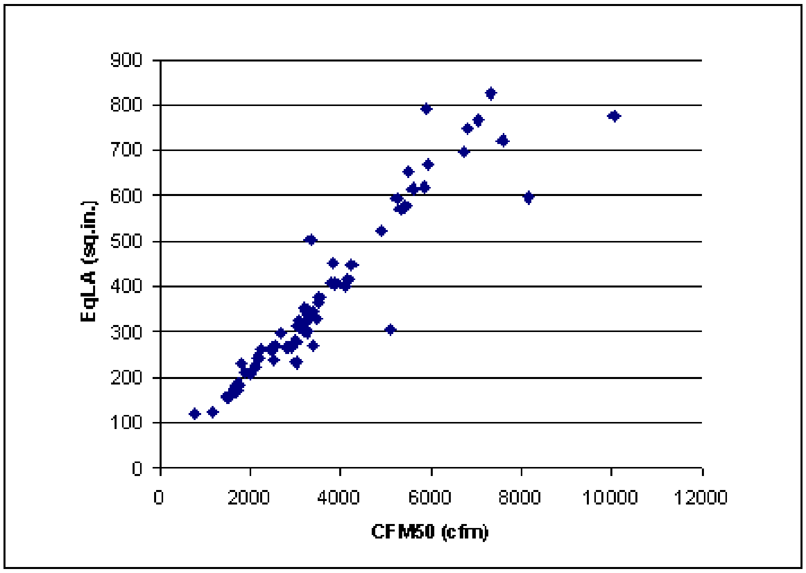


Figure 3-4. Plot of EqLA vs. CFM50.

The correlation coefficient between CFM50 and EqLA was determined to be 0.94, which indicates a high correlation. The average of ratio of EqLA to CFM50 was determined to be 0.105018 with a standard deviation of 0.014734. The value of 0.105018 is approximately twice the average of ratio of ELA vs. CFM50; which corresponds to the fact that the measured value of EqLA is approximately twice that of ELA.

3.4 MODEL BUILDING PROCESS

A sample of 46 observations (estimation sample) from the total of 66 observations was used in the model building process. To build the empirical model for determining the air-tightness based on physical information, we applied the multiple linear regression technique. Three regression models of the form

$$Y = B_0 + B_1 X_1 + B_2 X_2 + B_{p-1} X_{p-1} + e$$

were developed, where

Y = air-tightness (CFM50 or ELA)

X_i = home parameters, i = 1, 2, … p-1.

In the above model, Y (CFM50/ELA/EqLA) is the dependent/response variable where as house parameters constitute the independent/predictor variables. The home parameters considered in the model building process were Year of Construction/Built (YB), Floor Area (FA), Number of Stories (NOS), and Number of Bedrooms (NOB). These independent variables are easily available for a given home in a given region.

Table 3.1 shows the details of the predictor variable with their respective range and units for the total sample size of 66 homes. For example, Year Built has houses built between 1920 and 2004. The 42-home data consist of homes with 1, 1.5 and 2 stories and the number of bedrooms ranging from 2 to 5. The variables Number of Stories (NOS) and Number of Bedrooms (NOB) were considered as categorical variables while performing the regression analysis. Therefore, dummy variables also called indicator variables were introduced into the model building process. In general, a qualitative variable with 'a' levels is represented by 'a-1' indicator variables, each taking on the values 0 and 1 [36]. Tables 3.2 and 3.3 show the levels of the indicator variables for NOS and NOB.

Table 3-1. Predictor details.

Predictors	Units	Range	House Parameters
Year Built	Numerical Value	1920–2004	X1
Floor Area	Square Feet	1041-3866	X2
Number of Stories	Numerical Value	1, 1.5 or 2	X3
Number of Bedroom	Numerical Value	2, 3, 4 or 5	X4

Table 3-2. Levels of indicator variable for story

X_{31}	X_{32}	
1	0	If the observation is a home with 1 story
0	1	If the observation is a home with 1.5 story
0	0	If the observation is a home with 2 story

Table 3-3. Levels of indicator variable for bedroom.

X_{41}	X_{42}	
1	0	If the observation is from a home with 2 bedrooms
0	1	If the observation is from a home with 3 bedrooms
0	0	If the observation is from a home with 4 or more bedrooms

The house parameter NOS represented by X_4 in Table 3.1 was categorized as X_{41} and X_{42} as shown in Table 3.2. The house parameter NOB, X_5 was similarly categorized as X_{51} and X_{52} as shown in Table 3.3. The response for the above model was the air-tightness measure of CFM50 or ELA or EqLA. The independent variables considered in Tables 3.1, 3.2 and 3.3 were used for regressing against CFM50, ELA and EqLA.

The initial regression model was modeled using the 46 observations from the estimation sample including the following variables:

Dependent variable: ELA/CFM50/EqLA

Independent variable: YB, FA, NOS (S1 and S2 are the indicator variables), NOB (B2 and B3 are the indicator variables)

The model developed with CFM50 as the dependent variable will be termed CFM50 and the one developed with ELA will be termed ELA and so forth in the entire report unless otherwise stated. This regression model was constructed separately for ELA, CFM50 and EqLA with the help of the SAS^{TM} software. The presence of multi-collinearity was checked by determining the variance inflation factors (VIF). These factors measure how much the variances of the estimated regression coefficients are inflated as compared to when the independent variables are not linearly related [36]. A maximum VIF value in excess of ten is often taken as an indication that multi-collinearity may be unduly influencing the least squares estimates. The SAS^{TM} program and the output of the above result are presented in Appendix A (Figures A.1 and A.2). The outputs of the SAS^{TM} results do not show any multi-collinearity effects.

To know which variables will contribute significantly to the model and overcome the problems of multi-collinearity, we performed the Stepwise selection method. Stepwise regression is a modification of forward selection in which at each step all regressors entered into the model previously are reassessed via their partial F-statistics [43]. Stepwise regression requires two cutoff values F_{IN} and F_{OUT}. In most applications, we choose $F_{IN} > F_{OUT}$ and in our case, we apply $F_{IN} = 0.10$and $F_{OUT} = 0.05$. Applying the Stepwise regression technique to the three models (CFM50, ELA and EqLA), the results show that the variables Year Built, Area and S1 were significant for ELA and EqLA models. For CFM50 as the response variable, the results show that Year Built, and Area are significant. It is important to note that in all three models, the VIF is much less than 10 and hence there are no problems of multi-collinearity associated with these models. The results of the Stepwise selection process are summarized in Tables 3.4, 3.5 and 3.6. The detailed results of these runs using SAS^{TM} is presented in Appendix A. From Table 3.4, the included predictor variables in the model ELA are Area, YB and S1. Therefore the regression equation for the response ELA becomes

$$Y_{ELA} = B_0 + B_1 X_1 + B_2 X_2 + B_{31} X_{31} + e \qquad (3.2)$$

Incorporating the parameter estimates we obtain the following regression Eq. 3.3

$$Y_{ELA} = 5217.08 - 2.63 X_1 + 0.10 X_2 - 57.52 X_{31} + e \qquad (3.3)$$

Table 3-4. Summary of Stepwise regression for ELA.

Step	Variable entered	Label	Number Vars In	Partial R-Square	Model R-Square	C (p)	F Value	Pr > F
1	Area	Area	1	0.4914	0.4914	41.6032	42.52	<.0001
2	YB	Year Built	2	0.1828	0.6743	13.5485	24.13	<.0001
3	S1		3	0.0544	0.7286	6.6134	8.41	0.0059

Table 3-5. Summary of Stepwise regression for CFM50.

Step	Variable entered	Label	Number Vars In	Partial R-Square	Model R-Square	C (p)	F Value	Pr > F
1	Area	Area	1	0.4449	0.4449	42.6889	35.27	< 0.0001
2	YB	Year Built	2	0.2635	0.7085	4.4778	38.88	< 0.0001
3	S1		3	0.0334	0.7419	1.3806	5.44	0.0246

From Table 3.5, the included predictor variables in the CFM50 model are YB and Area. Therefore the regression equation for the response CFM50 becomes

$$Y_{CFM50} = B_0 + B_1 X_1 + B_2 X_2 + e \quad (3.4)$$

Incorporating the parameter estimates we obtain the following regression Eq. 3.5

$$Y_{CFM50} = 115105 – 58.64 X_1 + 2.14 X_2 + e \quad (3.5)$$

The summary of Stepwise regression for EqLA as the response variable is presented in Table 3.6 with significant predictor variables YB, Area and S1.

Table 3-6. Summary of Stepwise regression for EqLA.

Step	Variable entered	Label	Number Vars In	Partial R-Square	Model R-Square	C (p)	F Value	Pr > F
1	Area	Area	1	0.5029	0.5029	49.7899	44.52	< 0.0001
2	YB	Year Built	2	0.2228	0.7257	10.6565	34.92	< 0.0001
3	S1		3	0.0483	0.7739	3.7462	8.96	0.0046

The regression equation for the response EqLA is

$$Y_{EqLA} = B_0 + B_1 X_1 + B_2 X_2 + B_{31} X_{31} + e \quad (3.6)$$

Incorporating the parameter values, we obtain the Eq. 3.7

$$Y_{EqLA} = 10732 – 5.40 X_1 + 0.19 X_2 - 102.40 X_{31} + e \quad (3.7)$$

Both EqLA and ELA have the same predictor variables significant as seen from Eqs. (3.2) and (3.6). In addition, the parameters also have the same sign indicating that the variables have a similar effect on the response variables in both models.

In general, all three models have a negative sign for the predictor variable Area. This suggests that as the age of the house increases, the values of air-tightness decreases. The positive sign of the parameter Area in all three models indicate that as the conditioned area increases the air-tightness value decreases. It is important to note that higher the value of air-tightness, the more leaky the house is. Also, in the ELA and EqLA models, single story buildings are significant. However, this conclusion on the number of stories cannot be generalized because of the small sample size considered for single and 1.5 story residential buildings. To make the model simpler and to avoid the negative consequences of the small sample size on the independent variables-NOS and NOB; we performed regression considering only Year Built and Area of home as independent variables. Therefore, similar equations obtained in Eqs. (3.3), (3.5), (3.7) for ELA, CFM50 and EqLA are obtained for the new model respectively. The detailed multiple regression for this analysis are presented in Figures A1 and A2 respectively.

$$Y_{EqLA} = 9859.40 – 5.02\ X_1 + 0.21\ X_2 + e \tag{3.8}$$

$$Y_{CFM50} = 115105 – 58.64\ X_1 + 2.14\ X_2 + e \tag{3.9}$$

$$Y_{ELA} = 4726.77 - 2.41\ X_1 + 0.11\ X_2 + e \tag{3.10}$$

Eqs (3.8), (3.9) and (3.10) are the models considering only Area and the Year Built as independent variables. Eq. (3.9) is the same as Eq. (3.5) because the Stepwise regression concluded that Area and the Year Built were the only significant independent variables at a significance level of 0.01. All analyses from this point till the end of this chapter deal with these three equations unless otherwise stated.

3.5 APTNESS OF THE REGRESSION MODEL

The regression models for CFM50, ELA and EqLA (Eqs. (3.8), (3.9) and (3.10)) were checked for aptness in order to verify the major assumptions behind the regression analysis. The major assumptions behind the regression analysis are [36]:

1. The relationship between the response and regressors is linear, at least approximately.
2. The error terms have constant variance.
3. The errors are normally distributed.
4. The error term has zero mean.
5. The error terms are independent.

3.5.1 Nonlinearity of Variables

To review the relationship between the dependent variable and each of the independent variables, plots were generated with each of the dependent variables (CFM50, ELA and EqLA) against each of the independent variables. The plots are presented in Appendix A (Figures A.3 to A.8) and are not displaying any non-linear characteristics. The conditioned area vs. the response variable shows a linear effect. The residual plots, i.e. the plot of residuals vs. predicted for the three dependent variables, were plotted and is presented in Appendix A (Figures A.9 to A.11). Review of the plots shows that residuals are not displaying much of systematic tendencies or trends. Therefore, no transformations were done on these data. The interpretation of outliers, if present, is dealt with in detail in Section 3.7.

3.5.2 Nonconstant Error Variance

The plots of the residuals against the predicted values were used to test for a nonconstant error variance. The plots do not show any definite pattern. Hence, the regression model satisfies the assumption of nonconstant variance implying that the data are homoscedastic. The plots are presented in Appendix A (Figures A.9 to A.11).

3.5.3 Normality of Error Terms

A significant departure from normality is a serious violation of the assumptions in regression. A simple method of checking the normality assumption is to construct a normal probability plot of the residuals [36]. The error terms are expected to fall approximately along a straight line if the normality assumption is satisfied. The normal probability plots in Figures 3.5, 3.6 and 3.7 shows that the resulting points lie approximately on a straight line (except for few outliers) verifying the assumptions of normality.

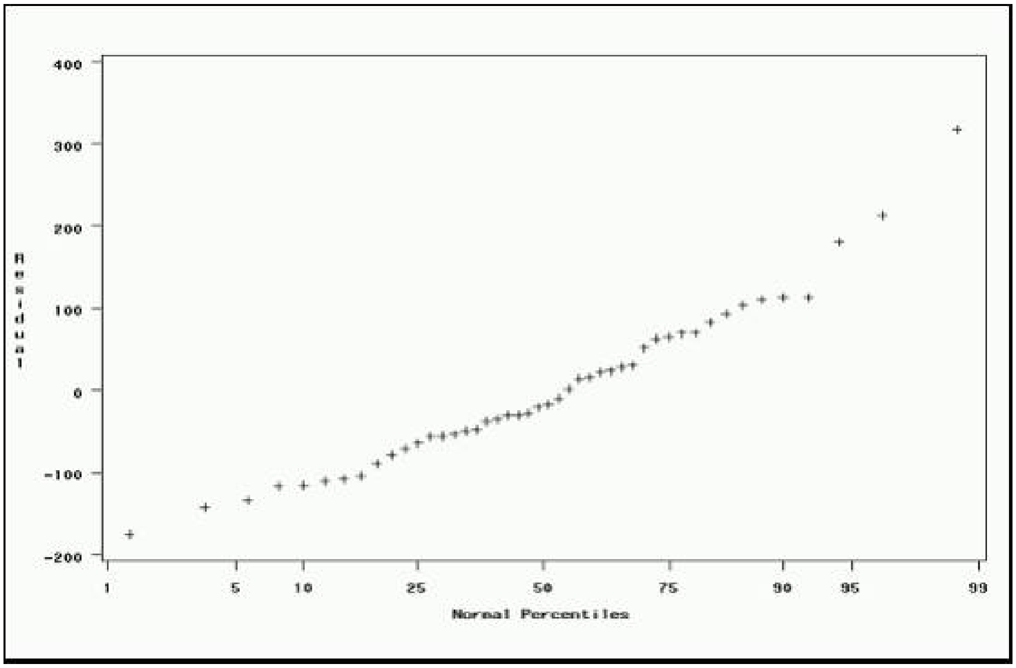


Figure 3-5. Normal plot for error terms of CFM50.

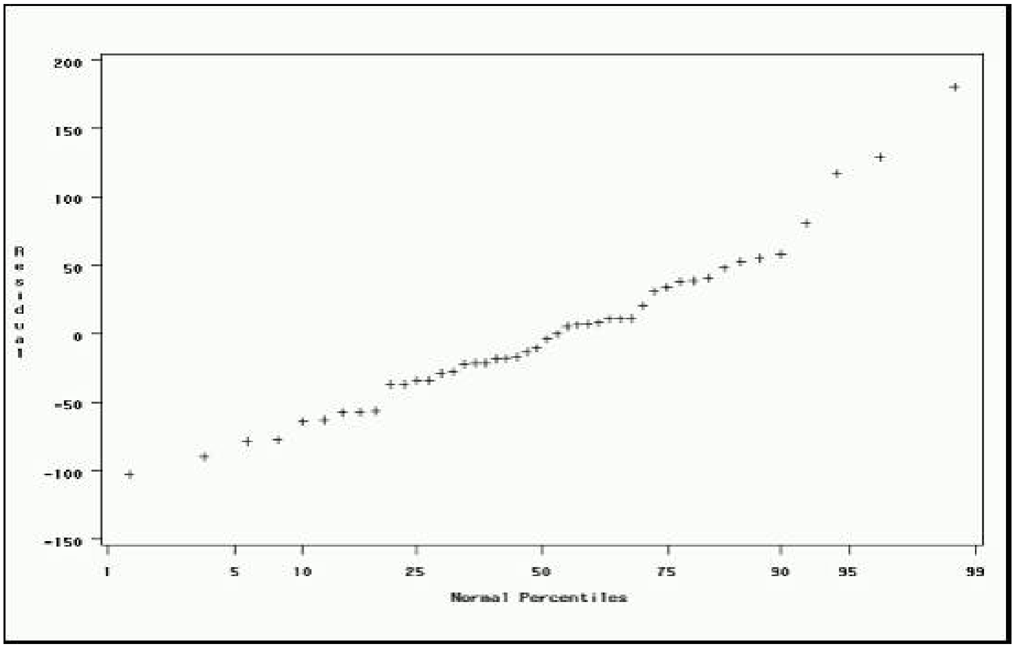


Figure 3-6. Normal plot for error terms of ELA.

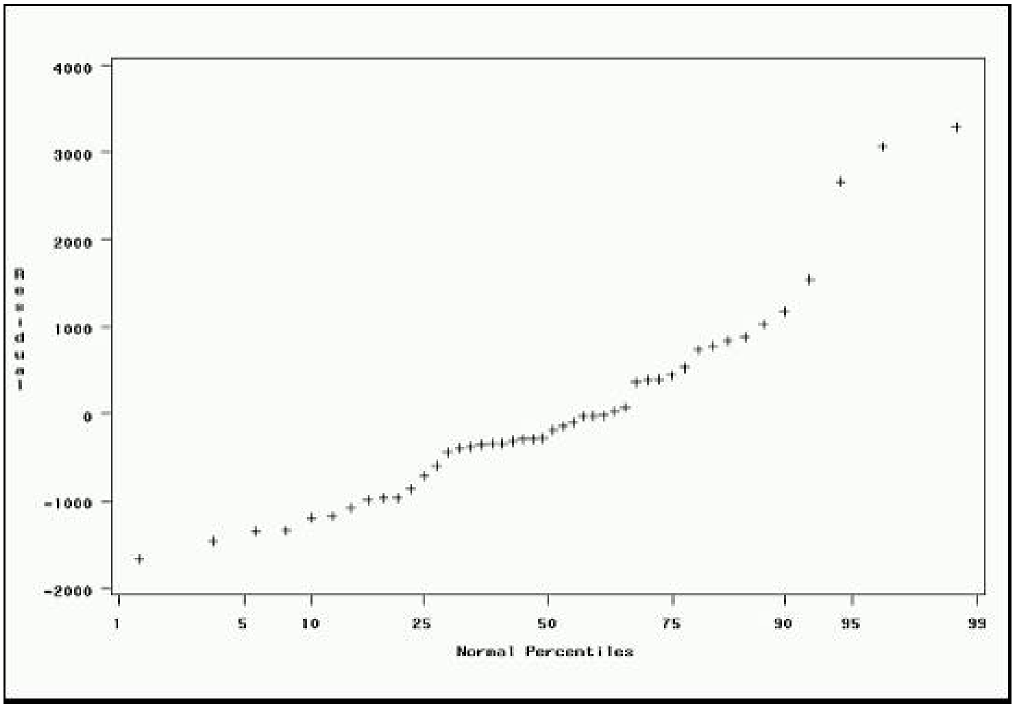


Figure 3-7. Normal plot for error terms of EqLA.

3.5.4 Independence of Error Terms

A regression model requires independence of the error terms. Again, a residual plot can be used to check this assumption. The independence of errors is verified by plotting predicted values against the residuals. A random, pattern-less lot with a scatter within +/- 2 standard deviations implies independent errors. The figures in Appendix A show the plot of residual vs. the predicted values for the three models. The graphs do not show dependence of error terms.

3.6 OUTLIERS

The outliers for the data under study were investigated and are presented in Sections 3.6.1, 3.6.2, 3.6.3, and 3.6.4.

3.6.1 X Outliers

Leverage values (diagonal element h_{ii} in the Hat matrix) greater than 2p/n are considered to be outlying cases. The target value is 2x(3)/46 = 0.13 for all the three models-ELA, EqLA and CFM50. Comparison of h_{ii} to the target value detected observations 1, 4, 11, 14, 35 and 36 as X outliers in the case of CFM50, ELA and EqLA. These observations need to be examined to determine if they are really influential or not. The outputs of the Hat diagonals are presented in Figure A.2.

3.6.2 Y Outliers

To identify outlying Y observations, an examination of the studentized deleted residuals (d_i) for large absolute values and the appropriate t-distribution is necessary. Taking an alpha of 0.10, t_{tab} = (0.9998, 42) = 2.970. Comparison of d_i^* to t_{tab} for the case of EqLA and ELA, we find observation 22 as the outlying Y observation where as 37 as the outlying Y observation in the case of CFM50. The detailed output is presented in Appendix A (Figure A.2).

3.6.3 Influence of Outliers

To identify the influence of observations identified as X and Y outliers, the measures DFFITS were used. The results of all DFFITS measures are shown in Appendix A (Figure A.2) respectively.

3.6.4 DFFITS

An observation is considered influential if the absolute value of DFFITS exceeds twice the square root of p/n for large datasets. The target value calculated was 0.51. Observations 11, 22, 35 and 37 are found to be influential in the case of CFM50 where as 4, 7, and 22 were found to be influential in the case of ELA. In the case of EqLA, observations 4, 7, 35 and 22 were found to be influential.

Examination of the data associated with the observations did not reveal any typographical errors or miscalculations and therefore all the observations were retained. The regression equations of CFM50, ELA and EqLA were maintained as obtained before and the predictive power of these three models was determined. The details of predictive power of the three models are described in Section 3.7.

3.7 MODEL VALIDATION AND PREDICTIVE POWER

The air-tightness model for EqLA, CFM50, and ELA was given in Eqs. (3.8), (3.9) and (3.10) respectively. The final step in a model-building process is validation of the above selected regression models. Model validation involves checking a candidate model against independent data. For this study, we employed the preferred method [35] of data splitting. The first set called the model-building set was used to develop the model. In this report, we term this data set as the estimation sample. The second data set called the validation set or the validation sample was used to determine the predictive ability of the selected model. In this study, the predictive ability of the three models was determined in order to the find the best predictive model. Splits of the data can be made random [35]. However, it is important that the model-building data should be large enough to obtain a reliable model. In this case, we have 46 observations in the estimation sample and 20 observations in the prediction sample with a total of 66 observations. Predictive capability can be determined by calculating the mean of the squared prediction errors (MSPR).

$$MSPR = \frac{\sum_{i=1}^{n^*} (Y_i - Y_i^{\wedge})^2}{n^*} \tag{3.11}$$

where, Y_i is the value of the response variable in the i^{th} validation case,

Y_i *hat* is the predicted value of the i^{th} validation case based on the model building data set, and n^* is the number of cases in the validation data set.

If the MSPR is fairly close to the error mean square (MSE) based on the regression fit to the model building data set, then the MSE for the selected regression model is not seriously biased and gives an appropriate indication of the predictive ability of the model.

From Table 3.7, we can conclude that MSPR of CFM50 is very far from the MSE of model building data set, whereas the MSPR of ELA and EqLA is greater than twice that of the MSE of their respective model building data set.

The validation results suggest that the predictive ability of these two models may not be high. However, the predicting model should have an estimate of their predictive power. When a given process is represented by competing models, their respective predictive power can be used to select the most appropriate model [38, 39]. One approach to discriminate among alternative models is through assessing the predictive power of such models. In this study, the three competing models are CFM50, ELA and EqLA. We have employed the Theil's statistic [40] and Root-Mean-Square Percent Error (RMSPE) [47] to determine the predictive power of the two regression models.

Table 3-7. Validation results.

Model Estimation Sample	MSPR	MSE	β_1	β_2
			95% confidence limits	
CFM50	-	1252981.00	-77.60872	1.61156
			-39.67393	2.66746
ELA	-	3405.49	-3.39765	0.08316
			-1.41997	0.13821
EqLA	-	10240.00	-6.73866	0.16399
			-3.30936	0.25944
Validation Sample				
CFM50	1218783.00	1433863.00	-113.40811	-0.37415
			-32.28458	2.95292
ELA	8535.04	10041.00	-8.20149	-0.09010
			-1.41279	0.18832
EqLA	23294.50	27405.00	-13.91515	-0.11737
			-2.69988	0.34260

Theil's Statistic is given by

$$U = \sqrt{\sum_i (Y_i - Y_i^{\wedge})^2 / \sum_i Y_i^2} \qquad (3.12)$$

whereas RMSPE is defined as

$$RMSPE = \frac{1}{n^*} \sum_{i=1}^{n^*} \left(\frac{Y_i - Y_i^{\wedge}}{Y_i^{\wedge}}\right)^2 \qquad (3.13)$$

In both Theil's Statistic and RMSPE, Y_i and Y_i^0 represents the actual and the predicted response value for the i^{th} observation respectively. Table 3.8 shows the predictive power of the competing models with respect to Theil's Statistic and RMSPE.

Table 3-8. Predictive power of competing models.

Statistic	CFM50	EqLA	ELA
Theil's U	0.3055	0.3720	0.4077
RMSPE	0.0042	0.006	0.0068

From Table 3.8, we can conclude that the CFM50 model outperforms the ELA as well as EqLA model since both Theil's U Statistic and RMSPE for CFM50 are lower than ELA and EqLA respectively.

3.8 AIR-TIGHTNESS CLASSIFICATION OF RESIDENTIAL HOMES

In Section 3.7, we determined that CFM50 model is a better model in estimating air-tightness. This section attempts to characterize the data of whole house leakiness to meaningful structures based on CFM50, Floor Area and Year Built. Due to the small sample size, additional data from

New Orleans was added to increase the sample size of homes to 83. The study attempted will enable us to:

1. Characterize the homes based on observable factors such as age and conditioned area.
2. Develop a classification chart by which we can segregate the homes based on the most influential factors.
3. Verify the model building outcomes of Section 3.4.

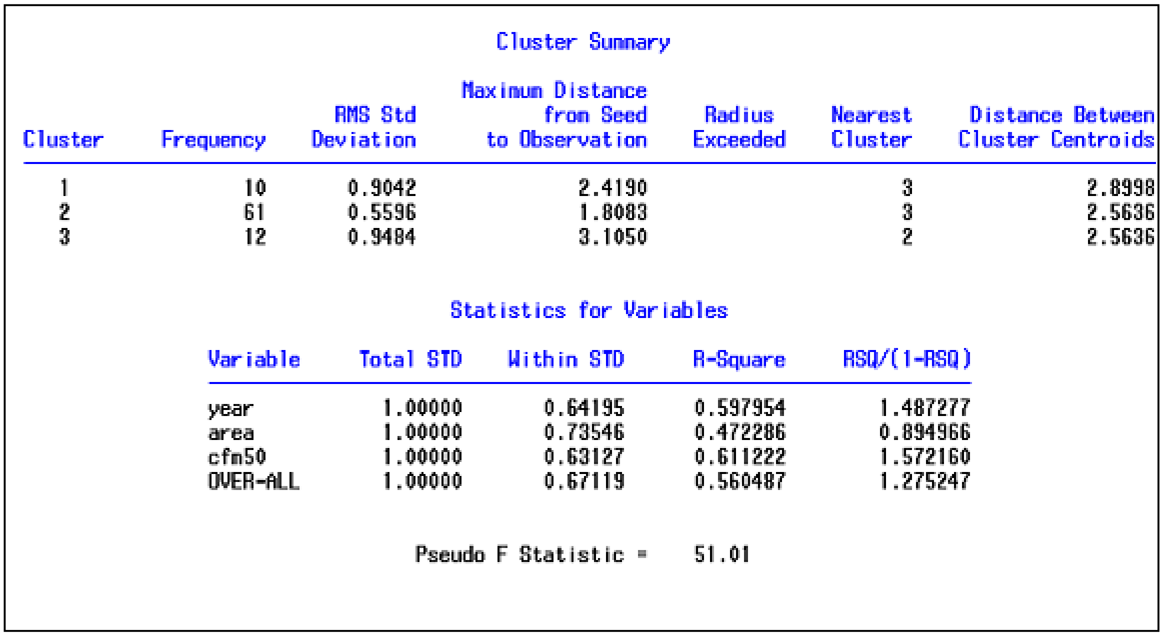
We have employed the Cluster Analysis technique to classify the data of 83 homes. Cluster Analysis comprises of classification algorithms that organize observed data into meaningful structures [41]. There are basically two methods of clustering, hierarchical and non-hierarchical clustering methods [42]. In this study, we have used the non-hierarchical method to cluster the data into meaningful structures. We have used SAS^{TM} software to perform cluster analysis. The SAS's^{TM} FASTCLUS procedure was used to perform a disjoint cluster analysis on the basis of distances computed from one or more quantitative variables [43]. The FASTCLUS procedure combines an effective method for finding initial clusters with a standard iterative algorithm for minimizing the sum of squared distances from the cluster means. For all the details, refer to *Applied Multivariate Methods for Data Analysts* by Dallas E. Johnson.

The variables used in the cluster detection algorithm are called basis variables. From a purely exploratory point of view, all available information should be included as basis variables in the analysis. From a practical point of view, however, it is desirable to select basis variables that have the potential to be both analytically and strategically useful. Myers [44] provides an excellent discussion on the types of basis variables and the need for careful forethought when selecting basis variables for use in cluster identification algorithms. In this case, we select the base variables as CFM50, Year Built and Floor Area as per the conclusions obtained in Sections 3.4 and 3.7.

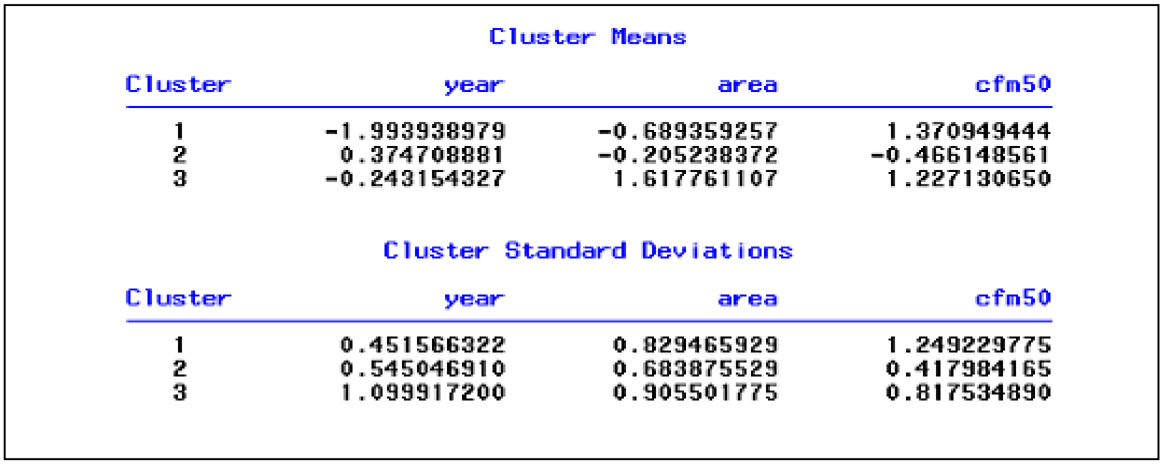
The SAS^{TM} program and the detailed output using the PROC FASTCLUS are presented in the Appendix A (Figures A.12 and A.13). The procedure (PROC FASTCLUS) was run twice (Run1 and Run2) to test whether or not the number of clusters generated was significant or not. In the first run, we set a predetermined number of clusters to be formed. In this case, we set the maximum number of clusters to be three, as it seemed very reasonable based on the sample size and the range of basic variables. It is important to note that the values of the variables were standardized with mean equal to 0 and standard deviation equal to one.

The output of PROC FASTCLUS for the first run is presented in Table 3.9 and the output obtained is in the standardized form. We can see that there are 10, 61, and 12 homes respectively in clusters one, two and three. From the cluster means, we can conclude that as the age of the house and the conditioned area increases the air-tightness decreases. This observation can be seen in the case of cluster three. However, in the case of cluster two, we observe that smaller area and newly built homes have a smaller CFM50 values. The negative and positive sign indicates the direction of the magnitude of values.

Table 3-9. Run1 results from PROC FASTCLUS procedure.



```
                                    Cluster Summary

                                 Maximum Distance
                        RMS Std         from Seed     Radius    Nearest    Distance Between
Cluster     Frequency  Deviation   to Observation   Exceeded    Cluster   Cluster Centroids

   1              10      0.9042           2.4190                     3              2.8998
   2              61      0.5596           1.8083                     3              2.5636
   3              12      0.9484           3.1050                     2              2.5636


                               Statistics for Variables

              Variable     Total STD    Within STD     R-Square    RSQ/(1-RSQ)

              year           1.00000       0.64195     0.597954       1.487277
              area           1.00000       0.73546     0.472286       0.894966
              cfm50          1.00000       0.63127     0.611222       1.572160
              OVER-ALL       1.00000       0.67119     0.560487       1.275247


                            Pseudo F Statistic =     51.01
```



```
                           Cluster Means

Cluster              year              area             cfm50

   1         -1.993938979      -0.689359257       1.370949444
   2          0.374708881      -0.205238372      -0.466148561
   3         -0.243154327       1.617761107       1.227130650

                    Cluster Standard Deviations

Cluster              year              area             cfm50

   1          0.451566322       0.829465929       1.249229775
   2          0.545046910       0.683875529       0.417984165
   3          1.099917200       0.905501775       0.817534890
```

The clustering of the data points is presented in Figure 3.8. The numerical data points correspond to the respective clusters and we can see that cluster one is separated from the other two clusters distinctly. Prin2 and Prin1 on the axes are the principal components output obtained using FASTCLUS procedure. The principal components are artificial variables generated that will account for most of the variance in observed variables.

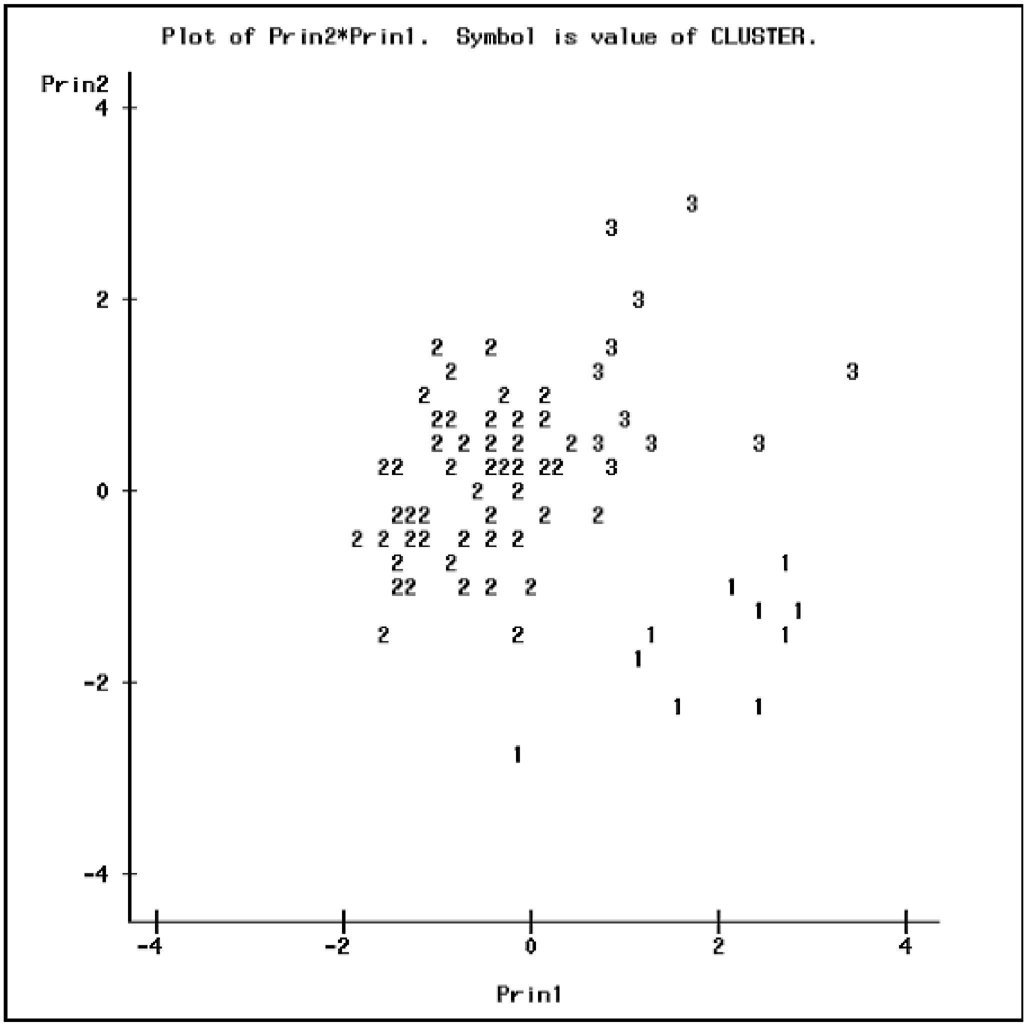
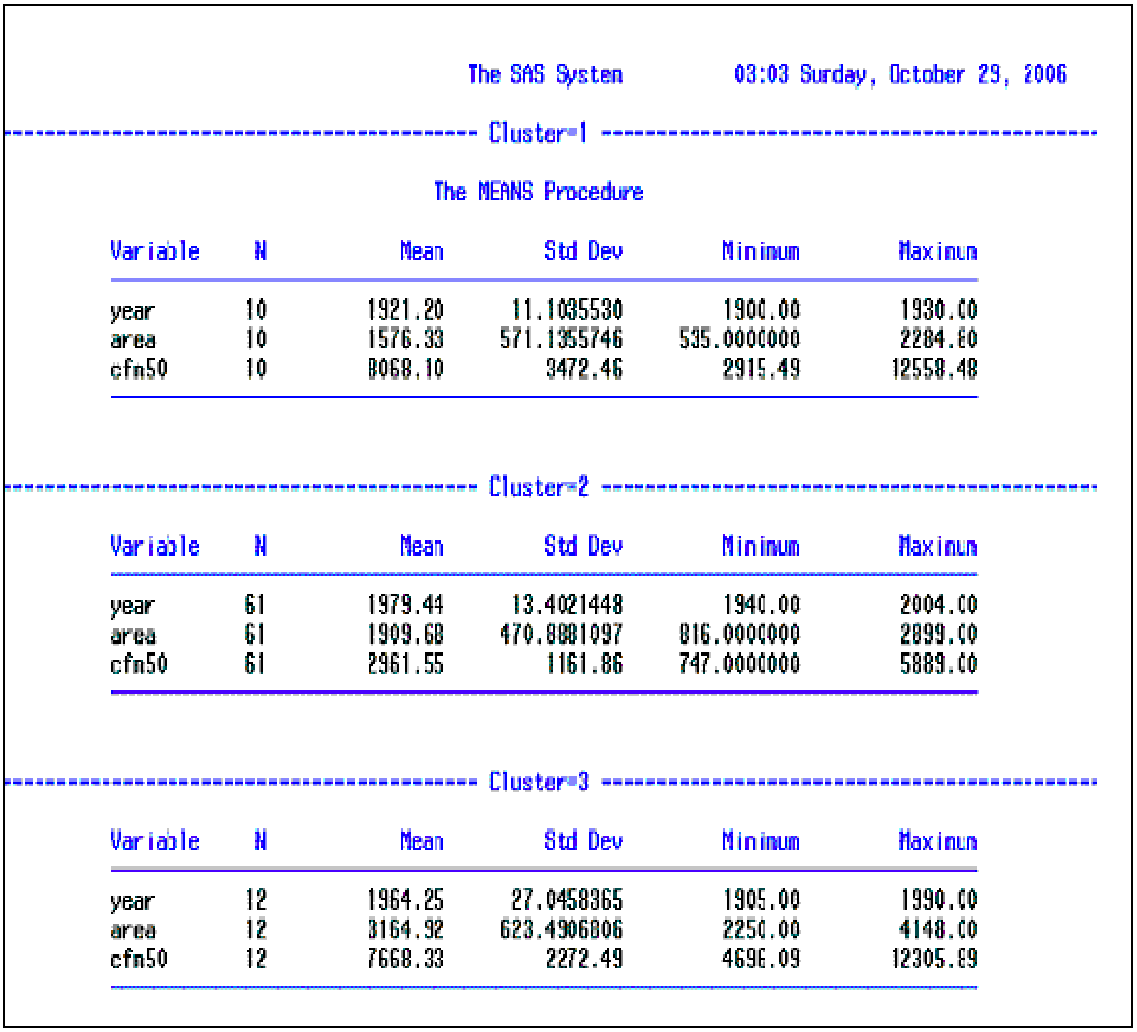


Figure 3-8. Plot of the clusters using run1.

The cluster means on the original data from Run1 is presented in Table 3.10. The mean values of CFM50 for cluster one is 8068 cfm with mean year 1921 and mean area 1576 sq. ft. whereas cluster three has mean cfm50 of 7668 with mean area equal to 3164 sq. ft. with mean year of construction 1964. Comparing clusters one and three with two, we can conclude that newer and smaller homes have higher air-leakage rates.

Table 3-10. Cluster means on the original data from run1.



```
                          The SAS System         03:03 Sunday, October 29, 2006

------------------------------------------ Cluster=1 ------------------------------------------

                                The MEANS Procedure

        Variable     N           Mean        Std Dev        Minimum        Maximum
        ---------------------------------------------------------------------------
        year        10        1921.20     11.1035530        1900.00        1930.00
        area        10        1576.33    571.1355746    535.0000000        2284.60
        cfm50       10        8068.10        3472.46        2915.49       12558.48
        ---------------------------------------------------------------------------


------------------------------------------ Cluster=2 ------------------------------------------

        Variable     N           Mean        Std Dev        Minimum        Maximum
        ---------------------------------------------------------------------------
        year        61        1979.44     13.4021448        1940.00        2004.00
        area        61        1909.68    470.8881097    816.0000000        2899.00
        cfm50       61        2961.55        1161.86    747.0000000        5889.00
        ---------------------------------------------------------------------------


------------------------------------------ Cluster=3 ------------------------------------------

        Variable     N           Mean        Std Dev        Minimum        Maximum
        ---------------------------------------------------------------------------
        year        12        1964.25     27.0458365        1905.00        1990.00
        area        12        3164.92    623.4906806        2250.00        4148.00
        cfm50       12        7668.33        2272.49        4696.09       12305.89
        ---------------------------------------------------------------------------
```

It is important to note that the number of homes in cluster four is only three. This low frequency of homes in cluster four suggests an ineffective clustering process. However, the significance tests in regards to the appropriate number of clusters were tested using Beale's pseudo F-statistic [42].

The Beale's pseudo F-statistic is given by

$$F^* = J \times (U) \times (L)^{-1} \qquad (3.14)$$

where,

F^* = Beale's psuedo F-statistic

w_2 = intracluster residual some of squares from run two (Run2)

w_1 = intracluster residual some of squares from run one (Run1)

N = total number of observations

c_1 = Number of clusters in Run1

c_2 = Number of clusters in Run2

$k_1 = c_1^{-2/p}$

$k_2 = c_2^{-2/p}$

p= number of variables

$J = (w_1 - w_2) / w_2$

$U = (N - c_2) k_2$

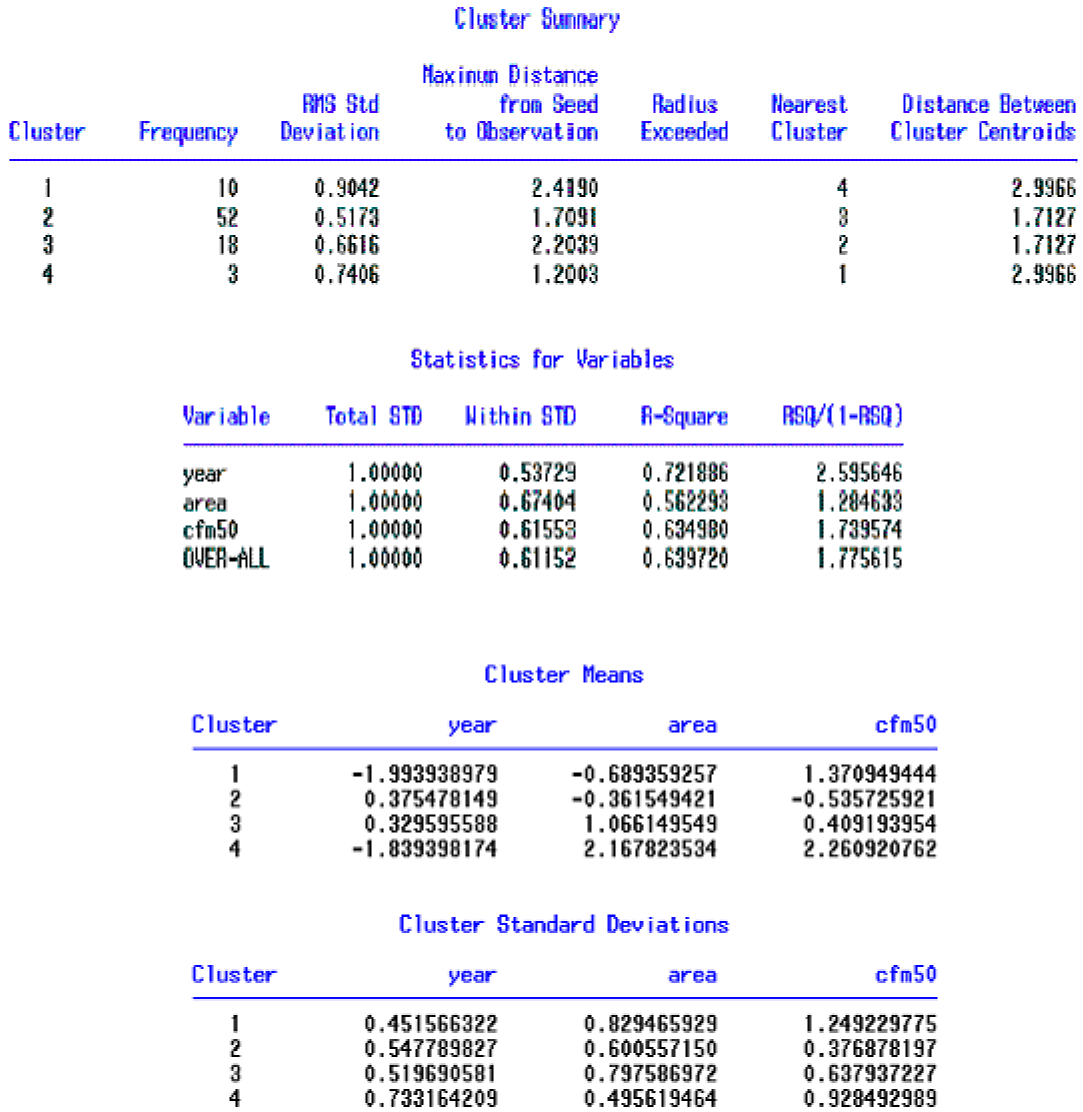
$L = (N - c_1) k_1 - U$

In this analysis, the respective substitutions for the Beale's pseudo F-statistic are as follows:

$w_2 = 88.70$, $w_1 = 108.12$, N=66, $c_1=3$, $c_2=4$, $k_1=0.4807$, $k_2=0.3968$, p=3

The Beale's pseudo F-statistic was determined to be 0.9694. The table value with numerator degrees of freedom seven and denominator degrees of freedom 31 was determined to be 2.49. Since the F calculated value (0.9694) is less than F table value (2.33), we can conclude that four-cluster solution is not significantly better than the three-cluster solution. The SAS™ output for the cluster analysis is presented in Figure A13. Table 3.11 shows the results obtained from Run2 of PROC FASTCLUS. Run2 has produced four clusters.

Table 3-11. Run2 results from PROC FASTCLUS procedure.



```
                                 Cluster Summary

                                Maximum Distance
                       RMS Std         from Seed    Radius    Nearest    Distance Between
Cluster    Frequency  Deviation   to Observation  Exceeded    Cluster   Cluster Centroids
------------------------------------------------------------------------------------------
   1          10        0.9042          2.4190                   4              2.9966
   2          52        0.5173          1.7091                   3              1.7127
   3          18        0.6616          2.2039                   2              1.7127
   4           3        0.7406          1.2003                   1              2.9966

                           Statistics for Variables

              Variable     Total STD    Within STD     R-Square    RSQ/(1-RSQ)
              ------------------------------------------------------------------
              year           1.00000       0.53729     0.721886       2.595646
              area           1.00000       0.67404     0.562293       1.284633
              cfm50          1.00000       0.61553     0.634980       1.739574
              OVER-ALL       1.00000       0.61152     0.639720       1.775615


                                 Cluster Means

              Cluster              year              area             cfm50
              ---------------------------------------------------------------
                 1         -1.993938979      -0.689359257       1.370949444
                 2          0.375478149      -0.361549421      -0.535725921
                 3          0.329595588       1.066149549       0.409193954
                 4         -1.839398174       2.167823534       2.260920762

                          Cluster Standard Deviations

              Cluster              year              area             cfm50
              ---------------------------------------------------------------
                 1          0.451566322       0.829465929       1.249229775
                 2          0.547789827       0.600557150       0.376878197
                 3          0.519690581       0.797586972       0.637937227
                 4          0.733164209       0.495619464       0.928492989
```

From Table 3.10, Run1 shows that homes in clusters one and three have higher CFM50 values. These high CFM50 values correspond to homes, which are built between 1900 and 1990 with maximum conditioned area of 4148 sq. ft. From Cluster two, we see that houses with a slightly larger conditioned area and built between 1940 and 2004 have lower CFM50 values. However, there are no concrete indicators suggesting that homes between 1990 and 2004 are much tighter. To be more accurate, a larger sample is recommended to perform the cluster analysis. However, this analysis has indicated that older and larger homes tend to be leakier. Therefore, this study has attempted to characterize the air-tightness of homes based on age of the house and the conditioned area. The study also verifies that age of the house and the conditioned area are some of the major observable factors influencing air-tightness as modeled in Section 3.4.

3.9 CONCLUSIONS

Three models (CFM50, ELA and EqLA) to determine air-tightness based on the age of the home and conditioned area were developed using multiple regression analysis (Eqs. (3.9), (3.10) and (3.11)). The parameter estimates from these three models shows that as the age of the house increases, the air leakage increases in Louisiana homes. The conditioned area also shows a similar trend with respect to air leakage. Based on the predictive power, we can conclude that CFM50 is a better predictive model than ELA and EqLA. The proposed model will be very beneficial to those who are involved with building science, especially those who want quick and reasonable estimate of air-tightness. The model will be advantageous for energy raters as well as those involved in real estate. Basically, the model will be useful for regional energy estimates and policies regarding duct leakage and savings, which can be obtained by fixing them. However, it should be stressed again that the model is region-specific and cannot be applied without having prior knowledge of building characteristics in that specific region.

The cluster analysis performed in Section 3.8 gives an insight in segmenting homes with respect to age and conditioned area. From the air-tightness tests performed in 83 homes in the State of Louisiana, those constructed before 1990 and maximum conditioned area of 4148 sq. ft. have higher air leakage rates.

4.0 GENERALIZED SUBTRACTION ALGORITHM

The Subtraction Method measures duct-leakage-to-outside (hereinafter referred to as "duct-leakage") by subtracting Blower Door^{TM} induced airflow out of a home during two consecutive tests, the only difference between these two tests being the taping of the duct registers in the second test. These test procedures are best presented in the research report "Testing HVAC Duct Leakage in Existing Residential Buildings in North Louisiana" [2]. Since these measurements involve changes in a variety of environmental parameters, duct-leakage is often underestimated. To correct for these differences [2], Modified Subtraction calculates duct-leakage by multiplying the result of a pure Subtraction Method by a Subtraction Correction Factor (SCF), where $SCF = 50^{0.65} / [\ 50^{0.65} - D^{0.65}\ ]$ and D is the pressure difference between the ducts and attic when the registers are taped while the home is depressurized to 50 Pa.

Modified Subtraction assigns the calculated duct-leakage to 50 Pa. However, Modified Subtraction assumes that the attic pressure does not change when the home is depressurized–an assumption that does not match conditions usually found in practice. This and other practical problems are addressed and included in the derivation of the Generalized Subtraction Correction Algorithm (GSCA). GSCA principally differs from Modified Subtraction by using the attic pressure to calculate a generalized SCF. The study on 55 homes in North Louisiana provided in Chapter Four will illustrate this methodology. GSCA's accuracy heavily depends upon the accuracy of a pair of house-leakiness tests, determination and characterization of house-leakiness are other practical problems addressed and ameliorated in this study. House-leakiness testing is also discussed here because both objectives, ascertaining duct-leakage and house-leakiness, can be accomplished simultaneously by performing a standard set of flow measurements via depressurizations of the home at a series of pressures. While the ASTM Standard E779-03, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 136, and the Canadian General Standards Board (CGSB) Standard 149.10-M86 already require that house-leakiness should be tested at a series of pressures [45, 46], this study explains how house-leakiness tests taken at a series of pressures also enhance the estimation of duct-leakage. Conversely, since GSCA collects pressure and pressure-coupling data with registers taped and again with registers untaped, and these data are not normally used in a house-leakiness test, GSCA can uncover errors in house-leakiness data collection. Thus, provided herein is a testing technique and system analysis that will improve the determination of the two most important energy-performance tests of a home: house-leakiness and duct-leakage.

In addition, our characterization of house-leakiness contains an enhancement of the standard by introducing a new parameter, the attic-to-home pressure-coupling ratio. This pressure-dependent function can be used to estimate the proportion of the house-leakiness associated with the home's connection to its attic. Moreover, the attic-to-home pressure-coupling ratio is pivotal to checking the applicability of GSCA.

Although originally derived for the case when ducts are installed in attics, GSCA can be applied to crawlspaces or other semi-exposed locations; in that case, the energy rater should merely measure the pressure of the volume enclosing the ducts instead of the attic. It should be noted that even GSCA in its present form cannot be applied to a home with two or more independent duct-systems or a single duct-system in more than one independent pressure-volume adjoining a home, for example: an attic and a crawlspace. It should also be noted that in this derivation, it is assumed that the pressure in the ducts is uniform throughout.

4.1 MERITS OF GSCA

GSCA generalizes and corrects Modified Subtraction [22] by:

1. Incorporating the change in attic pressure,
2. Assigning duct-leakage to the actual pressure difference between ducts and attic,
3. Using an average duct-leakage instead of house-leakiness flow-exponent,
4. Incorporating the change of the duct-system pressure when the registers are untaped,
5. Allowing the calculation of duct-leakage at house depressurizations other than 50 Pa,
6. Calculating duct-leakage when the pressure difference between attic and ducts is 25 Pa, and
7. Allowing for a posteriori reviews of the calculated and observed parameters that help confirm the accuracy of data collection and check the reliability of both house-leakiness tests.

4.2 DATA COLLECTION PROCEDURE

1. Perform a depressurization test with a Blower Door^{TM} to depressurize the house to P.
   a) Record the flow as Q for untaped.
   b) Record the pressure in the duct system with respect to the attic, P_D.
   c) Record the pressure in the attic with respect to inside, P_A.
2. Remove the HVAC filters and tape all the registers. Perform a second depressurization test with a Blower Door^{TM} to depressurize the house to P.
   a) Record the flow as $Q'$for taped.
   b) Record the pressure in the duct system with respect to the attic, P'_D.
   c) Record the pressure in the attic with respect to inside, P'_A**.**

Under these conditions, duct-leakage at 25 Pa (also called CFM25) is defined as the flow from the ducts to the attic when the pressure between the ducts and the attic is 25 Pa. This value of duct-leakage cannot be measured directly by the procedure just described since the measurement apparatus is set to the house depressurization with respect to the outside, P, and not the duct-system's depressurization with respect to the attic, PD. This procedure calculates duct-leakage but the pressure between the ducts and the attic, PD, at which the measurement is performed, cannot be known at the time the house depressurization pressure, P, is chosen. We first show that, although we cannot expect to directly obtain the duct-leakage at 25 Pa or at 50 Pa by a single application of this procedure at one pressure, P, it is possible to extract these values through a coordinated set of two or more runs of this same experiment, i.e., each set at a specific value of P for two or more different values of P.

When the home is depressurized twice (once before, and once after the duct-registers are taped), the difference in the flow through the Blower Door^{TM} is taken to be, as a first approximation, the duct-leakage (to outside the conditioned space) at some specific pressure. However, for the same pressure regime P, the pressure difference between the ducts and attic differs in the taped and untaped cases; i.e., P_D does not equal P'_D. To correct for this experimental situation, a Subtraction

Correction Factor (*SCF*) is introduced in which the two flows, Q and Q', are taken at different pressures, P_D and P'_D where, Duct-Leakage (to Outside) is the difference between the untaped and taped flows times the *SCF*.

4.3 DERIVATION OF THE GENERALIZED SCF

We start by deriving the formula for the *SCF*. Several limiting conditions on this derivation will be addressed in the comments that follow the description of GSCA. Figure 4.1 shows the typical airflows in residential homes.

Holes between the ducts and the attic provide the area where duct-leakage must occur.

Q = flow from house to outside = flow through Blower Door™

= flow not via ducts+ flow via ducts $= Q_{nvd} + Q_{vd}$ (4.1)

Notice that both of these flows are divided into two flows as described in the diagram.

Q_{vd} = flow via ducts = flow via registers + flow via ducts but not registers

$= Q_{vr} + Q_{vdbnr}$ (4.2)

Q_{nvd} =flow not via ducts = flow not via attic + flow via attic but not ducts

$= Q_{nva} + Q_{vabnd}$ (4.3)

However, for the remainder of the derivation of *SCF*, the distinction between these last two flows, Q_{nva} and Q_{vabnd}, will not be needed; therefore, only Q_{nvd} will be utilized.

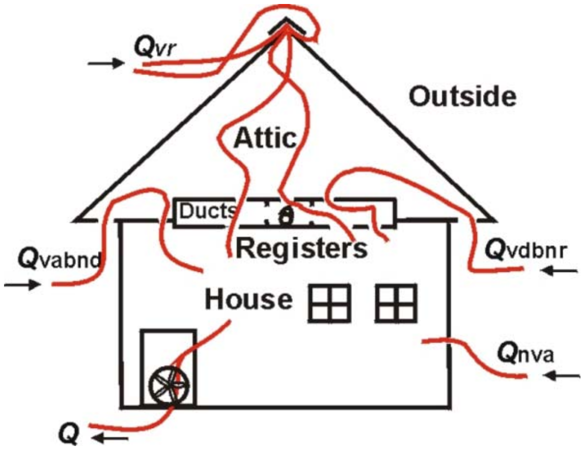


Figure 4-1. Airflows generated by using a Blower Door™ to depressurize a home.

Thus:

$$Q = Q_{nvd} + Q_{vd} = Q_{nvd} + Q_{vr} + Q_{vdbnr}$$

Q_{dlo}= duct-leakage (to outside) = flow into the ducts from the attic

Therefore,

$$Q_{dlo} = Q_{vr} + Q_{vdbnr} \quad (4.4)$$

Thus:

$$Q = Q_{\mathrm{nvd}} + Q_{\mathrm{dlo}} \qquad (4.5)$$

Empirically it has been found [47] that airflow for house-leakiness, as a function of the pressure difference between the home and outside, typically follows a power-law over the range of pressures utilized in these measurements

$$Q = \kappa P^{n} \qquad (4.6)$$

Experience from alternative testing methods [2, 48] has confirmed that the same power-law relationship applies to duct-leakage, namely

$$Q_{\mathrm{dlo}} = \kappa_{\mathrm{D}} P_{\mathrm{D}}{}^{m} \qquad (4.7)$$

where κ_{D} is the coefficient for the flow-equation for duct-leakage as a function of the pressure difference between the attic and the ducts. Note that the exponent for duct-leakage, m, may be different from n, the exponent for house-leakiness. Also note that P_{D} is the pressure difference between the ducts and the attic with the registers untaped. In each case, the exponents, n and m apparently depend on all of the conditions of the test, and κ, κ_{D}, n and m are constants for any particular home. For each home, the empirically obtained values of n and m have been found to vary within the range of 0.5 to 0.8, while their average values over a large number of homes were reported to be close to 0.65 for n and 0.60 for m [2, 48].

We define

Q'= the flow with the registers taped.

$$Q' = Q'_{\mathrm{nvd}} + Q'_{\mathrm{vr}} + Q'_{\mathrm{vdbnr}} \qquad (4.8)$$

Since the registers are taped, $Q'_{\mathrm{vr}} = 0$ and

$$Q' = Q'_{\mathrm{nvd}} + Q'_{\mathrm{vdbnr}} \qquad (4.9)$$

During the taped case, the flow into the ducts must equal the flow out of the ducts. Thus:

$$Q'_{\mathrm{dlo}} = Q'_{\mathrm{vdbnr}} = \kappa'_{\mathrm{D}} P'_{\mathrm{D}}{}^{m'} \qquad (4.10)$$

$$Q' = Q'_{\mathrm{nvd}} + Q'_{\mathrm{dlo}} \qquad (4.11)$$

As defined in Step 2 of the data-collection procedure, P'_{D} is the pressure difference between the ducts and the attic with registers taped. The m' in Eq. (4.10) is primed because it refers to the taped case and, from our measurements, depends on all the parameters of the test. Similarly, κ'_{D} is the (constant) coefficient for the flow-equation restricted to flow through the attic to the ducts.

From Eq. (4.5) and Eq. (4.11) we obtain

$$Q - Q' = (Q_{\mathrm{nvd}} + Q_{\mathrm{dlo}}) - (Q'_{\mathrm{nvd}} + Q'_{\mathrm{dlo}}) \qquad (4.12)$$

Assuming house-leakiness to be independent of the change in the flow through the ducts, $Q_{\mathrm{nvd}} = Q'_{\mathrm{nvd}}$ (this relationship can be relied upon when empirical observation confirms that P_{A} is essentially the same as P'_{A}; see the Untaped and Taped Attic Pressures comment), we obtain

$$Q \quad - Q' = Q_{\mathrm{dlo}} - Q'_{\mathrm{dlo}}$$

Substituting Eq. (4.10) into this equation, we obtain

$$Q \quad - Q' = \kappa_{\mathrm{D}} P_{\mathrm{D}}^{m} - \kappa'_{\mathrm{D}} P'_{\mathrm{D}}{}^{m'} \tag{4.13}$$

By definition

$$SCF = \text{duct-leakage} \quad / [\ Q \quad - Q'\ ] \tag{4.14}$$

Thus

$$SCF = \kappa_{\mathrm{D}} P_{\mathrm{D}}^{m} / \ [\ \kappa_{\mathrm{D}} P_{\mathrm{D}}^{m} - \kappa_{\mathrm{D}}' P'_{\mathrm{D}}{}^{m'}] \tag{4.15}$$

We now assume that $\kappa_{\mathrm{D}} = \kappa_{\mathrm{D}}'$. This is a reasonable assumption since the flow coefficient for the flow across the boundary between the duct system and the attic, at various pressure differences between the ducts and attic, is clearly independent of whether the registers are taped or not; similarly, $m = m'$. Thus

$$SCF = P_{\mathrm{D}}^{m} \ / \ [P_{\mathrm{D}}^{m} - P'_{\mathrm{D}}{}^{m}\ ] \tag{4.16}$$

We believe that the best assumption for the value of m is to use a value obtained by averaging a large set of duct-leakage results, $m = 0.60$ [2, 48] (as opposed to that obtained by averaging over a large set of house-leakiness results, namely $n = 0.65$; see the Choice of Flow Exponent comment). Therefore

$$SCF \ = \ P_{\mathrm{D}}^{0.6} \ / \ [\ P_{\mathrm{D}}^{0.6} - P'_{\mathrm{D}}{}^{0.6}\ ] \tag{4.17}$$

This completes the derivation of *SCF* for any depressurization pressure, *P*; but it should be stressed again that, the calculated *SCF* should be assigned to the value of P_{D}, not the value of *P*. However, although it seems that the value of *SCF* depends upon *P* or P_{D}, as we shall see below, in most cases *SCF* does not depend upon the choice of either *P* or P_{D} used for the test.

THEOREM: IF THE VALUES OF $\mathrm{P_D}$ AND $\mathrm{P'_D}$ ARE DIRECTLY PROPORTIONAL TO P, THEN THE VALUE OF SCF DOES NOT DEPEND UPON P.

Proof: The values of P_{D} and P'_{D} are proportional to *P*. That is, for any given home

$$P_{\mathrm{D}} = K * P \tag{4.18}$$

$$P'_{\mathrm{D}} = K' * P \tag{4.19}$$

for some constants *K* and *K′*.

Then, substituting Eqs. (4.17) and (4.18) into Eq. (4.15)

$$SCF \ = (K * P)^{\,0.6} / \ \ [\ (K * P)^{\,0.6} - \ (K{*}\ P)^{\,0.6}] = K^{0.6} \ / \ \ [\ K^{0.6} \ - \ K^{0.6} \ \ ] \tag{4.20}$$

GSCA has proven to provide a significant benefit over Modified Subtraction for homes that have all of their duct-systems limited to conditioned space and a single attic, and when the attic's pressure changes by more than 2 Pa when the home is depressurized to 50 Pa. In almost one hundred homes investigated within Louisiana, each with a single HVAC system, almost invariably P_D and P'_D appeared to be directly proportional to P and GSCA was applicable. The following result characterizes the situation where we should expect this very common linearity and gives insight into the physical situation in a home when this condition is not met.

THEOREM: WHEN DUCT-LEAKAGE (TO THE ATTIC) IS VERY SMALL WITH RESPECT TO HOUSE LEAKAGE TO THE ATTIC, P_D IS PROPORTIONAL TO P.

Proof: All singly-subscripted pressures are referenced to outside unless otherwise stated,

Q_{ad} = flow from attic to ducts and Q_{dh} = flow from ducts to house. Therefore

$$Q_{dh} = Q_{ad}$$

From Eq. (4.10), assuming the same exponent, m, for all duct-leakage flows

$$\kappa_{dh} (P_d - P_h)^m = \kappa_{ad} (P_a - P_d)^m \tag{4.21}$$

Therefore, solving for P_h

$$P_h = \{[1 + (\kappa_{ad}/\kappa_{ah})]^{1/m}\}P_d - (\kappa_{ad}/\kappa_{ah})^{1/m}P_a \tag{4.22}$$

We shall now show that P_d and P_a are proportional to P_h.

Consider the flows into and out of the attic:

Q_{oa} = flow from outside to attic

Q_{vabnd} = flow (from attic to house) via attic but not ducts

Q_{vd} = flow (from attic to house) via ducts

By conservation of mass out of and into the attic, respectively

$$Q_{oa} = Q_{vabnd} + Q_{vd}$$

Utilizing Eq. (4.6) and assuming all the exponents are the same (to within a reasonable approximation; see the *Choice of Flow Exponent* comment)

$$\kappa_{oa} (P_a)^m = \kappa_{vabnd} (P_h - P_a)^m + \kappa_{vd} (P_d - P_a)^m \tag{4.23}$$

Since, for the vast majority but not necessarily all homes, the leakage from the house to the attic is much greater than the leakage from the ducts to the attic, i.e.

$$\kappa_{vabnd} (P_h - P_a)^m >> \kappa_{vd} (P_d - P_a)^m \tag{4.24}$$

Eq. (4.24) becomes

$$\kappa_{oa} P_a{}^m \simeq \kappa_{vabnd} (P_h - P_a)^m \tag{4.25}$$

Thus, for homes satisfying the approximation of Eq. (4.25), the pressure in the attic, P_a, is essentially proportional to P_h, the house pressure. Since P_a is proportional to P_h, then from Eq (4.22), P_d is also proportional to P_h.

Corollary: When duct-leakage (to the attic) is very small compared to house leakage to the attic, *the attic-to-home pressure-coupling ratio,* P_A/P*, is constant.*

Calculation of Duct-Leakage at 25 Pa

As mentioned above, when the data is appropriate, GSCA takes the next step–the calculation of duct-leakage when the pressure difference between the ducts and attic is 25 Pa. With data collection at two or more values of P, the value of *SCF* can be calculated for each P to see if *SCF* is constant. (As explained by the previous two theorems, for nearly all homes, the calculation of the generalized *SCF* is applicable and the value of *SCF* for a home is independent of P.) Since in both the untaped and taped cases house-leakiness has been measured at two (or more) pressures, one can calculate two flow exponents and coefficients for house-leakiness and use these flow-equations to express the difference between untaped and taped house-leakiness flows as a function of P.

$$Q \; - Q' = \kappa P^{n} - \kappa' P^{n'} \tag{4.26}$$

From Eq. (4.8), duct-leakage at 25 Pa equals *SCF* times this difference when P is chosen so that $P_D = 25$. Since P_D is proportional to P, the choice of P required is $25*(25/P_{D25})$ where P_{D25} is the pressure difference between the ducts and attic when the house is depressurized to 25 Pa.

$$\text{Duct-leakage at 25 Pa} = SCF\,\{\kappa[25\,(25/P_{D25})]^{n} - \kappa'[25\,(25/P_{D25})]^{n'}\} \tag{4.27}$$

GSCA Generalizes Modified Subtraction

When tests are performed at $P = 50$ Pa, $P_A = 50$ Pa, and the untaped duct-system has the same pressure as the house, the *SCF* just derived reduces to the one provided by Modified Subtraction [22], except the exponent of *SCF* for GSCA is taken to be 0.60.

4.4 COMMENTS

1. Accuracy of House-Leakiness Data: When Q and Q' (the flow of the home when it is depressurized to a pressure P, taped and untaped, respectively) have measurement errors similar in size to the difference between their values, it is hard to put any confidence in the accuracy of that difference. Since the most common application of Modified Subtraction derives from manually collected data, it is very important to minimize the size of the error of these measurements. A common method employed to ameliorate these errors is to repeat the collection of the value of Q and Q' three or more times. We believe that an automatic data-collection procedure, wherein a very large number of data are collected at each of a series of pressures, provides much greater accuracy. The system we employed collects such data and provides the required flow-equation data via a regression analysis performed to model the house-leakiness flow-equation, Eq. (4.2) [22]. Experience indicates that when the resulting correlation coefficient is less than 99%, such data is of dubious value for ascertaining duct-leakage. However, when this level of accuracy is not obtained, the requested data collection can be easily modified, extended and/or errors in test procedures repaired, thereby obtaining acceptable data in almost all homes and weather conditions.
2. Untaped and Taped Attic Pressures: The derivation of the generalized *SCF* assumes that the airflow Q_{vabnd}, between the attic and the home not via the ducts, is essentially independent of whether or not the ducts are taped. The essential equality of P_A and P'_A is the primary check

to confirm this condition. Clearly the greater the duct-leakage, the greater will be the potential change in attic pressure. Moreover, empirical evidence gives good insight: we have found that in over fifty homes [2], when calculated duct-leakage was less than 200 CFM 25, the change in attic pressure did not exceed 1 Pa. Since the greatest accuracy is desired only when duct-leakage is smaller than 200 CFM 25, the derivation of GSCA can be considered to be essentially complete since the only dubious assertion in the derivation can be empirically quantified when needed.

Data from more than fifty homes in the greater New Orleans area indicate that the magnitude of P_{A} is rarely greater than 48 Pa when the house is kept at negative 50 Pa with respect to outside and less than 40 Pa for one third of the sample. As stated earlier, this observation is quite different from the assumption of Modified Subtraction that P_{A} will always be negligibly different from P (= 50 Pa). P_{A} and P'_{A} can be used to help predict the numerical accuracy of the *SCF*: as the magnitudes of P_{A} and P'_{A} decrease, the magnitudes of P_{D} and P'_{D} must decrease, thus any error in the denominator will be grossly exaggerated in *SCF*.

This study on GSCA reintroduces the need for collecting P_{A} in order to calculate P_A/P, and calls this quantity the attic-to-home pressure-coupling ratio. This parameter is important for interpreting house-leakiness since it gives an indication of the airflow between the house and the attic at various pressures. As the corollary to the second theorem indicates, it is normally independent of the pressure P used to observe it and takes a constant value. However, when P_A/P is variable, GSCA may not be applicable.

3. Pressure in the Ducts with respect to the Home during the Untaped Test: Unlike the implicit assumption of Modified Subtraction [22], the pressure in the ducts with respect to the home during the untaped test is not assumed to be zero by GSCA. Using a pressure pan, the authors have found pressure differences as high as 15 Pa [49]. This same issue has also been considered significant by Sherman and Palmiter [50].

   Although this datum can be collected at any register by sealing that register alone and piercing that seal with a pressure-probing tube, one cannot expect every register to be equally representative. In fact, by sampling all of the untaped duct registers, it is not unusual to find a 5 to 10 Pa difference between the highest and lowest values. Thus the question arises as to where to place the probe for untaped and taped data. We recommend the following procedure: The energy rater should precede the data collection for *SCF* with a duct-testing regime consisting of a complete set of pressure-pan tests [49]. These tests will demonstrate the range of pressures for that particular duct-system. Once the tester has found the range, the tester should pick a register that exhibits a value closest to the average value. This procedure does not add additional time to the house measurement process since pressure-pan tests are normally performed for other diagnostic purposes. This procedure is also applicable to choosing the best place to probe the supply registers when setting up duct-testing with a Duct Blaster$^{\mathrm{TM}}$ [51].

4. Linear Dependency of P_{D} upon P: The proof of the linear dependency of P_{D} upon P assumed that 1) the exponents of all the leakages are the same (a passable assumption in relation to the accuracy of the testing procedure), 2) the pressure of the ducts are uniform throughout the ducts (an assumption not satisfied in most houses, and in some houses to a rather significant extent), and 3) the attic pressure in the taped and untaped cases are approximately the same

(a reasonable assumption in most houses since attic pressure is determined much more by leaks from the house than from the ducts).

5. Checking the Applicability of GSCA: Both the *SCF* and the attic-to-home pressure- coupling ratio are constant with respect to the house pressure if the leaks from the house to the attic are much greater than the leaks from the ducts to the attic. In such a case, P_{A} would be negligibly different from P'_{A}, and the GSCA is applicable. Thus, a non-constant value of *SCF* or a variable attic-to-home pressure-coupling ratio raises doubts about the applicability of GSCA.
6. Choice of Flow Exponent: In the original derivation of the *SCF* in Modified Subtraction, the value of m was set at 0.65; namely, the mean value of the exponent, n, of the flow-equation for house-leakiness obtained phenomenologically from data taken from thousands of tested homes [22]. Our testing of 55 homes in Ruston, Louisiana found a similar value of 0.64 [2]. Alternatively, m can be taken to be the average of two values of n, obtained for the flow-equation for house-leakiness for the specific home being tested from the two sets of data collected, namely the untaped and taped cases. Although there are plausible arguments for each of the above choices, we believe the best recommendation is to use a value of m derived from the data obtained by averaging a sample of a large set of duct-leakage (as opposed to house-leakiness) results, $m = 0.60$ [2, 46]. Although 0.60 seems to be a better choice, we have found that the resulting calculated duct-leakage to be only slightly affected by the choice of exponent.

4.5 CONCLUSIONS

Since GSCA is applicable to arbitrary values of P, various a posteriori considerations and improvements are realized. If manual collections are the best practical choice, we recommend that GSCA be performed at three or more different depressurization pressures. Since standard testing for house-leakiness with automated testing equipment [60] performs tests at more than three pressures, all of the following benefits follow.

1. Calculation of the Coefficient and Exponent of the House-Leakiness Flow-

Equation: When two or more depressurization pressures are used in a house-leakiness test, the coefficient and exponent of the flow-equation can be calculated. In the homes that cannot be depressurized to 50 Pa but, nevertheless, allow the flow-exponent to be calculated to sufficient accuracy, the use of the “Can’t-Reach-Fifty-Factor” becomes superfluous [22].

2. Calculation of Effective Leakage Area: When two or more depressurization pressures are used in a house-leakiness test, the Effective Leakage Area (ELA) can be calculated directly [22]. This is the most unbiased house-leakiness descriptor. It provides the best input for energy auditing software to estimate whole-house infiltration. It is clearly better than CFM50 or NACH (Natural Air Changes per Hour, as normalized over a year, is a measure of infiltration), which are otherwise sometimes used. ($1.00 \text{ CFM} = 4.72 \times 10^{-4} \text{ m}^3/\text{s}$). The first of these, CFM50 (the flow through a Blower Door$^{\text{TM}}$ when the home is depressurized to 50 Pa), is biased by the assumption that the home being measured has the same flow exponent as the average home, namely 0.65. This can be a gross error since, in practice, that exponent can be as low as 0.50 or as high as 0.80. NACH is also defective because it often assumes the preceding value of the flow exponent and, in addition, wind-flow and height characteristics of the home that will normally be

recalculated by the energy rating software.

3. Confirmation that SCF is Constant: When two or more depressurization pressures are used in the pair of house-leakiness tests, the value of the *SCF* can be calculated for each pressure to determine if it is constant. For nearly all homes where the calculation of the generalized *SCF* is applicable, the value of *SCF* for a home is independent of the pressure, P, used in the depressurization of the house. Thus, energy auditing software has a tool to test the accuracy of the input data, correct for slightly inaccurate data collection, and determine if the *SCF* should be calculated at all for this home.

4. Confirmation that the Attic-to-Home Pressure-Coupling Ratio is Constant: When two or more depressurization pressures are used in a house-leakiness test, the value of the attic-to-home pressure-coupling ratio can be observed for each pressure to see if it is constant. For nearly all homes where the GSCA is applicable, the value of the attic-to-home pressure-coupling ratio is independent of the pressure, P, used in the depressurization of the house. Thus energy auditing software has another tool to test the accuracy of the input data, correct for slightly inaccurate data collection, and determine if GSCA should be used.

5. Calculation of Duct-Leakage at 25 Pa: When two or more depressurization pressures are used in the pair of house-leakiness tests, the energy rater has the ability to calculate duct-leakage at 25 Pa. This calculation can be performed since in both the untaped and taped cases house-leakiness has been measured at two (or more) pressures. One can then calculate two sets of flow exponents and coefficients for house-leakiness and use these flow-equation parameters to express the difference between untaped and taped house-leakiness as a function of the untaped pressure between the ducts and attic. Since the *SCF* of GSCA is constant, duct-leakage at 25 Pa can be directly calculated.

6. Checking Reliability and Confidence in House-Leakiness Data: With three or more depressurization readings for each untaped and taped case, it is possible to calculate a correlation coefficient for the regression analysis that is used to best fit the data and calculate the duct-leakage flow exponent and coefficient [52]. This correlation coefficient provides a reliability indicator for the house-leakiness test procedure, thereby determining the confidence level in the data.

When a house-leakiness test is performed as part of data collection for GSCA, at least two additional data, P_D and P_A, are collected for each P, the depressurization pressure of the home. Since a standard house-leakiness test includes tests at a series of pressures, these data effectively arrive as a series of triplets. Since a GSCA measurement requires two house-leakiness tests, two sets of series of triplets are available for a posteriori review–one for a registers untaped test and one for a registers taped test. If:

- P_A and P'_A differ by more than 2 Pa when estimated duct-leakage is less than 200 CFM25,
- P_D is negative when P and P_A are positive, or
- P_A/P is not constant even though P_A and P'_A differ by less than 1 Pa,

then the energy rater should suspect that something is probably wrong with the data collection. In such a case, the setup should be rechecked and one or both of the house-leakiness tests should be repeated.

7. Enhancing the Characterization of House-Leakiness: Both the magnitude and variability of the attic-to-home pressure-coupling ratio, P_A/P, give insights into the leakiness of the pressure-boundary between the home and attic.

Example Calculations

Duct-leakage calculations on data collected from homes in Northern Louisiana are presented in Table 4.1. Table 4.1 shows the duct leakage values as well as Subtraction Correction Factor obtained using both Generalized Subtraction Algorithm and Modified Subtraction Algorithm. The data presented in Table 4.1 consists of all 55 homes with reliable house leakiness data as described in the conclusions. Also, data without attic readings were omitted from this comparative analysis. The details of the data in regards to zone-pressure, flow exponent, flow coefficients and associated calculations are presented in Appendices B8, B9 and B10.

Table 4-1. GSCA vs. MSA of homes tested in North Louisiana.

Home #	Coupling Ratio (P_A/P)	SCF (GSCA)	Duct Leakage (GSCA)	SCF (MSA)	Duct Leakage (MSA)	GSCA-MSA
3	0.97	1.36	565.95	1.38	554.81	11.13
5	0.95	2.26	193.41	2.23	169.57	23.83
6	0.99	4.25	149.33	3.81	132.25	17.09
11	0.96	1.25	269.49	1.31	264.39	5.10
12	0.97	3.78	116.03	3.51	105.62	10.40
13	0.93	1.22	373.72	1.31	379.43	-5.70
14	0.91	1.43	776.60	1.52	772.91	3.68
19	0.96	3.17	561.89	2.91	495.05	66.85
20	0.98	2.00	383.26	1.92	360.56	22.71
21	0.99	1.48	160.05	1.47	156.24	3.81
26	0.94	2.86	202.53	2.78	186.52	16.01
27	0.92	1.43	181.06	1.59	191.95	-10.89
28	0.97	1.50	136.20	1.49	131.24	4.96
29	0.97	1.26	287.40	1.30	291.56	-4.16
31	0.73	2.64	1092.26	3.39	1134.60	-42.34
33	0.93	1.24	382.01	1.35	393.39	-11.38
34	0.96	1.27	341.45	1.28	324.87	16.58
35	0.87	4.14	292.06	4.34	296.14	-4.08
36	0.99	1.46	235.46	1.50	231.00	4.46
37	0.88	1.25	308.67	1.45	316.53	-7.87
38	0.96	1.35	357.03	1.36	345.33	11.71
39	0.90	1.15	228.84	1.33	237.65	-8.81
40	0.99	1.25	112.83	1.21	108.01	4.82
42	0.97	3.76	144.93	3.53	132.41	12.52
43	0.93	1.92	338.81	1.97	334.99	3.82
44	0.98	2.47	609.11	2.51	603.28	5.83
45	0.95	1.54	442.63	1.54	423.99	18.64
47	0.92	1.45	244.78	1.55	237.81	6.98
53	0.92	1.72	340.86	1.75	310.55	30.31
54	0.95	1.55	567.80	1.54	540.13	27.67
55	0.96	2.65	383.40	2.62	385.74	-2.34

Figure 4.2 shows the comparison of duct leakage obtained using GSCA as well as MSA for the 55 homes sampled in Northern Louisiana. From Figure 4.2, the duct leakage obtained using GSCA is nearly equal to MSA. In some homes the duct leakage using GSCA is higher than MSA where as in other homes it is lower. From Table 4.1, the duct leakage was found to be comparatively high in homes with low coupling ratios. Figure 4.3 shows the comparison of *SCF* with regards to GSCA and MSA. The comparison of *SCF* is very similar to that of duct leakage with *SCF* high in some cases and low in other cases in regards to the comparison of MSA and GSCA.

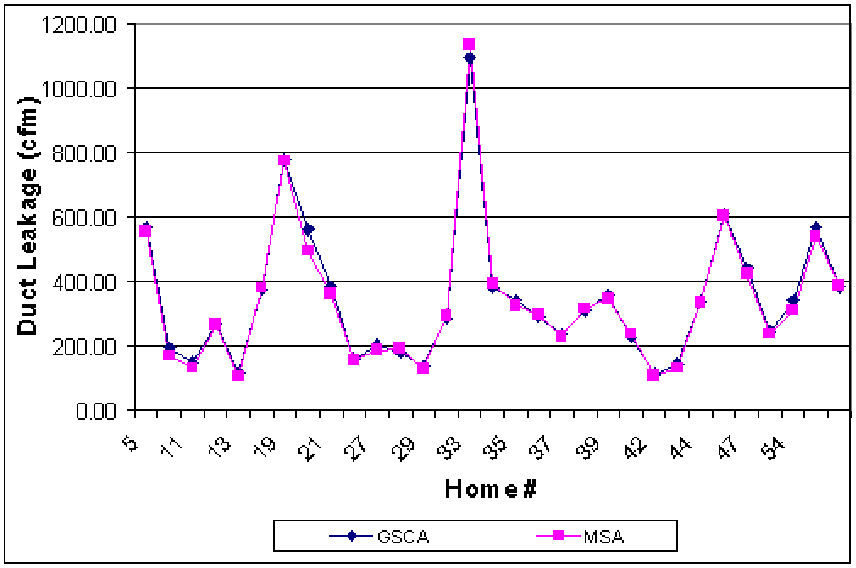


Figure 4-2. Duct leakage comparison of GSCA vs. MSA–North Louisiana

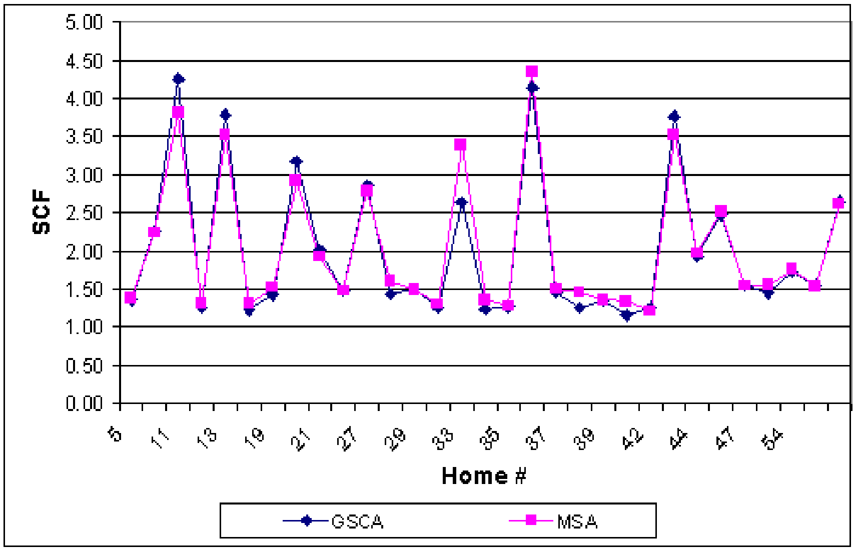


Figure 4-3. SCF comparison of GSCA vs. MSA–North Louisiana.

A plot of the difference in duct leakage values between the GSCA and MSA is presented in Figure 4.4. From Figure 4.4, the differences between the duct leakage values with respect to the pressure coupling ratio do not show a pattern or trend. However, a statistical t-test on the differences between the two tests concludes that there are differences between the duct leaks obtained by GSCA and MSA. The mean difference was determined to be 7.4 cfm with a 95% confidence in the differences ranging between 0.87 cfm and 14.1 cfm, a relatively small difference. The SAS^{TM} program and the output is presented in Appendices B11 and B12 respectively.

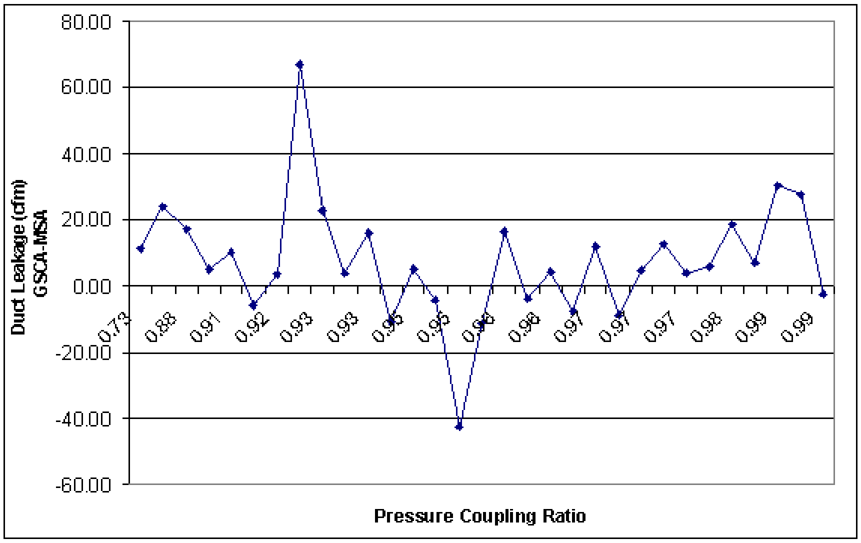


Figure 4-4. Plot of (GSCA-MSA) and pressure coupling ratio–North Louisiana.

Most of the homes tested in Northern Louisiana have a pressure-coupling ratio above 0.90. Homes with low coupling ratios generally have relatively high duct leakage. Also, homes with low pressure coupling ratio, have higher differences between *SCF's* of GSCA and MSA.

In order to determine if the results are similar for a different geographic region in Louisiana, we obtained a small data sample for the New Orleans area from Dr. Myron Katz. Table 4.2 shows the results of the duct leakage, *SCF* and pressure coupling ratios for the data obtained from New Orleans. It is important to note that most of the homes in Southern Louisiana have coupling ratios less than 0.90, which is the reverse of the coupling ratios in Northern Louisiana where they are generally higher than 0.90.

Table 4-2. GSCA vs. MSA of homes tested in South Louisiana.

Home #	Coupling Ratio (PA/P)	SCF (GSCA)	Duct Leakage (GSCA)	SCF (MSA)	Duct Leakage (MSA)	GSCA-MSA
1	0.81	10.41	4834.66	13.24	5032.09	18.12
2	0.86	6.80	789.67	7.35	854.97	-197.43
3	1.00	1.32	341.01	1.27	321.80	21.69
4	0.89	2.21	177.76	2.29	178.03	424.58
5	0.85	4.14	313.29	4.09	291.59	-65.30
6	0.96	1.71	97.23	1.70	92.95	-43.58
7	0.74	2.18	262.01	2.61	243.89	-0.27
8	0.85	1.53	8215.89	1.56	7791.32	20.01
9	0.87	1.39	217.69	1.57	261.27	4.28
10	0.96	1.36	287.35	1.36	267.35	19.20

From Figure 4.5, we see that the duct leakage obtained from GSCA and MSA are similar, differences appear only for high values of duct leakage. From Figure 4.6, the difference between the *SCF's* of MSA and GSCA is not high except for homes with low pressure coupling ratios.

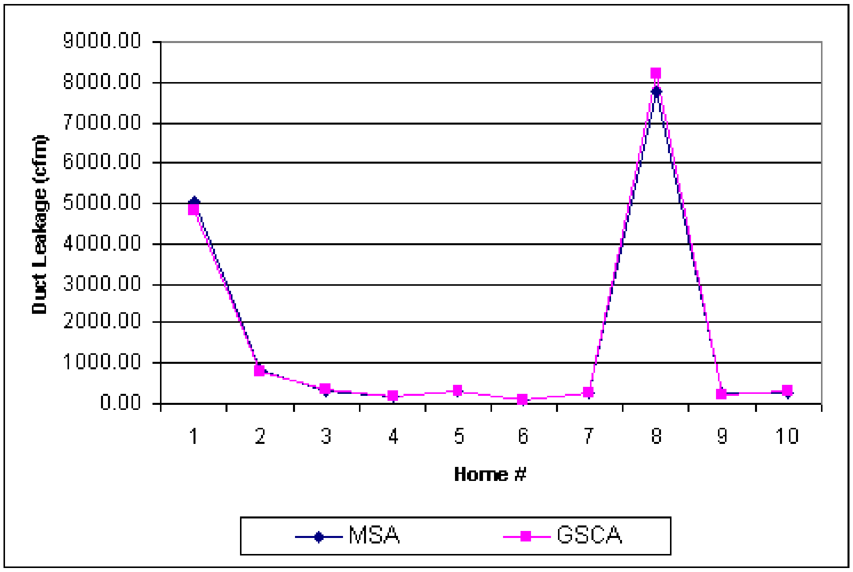


Figure 4-5. Duct leakage comparison of GSCA vs. MSA–South Louisiana.

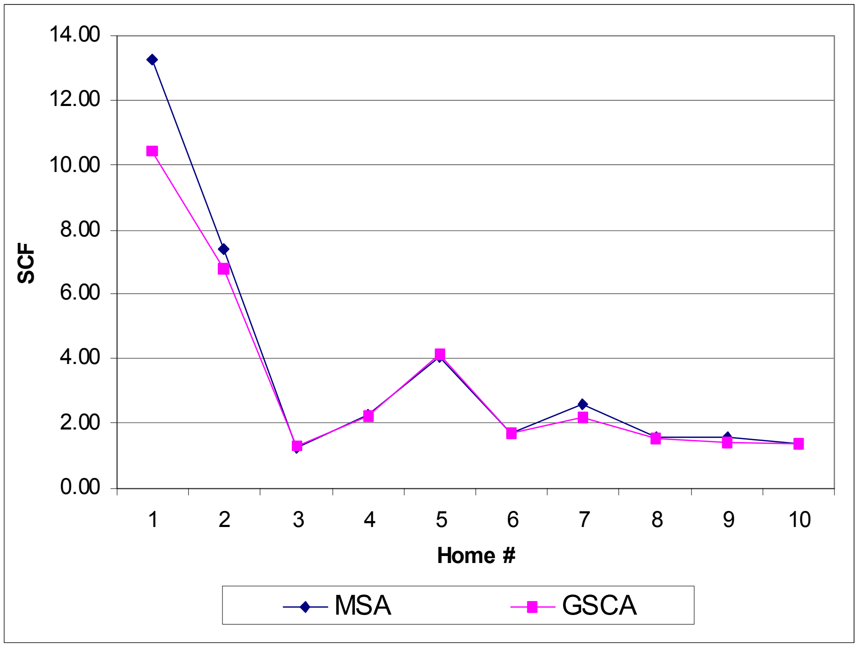


Figure 4-6. SCF comparison of GSCA vs. MSA–South Louisiana.

A plot of the difference in duct leakage values between the GSCA and MSA in Figure 4.7 shows that homes with pressure coupling ratio less than 0.86 mainly tend to have higher differences in duct leakage values between GSCA and MSA. However, this cannot be generalized due to small data sample. In addition, note that these homes have higher *SCF's* both for GSCA and MSA. Due to the small sample data, statistical tests were not performed on the data obtained from Southern Louisiana.

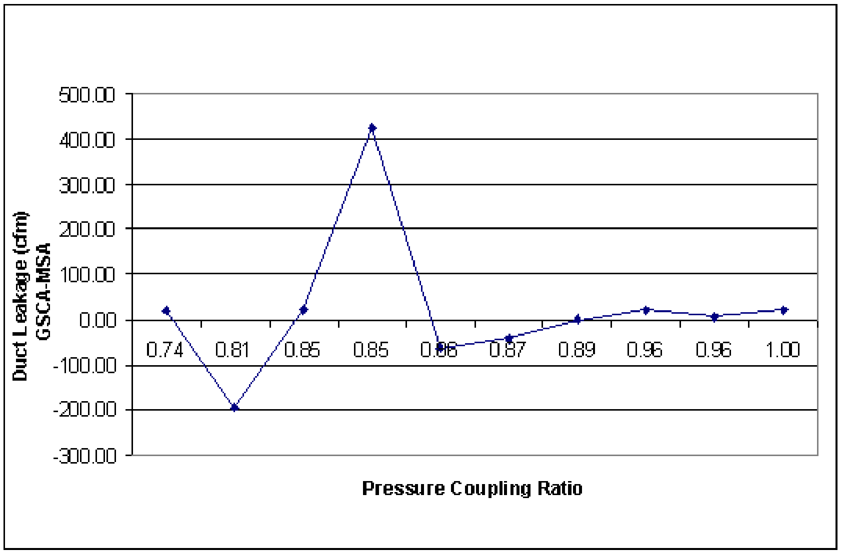


Figure 4-7. Plot of (GSCA-MSA) and pressure coupling ratio–South Louisiana.

Figure 4.8 shows that as the pressure-coupling ratio decreases, the *SCF* increases for GSCA in the case of Southern Louisiana as shown by the trend line. In the case of North Louisiana, we do not see a distinct trend and the value of *SCF* remains around two on an average as shown in Figure 4.7 by the scatter of individual data points.

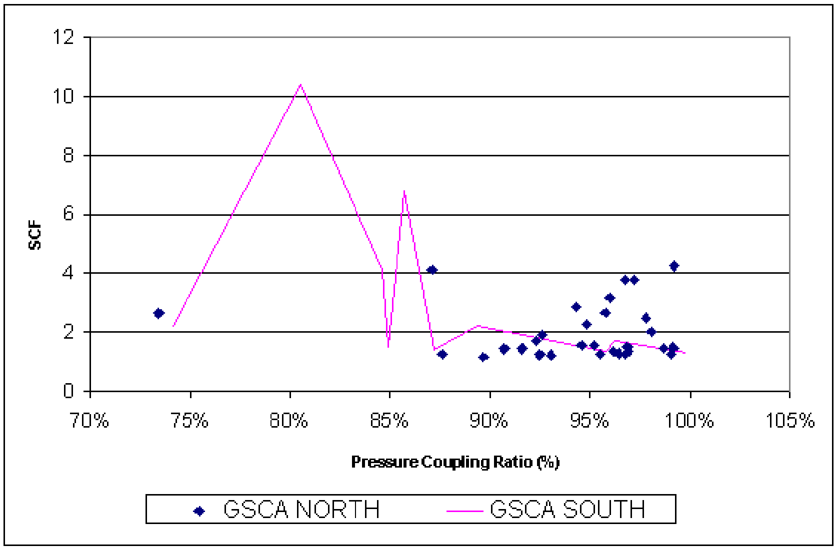


Figure 4-8. Comparison of North and South Louisiana in regards to SCF of GSCA and pressure coupling ratio.

From the data example calculations and comparisons, it can be seen that pressure to attic coupling ratio is higher in North Louisiana than in South Louisiana. Thus, air flow between the attic and the conditioned space is less in North Louisiana homes than in South Louisiana homes. The average pressure-coupling ratio determined from this study for North Louisiana is 0.94 whereas for South Louisiana it is 0.88. The difference in *SCF* between GSCA and MSA may widen as the pressure coupling ratio decreases. However, this may or may not increase the differences in the duct leakage values between MSA and GSCA. A more comprehensive discussion of the relationship of the *SCF's* is discussed in a study by Katz, Witriol and Erinjeri [53].

5.0 RETURN LEAK MEASUREMENT

Duct leakage can occur both at the supply side as well as the return side of the duct system. Figure 5.1 shows the supply side as well as the return side of the duct system. Most of the research has been on the supply side of the duct system. Therefore, there is need to study the return side of the duct system for the following reasons:

1. To quantify return leaks.
2. To detect and seal return leaks, thereby saving energy.
3. To seal returns if return leaks dominate the supply leaks, as it is easier to seal return leaks.
4. To emphasize the need of constructing sealed return systems.

In most of the homes in Louisiana, the return side of the duct system constitutes a smaller part of the duct system. However, a smaller part of the duct system need not imply a smaller percentage of the total duct leakage of a given home. Return leaks can be severe in homes even though they constitute the smallest portion of the duct system.

Of the 43 homes studied in North Louisiana 27% of the houses had dominant return leaks, whereas 51% of them had dominant supply leaks. Return leaks occur at various sites of the return duct leakage system. Figure 5.2 shows some of the common sources of return leak.

The importance of this chapter on return leaks is to develop a protocol to measure return leaks. The protocol developed should be such that we could resourcefully use the hardware equipment readily available by an energy auditor to measure return leaks. Measuring return leaks is an important input to measuring energy losses in residential houses. The ASHRAE^{TM} 152 [54] standard used in estimating distribution system efficiencies, a quantity used in energy loss calculations, also requires return leakage as one of the inputs. In practical applications, return leaks are frequently estimated based on the total duct leakage of the system. This estimate of return leakage is biased because of the following:

- The operating pressures at the supply as well as return side of the duct system are different.
- The operating return system pressures are negative while total duct leakage measurements are frequently based upon positive pressures.

In this study of return leak measurement, we have developed the measuring process of return leakage and appropriately incorporated the critical parameters in determining return leakage. The results of homes tested with the newly developed protocol were used to:

1. Determine the return leakage to outside.
2. Determine the actual supply duct leakage to outside as described in Chapter Six.
3. Statistically analyze the differences between pressurization and depressurization measurements as presented in Chapter Seven.
4. Incorporate the measured return leakage to determine energy losses for a given home as presented in Chapter Eight.

Figure 5.1 shows the components of the duct system. In the overall view of the duct system in

Figure 5.1, the return side components of the duct system mainly comprises of return grille, return plenum and air filter. The source of Figure 5.1 is http://www.mbmairduct.com/images/design04.jpg [55].

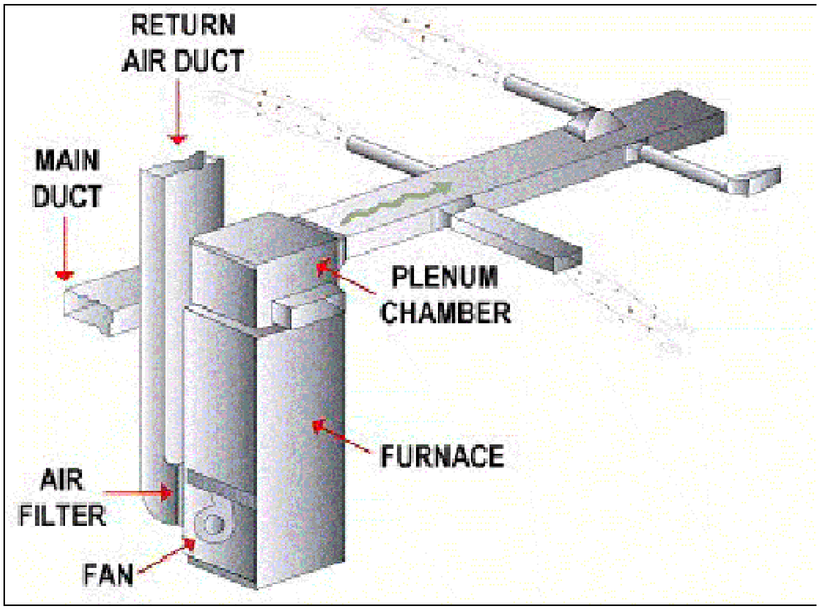


Figure 5-1. Typical components of duct system.

5.1 TESTING RETURN LEAKS

Testing return leaks involves two stages, namely measurement of return leakage and detection of return leaks. Figure 5.2 shows some of the common leak spots found in the return side of duct system during this study in 43 homes. For more pictures in regards to this research visit http://www2.latech.edu/~witriol/DNR/DNRhome.htm [56].

Figure 5-2. Common spots of return leaks.

Return leaks can have significant impact on energy consumption as well as human comfort. Return leaks connected to the outside can change the return air temperature in a hot humid climate, thereby reducing the system performance. A return leak in an attic in summer time may draw 150°F humid air into the system rather than 75-80°F conditioned house air. The higher return temperature can overwhelm the system capacity and make it impossible to cool the home. Other effects of return leaks include:

- Oversized air handling systems to compensate for duct leaks.
- Increased relative humidity in the summer and thus a high potential for mold and mildew growth.
- Condensation on surfaces and on the cooling coil leading to moisture problems and thus to durability and health issues associated with mold and mildew.

A significant leak in the return side of the duct system leads to the infiltration and circulation by the HVAC system of unconditioned air in the home Therefore, it is important to study return plenum leakage.

5.2 MEASURING RETURN LEAKAGE

In this study of 43 homes in North Louisiana, we developed a measuring process with hardware commonly possessed by energy auditors. The main reason for using commonly possessed hardware was to avoid unnecessary expenditure on specialized equipments as well as saving set-up time for measuring return leakage. This study has recommended two approaches for measuring return leaks. The hardware for measuring return leaks using the first approach consists of the following equipment:

1. Blower Door^{TM}: to pressurize/depressurize the house.
2. Duct Blaster^{TM}: to pressurize/depressurize the duct system.
3. APT (Automated Performance System) Hardware and TECTITE^{TM} Software: to automatically control the Blower Door^{TM} to the set pressures and number of data points.
4. Digital Manometer (DG-3 Gauge): used in conjunction with Duct Blaster^{TM} to measure the flow.
5. Pressure Probes: for measuring the pressure at the respective points.
6. Notebook/Laptop.

Henceforth, we will term this approach as the Blower Door-Duct Blaster approach (BDDB).

The hardware for measuring return leaks using the second approach consists of the following:

1. True Flow Meter^{TM}: for measuring the flow across the blower of the HVAC unit and at the return register.
2. Digital Manometer (DG-3 Gauge): used in conjunction with True Flow Meter^{TM} to measure the flow.

Henceforth, we will term the second approach as the True Flow Meter^{TM} approach (TFM). The theory behind the testing procedure for both the testing approaches is described below. Figure 5.3 shows a typical home in 2-dimensional view with the majority of the duct system installed in the attic. This layout of the duct system in the attic is very common in homes in the State of Louisiana.

In Figure 5.3, the Blower Door^{TM} used to pressurize/depressurize the house; the flow is given by F_1. The Duct Blaster^{TM} used to pressurize/depressurize the return side of the duct system, the flow is given by F_2. Note that the air to the supply side of the duct system is blocked and this blockage is shown as a darkened line in Figure 5.3. The detail of this blockage is described in detail in Section 5.3.

The derivation of the equation for determining return leaks is as follows:

Notationally,

F_1 = flow from the Blower Door^{TM}

F_2 = flow reading measured using Duct Blaster^{TM}

F_{HR} = flow from home to the return

F_{RH} = flow from return to the home

F_{HO} = flow from home to the outside which includes all leaks to the unconditioned space such as attic, garage space etc.

F_{RA} = flow from return to the attic

F_{RS} = flow from return to the supply

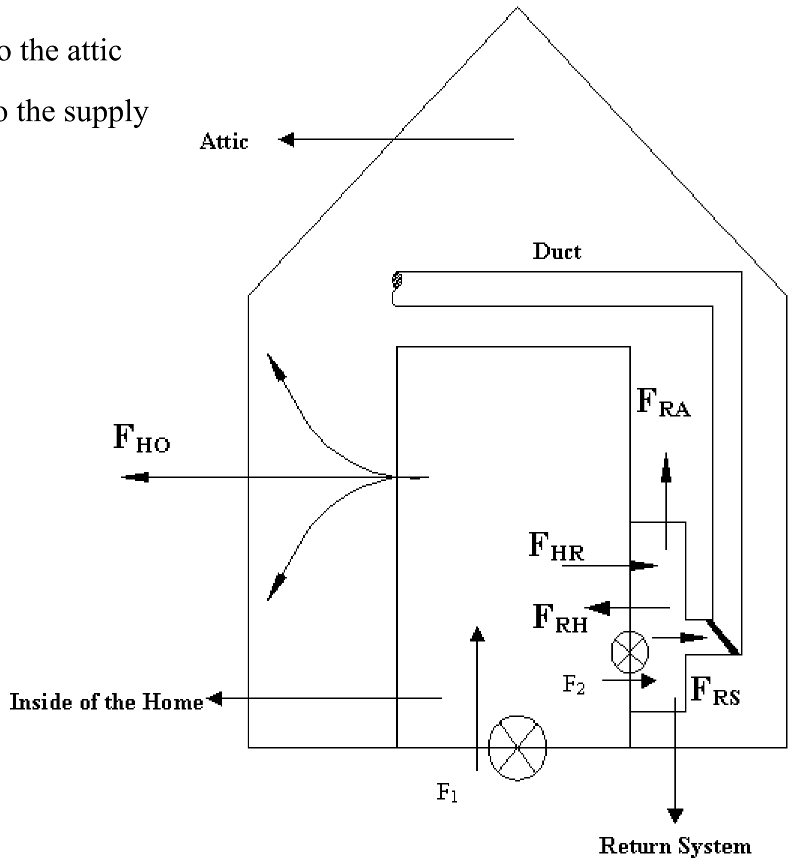


Figure 5-3. Two-dimensional view of a typical home with ducts in attic.

In a combined operation of both Blower Door^{TM} and Duct Blaster^{TM}, the actual flow recorded at the Duct Blaster^{TM} is nothing but the total of airflow into the return plenum, supply plenum, and outside of the home minus the flow into the conditioned space.

$$F_2 = (F_{RA} + F_{RS} + F_{RH}) - F_{HR} \tag{5.1}$$

Since the flow to the supply is blocked,

$$F_{RS} = 0 \tag{5.2}$$

Therefore Eq. (5.1) becomes

$$F_2 = F_{RA} + F_{RH} - F_{HR} \tag{5.3}$$

Considering the Blower Door^{TM} we have,

$$F_1 = F_{HR} + F_{HO} \tag{5.4}$$

Since we have simultaneous pressurization of home and ducts to the same pressure i.e. pressure in the home is equal to the pressure in the return plenum. Therefore,

$$F_{HR} = F_{RH} \tag{5.5}$$

Therefore substituting Eq.(5.5) in Eq.(5.3), we have

$$F_2 = F_{RA} \tag{5.6}$$

Hence, we have proved that leaks in the return plenum are airflows from the return plenum to the attic, which is measured by the Duct Blaster^{TM}. By setting the desired pressures, we can determine the flow (return leakage) at any given pressure. However, the objective of this study is to determine the return leakage at operating pressure, which is the actual return leakage at operating conditions. Measuring the operating pressure in the return plenum in many cases varies from point to point in the return. Measurements made using an anemometer to determine airflow found that the airflow varied in location on the return grille. To simulate the operating pressure in the return by means of Duct Blaster^{TM}, we measured the pressure at various points in the return and used the average value as the best estimate of operating pressure. It is also important to note that the value of the operating pressure varies from home to home. Therefore, to measure the actual return leakage, it is recommended to measure the operating pressure and the corresponding flow at additional pressure points.

5.3 BLOCKING OF SUPPLY DUCT SYSTEM FROM RETURN DUCT SYSTEM

The supply side has to be blocked in order to prevent any airflow through the supply duct system. This blocking is essential to obtain accurate measurements of return duct leakage. In this study, we have proposed two techniques of blocking and will discuss their advantages and disadvantages. The blockage can be introduced just below the blower of the HVAC unit or above the return box as shown in Figure 5.4. The arrows indicate that the blockage can be placed above or below the return box.

Figure 5-4. Placement of blockage to seal of the supply side.

The first approach was to introduce an acrylic sheet to seal off the supply from the return side as shown by the left arrow mark in Figure 5.4. Figure 5.5 shows a design of a flexible blockage system, which can be used in most homes but is not sufficient.

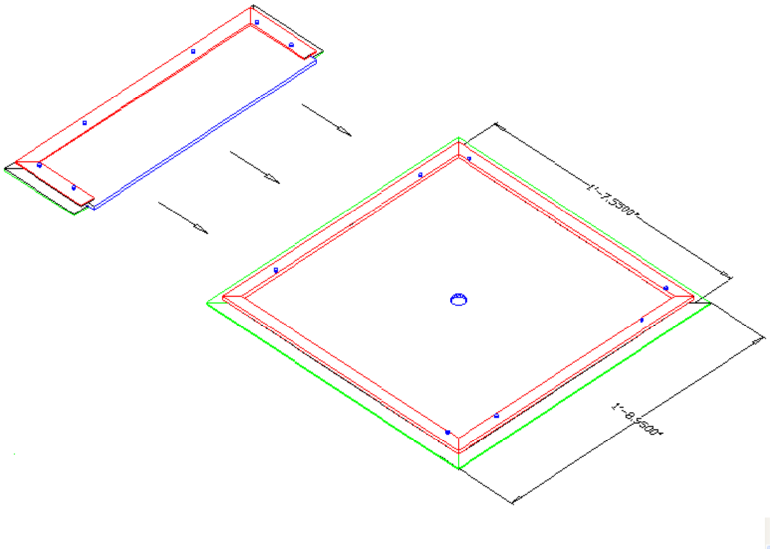


Figure 5-5. Blocking above the return box (BARB).

We will refer to the first blocking system as BARB–blocking above the return box. The standard dimensions of BARB were determined by considering the True-Flow Meter^{TM} dimensions manufactured by the Energy Conservatory. In most of the homes, the filter at the filter slot can be replaced with the BARB. The BARB design has rubber flaps with a groove so that additional spacers can be joined to the main plates as required to provide a tight fit. The design of BARB is more clearly presented in Figures 5.5, 5.6 and 5.7. Figure 5.6 also shows the direction of fit of the spacers to the main plate.

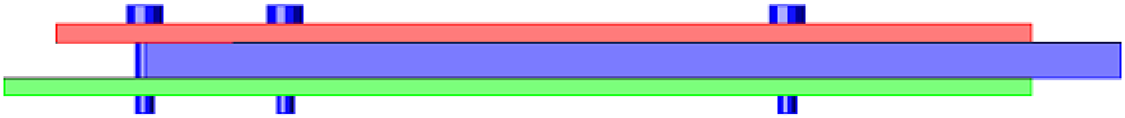


Figure 5-6. Side view of BARB.

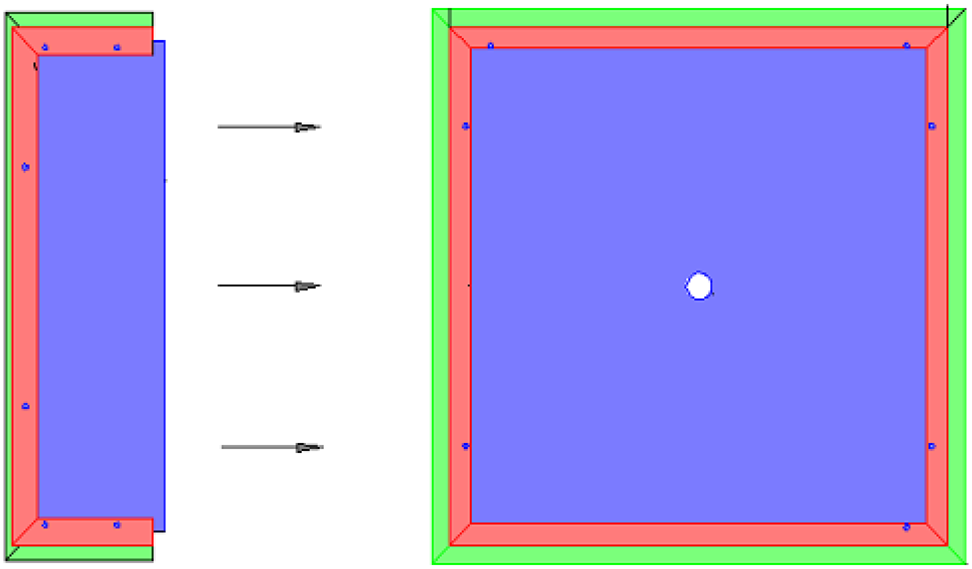


Figure 5-7. Top view of BARB.

It is important to note that the design has a hole at the center to introduce a pitot tube to measure the pressure in the return. The BARB has the same dimensional characteristics as that of the True Flow Meter^{TM}. The BARB has two plates, which will fit for the following dimensions (in inches):

Plate #1 - 14 x 20, 14 x 25, 16 x 20, 16 x 24, 16 x 25, 18 x 20.

Plate #2 - 20 x 20, 20 x 22, 20 x 24, 20 x 25, 20 x 30, 24 x 24.

The two plates–1 and 2 are the main plates to which additional spacers are added to obtain the standard sizes. Figures 5.4 and 5.6 shows the direction in which spacers are added to the plates.

The second method of introducing blockage is to block the return from below the return box (BBRB). The direction of the way in which the blockage is introduced is shown by the right arrow mark in Figure 5.4. The design of this blockage system BBRB is presented in Figure 5.8. The BBRB is designed using an acrylic sheet with a layer of foam applied on one side of the acrylic sheet. The foam is introduced to make a tight fit when it is pressed against the return side. The dimension of the acrylic sheet is such that it fits all the homes. In our study, we used a dimension of 23” by 23”. The holder enables the acrylic sheet to be held in position with an exact fit. A provision for placing a pilot tube, as in the case of BARB, can be introduced by drilling a hole.

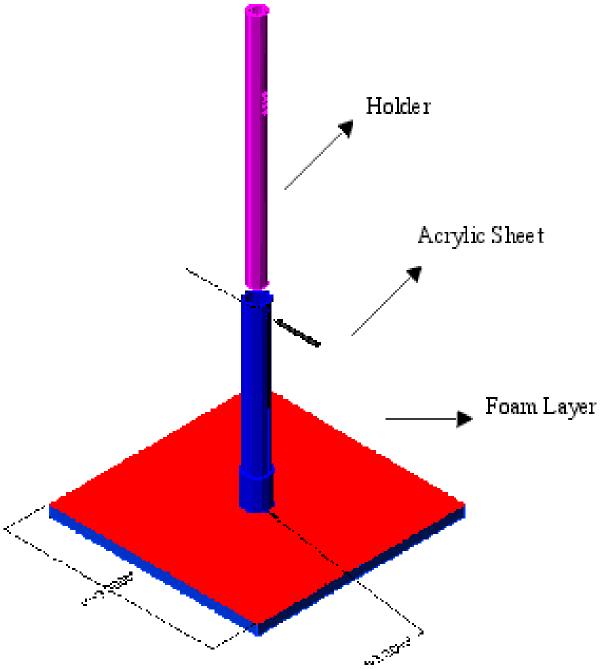


Figure 5-8. Blocking below the return box (BBRB).

There are advantages and disadvantages of using these two designs of blocking returns. The BARB is limited to houses with standard return slot sizes. Homes with restructured duct systems are most likely to face such standardization restrictions in using BARB. On the other hand, BBRB can be used widely in most of the homes and is a better option than BARB for blocking the return from the supply side of the duct system. However, both of these blocking systems have a common drawback in homes with long return chases, generally extending from the return plenum on a lower floor of the building to the attic. Figures 5.9 and 5.10 show situations where the BBRB system is inapplicable.

Figure 5-9. Non-standardized return chase.

Figure 5-10. HVAC unit in attic.

In our study, the BBRB could block return in most of the homes. In addition, the BBRB is easy to install and is less time consuming. In regard to effectively blocking the return, the BBRB provides a tighter fit than the BARB.

5.4 MEASUREMENT OF RETURN LEAKS

In this study, we have employed two techniques to measure return leaks. The first method uses Blower Door^{TM}, Duct Blaster^{TM} and APT hardware (BDDB) where as the second method uses True Flow Meter^{TM} (TFM) as described in Section 5.2. The detailed procedure of these two methods is described in Section 5.4. The BDDB and TFM are used to determine return leakage to the attic. In addition, we also measured total return leakage using the Duct Blaster^{TM} alone. Total return leakage means the leakage to the attic plus the leakage to the inside of the home as a consequence of pressurization/depressurization. All the above tests were attempted for both pressurized and depressurized states. The step-by-step procedure for the various tests performed is described below:

Total Return Leakage (TRL)–Pressurized (TRL+) and Depressurized (TRL-):

This test is used to measure total return leakage that is leaks both to inside and outside of the home. It is important to note that this test is neither the BDDB nor the TFM since this test used the Duct Blaster^{TM} alone to measure the flow readings. The procedure is as follows:

1. Turn off the HVAC system.
2. Insert a probe near to the blower of the HVAC unit.
3. Turn on the HVAC system and measure the operating pressure at the return side using the DG-3 gauge.
4. Turn off the HVAC system.
5. Replace the filter at the blower fan of the HVAC and employ the BBRB method to block the air flowing into the blower and the supply side of the duct system.
6. Seal off the return register.
7. Connect the Duct Blaster^{TM} to an opening through the sealed return register and seal off all other return registers if present.
8. Insert a probe through the return register seal to measure the pressure in the return duct system in Pa.
9. Pressurize/Depressurize the return duct system to 15 Pa. using the Duct Blaster^{TM}.
10. Record the flow reading in cfm using a DG-3 pressure gauge.
11. Repeat steps 8-9 for a total of three readings.
12. Repeat steps 8 and 9 at 25 Pa and at the operating pressure in Pa for a total of three readings. Note that we limited the depressurization to 30 Pa. Thus no readings at the operating pressure were recorded if the operating pressure was greater than 30 Pa.

Combined Return Leakage (CRL) using the BDDB–Pressurized (CRL+) and Depressurized (CRL-):

The procedure is as follows:

1. Follow all the steps from 1 to 7 of testing TRL.
2. Pressurize/Depressurize the home and the return duct system simultaneously with Blower Door^{TM} and Duct Blaster^{TM} respectively to 15 Pa. The Blower Door^{TM} maintains the home at a given pressure with respect to the outside while the Duct Blaster^{TM} maintains the return duct system at the same pressure with respect to outside.
3. Record the flow reading in cfm using a DG-3 pressure gauge.
4. Repeat steps 2-3 for a total of three readings.
5. Repeat steps 2-4 at 25 Pa and at operating pressure.

Combined Return Leakage (CRL) using TFM:

This test uses True Flow Meter^{TM} to measure the return leaks to outside. The procedure is as follows:

1. Insert a probe into the supply plenum as described in the True Flow^{TM} manual.
2. Set the fan to ON and measure the pressure in the supply plenum with respect to inside.
3. Remove the filter attached to the return grill of the HVAC system and replace the filter with the True Flow Meter^{TM}.
4. Set the fan to ON and measure the pressure in the supply plenum with respect to inside.
5. Measure pressure drop across the True Flow Meter^{TM} pressure tubes using the G-3 gauge.
6. Normalize these values as described in the True Flow Meter^{TM} Manual to obtain a reading, R1.
7. Replace the filter below the blower of the HVAC unit with the True Flow Meter^{TM}.
8. Repeat steps 4 to 6 as described above to obtain a normalized reading R2.
9. Determine the difference in flow readings between the two measurements R2 and R1 which gives the return leakage to outside.

5.5 COMPARISON OF CRL WITH BARB AND BBRB

For comparison purposes, we used the True Flow Meter^{TM} plates and covered it with polythene sheet. Table 5.1 shows the results of the comparison of using BARB and BBRB as blocking media.

From Table 5.1, all the readings of BARB are higher than that of BBRB. The maximum difference at 15 Pa is 28 cfm. Performing a statistical test on these differences, one could see a significant difference between the two readings. Performing a Paired t-test on the differences, the Pr > |t| =0.0007 which suggests that there are differences between these two readings. The BARB readings are always higher than that of BBRB with an average of 20 cfm. It should be noted that at higher readings the differences are going to be much higher due to the power law equation of airflow. The fact that BARB gives a higher reading is because there is no perfect fit and leaks occur along the sides. Visual inspections of these leaks have further supported the reason behind these higher readings.

Table 5-1. BRB vs. BARB.

	BBRB		BARB	DIFFERENCE
Observations	**Pressure**	**Flow**	**Flow**	**Flow**
	Pa	cfm	cfm	cfm
1	15.00	88.67	115.00	-26.33
2	15.00	258.67	272.00	-13.33
3	5.00	105.00	133.00	-28.00
4	10.00	86.00	101.00	-15.00
5	5.00	176.67	191.00	-14.33
6	10.00	47.33	72.00	-24.67
Average		127.06	147.33	-20.28

5.6 ANALYSIS OF RETURN LEAK EXPONENTS

We have proved from Eq. (5.6) that leaks in the return plenum are airflows from the attic to the return plenum as described in Section 5.2. Rewriting Eq.(5.6) as

$$F_{\mathrm{HR}} = F_{\mathrm{RA}} \tag{5.7}$$

where, F_2 is notated by F_{HR} for the purpose of distinguishing the flow. F_{HR} does not indicate flow from home to return but the flow measured by Duct Blaster$^{\mathrm{TM}}$ (F_2) during simultaneous pressurization of home and return plenum as described in Section 5.2.

Relation of Flow and Pressure is given by

$$F = CP^{n} \tag{5.8}$$

(Power Law Equation)

where F= air flow in cubic feet per minute (cfm)

C=leakage coefficient

P=pressure in Pascal (Pa)

n=flow exponent

From Eqs. (5.7, 5.8), we have

$$C_{\mathrm{HR}}P_{\mathrm{HR}}{}^{n}{}_{\mathrm{HR}} = C_{\mathrm{RA}}P_{\mathrm{RA}}{}^{n}{}_{\mathrm{RA}} \tag{5.9}$$

If we measure the values of left hand side at two different pressures say P_1 and P_2 then we have F_{HR1} and F_{HR2} as the respective Duct Blaster$^{\mathrm{TM}}$ readings. If we measure the respective P_{RA} at pressures P_1 and P_2 then

$$C_{HR1}P_{HR1}^{n_{HR1}} = C_{RA2}P_{RA2}^{n_{RA2}} \tag{5.10}$$

Since $C_{RA1} = C_{RA2} = C_{RA}$ and $n_{RA1}= n_{RA2}= n_{RA}$, we can determine the flow exponent n_{RA1} by taking log on both sides of the equation.

$$n_{RA} = \log(F_{HR1} / F_{HR2}) \; / \; \log(P_{RA1} / P_{RA2}) \tag{5.11}$$

The flow coefficient values of C_{RA} can also be determined by substituting the values of n_{RA} shown in Eq. (5.12.)

$$C_{RA} = F_{HR1} / P^{n_{RA}} \tag{5.12}$$

Similarly, we can find the values of the n_{HR} and C_{HR} using the Eqs. (5.10, 5.11 and 5.12). Tables 5.2 to 5.5 are all the readings collected from the sample of 43 homes. Values of flow exponent and leakage coefficients are obtained from Eqs. (5.11) and (5.12) for return to attic as well as house to return cases. Flow exponent values between 0.25 and 0.75 were only considered for statistical analysis as values outside this range are not reasonable [64]. For Tables 5.2 to 5.5, the following variables are abbreviated as,

a) Exponent–EXP
b) Leakage Coefficient–COE
c) Operating Pressure in Pascal–OPP
d) Return Leaks at Operating Pressure in cubic feet per minute–RLOP

Table 5-2.Return leaks and parameters for combined return leaks (PRA).

Home #	CRL-				CRL+			
	EXP	COE	OPP	RLOP	EXP	COE	OPP	RLOP
11	0.485	24.911			0.624	16.657		
15	0.623	7.899	-63.000	104.343	0.498	17.255	-63.000	135.577
18			-12.000		0.540	28.236	-12.000	107.988
19	0.710	3.663	-15.000	25.050	0.741	10.208	-15.000	75.951
25	0.297	44.066	-18.000	103.890	1.241	3.545	-18.000	128.218
33	0.533	16.846	-67.000	158.414	0.748	16.780	-67.000	389.192
37	0.428	24.862	-31.000	108.191	1.138	3.852	-31.000	
38					0.499	25.755		
Average	**0.513**	**20.375**	**-34.333**	**99.978**	**0.753**	**15.286**	**-34.333**	**171.472**

The 95% confidence interval for the average value of flow exponent was determined to vary between 0.3599 and 0.6654 with a mean of 0.513 in the case of CRL- where as it ranged between 0.4876 and 0.729 with a mean of 0.6083 for CRL+.

Table 5-3. Return leaks and parameters for total return leaks (PRA).

Home #	TRL-				TRL+			
	EXP	COE	OPP	RLOP	EXP	COE	OPP	RLOP
11	0.531	81.093			0.512	72.379		
15	0.486	69.409	-63.000	519.901	1.017	14.213	63.000	960.264
18	0.608	54.660	-12.000	247.740	0.623	50.888	-12.000	239.120
19	0.639	8.484	-15.000	47.860	0.696	7.263	-15.000	47.877
25			-18.000		0.677	27.877	-18.000	197.462
33	0.519	28.373	-67.000	251.967	0.558	19.912	-67.000	208.011
37	0.532	73.987	-31.000	460.515	0.584	50.210	-31.000	373.040
38	0.538	58.282			0.581	45.301		
Average	**0.550425**	**53.46979**	**-34.3333**	**305.5965**	**0.655984**	**36.00533**	**-34.3333**	**330.5467**

The 95% confidence interval for the average value of flow exponent ranged between 0.501 and 0.5999 with a mean of 0.5504 in the case of TRL- and it ranged between 0.5439 and 0.6649 with a mean 0.6044 in the case of TRL+.

Table 5-4. Return leaks and parameters for combined return leaks (PHR).

Home #	CRL-				CRL+			
	EXP	COE	OPP	RLOP	EXP	COE	OPP	RLOP
9	0.747	13.013	-16.700	106.538	0.703	16.011	-16.700	115.739
11	0.527	21.770			0.523	20.044		
15	0.608	8.281	-63.000	102.940	0.514	10.782	-63.000	90.556
18			-12.000		0.714	9.650	-12.000	56.854
19	0.714	3.618	-15.000	25.000	0.627	5.545	-15.000	30.330
20	1.826	0.057	-19.000	12.318	0.794	4.196	-19.000	43.430
21			-31.000				-31.000	
24			-65.000		0.616	8.683	-65.000	113.455
25	0.442	30.354	-18.000	108.925	0.755	16.064	-18.000	142.325
26	0.384	40.142	-31.000	150.253	0.344	45.224	-31.000	147.154
31	0.837	137.397	-8.000	782.928	0.498	145.030	-8.000	408.627
33	0.515	17.847	-67.000	155.640	0.689	10.884	-67.000	197.240
37	0.477	21.246	-31.000	109.334	0.549	20.521	-31.000	135.032
38					0.423	51.934		
40	1.894	0.172	-34.000	136.561	0.506	15.674	-34.000	93.291
41	0.432	34.755	-15.500	113.598	0.407	45.819	-15.500	139.855
43			-150.000		0.632	4.973	-150.000	117.861
81	0.578	33.629			0.530	41.562		
82					0.761	15.288		
221			-32.000		0.843	2.211	-32.000	41.039
222			-33.000		1.317	0.706	-33.000	70.638
Average	**0.768**	**27.868**	**-37.718**	**164.003**	**0.637**	**24.540**	**-37.718**	**121.464**

The 95% confidence interval in the case of house to return flow exponent varied from 0.4566 to 0.682 with a mean value of 0.5424 for CRL- and it varied from 0.4902 to 0.6132 with a mean of 0.5517 for CRL+.

Table 5-5. Return leaks and parameters for total return leaks (PHR).

Home #	TRL-				TRL+			
	EXP	COE	OPP	RLOP	EXP	COE	OPP	RLOP
9	0.969	13.244	-16.700	202.697	0.709	24.972	-16.700	183.801
11	0.526	82.391			0.517	71.102		
15	0.520	62.739	-63.000	540.414	0.558	56.225	-63.000	567.073
18	0.621	52.536	-12.000	246.071	0.620	51.343	-12.000	239.483
19	0.633	8.641	-15.000	48.000	0.705	7.068	-15.000	47.670
20	0.550	75.294	-19.000	379.976	0.714	28.433	-19.000	232.401
21			-31.000		0.318	7.183	-31.000	21.417
24			-65.000		0.525	41.589	-65.000	372.097
25			-18.000		0.710	25.128	-18.000	195.380
26	0.508	68.607	-31.000	392.254	0.512	63.549	-31.000	368.796
31	0.431	564.528	-8.000	1383.344	0.533	225.191	-8.000	682.711
33	0.562	24.753	-67.000	262.723	0.592	17.830	-67.000	215.165
37	0.535	73.476	-31.000	460.982	0.471	72.281	-31.000	364.066
38	0.538	58.183			0.648	36.975		
40	0.828	13.013	-34.000	241.640	0.808	13.387	-34.000	231.122
41	0.615	67.418	-15.500	363.526	0.556	72.244	-15.500	331.264
43			-150.000		0.705	9.328	-150.000	319.654
81	0.521	57.746			0.507	58.480		
82					0.358	107.933		
221			-32.000		0.613	18.231	-32.000	152.803
222			-33.000		0.653	18.065	-33.000	177.437
Average	**0.597**	**87.326**	**-37.718**	**411.057**	**0.587**	**48.883**	**-37.718**	**276.608**

The 95% confidence interval in the case of house to return flow exponent varied from 0.5109 to 0.5824 with a mean value of 0.547 for TRL- and it varied from 0.523 to 0.6294 with a mean of 0.576 for TRL+.

Let us consider the difference between the values of the flow exponent in the house to return (P_{HR}) and return to attic (P_{RA}). A Paired t-test was performed on the values of flow exponent between the two cases for both CRL- and CRL+. The Paired t-test did not show any significant difference between the values of flow exponent in both cases of CRL+ and CRL- for the house to return verses return to attic case since the Pr > |t| was greater than level of significance 0.05. The statistical analysis on such a small sample size is unreliable; hence, a bigger sample size is recommended in future studies for determining statistical significance. However, the best estimate of the value of the flow exponent for return leaks from our data would be the weighted average exponent on the collected data of 43 homes and is presented in Table 5.6.

Table 5-6. Weighted mean flow exponent.

Tests	N	Flow exponent
CRL- (P_{RA})	6	0.5130
CRL+ (P_{RA})	6	0.6083
CRL- (P_{HR})	10	0.5242
CRL+ (P_{HR})	15	0.5517
Weighted	**37**	**0.5472**

The weighted mean value of return flow exponent is 0.55 which is close to 0.60, the duct system flow exponent measured by Katz, Witriol and Erinjeri [53]. However, it is important to note that this value of flow exponent 0.55 is for return leaks and not for the total duct leakage.

There are some missing values from the total sample of 43 homes. This omission is due to some homes having return chases with HVAC unit in the attic, where it was not possible to block the supply from the return duct system. This construction is not uncommon in modern homes.

The second approach considered for measuring return duct leakage is the True Flow Meter^{TM} method, as described in Section 5.4. As described, this approach has some limitations due to the various sizes of filter slots. We had only four homes with a complete set of flow reading both on the return side as well as the blower side. A further investigation of this approach using anemometer was performed to determine whether True Flow Meter^{TM} readings matched the anemometer readings at the return grille. For the small sample size of data, we found that there were differences but are unable to confirm its significance due to small data sample.

5.7 EQUIVALENT ORIFICE LEAKAGE AREA OF RETURN LEAKAGE

Quantifying the leakage rate with respect to the size of a hole enables the visualization of the physical size of all cumulative leaks in the return. Equivalent Orifice Leakage Area defined in the Duct Blaster^{TM} Manual [51] can be used to calculate the Equivalent Orifice Leakage Area (EOLA).

EOLA is given by

$$\text{EOLA (sq. in.)} = (\text{Return System Leakage Rate})/1.06 \times (\text{Return Duct System Pressure})^{0.5} \tag{5.13}$$

where,

Return System Leakage Rate = leakage rate of return duct system in CFM measured by Duct Blaster^{TM} at operating pressure

Return Duct System Pressure = operating pressure of return duct system

Table 5.7 shows the EOLA for the homes tested in Northern Louisiana. The average size of all the cumulative leaks in the return for a given home using the pressurized and depressurized data was determined to be 28.5 sq. in. with a 95% confidence interval ranging between 12.52 and 43.88. This hole of mean size 28.5 sq. in. is about 14% of whole house leakiness based on the average value of Effective Leakage Area (ELA) obtained from Chapter Three.

Table 5-7. Equivalent orifice leakage area (EOLA).

Home #		CRL+			CRL-	
	OPP	RLOP	EOLA	OPP	RLOP	EOLA
	Pa	cfm	sq. in.	Pa	cfm	sq. in.
1	-19.000			-19.000	27.660	5.999
2	-34.000			-34.000	97.670	15.801
3	-17.000	110.000	25.169	-17.000	69.500	15.902
4	-25.700	50.330	9.366	-25.700	65.670	12.221
5	-17.400	44.330	10.026	-17.400	79.330	17.941
7	-16.700	106.538	24.595	-16.700	115.739	26.719
9	-63.000	102.940	12.235	-63.000	90.556	10.763
15	-12.000			-12.000	56.854	15.483
18	-15.000	25.000	6.090	-15.000	30.330	7.388
19	-19.000	12.318	2.666	-19.000	43.430	9.400
20	-65.000			-65.000	113.455	13.276
24	-18.000	108.925	24.221	-18.000	142.325	31.647
25	-31.000	150.253	25.459	-31.000	147.154	24.934
26	-8.000	782.928	261.138	-8.000	408.627	136.294
31	-67.000	155.640	17.938	-67.000	197.240	22.733
33	-31.000	109.334	18.525	-31.000	135.032	22.880
37	-34.000	136.561	22.094	-34.000	93.291	15.094
40	-15.500	113.598	27.221	-15.500	139.855	33.512
41	-150.000			-150.000	117.861	9.079
43	-32.000			-32.000	41.039	6.844
221	-33.000			-33.000	70.638	11.600
222						
Averages:	**-40.761**	**143.478**	**34.767**	**-40.761**	**108.726**	**22.167**

5.8 AVERAGE RETURN LEAKAGE

The operating pressure of the return in homes varies significantly from home to home. The reasons for these variations may be return register sizing, clogged evaporator coils, return leaks, equipment capacity and/or the return structure itself. This operating pressure is required in the determination of return leaks to the outside.

The average return leakage to the outside was determined using weighted average technique based on all the observations of combined return leakage to outside using both house to return as well return to attic case. In this calculation of weighted average return leakage, only readings with flow exponents in the range 0.25 to 0.75 were considered. The weighted average return leakage is presented in Table 5.8. In addition, homes with direct readings of return leakage at operating pressure were also included. Homes with flow readings at more than two points were also included in the CRL- or CRL+, depending on the return to attic or house to return case.

Table 5-8. Weighted average return leakage.

Tests	N	Return Leakage (cfm)
CRL- (P_{RA})	5	99.978
CRL+ (P_{RA})	4	177.172
CRL- (P_{HR})	8	109.281
CRL+ (P_{HR})	12	137.161
Direct Reading CRL-	3	68.220
Direct Reading CRL+	5	71.500
Weighted	**37**	**115.970**

The weighted average return leakage to outside was determined to be 116 cfm. This value of return leakage to outside is very high because Energy Star qualified homes recommends duct leakage to outside to be less than 6 cfm/100 sq. ft. [57]. Considering this recommended duct leakage value and the home with the smallest area from the sample-1041 sq. ft., we estimate the recommended value to be about 62 cfm. This value of 62 cfm is the total of supply leakage and return leakage. However, this study has determined the return leakage to be about 1.5 times the recommended total duct leakage value-contributing to high utility bills as well as discomfort to residents.

The duct leakage to outside was determined to be about 348 cfm from an earlier study by Witrol, Erinjeri et al. [2]. Taking this value of 348 cfm into account, we can say that return leaks contribute nearly 26% of the total duct leakage at 25 Pa. This chapter covered the measurement of return leakage in operating conditions. The actual measurement of supply duct leakage under operating conditions is presented in Chapter Six.

6.0 SUPPLY LEAK MEASUREMENT

Return leak measurements were treated in detail in Chapter Five. This chapter will treat supply leak measurements. Supply leak measurements are important, as supply leaks are the most common source of duct leaks. As mentioned earlier in Chapter Five, a study on 43 homes in North Louisiana concluded that 51% of them had dominant supply leaks and 27% of the homes had dominant return leaks. Figure 5.1 in Chapter Five shows the typical components of the duct system. Supply leaks occur at various sites in the supply duct leakage system.

The objective of this study is to develop an accurate procedure in measuring supply leaks. Various methods are currently used to measure supply leaks. However, all these methods measure the leakage rates at a predetermined pressure; normally at 25 Pa. In this study, we have presented an approach that can measure supply leaks based on the operating pressure of the system; the reason being that not all houses have the same operating pressure in the duct system. The operating pressure in the supply plenum can vary due to various factors such as:

1. Capacity of the air-conditioning unit.
2. Pressure drop across the coil due to various factors such as inherent drop or drop due to clogging.
3. Return Leaks.

The following are the additional contributions from this study to the measurement procedure in estimating supply duct leakage:

- The operating pressures at the supply as well as the return side of the duct system are generally different, and that is incorporated in the measurement procedure.
- The supply leaks obtained using this procedure is more realistic as the operating pressure measured gives the supply leak estimate under operating conditions.

In this study of supply leak measurement, we have incorporated the above contributions in the measurement of supply leakage. However, this chapter is limited to the theoretical procedure of the supply leak measurements and has limited data from the 43 homes tested in Northern Louisiana. Certain data required for the above procedure were not collected in all the houses due to various reasons as mentioned in Chapter Five and Section 6.2.

6.1 TESTING SUPPLY LEAKS

Supply leaks are generally measured using the same measuring equipment as used in measuring the return leakage described in Section 5.2. The recommended approach consists of the following tests:

Combined Duct Leakage (CDL):

Step 1: Seal all the registers and connect the Duct Blaster^{TM} to an opening through the seal of the return register.

Step 2: Pressurize/Depressurize the duct system to 25 Pa through this opening with respect to the outside.

Step 3: Pressurize/Depressurize the house to 25Pa with the Blower Door^{TM}.

Step 4: Adjust the pressure reading in cfm using a DG-3 pressure gauge to 0 Pa and measure the corresponding flow in cfm.

Step 5: Repeat the test for a total of three readings.

Step 6: Repeat the tests at 35 Pa.

Figure 6.1 shows some common sources of supply leaks in residential homes.

Figure 6-1. Common sources of supply duct leakage.

Combined Return Leakage (CRL):

Follow the test procedure as described in Section 5.4 of Chapter Five to obtain flow readings at 25 Pa and 35 Pa respectively.

After recording flow readings for CDL and CRL, measure the operating pressure in the return as well as in the supply plenum. Operating pressure at the return plenum is obtained using BBRB as described in Sections 5.3 and 5.4 of Chapter Five. For determining the operating pressure at the supply plenum, it is preferable to introduce the pressure probe into the supply plenum without drilling, both for easy of the technician performing the measurement, and for the comfort of the homeowner. However, if there are no easily penetrated gaps available, a hole should be drilled to place the probe in an appropriate location within the supply plenum. The placement of probe is critical in measuring the supply plenum pressure. The most accurate way will be to place the probe in five different locations and measure the reading at each location three times with different depths. However, drilling of a hole may not be very comfortable to the homeowner, as holes may have to be drilled at three different locations. However, we recommend placing the probe in one location close to the blower and measure the reading at three different depths. The average of the three readings is the operating pressure of the supply plenum. It is advisable to use multi-hole pitot tube to get a accurate readings of the pressure in the supply plenum. The same kind of pitot tube is also recommended for measuring the pressure at the return plenum.

The CDL and CRL at 25 Pa and 35 Pa can be used to determine the supply leak at the respective pressures. From these two results and the operating pressure recorded, we can determine the actual flow (supply leaks) at operating pressure. The calculations are presented in detail in Section 6.2.

6.2 ESTIMATING SUPPLY LEAKAGE AT OPERATING CONDITIONS

We will assume that the return plenum has a constant pressure throughout the return plenum and similarly the supply plenum maintains a constant pressure throughout the supply plenum. In real time conditions, the assumptions may not be ideal but they are necessary to obtain any result, and in most cases, accurately approximate the actual system.

The relation of flow and pressure is given by

$$F = CP^n \tag{6.1}$$

where,

F= air flow in cubic feet per minute (cfm)

C=leakage coefficient

P=pressure in Pascal (Pa)

n=flow exponent

The notations for the variables in this chapter are as follows:

CRL_{35} = combined return leakage in cfm at 35 Pa

CRL_{25} = combined return leakage in cfm at 25 Pa

CDL_{35} = combined duct leakage in cfm at 35 Pa

CDL_{25} = combined duct leakage in cfm at 25 Pa

CSL_{35} = combined supply leakage in cfm at 35 Pa

CSL_{25} = combined supply leakage in cfm at 25 Pa

CSL_{OP} = combined supply leakage at operating pressure

OPS = Operating pressure in the supply plenum

OPR = Operating pressure in the return plenum

Also, note that P1 and P2 represent pressures at any two given points. We know that at any given pressure combined duct leakage is equal to sum of combined return leakage and combined supply leakage i.e.

$$CDL = CRL + CSL \tag{6.2}$$

Therefore,

$$CSL = CDL – CRL \tag{6.3}$$

Assuming two pressure points 35 and 25 Pa and using Eq. 6.1, we have

$$CRL_{35} = C_{\mathrm{RL}}P_{35}^{n_{\mathrm{RL}}} \tag{6.4}$$

$$CRL_{25} = C_{\mathrm{RL}}P_{25}^{n_{\mathrm{RL}}} \tag{6.5}$$

Dividing Eq. 6.4 by Eq. 6.5 we get,

$$CRL_{35}\, P_{25}^{\,n_{\mathrm{RL}}} = CRL_{25}\, P_{35}^{\,n_{\mathrm{RL}}} \tag{6.6}$$

$$n_{\mathrm{RL}} = \log(CRL_{35} / CRL_{25}) \;/\; \log(P_{35} / P_{25}) \tag{6.7}$$

$$\mathrm{C}_{\mathrm{RL}} = CRL_{35} /\; P_{35}^{\,n_{\mathrm{RL}}} \tag{6.8}$$

Similarly Eqs. (6.6), (6.7), (6.8) can be used to determine $n_{\mathrm{DL},}$ $C_{\mathrm{DL},}$ n_{SL} and C_{SL}. Note that at 35 Pa or 25 Pa, it is straightforward to determine the supply leaks as we have measured the leaks using Blower Door$^{\mathrm{TM}}$ and Duct Blaster$^{\mathrm{TM}}$ at these pressures.

However, our objective is to determine the duct leakage at the actual operating pressure, obtained through our measurements. It is important to note that the return plenum and the supply plenum operate at different pressures. Therefore, it becomes critical to measure the operating pressure both in the return as well as the supply and to consider these actual operating pressures in duct leakage calculations.

If we assume *OPS* and *OPR* as the actual operating pressures in the supply and return plenums, then applying Eqs. (6.2) and (6.3) is not straightforward. In such situations, we have to determine CSL_{35} and CSL_{25} from which we can determine n_{SL} and C_{SL} respectively. Then we can apply the Eq. (6.1) to obtain the supply leakage at the operating pressure *OPS*.

$$CSL_{\mathrm{OP}} = C_{\mathrm{SL}}\, OPS^{\,n_{\mathrm{SL}}} \tag{6.9}$$

To obtain the combined duct leakage at the actual operating condition we use Eq. (6.2). This flow measures the duct leakage at operating conditions with the supply operating at *OPS* and return operating at *OPR*. The above procedure is explained with the aid of the flow chart shown below in Figure 6.2.

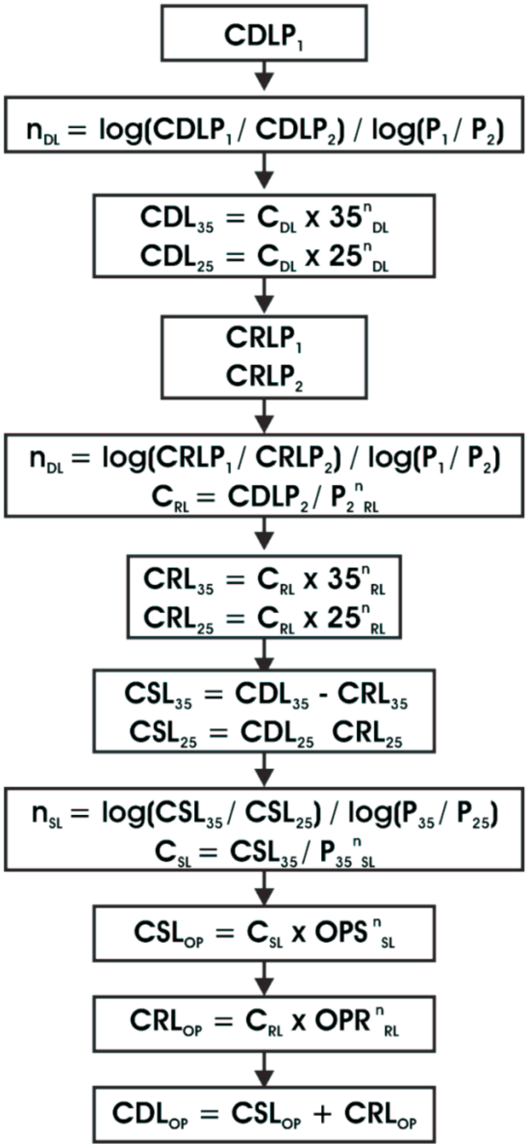


Figure 6-2. Flow chart for calculating actual duct-leakage at operating pressure.

Note that in this context, the combined duct leakage at operating pressure does not imply that the ducts operate at a specific pressure but represents the summation of the supply leaks of the supply at the operating pressure of the supply plenums and the return leaks of the return at the operating pressure of the return plenum. Homes in which it is impossible to pressurize or depressurize to 35 Pa or 25 Pa, readings should be taken at two different pressure points and follow the flow chart in Figure 6.2 with the respective recorded pressures and flows. The important point is that we need to have data at two different pressures to determine leakage coefficients and flow exponents.

The example for calculating duct leakage at operating conditions as described in flow chart (Figure 6.2) is presented in Tables 6.1, 6.2, 6.3 and 6.4.

Table 6-1: Combined duct leakage at 35 Pa and 25 Pa.

Home #	CDL Pressure 1	CDL Flow 1	CDL Pressure 2	CDL Flow 2	n_{DL}	C_{DL}	CDL_{35}	CDL_{25}
	Pa	cfm	Pa	Cfm			cfm	cfm
9	25.00	365.67	15.00	285.33	0.49	76.59	430.58	365.67
15	25.00	178.33	15.00	122.67	0.73	16.88	228.17	178.33
19	25.00	249.33	15.00	195.00	0.48	52.99	293.14	249.33
24	25.00	230.37	15.00	188.33	0.39	64.72	263.07	230.37
25	35.00	390.00	25.00	308.00	0.70	32.20	390.00	308.00
40	15.00	270.67	10.00	207.67	0.65	46.12	470.86	377.93
41	15.00	358.67	10.00	302.67	0.42	115.42	511.40	444.20
43	25.00	137.00	15.00	92.67	0.77	11.66	177.24	137.00

For example, let us consider home number 15. From Table 6.1, n_{DL} (=0.73) and C_{DL} (=16.88). Using the equations given in the flow chart (Figure 6.2) we obtain CDL_{35} (=228.17 cfm) and CDL_{25} (=178.33 cfm).

The data n_{RL} and C_{RL} from Table 6.2 is used with Eq. (6.4) to obtain CRL_{35} and CRL_{25}. CRL_{OP} is then determined using equation provided in the flow chart. For example, for home number 15, we determine CRL_{OP} to be 90.56 cfm ($10.78 \times 63^{0.54}$).

Table 6-2. Combined return leakage at 35 Pa and 25 Pa.

Home #	n_{RL}	C_{RL}	CRL_{35}	CRL_{25}	OPR	CRL_{OP}
			Cfm	cfm	Pa	cfm
9	0.70	16.01	194.65	153.67	-16.70	115.74
15	0.51	10.78	66.96	56.33	-63.00	90.56
19	0.63	5.55	51.61	41.79	-15.00	30.33
24	0.62	8.68	77.50	63.00	-65.00	113.45
25	0.75	16.06	235.10	182.37	-18.00	142.32
40	0.51	15.67	94.67	79.85	-34.00	93.29
41	0.41	45.82	194.85	169.90	-15.50	139.85
43	0.63	4.97	47.00	38.00	-150.00	117.86

Table 6.3 gives the combined supply leakage at the operating pressure in the supply plenum. For example, for home number 15 using Eq. (6.3), we determine CSL_{35} to be 161.21 cfm. The *OPS* is measured as described in Section 6.1. These values are then substituted into the power law equation, Eq. (6.1) to obtain the supply leaks at operating pressure as described in the flow chart (Figure 6.2). For home number 15, the *OPS* was determined to be 45.67 Pa which using Eq. (6.9) gives the combined supply leakage at operating pressure of 200.96 cfm. As discussed in Chapter Five, Section 5.8, we only consider homes with flow exponents in the range 0.25 to 0.75, as other values are not physically realistic, and represent erroneous measurements.

Table 6-3: Combined supply leakage at 35 Pa and 25 Pa.

Home #	CSL_{35}	CSL_{25}	n_{SL}	C_{SL}	OPS	CSL_{OP}
	cfm	cfm			Pa	cfm
9	235.93	212.00	0.32	76.20	23.00	206.45
15	161.21	122.00	0.83	8.48	45.67	200.96
19	241.53	207.54	0.45	48.63	40.00	256.52
24	185.57	167.37	0.31	62.36	45.33	200.88
25	154.90	125.63	0.62	16.94	21.00	112.71
40	376.19	298.07	0.69	32.16	49.17	475.93
41	316.55	274.30	0.43	69.66	79.30	448.43
43	130.24	99.00	0.82	7.18	76.67	246.77

Table 6.4 gives the actual duct leakage at operating pressure; the summation of CSL_{OP} and CRL_{OP}. For example, home number 15 has a CDL of 291.51 cfm at operating pressure. All the above data are with respect to pressurization of the supply ducts, the home and the return plenum. Note that depressurization data is not presented in this chapter due to the small sample of data.

As described earlier, this approach of determining duct leakage at operating conditions was only possible in a few houses due to the following reasons:

1. Determining the operating pressure at the supply plenum required drilling a hole in the supply plenum. This procedure was a limitation on many subjects.
2. Measuring return leaks was not possible in many homes as discussed in Chapter Five.
3. In some homes, combined duct leakage was not measured at two pressure points.
4. As mentioned earlier, this chapter deals only with the theoretical approach rather than a comprehensive study. However, we have provided the new approach in determining duct leakage at operating pressures with practical examples.

Table 6-4. Combined duct leakage at operating pressure.

Home #	CSL_{OP}	CRL_{OP}	CDL_{OP}
	cfm	Cfm	cfm
9	206.45	115.74	322.19
15	200.96	90.56	291.51
19	256.52	30.33	286.85
24	200.88	113.45	314.34
25	112.71	142.32	255.03
40	475.93	93.29	569.22
41	448.43	139.85	588.28
43	246.77	117.86	364.63

6.3 Duct Leakage at Operating Pressure and Standard Pressure of 25 Pa

In this Section, we attempt to compare the duct leakage at operating pressure and standard pressure 25 Pa. Table 6.5 shows the comparison of duct leakage values both with 25 Pa and 35 Pa. From Table 6.5, we see that on average the combined duct leakage at operating pressure is greater than the combined duct leakage at 25 Pa by 68 cfm. Also, it is about 6 cfm greater than the combined duct leakage at 35 Pa. In addition, we observe that the actual operating pressure of the duct system is above 35 Pa. It is important to note that there is no such standard pressure for the duct system as a whole because the return is depressurized whereas the supply is pressurized. These two opposite effects, pressurization and depressurization, are impossible to quantify to get a single standard pressure.

Table 6-5. Comparison of combined duct leakage.

Home #	CDL_{35}	CDL_{25}	CDL_{OP}	CDL_{25} -CDL_{OP}	CDL_{35} -CDL_{OP}
	cfm	cfm	cfm	cfm	cfm
9	430.58	365.67	322.19	43.48	108.39
15	228.17	178.33	291.51	-113.18	-63.35
19	293.14	249.33	286.85	-37.52	6.30
24	263.07	230.37	314.34	-83.97	-51.27
25	390.00	308.00	255.03	52.97	134.97
40	470.86	377.93	569.22	-191.29	-98.35
41	511.40	444.20	588.28	-144.08	-76.88
Average:	**369.60**	**307.69**	**375.35**	**-67.66**	**-5.74**

We have considered in Chapter Seven whether the duct leakage is the same for the pressurized and the depressurized conditions and found that the differences are significant statistically. Hence, the approach described in this chapter for determining combined duct leakage at operating pressure is significant. That said, performing t-test statistics on the data, we find that there is no difference between the flows at 25 Pa and operating pressure. This difference is significant as all the present day measurements and estimations of duct leakage are reported at 25Pa for the residential HVAC systems. However, it should be noted that the sample considered is small and thus the result is not trustworthy. We therefore recommend performing this procedure for a larger sample to determine whether there is a meaningful statistical difference.

7.0 STATISTICAL ANALYSIS OF PRESSURIZED AND DEPRESSURIZED CONDITIONS

The *pressure-flow* relationship for air leakage, also referred to as the power law, has the form

(7.1) $F = C\Delta P^{\cdot}$

where,

F = flow

C = the leakage coefficient,

ΔP = the pressure difference,

n = flow exponent.

The flow exponent (n) has limiting values of 0.5 and 1 for fully developed turbulent and laminar flow respectively [58]. However, it is important to note that the value of flow exponent should be differentiated from the measurements of whole house leakiness and duct leaks [2, 48].

The Eq. (7.1) is applied for air-leakage calculations for whole house leakiness and duct leakage. The same equation is also applied for both pressurization and depressurization conditions of determining whole house leakiness and duct leakage. The homes sampled in the second phase of this research provided data with regards to the two conditions, pressurized and depressurized. The data collected included the following tests:

1. Total Duct Leakage (TDL).
2. Combined Duct Leakage (CDL).
3. Total Return Leakage (TRL).
4. Combined Return Leakage (CRL).

All the above tests were measured in both the pressurized and the depressurized conditions. Comparisons between the two conditions were analyzed statistically. The importance of this study is that if a difference exists between the two conditions, then the research community has to determine which is the most reasonable estimate. Also, the study initiates the need to determine causes of such differences and the solution to this problem of measurement. It is important to note that TDL and TRL are performed using Duct Blaster^{TM} only whereas both CDL and CRL involve both Duct Blaster^{TM} as well as Blower Door^{TM} as described in [2]. All the statistical tests were performed using SAS^{TM} and the detailed output is presented in Appendices B13 and B14.

7.1 TOTAL DUCT LEAKAGE (TDL)

This section investigates whether there is a statistically significant difference between the average value of the total duct leakage between the pressurized and depressurized conditions. Twenty-six observations formed the sample size for performing the Paired t-test on the total duct leakage measurements. The result of the Paired t-test is presented in Table 7.1.

Table 7-1. Non-Parametric and normality test for TDL.

```
                    Tests for Location: Mu0=0


        Test           -Statistic-    -----p Value------


        Student's t    t  1.489723    Pr > |t|    0.1488

        Signed Rank    S        -4    Pr >= |S|   0.9214



                       Tests for Normality


     Test                  --Statistic---    -----p Value------


     Shapiro-Wilk          W      0.47145    Pr < W     <0.0001

     Kolmogorov-Smirnov    D     0.425156    Pr > D     <0.0100

     Cramer-von Mises      W-Sq  1.181899    Pr > W-Sq  <0.0050

     Anderson-Darling      A-Sq  5.928336    Pr > A-Sq  <0.0050
```

A p-value of less than 0.05 for all the normality tests as shown in Table 7.1 suggests that the distribution does not follow a normal distribution. Therefore, distribution-free or Non-Parametric tests were performed on the data. The Wilcoxon signed-rank sum test, the Non-Parametric version of a Paired samples t-test is mainly applied when the difference between the two variables is not normally distributed.

The results of the Non-Parametric tests with a p-value greater than 0.05 shows that there is no difference between the pressurized and depressurized readings in the case of total duct leakage. It is also important to note that the p-value of Paired t-test is also greater than 0.05 suggesting that there are no differences between the two conditions even when normality assumption is violated.

Applying the Two-Sample t-test at α equal to 0.05; we can say that–34.11 to 212.46 is the 95% confidence interval for the difference in the mean values of the total duct leakage between the pressurized and the depressurized conditions. The detailed output is presented in Appendix A (Figure A.16).

7.2 COMBINED DUCT LEAKAGE (CDL)

The CDL is performed using both Blower Door^{TM} and Duct Blaster^{TM} in conjunction to determine duct leakage to the outside. The difference between the pressurized and the depressurized conditions for the combined duct leakage was statistically analyzed for 27 observations. Results in Table 7.2 show that the distribution is not normal as all the p-values for normality tests are less than 0.05.

Table 7-2. Non-Parametric and normality test for CDL.

```
                    Tests for Location: Mu0=0

         Test           -Statistic-    -----p Value------

         Student's t    t   2.31873    Pr > |t|    0.0285
         Signed Rank    S       125    Pr >= |S|   0.0013


                       Tests for Normality

    Test                  --Statistic---    -----p Value------

    Shapiro-Wilk          W     0.628908    Pr < W     <0.0001
    Kolmogorov-Smirnov    D     0.317658    Pr > D     <0.0100
    Cramer-von Mises      W-Sq  0.813075    Pr > W-Sq  <0.0050
    Anderson-Darling      A-Sq  4.196256    Pr > A-Sq  <0.0050
```

The results of the Wilcoxon Non-Parametric test show a difference between the pressurized and depressurized state for combined duct leakage measurements. The Paired t-test also shows a difference between the pressurized and depressurized readings. The 95% confidence interval for the difference between the two conditions range from 15.056 cfm to 250.23 cfm. The positive difference between the two readings implies that the reading of depressurized conditions is generally higher than that of the pressurized state. The detailed output is presented in Figure A.17. The % difference in readings between the pressurized and depressurized conditions is shown in Table 7.3. The depressurized reading on an average is about 20% higher than the pressurized readings.

Table 7-3. % Difference in measurements between pressurized vs. depressurized.

House #	Pressure	Flow Depressurized	Flow Pressurized	%Difference
	(Pa)	(cfm)	(cfm)	
10	25	143.33	168.67	-15.02%
11	25	309.33	282.67	9.43%
12	25	282	263.33	7.09%
13	25	125	137	-8.76%
14	25	339	243.67	39.12%
15	25	138.67	178.33	-22.24%
16	25	257.67	242.33	6.33%
17	25	425.33	406.33	4.68%
19	25	238.33	249.33	-4.41%
20	25	143.33	164.33	-12.78%
26	25	339.33	328	3.45%
27	25	115.53	126	-8.31%
28	15	152.67	140.67	8.53%
30	25	263	234.67	12.07%
31	10	2096.33	900	132.93%
32	25	76.67	109.33	-29.87%
33	25	169	174.67	-3.25%
34	25	254.67	265.67	-4.14%
35	15	1195.67	223.67	434.57%
36	25	238.33	249.33	-4.41%
37	5	181	270	-32.96%
39	15	150	201	-25.37%
40	15	220	270.67	-18.72%
41	15	331.67	358.67	-7.53%
42	25	141.67	179	-20.85%
81	25	751	392.67	91.25%

7.3 TOTAL RETURN LEAKAGE (TRL)

The average difference in total return leakage between the depressurized and the pressurized conditions was determined to be 27.18 cfm. The 95% confidence interval for the difference between the two conditions of total return leakage varies from–56.66 cfm to 111.02 cfm. However, the results of normality tests show that the data do not follow a normal distribution, as the p-values for all the normality tests are less than 0.05 as shown in Table 7.4.

We note there were limited data due to the limitations as described in Chapter Five. Accounting for this small sample data and violations of the normality assumptions, we performed Non-Parametric tests on the data. The results of the Non-Parametric tests show that is no difference between the pressurized and depressurized conditions in the case of TRL measurements. The detailed output of all the associated tests is presented in Figure A.17.

Table 7-4. Non-Parametric and normality test for TRL.

```
                     Tests for Location: Mu0=0


             Test          -Statistic-    -----p Value------


             Student's t   t  0.706342    Pr > |t|    0.4935

             Signed Rank   S     -21.5    Pr >= |S|   0.1421



                            Tests for Normality


        Test                  --Statistic---    -----p Value------


        Shapiro-Wilk          W     0.397412    Pr < W     <0.0001

        Kolmogorov-Smirnov    D     0.470439    Pr > D     <0.0100

        Cramer-von Mises      W-Sq  0.705757    Pr > W-Sq  <0.0050

        Anderson-Darling      A-Sq  3.530716    Pr > A-Sq  <0.0050
```

7.4 COMBINED RETURN LEAKAGE (CRL)

The CRL is performed using Blower Door^{TM} and Duct Blaster^{TM} to determine return leaks to the outside. Chapter Five presents details about the procedure carried out for performing this test. Statistical tests described in earlier sections were employed to determine if any difference existed between pressurized and depressurized conditions.

The average combined difference in return leakage between the depressurized and the pressurized conditions was determined to be 69.09 cfm. The tests for normality presented in Table 7.5 indicate that the small sample data do not follow a normal distribution as the p-values for all the normality tests is less than 0.05. Therefore, applying Wilcoxon Non-Parametric test, we determine that the p-values are less than 0.05 suggesting that difference existed between the depressurized and the pressurized conditions. The detailed output of all the associated tests is presented in Figure A.17. Table 7.6 shows the % difference in readings between the pressurized and depressurized conditions. On an average the depressurized readings is about 3% lower than the pressurized readings.

Table 7-5. Non-Parametric and normality test for CRL.

```
                     Tests for Location: Mu0=0


           Test           -Statistic-    -----p Value------


           Student's t    t  1.395293    Pr > |t|    0.1847

           Signed Rank    S        45    Pr >= |S|   0.0084



                        Tests for Normality


      Test                  --Statistic---    -----p Value------


      Shapiro-Wilk          W     0.428214    Pr < W     <0.0001

      Kolmogorov-Smirnov    D     0.428674    Pr > D     <0.0100

      Cramer-von Mises      W-Sq  0.711134    Pr > W-Sq  <0.0050

      Anderson-Darling      A-Sq  3.625748    Pr > A-Sq  <0.0050
```

Table 7-6. % Difference in measurements between pressurized vs. depressurized.

House #	Pressure	Flow Depressurized	Flow Pressurized	%Difference
	(Pa)	(cfm)	(cfm)	
9	25	144	153.67	-6.29%
11	25	118.67	108	9.88%
15	25	58.67	56.33	4.15%
19	25	36	36.33	-0.91%
20	25	20.33	54	-62.35%
25	13	94.33	111.33	-15.27%
26	25	138.33	136.67	1.21%
31	10	943.67	456.67	106.64%
33	25	93.67	100	-6.33%
37	25	98.67	120	-17.78%
40	20	50	71.33	-29.90%
41	15	112	138	-18.84%
81	25	216.33	229	-5.53%

7.5 CONCLUSIONS OF PRESSURIZED VS. DEPRESSURIZED CONDITIONS

Results of Sections 7.1 to 7.4 suggest that CDL and CRL readings differ statistically between the pressurized and the depressurized conditions. These two tests involve both Blower Door^{TM} and Duct Blaster^{TM}. However, it is important to note that tests with Duct Blaster^{TM} only (TDL and TRL) do not show any statistical difference between the pressurized and depressurized conditions. However, it should be noted that the CDL and CRL measure leaks to the outside while TDL and TRL measure total duct leakage. These results are significant as the interchangeability aspects of the tests are thus questionable. Therefore, the reasons for the above differences needs to be addressed and one should be very careful if performing and reporting these tests interchangeably.

Also noted is that the Blower Door^{TM} associated tests shows a difference between the pressurized and depressurized conditions. It is very important to understand that the measurements taken do not reflect the real time working scenario of the HVAC system wherein the return is depressurized, whereas the supply is pressurized. However, the Duct Blaster^{TM} is used for measurement purposes, the entire duct system is either pressurized or depressurized and is thus not equivalent to the actual functioning of the HVAC unit. Another factor that may contribute to the differences is the presence of valves and dampers (micro or macro) in the home. These valves or dampers may get activated or deactivated while using the Blower Door^{TM}, for pressurizing/depressurizing the whole house. Another factor, which may contribute to this difference, is the sensitivity of the Blower Door^{TM} to the environmental changes in contrast to the Duct Blaster^{TM}. All these factors mentioned in the preceding lines may also interact to give variations in readings between the pressurized and depressurized conditions.

8.0 COST IMPLICATIONS OF DUCT LEAKAGE

There has been a growing demand for energy. This increasing demand, not matched by an increase in desirable energy supplies, is causing a severe energy shortage problem. In particular due to the decreasing discoveries of new sources of oil and natural gas, there is an increasing need to find alternative sources of fuel, to overcome the dependence on these fossil fuels for energy. Developing alternative sources of energy is very beneficial but conserving energy is actually more important, as it has no negative effects such as increasing carbon dioxide in our atmosphere and the problems related to the storage of the resultant radioactive waste products. One of the areas where we can conserve energy is by building energy efficient homes, or by increasing the energy efficiency of existing homes. Air infiltration and duct leakage in homes are some of the main causes of energy wastage. Typical duct systems lose 25% to 40% of the heating energy or cooling energy put out by a central furnace, heat pump, or air conditioner [11]. Our measurements of duct leakage show that in many homes ducts passing through unconditioned spaces such as attics, garages, or crawl spaces lose energy through duct leakage, in addition to losing energy through heat exchange when the ducts are uninsulated or are poorly insulated (frequently R3). The energy used by forced-air heating and cooling systems is wasted because of leaks. The cooling systems may draw as much as 0.5 kilowatts (kW) of electricity during peak cooling periods [59]. It is estimated that each year, U.S. residential ductwork leakage costs consumers $5 billion [60].

This study deals with determining energy losses due to duct leakage in residential homes. Duct leaks create uncontrolled airflows with consequences that include low-pressure zones, increased infiltration that can increase or decrease humidity, and non-uniform temperatures and energy/capacity losses for the HVAC system [61]. In our study of 43 homes in North Louisiana, we have determined the effect of duct leakage on cooling/heating load and the corresponding costs associated with such leaks. For calculation purposes, we employed the ASHRAE^{TM} 152 standard for determining distribution system efficiency and REM/Rate^{TM} software developed by Architectural Energy Corporation for determining the cooling/heating load in each of the 43 homes tested.

REM/Rate^{TM} software calculates heating, cooling, domestic hot water, lighting and appliance loads, consumption, and costs based on a description of the home's design and construction features as well as on the local climate and energy cost data. REM/Rate^{TM} is Department of Energy (DOE)-approved for Weatherization Assistance Programs in all states [62].

In an earlier study by Witriol, Erinjeri et al., it was determined that more than 2.5 times as much energy is lost by the ducts than is actually delivered to our homes. The entire calculation was based on the chart published in Jeffrey S. Tiller’s book titled “Builders Guide to Energy Efficient Homes in Louisiana” which recommended that % loss of HVAC efficiency is equal to 2.5 times % duct leakage. Figure 8.1 is the reproduced chart that shows the efficiency losses due to attic return and supply leaks.

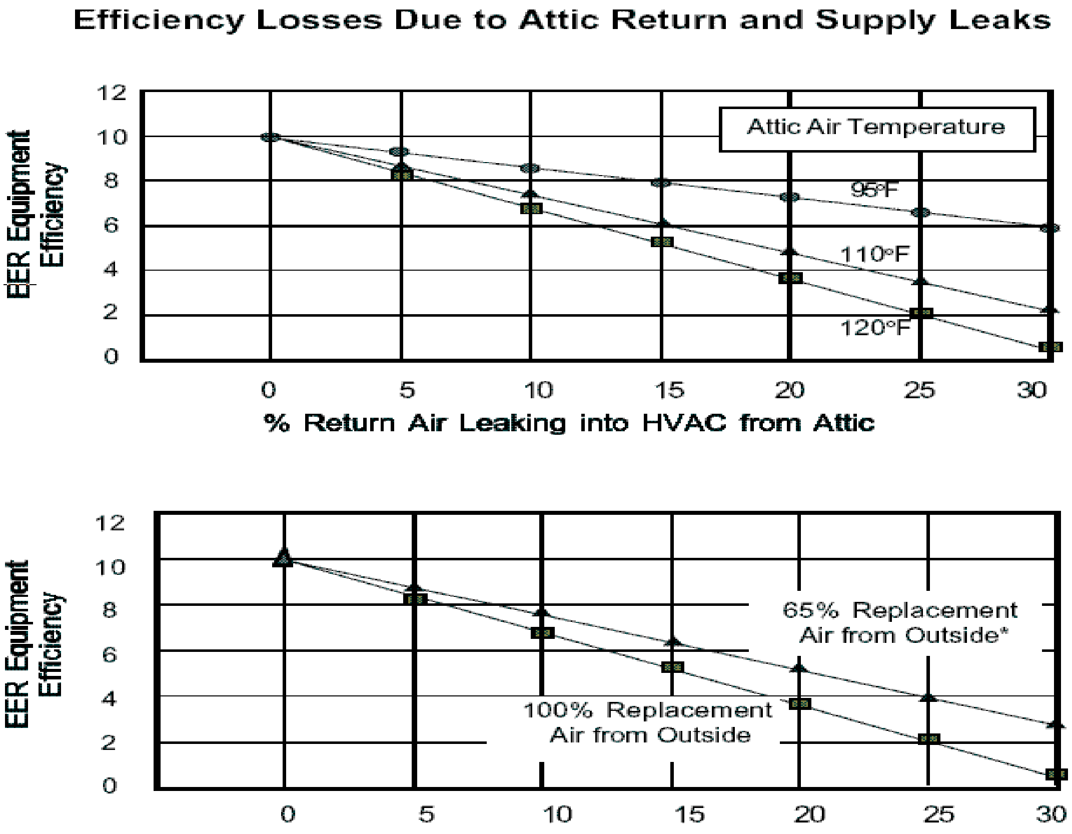


Figure 8-1. Energy losses due to attic return and supply leaks.

There are many drawbacks to adopting this chart, shown in Figure 8.1, for determining % loss of HVAC efficiency, mainly:

1. The graphs are linear over the entire range of parameters; thus, an AC can waste more energy than it uses; a scientifically inaccurate result.
2. The graphs do not consider the effects of the humidity in determining the % loss of HVAC efficiency. Moisture removal (latent energy) as well as reducing the temperature (sensible energy) of unconditioned air are the two basic functions of an air conditioning system.
3. Determining the efficiency for homes having both supply and return leaks simultaneously is not possible.
4. The charts do not clearly distinguish between peak-load efficiency losses and seasonal averages. Peak-load efficiency is relevant to sizing whereas the seasonal average is used to predict energy consequences.
5. The charts overlook the situation of a cooling-dominated (hot, humid) climate, wherein a dominating return leak with ducts in the attic is far more costly than a dominating supply leak because the air introduced into the home generally comes from the attic.
6. Actual flow over the evaporator coil directly affects the Energy Efficiency Ratio (EER). EER is the measure the amount of electricity required by an air conditioning unit to provide the desired cooling level in BTUs. If the airflow over the coil is too high then air moisture

removal is reduced. However if flow is too low, sensible cooling (reducing the temperature) is reduced with degradation of cooling system EER. This factor is not considered in Figure 8.1 [63].

To eliminate these problems, we decided to be more precise in our approach in estimating the cost associated with duct leakage, by using the professionally accepted REM/Rate^{TM} software along with ASHRAE^{TM} 152 standard to estimate energy losses due to duct leakage rather than using the chart presented in Figure 8.1. In the next two sections, we discuss REM/Rate^{TM} and ASHRAE^{TM} 152 in relation to this study, highlighting the significance of this study and its implications.

8.1 REM/RATE^{TM} INPUTS

REM/Rate^{TM} is an user-friendly software that calculates heating, cooling, domestic hot water, lighting and appliance loads, consumption, and costs based on a description of the home's design and construction features as well as the local climate and energy cost data. REM/Rate^{TM} is U.S Department of Energy (DOE)-approved software for Weatherization Assistance Programs in all states [62]. It also complies with the National Home Energy Rating Standards as promulgated by Residential Energy Services Network (RESNET).

There are two options to input data: simplified and detailed. Simplified inputs use general building design characteristics (e.g., house type) and built-in algorithms to determine building shell areas and other characteristics. Detailed inputs provide the user additional control over the calculations. These inputs include wall construction details, window conduction and solar gain values, HVAC efficiencies, duct system characteristics, passive and active solar design features, and infiltration rates [10]. In this study, we used the simplified input, as our objective was to find the costs associated with duct leakage rather than the whole house efficiency. The HVAC system efficiency was determined from the ASHRAE^{TM} 152 standard whereas REM/Rate^{TM} was used to determine the cooling load/heating load for the home. The output from REM/Rate^{TM} was used in conjunction with the results from the ASHRAE^{TM} 152 standard to determine the energy wastage in dollars due to duct leakage.

For each of the 43 homes tested and the additional data from New Orleans, we collected the data for the simplified input and followed the steps presented below to determine the energy cost.

1. Building/Property information

   This included the basic information such as the physical locations and name of the owner.

2. Site Information

   REM/Rate^{TM} site information includes both utility and weather location data. This information is necessary to calculate the energy costs and consumption. The main inputs are Climate Location and Utility expenses.

   To determine the heating and cooling energy consumption and cost, climate information is needed for the home's location. For the 43 homes tested in North Louisiana, Shreveport was used as the city since it was the only mutual choice of location in both REM/Rate^{TM} and ASHRAE^{TM} 152. New Orleans was used as the city of location for data obtained on nine homes from New Orleans. Note that, we had all the related observations for 38 and 7 homes in North Louisiana and New Orleans respectively. The corresponding fuel and the associated cost are entered for heating and cooling. There are options for fuel types used for heating; electricity, gas, propane, kerosene, oil. Local utility rates can be entered using the edit mode to obtain accurate readings.

3. Simplified Inputs: General Design Characteristics

   This input addresses the general design and construction characteristics of the building. Numerous assumptions are embedded in the Simplified Inputs and the input of appropriate entries is critical. Input parameters entered include house type–number of floors, conditioned area, volume, foundation type, number of bedrooms, distribution of conditioned area, number of corners, nominal flat ceiling height, and conditioned floor area.

4. Simplified Inputs: Building Envelope Characteristics

   This input addresses the basic construction characteristics of the building envelope. The construction components entered include Ceiling Type, Above-Grade Wall Type, Foundation Wall Type, Frame Floor Type, Door Type, Slab Type, Average Slab Depth Below Grade, Type of Infiltration, and Measured Infiltration Rate estimated from the Blower Door^{TM} test with Effective Leakage as the units of measurement.

5. Windows and Glass Door Properties

   This input describes the glazing in vertical walls and the glazed portions of doors namely the windows, and includes, the parameters necessary to estimate the heat gain such as U-Value, Solar Heat Gain Coefficient (SHGC), area of the windows, orientation, interior shading, adjacent shading and wall assignment. The Solar Heat Gain Coefficient (SHGC) is the fraction of incident solar radiance that enters through glazing as heat gain. Interior Shading is a value between 0.0 and 1.0 and represents the fraction of solar heat gain through the window that enters the home. A value of 1.0 indicates there are no interior blinds. This value is a function of the properties of both the glazing and the interior shades.

   Adjacent Shading defines the degree to which windows are shaded through exterior objects such as building's shape and form, trees and shrubs, which may seasonally lose and gain foliage, and nearby buildings and landforms that can provide shade in this form. In general, winter shading factors are greater than summer factors.

   The SHGC meter was used to determine SHGC and the U-value for the windows in all the homes tested.

6. Mechanical Equipment Properties

   This input describes the characteristics of all mechanical equipment in the building (heating, cooling, and water heating). The heating, cooling, and water heating systems for a building can be described by one or multiple pieces of equipment. Over time equipment efficiency can decline due to lack of maintenance and/or age. Furnace and boiler burners can degrade their proper mixing settings, or become dirty, and air-conditioners can lose their refrigerant charge and their condensers can become dirty. A performance adjustment of 100% means the equipment is operating at nominal efficiency. A performance adjustment of 90% means the equipment is operating at 90% of its nominal efficiency rating. For example, a furnace with an efficiency rating of 80 AFUE and a performance adjustment of 90% will have an actual annual efficiency of 80 * 0.90 = 72%. The performance adjustment is entered as a percentage value between 0 and 100.

There are two entries for the set point temperature one for heating and one for cooling. For comparison purposes a heating set point of 68° is used for heating and a set point of 78° is used for cooling.

7. Duct System Properties Summary

   This input describes the status of the heating and cooling supply ducts. Ducts within conditioned space may be included, but they have little impact on heating and cooling loads. The program can be used for ducts located in more than one location. The areas of the supply plenum, return plenum and the ducts are entered to determine the thermal losses associated with the distribution system. In our test homes we used the default values, which are values, generated in the code based on the average value of homes with the specified characteristics in the specified locations.

   In this study, our objective was to determine the cost associated with duct leakage. We have measured data on duct leakage, which can be added in the detailed input portion of the code. The supply leaks and return leaks at 25 Pa along with the supply pressure and return pressure are additional data that can be entered in the code. Note that in some of the homes we were unable to measure return leaks as described in Chapter Five. For those homes, the return leakage was estimated by multiplying the duct leakage by a factor equal to 0.25. The value of 0.25 is the average fraction of the return duct leakage on all the homes tested in this study. The average delta pressure outside and the average duct operating pressure for both the supply and return side in these measurements is also entered into the code. The average delta pressure outside is the average pressure between the home and the attic.

8. Whole House Infiltration

   The values of whole house infiltration and the remaining inputs are measured and entered in the code.

9. Detailed Lights and Appliances

   As we are only concerned only with the effective duct leakage, the default values for the Detailed Lights and Appliances options were used.

10. By using the quick analysis option, we obtained the annual heating and cooling load, design heating and cooling loads, and the annual consumption and annual energy cost.

11. To obtain the annual energy cost with zero duct leakage we entered the values of the supply leakage and return leakage as zero in step 7 and then proceeded to step 10 to obtain the readings. Table 8.1 presents the data of the energy use of the 43 homes tested using REM/Rate^{TM} following the above 11 steps. Table 8.2 shows the energy wastage due to duct leakage.

Table 8-1. Results on energy use from REM/Rate™.

Home #	Return Leakage	Supply Leakage	Energy Use with Measured Duct Leakage in $			Energy Use with Zero Duct Leakage in $		
	(cfm)	(cfm)	Heating	Cooling	Total	Heating	Cooling	Total
1	27.66	359.34	432	447	1754	401	420	1696
2	97.67	264.33	460	735	2453	444	716	2419
4	58.00	102.00	192	383	1322	186	365	1298
5	61.50	184.50	985	567	2354	958	547	2307
6	61.83	70.17	283	299	1354	278	289	1339
7	119.50	358.50	781	422	2369	754	408	2329
9	148.84	122.60	600	337	1861	585	325	1834
10	39.00	117.00	627	289	1688	597	272	1640
11	113.34	182.67	782	510	2231	759	487	2185
12	68.17	184.50	633	644	2335	611	624	2292
13	32.75	98.25	697	623	2269	681	610	2240
14	72.83	218.50	1034	542	2498	994	518	2435
15	57.50	101.00	515	548	1985	501	529	1952
16	62.50	187.50	367	382	1521	345	355	1472
17	103.96	311.87	525	399	1926	491	375	1867
18	48.00	187.67	400	396	1770	380	382	1744
19	38.89	204.94	668	450	1898	634	428	1843
20	37.17	116.67	320	466	1766	308	448	1737
21	42.50	127.50	363	477	1758	351	460	1729
22	82.33	65.34	350	416	1812	346	407	1795
23	67.83	203.50	563	551	2175	535	528	2122
24	63.00	167.37	457	463	1886	435	443	1843
25	154.16	153.84	498	421	1926	477	399	1803
26	137.50	196.17	428	498	1911	410	477	1873
27	30.19	90.57	352	448	1861	343	434	1839
28	54.07	127.50	278	289	1414	261	273	1385
29	89.92	269.75	546	578	2057	505	538	1976
30	62.21	186.63	291	309	1530	273	287	1489
32	23.25	69.75	354	401	1722	344	392	1703
33	96.84	75.00	314	318	1555	302	298	1521
34	65.04	195.13	371	454	1598	352	424	1549
36	60.96	186.63	395	465	1959	379	451	1928
37	109.34	355.99	499	558	1968	467	525	1903
38	202.97	127.09	551	585	1928	527	551	1869
39	58.88	128.88	463	452	1888	460	453	1886
40	78.07	328.52	679	421	1943	639	395	1876
42	40.08	182.87	392	439	1881	375	421	1846
43	38.00	99.00	292	400	1620	277	377	1581

From Table 8.2, we observe that the % cooling and heating energy wastage from duct leakage (100 x (Energy Use with Measured Duct Leakage in $-Energy Use with Zero Duct Leakage in $)/ (Energy Use with Zero Duct Leakage in $)) are very low as compared to % duct leakage ((return duct leakage + supply duct leakage) / (air flow through the system)). For example homes 1, 2, 4 and 5 with duct leakage ranging from 20% to 23% have % cooling and heating energy wastage in the range of 3% to 7%. These results are very low compared to results found in similar studies done by [64] and [65].

Table 8-2. Energy wastage due to duct leakage from REM/Rate™

	Energy Use w/ measured duct leakage Light & Appliances set as indicated in $			Energy Use w/ duct leakage set = 0 Light & Appliances set as indicated in $			% Duct Leakage using Nominal Blower Flow	% Cooling & Heating Energy Waste from Duct Leakage	Wastage due to Duct Leakage in $
	Using REM/Rate 12.2			Using REM/Rate 12.2					
1	432	447	1754	401	420	1696	24%	7%	58
2	460	735	2453	444	716	2419	23%	3%	34
4	192	383	1322	186	365	1298	20%	4%	24
5	985	567	2354	958	547	2307	15%	3%	47
6	283	299	1354	278	289	1339	8%	3%	15
7	781	422	2369	754	408	2329	24%	4%	40
9	600	337	1861	585	325	1834	17%	3%	27
10	627	289	1688	597	272	1640	13%	5%	48
11	782	510	2231	759	487	2185	19%	4%	46
12	633	644	2335	611	624	2292	34%	3%	43
13	697	623	2269	681	610	2240	8%	2%	29
14	1034	542	2498	994	518	2435	18%	4%	63
15	515	548	1985	501	529	1952	13%	3%	33
16	367	382	1521	345	355	1472	21%	7%	49
17	525	399	1926	491	375	1867	26%	7%	59
18	400	396	1770	380	382	1744	12%	4%	26
19	668	450	1898	634	428	1843	15%	5%	55
20	320	466	1766	308	448	1737	10%	4%	29
21	363	477	1758	351	460	1729	11%	4%	29
22	350	416	1812	346	407	1795	8%	2%	17
23	563	551	2175	535	528	2122	14%	5%	53
24	457	463	1886	435	443	1843	14%	5%	43
25	498	421	1926	477	399	1803	15%	5%	123
26	428	498	1911	410	477	1873	17%	4%	38
27	352	448	1861	343	434	1839	8%	3%	22
28	278	289	1414	261	273	1385	18%	6%	29
29	546	578	2057	505	538	1976	22%	8%	81
30	291	309	1530	273	287	1489	18%	7%	41
32	354	401	1722	344	392	1703	8%	3%	19
33	314	318	1555	302	298	1521	14%	5%	34
34	371	454	1598	352	424	1549	26%	6%	49
36	395	465	1959	379	451	1928	12%	4%	31
37	499	558	1968	467	525	1903	29%	7%	65
38	551	585	1928	527	551	1869	21%	5%	59
39	463	452	1888	460	453	1886	15%	0%	2
40	679	421	1943	639	395	1876	34%	6%	67
42	392	439	1881	375	421	1846	8%	4%	35
43	292	400	1620	277	377	1581	9%	6%	39
Ave								5%	52

The airflow through the homes HVAC blower is generally taken to be a reasonable estimate of the system flow in normal operating conditions**.** As noted in our discussion of the latent heat contribution in Figure 8.1 the % energy loss due to duct leakage should be much greater than the % duct leakage. This expectation is not satisfied in Table 8.2.

In many houses in the Southern Unites States, cooling equipment and/or air distribution or return ducts are located in the attic, or in spaces connected to the attic. Thus, as ducts are not usually air tight, the return duct leakage to the outside causes attic air to be drawn into the return plenum, and thus into the duct system by the blower motor. “In these climates, the outside air is much more humid than the inside air, which is cooled and dehumidified by air conditioning. In such climates, attic venting tends to increase rather than reduce moisture levels in the attic. Air conditioning ducts are commonly located in the attic space, and attic ventilation with humid outdoor air may therefore increase the danger of condensation on these ducts. When the ceiling is not airtight, attic ventilation may also increase the latent cooling load in the building” [66]. Thus, the cooling load on the building will be greater than just the sensible load. Therefore the percentage of the energy lost to duct leakage should be greater than the percentage of air loss due to duct leakage. As REM/Rate^{TM} frequently gives a lower percentage of energy loss due to duct leakage than the percentage of air loss itself, we decided to specifically investigate the results for the energy used by a home without duct leakage, as given by REM/Rate^{TM} 12, with that given by REM/Rate^{TM} 12 for a home with duct leakage. Our comparison model is the energy difference the air conditioning system would have to provide on the assumption that the air lost was replaced by air from the attic. In most of the homes the replacement air for return leaks is generally from the attic and for supply leaks from the outside. From Chapter Five, we found that return leaks contribute 26% of the duct leakage which means that 74% of the duct leakage is from the supply. For the temperatures in the attic and the outside of the home we used temperatures from the study titled “Roof Temperature Histories in Matched Attics in Mississippi and Wisconsin” [67]. The study in Mississippi showed that when the outside temperature was 95° F, the attic temperature was at 129.2° F. However the outside temperature varies throughout the day. Thus, we will use an average temperature, conservatively taken to be 86°, wherein the attic temperature can then, from the above quoted study, be taken to be 104°.

We will assume that the air conditioner is running when the outside air is 77° or greater. The study titled “Roof Temperature Histories in Matched Attics in Mississippi and Wisconsin” recorded data collected over a four-year period and hence all the numbers are averaged over the four years. It found that annually in Mississippi there were 1193, 783, and 176 hours for outside temperatures 77°, 86° and 104° F respectively. The number of hours corresponding to outside temperatures 77°, 86°, and 104° was then summed to get 2152 hours (1193+783+176=2152). Thus, we will assume that the air conditioner runs about 2152 hours with the average outside temperature of 86° F. It is reasonable to assume that these hours correspond the hours when the attic air is the hottest. The average attic temperature recorded for 104° F from the above study in Mississippi was for 639 + 494 + 507 + 398 + 130 + 2 = 2143 hours. Table 8.3 shows the conservative assumptions of temperature and relative humidity in this approach assuming that the cooling system has, almost all of the time, sufficient over-capacity compared to the load. The Humidity Ratio of air is the ratio between the actual mass of water vapor present in moist air to the mass of the dry air. In the table, it is expressed as pounds of moisture per pound of dry air.

Table 8-3. Conservative assumptions of temperature and relative humidity for cooling season.

	Temperature	Relative Humidity	Humidity Ratio	Enthalpy
Supply Air	65	1.00	0.01604	30.0021
Return Air	80	0.60	0.01604	33.6260
Ambient (outside)	86	0.60	0.01604	38.2728
Attic	104	0.40	0.01604	45.6348

Table 8.4 shows the air conditioner distribution efficiency with respect to % duct leakage in a cooling season assuming that 76% of leakage comes from outside air (supply leaks) and 24% of the leakage comes from attic (return leaks). The enthalpy at 0% duct leakage is the difference between the enthalpy of the return air and the supply air (Table 8.4). At 0% duct leakage, by this definition we have 100% air conditioning distribution efficiency, which is presented as 1 in Table 8.4.

Table 8-4. Air conditioner efficiency and % duct leakage for the cooling season.

% Duct Leakage	Enthalpy Removed	AC Distribution Efficiency
0	3.62	1.00
5	2.93	0.81
10	2.24	0.62
15	1.54	0.43
20	0.85	0.23
25	0.16	0.04
30	-0.54	-0.15
35	-1.23	-0.34
40	-1.92	-0.53

For 5% duct leakage, we calculate the enthalpy as the difference between the enthalpy of the return air and the enthalpy of the actual air in the ducts–namely the summation of 0.95 times the enthalpy of the supply air and 0.05 times the enthalpy of the replacement air; namely in the ducts resulting from the supply and the return leakage (33.626-0.95 x 30–0.05 {38.272 x 0.76 + 45.634 x 0.24} = 2.93). The enthalpy of this replaced air is the summation of 0.76 times the enthalpy of outside air (supply leaks) and 0.24 times the enthalpy of attic air (return leaks). The corresponding air conditioning distribution efficiency is the ratios of enthalpy at 5% to enthalpy at 0% (2.93/3.62 =0.81). In similar way, we calculate the air conditioning efficiency for all the % duct leakage.

During the heating season, the study in Mississippi homes showed that an average outside low temperature of 40° F for the heating season. Therefore, it is reasonable to consider the average heating temperature to be near 50° F. Since heat rises from a conditioned home into its attic, and since attics are heated by solar radiation, we will take the attic to average 55° F.

Tables 8.5 and 8.6 shows the conservative assumptions and related calculations for heating distribution efficiency with respect to % duct leakage. The calculations are similar to that as the cooling season. For 5% duct leakage, we calculate the enthalpy as the difference between the enthalpy of supply air and the summation of 0.95 times the enthalpy of return air and 0.05 times the enthalpy of the replacement air (27.512-0.95 x 20.231–0.05 {17.764 x 0.76 + 18.953 x 0.24}

= 6.81). The corresponding heating distribution efficiency is the ratios of the enthalpy at 5% to the enthalpy at 0% (6.81/7.28 =0.94). In similar way, we calculate the heating distribution efficiency for all the %duct leakage.

Table 8-5. Conservative assumptions of temperature and relative humidity for heating season

	Temperature	Relative Humidity	Humidity Ratio	Enthalpy
Supply Air	90	0.18	0.005352	27.512
Return Air	60	0.49	0.005352	20.232
Ambient	50	0.70	0.005352	17.764
Attic	55	0.58	0.005352	18.953

Table 8-6. Air conditioner efficiency and % duct leakage for heating season.

% Duct Leakage	Enthalpy Removed	Heating Distribution Efficiency
0	7.28	1.00
5	6.81	0.94
10	6.33	0.87
15	5.86	0.81
20	5.39	0.74
25	4.91	0.68
30	4.44	0.61
35	3.97	0.55
40	3.50	0.48

The air conditioning distribution efficiency and heating distribution efficiency for the respective % duct leakage values are presented in Tables 8.4 and 8.6. The % change in cooling distribution efficiency is a direct indicator of the % change in the energy needed for cooling due to duct leakage. From Tables 8.4 and 8.6, we observe that at 10% duct leakage the % wastage in cooling and heating distribution efficiency is 38% and 13% respectively. Almost all the homes tested in this study have % duct leakage above 10%. Comparing the % wastage in heating and cooling results from REM/Rate^{TM}, we see that the numbers are much smaller than expected. This small difference suggests that there is an inherent error in REM/Rate^{TM}'s calculation of energy wastage as it does not appropriately account for temperature and humidity. Table 8.7 depicts the comparison results for the first four homes.

In Table 8.7, the drop in air conditioning distribution efficiency and heating distribution efficiency for the respective % duct leakage values are obtained from Tables 8.4 and 8.6 (1-cooling distribution efficiency/heating distribution efficiency). For home number one, we determine the drop in AC distribution efficiency to be 1-0.23 = 0.77 and the drop in heating distribution efficiency to be 1-0.74 = 0.26. Note that we have rounded the % duct leakage to the nearest values as determined in Tables 8.4 and 8.6. The cooling cost in dollars for the drop in efficiency is calculated using cooling costs at zero duct leakage to the outside obtained (from REM/Rate^{TM}) from Table 8.2. For home number one, the cooling cost is obtained my multiplying, 1.77 by 420 (cooling cost at zero duct leakage from Table 8.2), which is equal to 743. The cooling cost as well as the heating cost is obtained in the similar way for all the four homes.

Table 8-7. Comparison of REM/Rate™ and the Conservative Model.

Home No	%Duct Leak Considered	Drop in AC distribution Efficiency	Cooling Cost in $	%Change in Cooling Cost	Drop in Heating Distribution Efficiency	Heating Cost in $	%Change in Heating Cost
1	20	0.77	743.40	66.31%	0.26	505.26	16.96%
2	20	0.77	1267.32	72.42%	0.26	559.44	21.62%
3	20	0.77	646.05	68.68%	0.26	234.36	22.06%
4	15	0.57	858.79	51.46%	0.19	1140.02	15.74%

The % change in cooling costs and heating costs with respect to REM/Rate^{TM} is also presented in Table 8.7. From Table 8.7, the differences in cooling cost vary by 50% and the heating costs vary by 15%. These high variations in results suggest that there are inherent inaccuracies associated with REM/Rate^{TM}'s calculation of energy costs.

We further investigated the results obtained from REM/Rate^{TM} for two simple conditions–first by setting the return leak to zero and varying the supply leaks, and second by setting the supply leaks to zero and varying the return leaks. The output for the above runs is presented in Table 8.8.

Table 8-8. REM/Rate™ results for varying supply and return leaks.

Supply	Return	Duct Leakage	Heating	Cooling	Heating	Cooling	*Heating*	*Cooling*	Remarks	Capacity	*Supply*	*Return*
cfm			***MMBTU /yr***		***$***		**% Change in Energy**				**%Leakage**	
0	0	0	31.3	11.6	278	289	0.00	0.00		1600	0.00	0
100	0	100	32.1	11.8	285	295	2.56	1.72		1600	6.25	0
500	0	500	34.7	12.7	309	317	10.86	9.48		1600	31.25	0
1000	0	1000	36.7	13.5	326	337	17.25	16.38		1600	62.50	0
1200	0	1200	37.2	13.7	331	343	18.85	18.10		1600	75.00	0
1600	0	1600	38	14	337	351	21.41	20.69	Warnings	1600	100.00	0
0	0	0	31.3	11.6	278	289	0.00	0.00		1600	0	0.00
0	100	100	31.8	12	282	300	1.60	3.45		1600	0	6.25
0	500	500	33.5	13.3	297	332	7.03	14.66		1600	0	31.25
0	1000	1000	34.7	14	308	349	10.86	20.69	Warnings	1600	0	62.50
0	1200	1200	35	14.3	311	358	11.82	23.28	Warnings	1600	0	75.00
0	1600	1600	35.5	13.4	315	334	13.42	15.52	Warnings	1600	0	100.00

Figures 8.2 and 8.3 show the plots for the % supply leakage and return leakage with % change in energy consumption respectively. From Figure 8.2, we see that at 100% supply leak there is only an approximate 21% change in heating as well as cooling energy. A 100% supply leak theoretically means that there is no air being delivered from the supply registers at all. If ducts are in the attic-which is the case in the most homes tested-then the conditioned air is leaked into the attic.

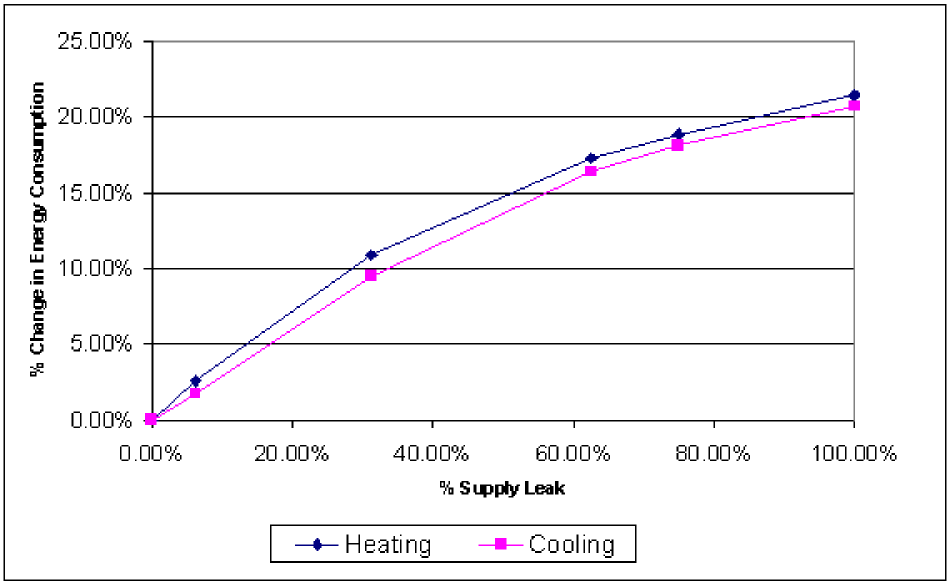


Figure 8-2. % Supply leak vs. % change in energy consumption.

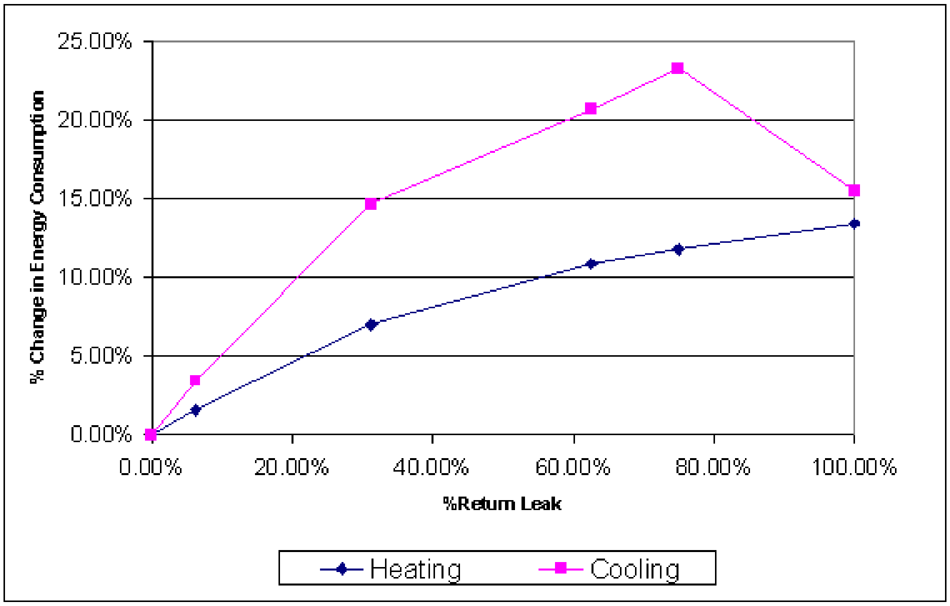


Figure 8-3. % Return leak vs. % change in energy consumption.

In the case of return leaks, from Figure 8.3 we observe that at 80% return leakage, there is only about a 23% change in energy consumption in the case of cooling where as in the case of heating it is only about a 12% change. Return leaks generally draw attic air from the attic to the conditioned space. In summer months, the attic air is hot and humid and can reach up to 140° F and the energy required in maintaining the set temperature in the home is directly proportional to the differences between these two temperatures and to the moisture content; or in more scientific terms, to the relative enthalpy. Also, from Figure 8.3, we observe that in cooling, the change in energy consumption decreases to 16% at 100% return duct leakage from 24% at 80% return duct leakage. This decrease in energy consumption is inconsistent with physical principles. Note that REM/Rate^{TM} outputs a warning message in certain cases as shown in Table 8.3. However, the low values associated with percent change in energy for higher duct leakage are unphysical. To accurately measure the energy wastage due to duct leakage, we employed the ASHRAE^{TM} 152 standard in combination with REM/Rate^{TM}, which is described in Section 8.2.

8.2 ASHRAETM 152 STANDARD

The ASHRAE^{TM} Standard 152 (ASHRAE 2004) "Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems" is a method of estimating the efficiency of HVAC energy distribution in residential buildings [54]. The standard quantifies how much energy and HVAC equipment capacity duct leaks actually waste [54]. The main objective of our study is to determine the dollar energy wastage due to duct leakage.

ASHRAE^{TM} Standard 152 was developed to provide a means for rating the performance of different thermal distribution systems. The primary inputs for rating a duct system include:

- Duct leakage (supply and return)
- Duct location (e.g., attic, crawlspace, basement)
- Duct insulation level (e.g.R1, R4.2, R2)
- House location (from a list of cities); and
- HVAC equipment characteristics (type, capacity, fan flow).

The ASHRAE^{TM}152 standard outputs two measures of the distribution system's ability to cool/heat a home.

1. Delivery Effectiveness (DE): is the ratio of the thermal energy transferred to or from the conditioned space to the thermal energy transferred at the equipment distribution system heat exchanger. Delivery Effectiveness is the ratio of energy that enters the house through the registers to the energy put into the distribution system by the heating or cooling equipment.
2. 2Distribution System Efficiency (DSE): is the ratio between the energy consumption by the equipment if the distribution system had no losses (gains for cooling) to the outdoors or effect on the equipment or building loads and the energy consumed by the same equipment connected to the distribution system under test.

To discern the differences, DE measures the percentage of the cooling/heating produced by the HVAC unit that gets into the home where as DSE measures the ratio of energy used by the system when there are no losses to that when there are losses. Therefore, the DSE is degraded by increases in cooling/heating load or decreases in equipment efficiency where as neither of these are influential on delivery effectiveness.

Based upon the inputs, Standard 152 first calculates the fraction of the conditioned air produced by the HVAC equipment that is delivered at the supply registers. The standard calculates this fraction, called the delivery effectiveness, using fixed algorithms to calculate the temperatures in each duct zone using the local climate conditions [54].

The local climate conditions are ASHRAE Handbook design values for the design efficiencies, while the seasonal climate conditions are based upon load-weighted seasonal averages of hour-by-hour climate data. Standard 152 then calculates the overall distribution efficiency, adjusting the delivery effectiveness by the fraction of energy losses that are recovered into the conditioned space. The regain factors are based upon the ratio of the thermal conductance between the duct zone and the conditioned space, to the overall thermal conductance of the duct zone. Typical regain values are 10% for a vented attic, 50% for an uninsulated basement, 75% for a basement with insulated walls, and 30% for a basement with an insulated ceiling [54].

The details of the ASHRAE™ 152 standard can be found in "Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems," ANSI/ASHRAE 152-2004. The input data collected for our study using ASHRAE™ 152 are as follows:

1. Location Index: The location index input is an important input as it inputs the design and seasonal temperatures, humidity and enthalpy values depending on the city.
2. Conditioned floor area: This the area of the home conditioned by the HVAC unit in square feet.
3. Number of return registers: This is the number of return registers installed in a home under test.
4. House volume: This is the volume of the house conditioned in cubic feet.
5. Supply duct and return duct surface area: Both these values are entered with the same values obtained from the default values used to obtain the building loads using REM/Rate™ output.
6. Equipment Heating Capacity: These are the values collected from individual HVAC units in Btu/hour.
7. Equipment Cooling Capacity: These are the values collected from individual condensing units in Btu/hour.
8. Heating Fan Flow: This value is the airflow when the fan operates in the heating mode.
9. Cooling Fan Flow: This value is the airflow when the fan operates in the cooling mode.
10. Heating/Cooling supply duct leakage: This is the supply duct leakage in the heating/cooling mode at 25Pa. These values were obtained as described in Chapter Six.
11. Heating/Cooling return duct leakage: This is the return duct leakage in the heating/cooling mode at 25Pa. These values were obtained as described in Chapter Five.
12. Duct Thermal Mass Correction: This is normally the default correction incorporated for insulation levels depending on metal or flex ducts.
13. Vented Attic: Enter V for vented attic or U for unvented attic. This parameter sets the default used by the code for determining the temperature and humidity levels in the attic.

The output includes DE and DSE for both heating and cooling modes. Our objective was to determine the unnecessary wastage associated with duct leakage. Therefore, the distribution system efficiency is the relevant output in our study as it measures the ratio between the energy consumption by the equipment if the distribution system had zero losses to the outdoors or effect on the equipment or building loads and the energy consumed by the actual equipment tested.

8.3 ENERGY WASTAGE DUE TO DUCT LEAKAGE

Energy wastage from duct leakage was calculated for homes both in North Louisiana and in New Orleans. The data for South Louisiana was used from home tests performed in New Orleans by Dr. Katz. The energy wastage from duct leakage from these two regions will enable us to generalize a better estimate the energy wastage due to duct leakage for the entire State of Louisiana than using data only from North Louisiana. The flow chart in Figure 8.4 shows the methodology involved in estimating the unnecessary cost associated with duct leakage. The calculation involves the combined use of REM/Rate^{TM} and the ASHRAE^{TM} 152 standard.

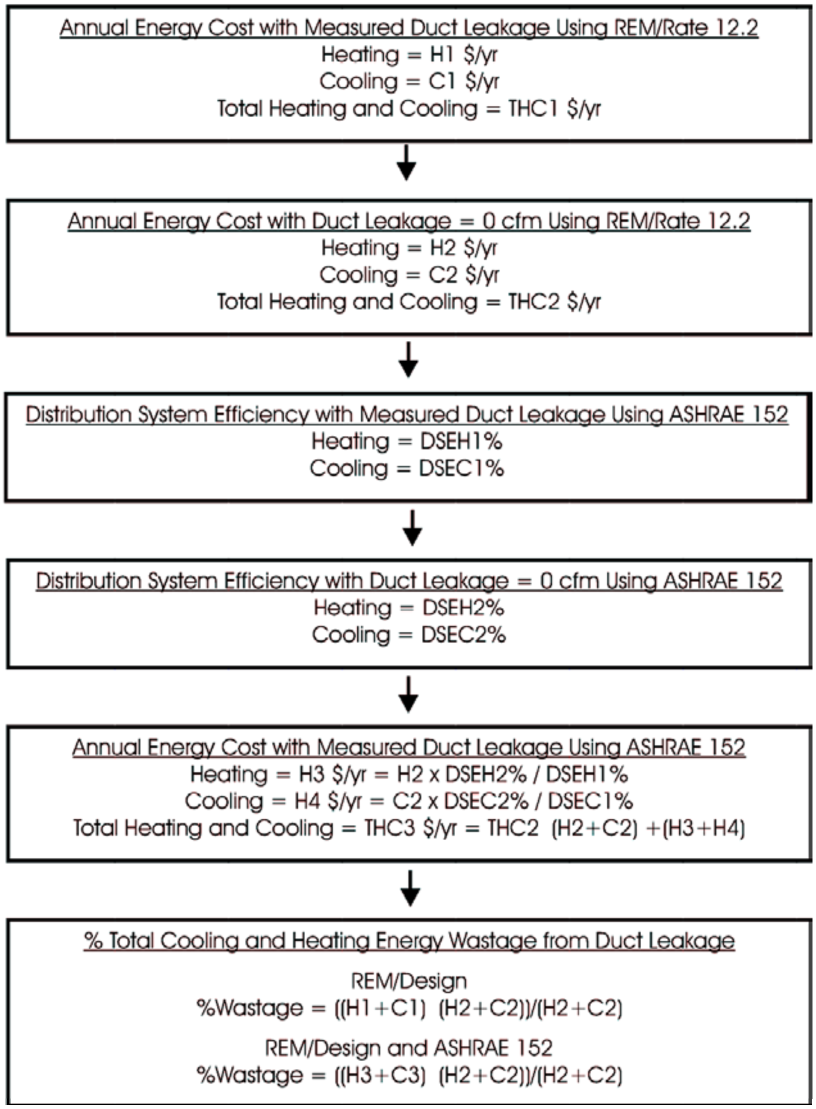


Figure 8-4. Flow chart for calculating % energy wastage from duct leakage.

The calculated values using the methodology described in Figure 8.4 is presented in Table 8.9. From Table 8.2, the average % cooling and heating energy waste for an individual home from duct leakage obtained from REM/Rate$^{\text{TM}}$ is 5% with an average annual duct leakage associated cost equal to $52.

Table 8.9 Energy wastage from duct leakage from ASHRAE™ 152 and REM/Rate™

	Energy Use w/ measured duct leakage Light & Appliances set as indicated in $			Energy Use w/ duct leakage set = 0 Light & Appliances set as indicated in $			% Duct Leakage using Nominal Blower Flow	% Cooling & Heating Energy Waste from Duct Leakage	Wastage due to Duct Leakage in $
	Calculation from the ASHRAE 152 Distribution System Efficiency			Using REM/Rate 12.2 with Duct Leakage = 0					
1	713	749	2337	401	420	1696	24%	78%	641
2	623	991	2874	444	716	2419	23%	39%	455
4	226	455	1428	186	365	1298	20%	24%	130
5	1209	707	2717	958	547	2307	15%	27%	410
6	300	323	1395	278	289	1339	8%	10%	56
7	1118	631	2915	754	408	2329	24%	50%	586
9	672	406	2003	585	325	1834	17%	19%	169
10	813	391	1975	597	272	1640	13%	39%	335
11	961	632	2531	759	487	2185	19%	28%	346
12	786	797	2639	611	624	2292	34%	28%	347
13	760	687	2396	681	610	2240	8%	12%	156
14	1343	711	2977	994	518	2435	18%	36%	542
15	590	563	2074	501	529	1952	13%	12%	122
16	487	549	1807	345	355	1472	21%	48%	335
17	780	601	2382	491	375	1867	26%	59%	515
18	463	468	1913	380	382	1744	12%	22%	169
19	835	568	2185	634	428	1843	15%	32%	342
20	358	517	1856	308	448	1737	10%	16%	119
21	415	540	1873	351	460	1729	11%	18%	144
22	364	449	1855	346	407	1795	8%	8%	60
23	663	650	2372	535	528	2122	14%	24%	250
24	498	526	1990	435	443	1843	14%	17%	147
25	560	492	1978	477	399	1803	15%	20%	175
26	509	602	2097	410	477	1873	17%	25%	224
27	383	487	1932	343	434	1839	8%	12%	93
28	316	338	1505	261	273	1385	18%	22%	120
29	720	812	2465	505	538	1976	22%	47%	489
30	374	386	1688	273	287	1489	18%	36%	199
32	391	442	1800	344	392	1703	8%	13%	97
33	342	356	1619	302	298	1521	14%	16%	98
34	525	601	1898	352	424	1549	26%	45%	349
36	458	547	2103	379	451	1928	12%	21%	175
37	769	945	2625	467	525	1903	29%	73%	722
38	605	711	2106	527	551	1869	21%	22%	237
39	579	565	2116	460	453	1886	15%	25%	230
40	1118	790	2750	639	395	1876	34%	85%	874
42	426	483	1958	375	421	1846	8%	14%	112
43	308	429	1664	277	377	1581	9%	13%	83
Average							17%	30%	280

Applying ASHRAE^{TM} 152 as described in flow chart (Figure 8.4), with energy cost at duct leakage equal to zero obtained from REM/Rate^{TM}, we obtain average % cooling and heating energy waste for an individual home to be 30% with average annual duct leakage associated cost equal to $280. Comparing Tables 8.2 and 8.8, there is no doubt that there are significant differences between the output results of REM/Rate^{TM} and ASHRAE^{TM} 152 results. However, ASHRAE^{TM} 152 standard is the presently accepted standard in the HVAC industry [66]. The accuracy of ASHRAE^{TM} 152 standard lies in the fact that it determines the distribution efficiency, which is directly related to duct leaks. Duct leaks affect the distribution efficiency– higher the duct leaks lower the distribution efficiency.

8.4 PROJECTING ENERGY WASTAGE FOR LOUISIANA

The energy wastage due to duct leakage for New Orleans was determined the same way as was for North Louisiana but it should be noted that we had a smaller sample from New Orleans. The energy wastage due to heating and cooling are presented in Table 8.10.

Table 8-10. Energy wastage from duct leakage from ASHRAE™ 152 and REM/Rate™ for New Orleans.

	Energy Use w/ measured duct leakage Light & Appliances set as indicated in $			Energy Use w/ duct leakage set = 0 Light & Appliances set as indicated in $			% Duct Leakage using Nominal Blower Flow	% Cooling & Heating Energy Waste from Duct Leakage	Wastage due to Duct Leakage in $
	Calculation from the ASHRAE 152 Distribution System Efficiency			Using REM/Rate 12.2 with Duct Leakage = 0					
1	1692	2021	4463	1011	1100	2861	46%	75.90%	1602
2	785	719	1981	671	618	1766.00	13%	16.67%	215
3	884	1250	2992	522	740	2120.00	11%	69.10%	872
4	375	1317	2248	285	984	1824.00	17%	33.38%	424
5	649	2886	4135	430	1791	2822.00	20%	59.13%	1313
6	295	827	1771	209	496	1354.00	24%	59%	417
7	899	2138	3681	660	1486	2790.00	80%	41.51%	891
Average							22%	52%	753

From Tables 8.9 and 8.10, we see that the % energy wastage is higher in New Orleans than North Louisiana. To project the energy savings for the State of Louisiana, we compared the homes sampled in North Louisiana and New Orleans based on conditioned area. The comparative result is presented in Table 8.10.

From Table 8.11, homes with conditioned area about 1400 sq. ft. have nearly same % energy wastage for North Louisiana and New Orleans. However, larger standard deviations in the case of New Orleans are due to a smaller sample size. Comparing homes with conditioned area of about 1700 sq. ft., and 3000 sq. ft., we see that New Orleans have a higher % energy change. The comparison may not be justifiable because of the small sample size in the case of New Orleans but for the purpose of projecting energy wastage due to duct leakage, we can conservatively assume that homes in the State of Louisiana are representative of homes in North Louisiana. The main reason for the sample being conservative is that homes in New Orleans generally have higher duct leakage values compared to North Louisiana.

Table 8-9. Comparison of % energy wastage-North Louisiana vs. New Orleans.

	North Louisiana			New Orleans		
	Area sq. ft.	**%Energy Wastage**	**%Duct Leakage**	**Area sq. ft.**	**%Energy Wastage**	**%Duct Leakage**
	1333	26.01%	18.02%	1304	59%	23.92%
	1370	29.81%	20.00%	1437	16.67%	13.33%
	1439	44.60%	13.00%	1416	33.38%	16.92%
	1445	37.13%	15.24%	1458	49.04%	23.86%
	1458	57.67%	20.83%			
Average	1409	39.05%	17.42%	1404	39.56%	19.51%
Standard Deviation	54	8%	3.08%	69	19%	5.27%
	1500	10.93%	8.25%	1546	59.13%	19.56%
	1548	30.36%	15.38%	1877	75.90%	45.83%
	1550	73.75%	26.02%			
	1600	19.08%	14.32%			
	1648	42.02%	17.77%			
	1674	31.96%	18.50%			
	1789	15.40%	7.75%			
	1850	19.65%	9.61%			
	1950	14.16%	9%			
Average	1679	28.59%	14.02%	1712	67.52%	32.70%
Standard Deviation	122.53	20.23%	6.19%	234	11.86%	18.58%
	2800	25.67%	12.19%	2939	69.10%	10.92%
	3593	57.12%	22.63%			
Average	3197	41.40%	17.41%	2939	69.10%	10.92%
Standard Deviation	560.74	22.24%	7.38%	-	-	-

The census data for Louisiana indicates that there are 1,656,053 households in Louisiana [67]. Of these households, 1-unit detached homes constitute 64.1% whereas 1-unit attached and 2-unit homes constitute 3.8% and 4% respectively. Of these 1,656,053 households only 79% of them have centralized air conditioners [68] meaning to say that only 1,308,282 households had centralized air conditioners. According to U.S. Census 1-unit structure is a housing unit detached from any other house; that is, with open space on all four sides. Table 8.12 shows respective breakdown of household with respect to with respect to units and the associated cost. Note that the average wastage of energy in dollars is taken to be $280 for all the units presented in Table 8.12. This average value of $280 was obtained from Table 8.9. There is not sufficient data to consider all the other types of units in this projection (more than 2 units, boat, mobile homes). Therefore, the actual wastage due to duct leakage will be much higher than the estimate made by this study, because the remaining 35.9% of the housing units have not been accounted in this projection. However, the projected annual energy cost due to duct leakage for the respective units considered in Table 8.12.was determined to be $263,383,306.

Table 8-10. Projected energy wastage for Louisiana due to duct leakage.

Units	Percent	Households	Energy Wastage in $
1-unit, detached	64.1	838608.6787	234810430.00
1-unit, attached	3.80	49714.7110	13920119.10
2 units	4.00	52331.2748	14652756.94
Average			263383306.10

The average annual savings of $280 for the homeowner by sealing duct leaks will be very beneficial. In addition, the State of Louisiana can save more than $263,383,306 annually by sealing duct leaks in residential homes. Therefore, sealing ducts cost-effectively is very important especially for the State of Louisiana, which has hot and humid summers. Chapter Nine presents the feasibility tests of one such sealing technique for sealing duct leaks in laboratory conditions.

9.0 PROPOSED RESIDENTIAL DUCT SEALING TECHNOLOGY–A FEASIBILITY STUDY

9.1 INTRODUCTION

The third part of this study is developing a sealing technology that can internally seal leaks in duct systems. To address this topic, a new duct sealing technology was developed. To determine the efficacy of this new technology, it was necessary to:

1. Assess the overall efficacy of this method by determining the before and after duct-leakage in the system.
2. Assess which types of leaks/components are/are not suitable to sealing by this method.

A feasibility study in developing the new duct sealing technology was conducted in our laboratory at Louisiana Tech University. As various technologies for sealing water leaks have been developed, we thought that an investigation of these technologies would prove useful. Originally we considered using an epoxy sealing technology that has proven itself in sealing water pipe leaks. After problems developed with a commercial supplier we decided to further investigate leak-sealing technology. We had found that spraying epoxy required expensive and heavy equipment due to the high viscosity of epoxy, and the need to spray the two components together, mixing them at the spray nozzle. The strength of epoxy is needed in water pipes due to the high pressure, whereas in air ducts, the pressure is fairly low, and thus a less robust compound can be utilized. Therefore, we investigated alternative commercially available sealants as possible candidates to solve this problem. We found a technology that has been used commercially for many years for coating metal (and in doing so, sealing minor water leaks) in various applications including food-processing equipment. This technology was investigated in detail for sealing air leaks, and the initial results seemed to be very promising. Thus, we devised a formal testing program, with the goal of cost-effectively sealing duct leaks with a material that was relatively safe to apply, non-toxic in use, and mold resistant. The above objectives were addressed in this feasibility study and the preliminary results are presented below.

9.2 FEASIBILITY STUDY

The feasibility study was performed in three different phases based on the material to be sealed and the point of application of the sealant. The sealant technology under investigation was applied to the following:

1. External Sealing of a Wooden Box: to determine the efficacy of the sealant in sealing a home's return plenum: As almost all homes have a wooden return plenum, a wooden box with holes and gaps was tested to determine the efficacy of this methodology in sealing those holes and gaps. Chapter Five has shown that there can be significant leaks in the return plenums of homes. Holes and gaps in the return plenum are the cause of such leaks and these leaks draw in unconditioned (in the summer–hot and humid) air from the attic. Therefore, the sealant technology was used to test its efficacy in sealing the wooden box.
2. External Sealing of Metal Ducts: Metal ducts were sealed externally with the sealant applied by means of a paintbrush. The ducts were sealed at the registers, joints and seam. The main

purpose of this study was to determine the efficacy of the technology before proceeding to the more difficult internal sealing problem. In addition, the technology is an alternative to the use of mastic to externally sealing ducts externally at registers, joints and along the seam, before applying insulation.

3. Internal Sealing of Metal Ducts: Metal ducts were sealed internally with the sealant applied using both a paintbrush and a cotton mop. The ducts were sealed at the same locations as those in the external study. The main objective of this phase of the study was to determine the efficacy of internal sealing, and to compare it with the external sealing results.

9.3 LABORATORY EXPERIMENTS

The sealant technology chosen was used in all of the three studies indicated above. Air leakage in cubic feet per minute (cfm) was measured using the Energy Conservancy Minneapolis Duct Blaster^{TM} following the application of the sealant. The results of these tests are shown in the following sections.

9.3.1 External Sealing of Wooden Box

A wooden box was constructed with a register as shown in Figures 9.1 to 9.4. Holes of varying diameters 0.078”, 0.104”, 0.144”, 0.193”, 0.201” and 0.228” were drilled as shown in Figure 9.1. In addition, gaps of less than 0.25” were made along the edges of the wooden box as shown in Figure 9.2. These holes and gaps were introduced to check the effectiveness of the sealant technology. The leaks prior to sealing were measured using the Duct Blaster^{TM}. After measuring the leakage rate, the sealing methodology was applied as shown in Figures 9.1 to 9.4. The final reading after the application was again measured using the Duct Blaster^{TM}. The difference between these initial and final readings is used to determine the efficacy of this methodology. Figures 9.3 and 9.4 show the visual aspect of the sealant methodology wherein the sealing is very effective. The results of external sealing of wooden box are shown in Table 9.1.

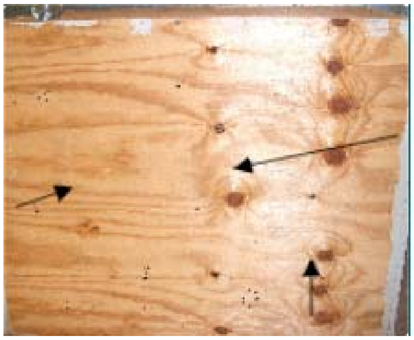


Figure 9-1. Drilled holes.

Figure 9-2. Gap along the edge.

Figure 9-3. Sealant applied on drilled holes

Figure 9-4. Sealant applied along the edges

Table 9-1. Results of external sealing of wooden box.

Readings	cfm at 15 Pa	cfm at 25 Pa
Flow before sealing	111.00	143.00
Flow after sealing	8.00	14.00
% Sealed	92.79	90.20

There is a reduction of total leakage of about 90% at 25 Pa and 93% at 15 Pa respectively, which concludes that this sealant technology does effectively seal the holes and gaps. The remaining leaks, of about 10% at 25 Pa, are mainly due to the hole created for placing the probe and the inherent inaccuracy of the measuring system at low air flows. The smoke tests performed on the wooden box confirmed the source of this leakage. As at least 91% of the leaks were sealed, the efficacy of this methodology for sealing small leaks in return plenums in residential housing has been demonstrated. In actual application, large leaks would be roughly sealed by existing methodologies, and this sealing technique would then be applied to effectively seal the return plenum.

9.3.2 External Sealing of Metal Ducts

The external sealing of metal components constitutes the second phase of this feasibility study. The steps followed in the external sealing of metal ducts are very much similar to those of sealing the wooden box described in Section 9.3.1. The only difference was that readings were measured separately at the registers, joints and seam.

Sealing registers

Registers are used to deliver the air into the house via a grille. Register boots are metal boxes, mostly insulated inside with fiberglass. Register boots contribute to duct leakage, as they are not completely sealed. Smoke tests performed in the laboratory showed air leaks through these boots. The arrowheads in Figures 9.5 and 9.6 point to the common leak sites found in register boots. A duct system of 12’ was constructed with ducts of sizes 6” and 8” in diameter with a supply register at one end.

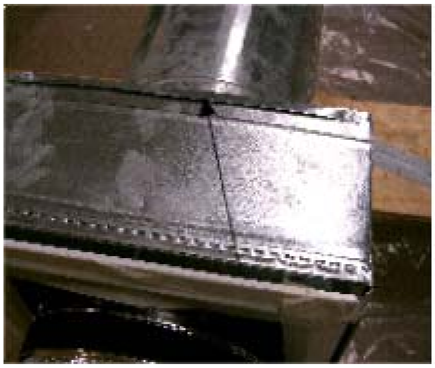


Figure 9-5. Leaks at register boot.

Figure 9-6. Leaks at register boot.

The ducts of varying size were connected using reducers. In addition, turns were provided to check for the feasibility of sealing these components. The experimental set up is shown in Figure 9.7; Figure 9.8 shows the sealant applied on the register.

Figure 9-7. Experimental set up.

Figure 9-8. Sealant applied on the register boot

The general procedure for sealing was followed but then an extra reading was taken after applying aluminized duct tape externally over the registers, which we shall assume, together with the sealing we performed, to produce a 100% leak-free seal.

From the results presented in Table 9.2, at 25 Pa, about 92% of the total existing register leaks were sealed. At 15 Pa, all the register leaks are completely sealed. Most of the houses have duct systems of varying duct sizes connected to the main trunk. The branches from the main trunk are generally smaller in diameter and end with a register at the other end. The reduction of flow from 41 cfm to 30 cfm at 25 Pa, when compared to the ideal of 29 cfm, is also an indicator that the sealant will enable sealing of the register boots externally.

Table 9-2. Results of sealing register boot externally.

Readings	cfm at 15 Pa	cfm at 25 Pa
Flow before sealing	30.00	41.00
Flow after sealing	23.00	30.00
Flow after taping	23.00	29.00
% Sealed	100.00	91.67

Sealing joints

Joints are ubiquitous in duct systems, occurring where one duct connects to another, where ducts curve, or where register boots connect to ducts. Smoke tests showed the presence of leaks at all these types of joints. The sealing procedure followed the same steps as followed in Section 9.3.1; the only difference being that the sealant was externally applied over the joints. The procedure followed was the same as that used in Section 9.3.1, and the results are presented in Table 9.3. Figures 9.9 and 9.10 depict the joints sealed using this sealing technology.

Figure 9-9. Sealant applied at joints with turns

Figure 9-10. Sealant applied at joints with registers

From Table 9.3, we can conclude that approximately 100% at 25 Pa and 83% at 15 Pa, or including experimental errors effectively all, of the total existing joint leaks can be effectively sealed. It is important to note that we are applying the sealing technology in this feasibility study to two types of joints-turns and register boot to duct. These two types of joints are presented in Figures 9.9 and 9.10.

Table 9-3. Results of sealing joints externally.

Readings	cfm at 15 Pa	cfm at 25 Pa
Flow before sealing	29.00	38.00
Flow after sealing	24.00	30.00
Flow after taping	23.00	30.00
% Sealed	83.30	100.00

Sealing seams

The ducts attain the cylindrical shape when they are snap-fitted forming a seam. Therefore, we considered the seam as a source of leakage in residential duct systems. The sealing procedure was the same as described in Section 9.3.1; the only difference being that the sealant was applied externally over the seam. Figure 9.11 shows the seam whereas Figure 9.12 shows the sealant applied over the seam.

Figure 9-11. Seam of the duct system.

Figure 9-12. Sealant applied on the seam

The results of leakage rates using Duct Blaster^{TM} after sealing the seam is presented in Table 9.4. From the results, we can see that there is negligible amount of duct leakage both at 15 and 25 Pa. The flow readings taken after sealing the seam externally with metal tape also suggest that there is no leakage at the seam.

Table 9-4. Results of sealing seam externally.

Readings	cfm at 15 Pa	cfm at 25 Pa
Flow before sealing	23.00	30.00
Flow after sealing	22.00	30.00
Flow after taping	22.00	30.00

The smoke tests performed did not show any visible leaks along the seam. Therefore, we conclude that the seams are essentially leak-free. However, that may not always be the case as there is always a possibility of damaging them while transporting or assembling them to form the duct system.

Internal Sealing of Metal Ducts

The feasibility study in the case of internal sealing of metal ducts is similar to that of external sealing as described in Section 9.3.2. The only difference being that the sealant is applied to the inner parts of the duct system using both a brush and a cotton mop. The areas of interest in this set up were turns, joints, seam and register boots.

Sealing turn/joint

A 6’ duct system was constructed with a 10” diameter duct with a register boot at one end. The experimental applied on the joints set up is shown in Figure 9.13 where as Figure 9.14. shows the sealant

Figure 9-13. Experimental set up.

Figure 9-14. Sealant applied on turns/joints.

The sealing procedure followed the same steps as followed in Section 9.3.1, the only difference being that the sealant was applied internally to the duct system. Figure 9.15 shows the application of the sealant internally in the ducts. Figure 9.16 shows that sealing the duct from inside at the register has resulted in sealant flowing outside through gaps and holes. These gaps and holes are points of leakage in residential duct systems.

Figure 9-15. Sealant applied on turns/joints.

Figure 9-16. Flow of sealant to outside

The results of leakage rates measured using Duct Blaster^{TM} are presented in Table 9.5.

The results from Table 9.5 show that at 25 Pa about 93% of the total existing leaks at the turns can be sealed via this sealing technology. On the other hand, at 15 Pa all the existing leaks are sealed at the turns.

Table 9-5. Results of sealing turns internally.

Readings	cfm at 15 Pa	cfm at 25 Pa
Flow before sealing	39.00	54.00
Flow after sealing	28.00	41.00
Flow after taping	28.00	40.00
% Sealed	100.00	92.86

Sealing register/joint

The steps for sealing the joint at the register are similar to that mentioned in Section 9.3.1. The results of the leakage rates are presented in Table 9.6. From Table 9.6, the results show that about 80% of the existing leaks at the joints can be sealed at the joints.

Table 9-6. Results of sealing joints internally.

Readings	cfm at 15 Pa	cfm at 25 Pa
Flow before sealing	28.00	40.00
Flow after sealing	22.00	32.00
Flow after taping	22.00	30.00
% Sealed	100.00	80.00

Figure 9.17 shows the joint prior to sealing where as Figure 9.18 shows the leakage spots after the sealant was applied. The arrows in the figures show the point of leakage. However, at 15 Pa, all of the existing leaks are measured to be sealed. It is important to note that the gaps were about 0.5”. Therefore, based on our experiments, we limit the applicability of this sealant to gaps of dimension less than 0.5”. Note the arrows in Figure 9.17 showing the damage to the ends of the duct. Namely the metal end is not a perfect circle, but is bent. Therefore, the gap can be too wide to seal using our current procedure. We will be testing additional sealing techniques to fix this type of problem. As of this stage, we will only state that in actual residential construction such damage, and its location, can be readily detected by internal camera inspection.

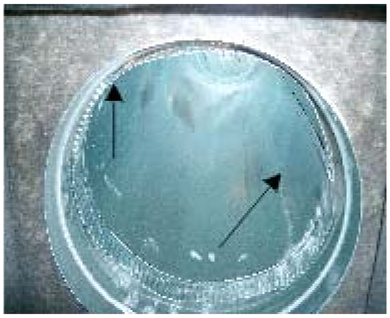


Figure 9-17. Leakage spot prior to sealing

Figure 9-18. Leakage spot after applying sealant

Sealing register boots

The register boot was sealed internally with the sealant as shown in Figures 9.19 and 9.20. The sealing methodology was similar to that followed in sealing the registers externally as described in Section 9.3.1. Many register boots have fiberglass insulation inside. Therefore, to prevent any leaks from the register, it becomes necessary to apply the sealant over the insulation to make it completely leak-proof.

Figure 9-19. Source of leaks in register.

Figure 9-20 Sealant applied on the register

The arrowheads in Figure 9.19 shows the source of leaks in the register boot whereas Figure 9.20

shows the sealant over the insulation. The results of the leak tests using the Duct Blaster™ are presented in Table 9.7. The results show that, at 25 Pa, the total existing leaks can be sealed by 88% at the registers whereas at 15 Pa, 92% of the existing leaks can be sealed. To determine where the remaining leaks occur a smoke test was performed. Small leaks were noticed at the interface of the Duct Blaster™ and the register grille. The interface region was taped and the readings were taken again. The reading at 25 Pa which is not shown in the table, was measured to be 10 cfm. This reading does not really include the effect of sealing and therefore can be ignored. It is also important to note that the Duct Blaster™ is not recommended for measuring possible leaks of this low magnitude. Thus effectively all the leaks were sealed.

Table 9-7. Results of sealing registers internally.

Readings	cfm at 15 Pa	cfm at 25 Pa
Flow before sealing	22.00	30.00
Flow after sealing	10.00	15.00
Flow after taping	9.00	13.00
% Sealed	92.31	88.3

Sealing seams

Seams were sealed internally with the help of a cotton mop. The sealing methodology followed was similar to that described in Section 9.3.3. The results presented in Table 9.8, show that the readings before and after sealing are the same. From this data, the leaks along the seam are negligible. This observation is similar to the case of sealing the seam externally as described in Section 9.3.3. However, this result may not always be the case.

Table 9-8. Results of sealing seams internally.

Readings	cfm at 15 Pa	cfm at 25 Pa
Flow before sealing	9.00	13.00
Flow after sealing	9.00	13.00
Flow after taping	9.00	13.00

9.4 CONCLUSIONS

The conclusions of this feasibility study are as follows:

1. The return plenums, made of wood, can be effectively sealed using this sealing technology, in addition to sealing the larger holes by conventional methodologies.
2. The metal ducts can be sealed externally and hence can used to seal the ducts at joints, seams, turns and register boots after the ductwork has been laid and prior to insulating the ducts.
3. The metal ducts can also be sealed internally at common points of leaks such as joints, seams, turns and register boots.
4. The sealant is effective for sealing gaps less than 0.325” (3/8”), and for sealing holes less than 0.5” (1/2”) diameter.
5. The sealant is safe to use, and, when dry, does not contain organic compounds, thus it cannot support the growth of mold**.**

10.0 FULL SCALE TESTING OF ALTERNATE SPRAY-ON SYSTEMS

10.1 INTRODUCTION

The objective of this phase in the project was to conduct an extensive experimental evaluation of the ability of the Polar Seal Prime Security and Polar Seal Top Security products to seal gaps in plywood panels that are in a horizontal, vertical or inverted position with respect to the tip of the sprayer. A secondary objective was to evaluate the effectiveness of the sprayer and various tip attachments for the task at hand. Images of the testing laboratory and shown below.

Figure 10-1. Leak Test Chamber 1

Figure 10-2. Various Test Specimens

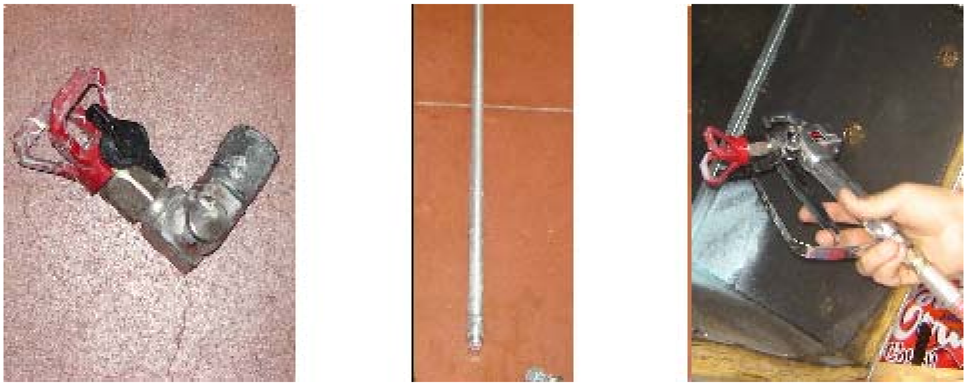
<u>Sealing Laboratory</u>

The lab consisted of a spray stand, two pressurized leak test chambers, flexible duct stand, and multiple test specimens. Multiple test specimens were created using quarter inch plywood. The specimens were cut into 12 x 24 inch sections. The spray stand was specifically constructed to hold the test specimens in three positions: inverted (ceiling), vertical (wall), and horizontal (floor). A leak test pressurized chamber was then constructed to hold the specimens for seal-leak testing.

10.2 DELIVERY SYSTEM CONSIDERATIONS

During the first phase of the experimental program the sealing material was applied using a paint brush to Leak Test Chamber 1. However, in practice, the optimal method of delivery will be spraying. A Spray Tech Airless sprayer Model EP2510 was utilized. With the high viscosity and thickness of the material, the EP2510 performance specifications were found to be adequate for the application at hand. The airless model allows for adjusting the coat thickness and spray pressure. Along with the airless sprayer, a six foot extension wand, a 90° angle adjustable spray adapter, 0.031 thousandths orifice spray tip, and an airless gun were also purchased as part of the spray delivery system.

Figure 10-3. Spray Tech Airless Sprayer

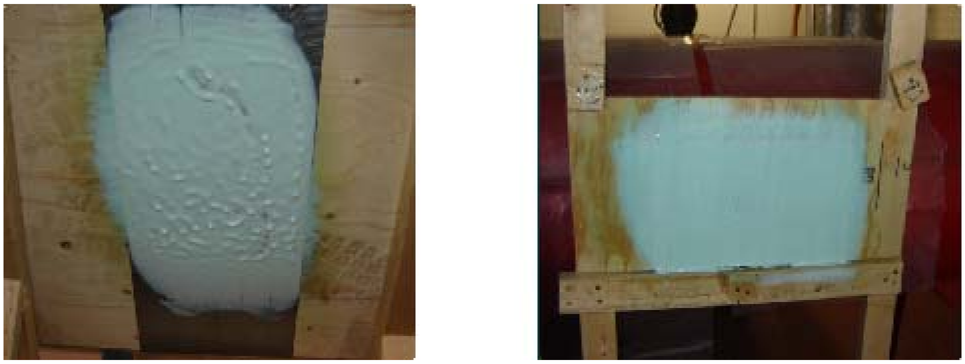


ANGLED ADAPTER EXTENSION WAND AIRLESS GUN

Figure 10-4. Components of the Spray Tech Airless Sprayer

10.3 PRELIMINARY TESTS

The initial tests examined the maximum thickness in which the seal material could be applied to an inverted surface prior to dripping. It was determined that it is possible to create an inverted dried material layer of approximately 0.04 inch in thickness without dripping. The dry time at this thickness was approximately 12 hours. The experiment was done in a relatively controlled environment with low humidity (less than 30%).



INVERTED SPRAY HORIZONTAL SPRAY

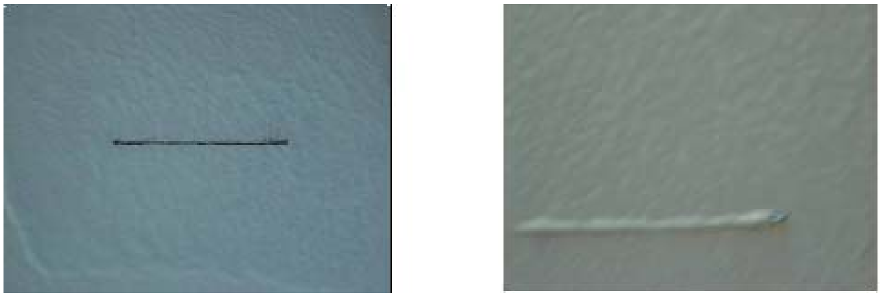
INVERTED DRY WITHOUT DRIP THICKNESS

Figure 10-5. Preliminary Tests

10.4 SEAL TESTING

The Polar Seal material consists of two components, namely an adhesive primer (Prime Security) for filling gaps and a top coat (Top Security). Both materials are latex based allowing for water cleanup. The manufacturer recommended two applications of the primer and one application of the top coat. The purpose of the primer is to adhere to any surface and seal. The primer is still adhesive once dried whereas the top coat is not. Therefore once the top coat is applied non-adhesive seal is created. Also the top coat only properly adheres to the primer, and once dried it is resistant to water.

Gaps were cut into the quarter inch test specimens. The gap sizes were 1/8”, 5/16”, and ¼” in width, and six inches long. The gapped specimens were placed in the spray stand as floor, sidewall and ceiling (or inverted) panels. The gun was aimed at a slight angle to allow build up between the gaps from a distance of 12 inches. Using of 0.031” orifice spray tip and operating pressure of approximately 1600 psi, the gaps were sprayed (with primer) in passes until the gaps were approximately filled or the material began to drip.



WALL PANEL CEILING (INVERTED) PANEL

FLOOR PANEL

Figure 10-6. Results for various surface orientations

The testing was repeated multiple times. During the tests it was noticed that in many cases that material “run” down along the gap, which is not a desirable performance. This behavior was mitigated when the material was sprayed at a lower rate, allowing a gradual “build up” inside the gap. It also appears that set and dry times are significantly affected by humidity. The humidity during testing (an uncontrolled environment) was 62%, and the material was observed to often “run” prior to the commencement of setting, resulting in uneven coating thickness. Also, the material did not completely dried when left overnight. Adjustment and optimization of the spraying operation appears to be keys to reduce run-off and minimize drying time, two characteristics essential for maximizing the commercial potential of this technology.

10.5 Evaluation of the Polar Seal Prime Security and Polar Seal Top Security Products Applied Using a Spray System.

Figure 10-7. Images of the spraying system prototype

The above depicted spray wand set up was fitted with a centering disk fabricated from plywood that facilitated keeping the spray tip centered in the duct so that the spray tip could be rotated and the coating sprayed on the duct section and fitting. The intent of the testing was to evaluate the capability to perform the gap filling and sealing inside of actual duct sections and fittings.

The test set up replicated a difficult spray scenario expected to be encountered in practice–an 8” with an adjustable 90° elbow set to a full 90° bend. Several different tips were evaluated for the distribution of the coating on the inside of the duct. It was found that all three tips (543, 532 and 517) deposited the material too quickly to be effective. Although the lower output tip #517 had the lowest flow rate. To compensate we changed the angle nozzle to 45° with the adjustable angle fitting on extension wand and performed further testing with the 517 tip. This configuration resulted in an improved performance–although the coating thickness was still somewhat excessive. We were able to successfully fill the 1/8” gap at the connection of the straight duct section to the 90° fitting, however the material was observed to run out of the gap at the crown of the metal duct under the action of gravity as it required a significant amount of time to cure.

One troubling observation was the long cure time of the thick coating. The literature stated that the coating would dry sufficiently for a second coat in 20 minutes but it became apparent that that time was for thin coats and a thick coating did not cure overnight. This is a significant impediment to cost effective commercial sealing operations.

A thickening agent, an ultra-fine powder named Metakaolin, was selected to thicken the primer to achieve the goal of changing the rheology of the coating to allow the material to “hang” or stay in the gap while curing. The Metakaolin successfully increased the viscosity of the primer but the sheer or thixotropic properties were not significantly improved. Thus, no noticeable improvement was realized with this modification.

Next, the top coat was successfully applied and preformed well filling the gaps. However, after been left for an overnight it was observed that the top coat had flowed out of the gaps and pooled in the bottom of the duct. It became evident that the rheology of these coatings is a significant issue. Also of concern is the cure time of the thickly applied top coat–although it dried somewhat faster than the primer, it still flowed out of the sections before curing. The second layer of top coat was applied to the duct section using the sprayer to the duct section. A pressure tested conducted using a dust blaster-a differential pressure measuring device which quantifies the amount of duct leakage–revealed that the duct was successfully sealed.

The capability to spray the material and fill a gap has been demonstrated during this testing. However, given the time required to cure this material it is unlikely that a cost effective commercial system for internal sealing would be feasible due to the long wait times between coats. A search was conducted for alternative sealant materials with better thixotropic and adhesion properties.

Figure 10-8. Primer being applied with 90° nozzle configuration

Figure 10-9. Elbow coated with polar seal primer

10.6 EVALUATING THE APPLICABILITY OF GEOPOLYMERS AS A DUCT SEALING MATERIAL

Based on the preliminary performance of the sealing coatings system it was determined that the proposed system, although successfully applied, was not a candidate for a cost effective and efficient method of fulfilling the objective. The materials took too long to cure and could not be applied in sufficient thickness, without running, to fill gaps larger than 1/8”. Research on alternative materials, including single component and two component coating materials, was performed and a highly desirable candidate for a sealing material identified. The material is geopolymer which has beneficial properties for this particular application including: low cost, environmentally benign, bacterial growth resistance, ease of application, great rheological properties, non flammable and excellent longevity. The laboratory evaluation focused on three areas:

a) Brush application–advantageous because it will better facilitate working bend sections.

b) Trowel application–while producing a smoother finish this approach could be problematic in bends–multiple small trowel sections that make up a whole unit could be employed.

c) Spin spray–using a centrifugal spinning head applicator.

Tests samples with varying viscosities were tested on actual duct sections using the following application methods: a) brush application; b) trowel application; and, c) pour application on a flat surface (simulated spray-on). The intent was to determine desirable thickness of coating material to be applied in terms of curing time and quality of the finish surface. The selection of the most suitable applicator is heavily dependent on viscosity and rheology, thus thixotropic properties were to be identified as well as surface tension and refill with applicators. Samples were cured in the oven at 100 °F and checked at 15 minute intervals to observe curing rates as a function of the concentrations, coating thickness, and application method. Control samples were prepared and allowed to cure at room temperature. Observations included: a) estimated rate of curing; b) cracking and crazing; c) shrinkage and pull away from the circular duct sections; d) apparent adhesion. A grand total of 32 samples were prepared and tested.

10.7 METAKAOLIN-BASED GEOPOLYMER AS A SEALANT

In testing medium viscosity metakaolin-based geopolymer the material was found to "hangs" well and to form a thick initial coating on first pass due to its high viscosity. Foam brush was found to work better than bristles. However, the material was found to flow down or "run" prior to setting. Tests on a thinner viscosity Metakaolin-based geopolymer revealed that the formulation's viscosity was too thin and flows readily. Other observations include:

- Room temperature curing did not seem to work well. Although the material can be brushed and forced into the gaps it flows out slowly within several minutes and the curing did commenced until approximately 20–30 minutes at room temperature.
- A range of curing temperatures (100-140 F) and curing period were used to evaluate the impact of these installation parameters on the quality of the final product. A summary of the results in given in Table 1.

Fly Ash-Based Geopolymer

Fly ash geopolymer sheeted away and formed droplets from surface tension when applied with a brush. Also, cracking of the cured geopolymer on the duct surface were observed; the final coat was found to be brittle.

Table 10-1. Summary of Testing Program

	Time Minutes:	5	10	15	20	30	45	60	75
Sample 1a	Too thick, set fast, runny					Set non adhesive still soft	Still soft non adhesive bubble formation	Soft and bubbly	Soft and bubbly non adhesive
Sample 1b	Too thick, drops, slides on sides			Start to harden, bubble formation, less adhesive		More bubbles formed, rolls down the sides	Starts to harden	Set	
Sample 2a	Thick good application with scrub brush and paint brush			Still wet and running, smaller bubbles by comparing with the heated sample					
Sample 2b	Thick good application with scrub brush and paint brush		Bubble formation no flow, curing started	Nearly curing, few more bubbles since last check no more flow	Set, no other changes				
Sample 3a	Sheets off the surface, too thin	Wet and runny		No changes		Curing started, no more flow			
Sample 3b	Sheets off the surface, too thin	Small bubbles forming, curing started, no running	Set no more changes						

Notes
"1b" sample was cured at 100f (38°C)
"a" samples were cured at room temp 71°F
2b and 3b samples were cured at 140°F

Due to the brittleness of the cured Geopolymer it did not perform well with ductwork sections (i.e., cracked and breaks off too easily). It was found that if applied in a sufficient thickness (1/4”) over the entire surface the coating was more robust, however for longevity the final costing product should be a flexible material. Also ¼” is considered excessive thicknesses for this application.

10.8 ACCELERATE CURING OF POLAR SEAL MATERIAL

To overcome its prolong curing time it was attempted to accelerated curing of the Polar Seal material by placing samples in the oven (at 140 F). A thin coat of the Primer was found to cure in 5 minutes, however a coat of Top Coat took 20 minutes to cure, during which the coating ran out of the gaps that were filled. It was concluded that it might be possible to apply a primer prior to the geopolymer with a quick cure. However, even with heat-based acceleration, the curing time of the Polar Seal top coat was found to be too long.

10.9 APPLICATION OF A MASTIC PRODUCT

Following failure of the single component spray-on system, it was decided that, before attempting complex multi-component spray-on system, a highly thixotropic mastic material that could be applied with a brush should be tested. This concept was found to work well and the material skinned over without running in 30 minutes. Low odor from this material was noted during curing. Although it took 48 hours to fully cure–the skinning of the mastic prevents it from becoming dislodged due to air flow when the ductwork was put back in service after the sealing operations are completed. Thus, mastic seems like a suitable sealant material, although it is unlikely that it can be effectively spray applied. Furthermore, our attempts to spray apply material resulted in inadequate penetration and filling of the gaps. What is required is a way to force the material into the gaps which is easily and effectively done with a brushing action. A method for applying the material with a rotating brush assembly was developed. It is based on a circular brush slightly larger than the duct diameter rotated at a 45° angle from the centerline of the duct while simultaneously being rotated 360° around the centerline of the duct would “push” the mastic into the gaps and cracks effectively (see Figure 10.10).

Thus, it is recommended to abandon the spray concept and pursue a brush applied duct sealing mastic solution. While pumping may be an issue, we are confident this can be overcome with a system, that has a 25 foot reach–perhaps even more. It is proposed to conduct a flow test to determine the pressure drop per unit length. It is worth noting that the above system is optimized for circular duct. Rectangular duct poses different challenges, and more importantly, has different joining methods that create different gaps–gaps that may be more applicable to a spray sealing method. This also applies to residential return plenums which can be nearly of any configuration–these represent a very difficult challenge. Thus, it is believed that a “one size fits all solution” short of a plural component spray application cannot be found. What rules the latter is the excessive amount of material that might be required to be sprayed on the surface to fill the gaps and the lack of an adequate fire rating of such materials.

Figure 10-10. Photo of duct sealed with brush applied duct sealing mastic (good filling of cracks; crusting within 30 min, thus preventing flowing out of filled areas)

10.10 SUMMARY

After a number of tests it was determined that the geopolymer material would not be a suitable material for this application due to its incompatibility with the zinc duct substrate. It was decided to abandon the concept of a spray system and utilize a brush applied material. A mastic material was evaluated and showed favorable results. The recommendation is to utilize a brush-applied, duct-mastic as the final solution. The preferred application method would be a rotating brush configured to rotate at an angle. The testing done showed this configuration would effectively perform the task of sealing the various leak locations within an 8 inch circular duct with 90° fittings. The mastic material used was a commercially available product; therefore, from an industry acceptance and code compliance standpoint, it is highly likely this material will be readily accepted for the application at hand

11.0 CONCLUSIONS AND FUTURE WORK

11.1 CONCLUSIONS

There were numerous conclusions in this study and the conclusions are presented in two sections as follows:

11.1.1 Analysis Conclusions

1. Three regression models were constructed to determine the whole house leakiness based on simple physical information. The study showed that age of the house and the conditioned area are some of the significant observable factors influencing air-tightness. Among the three regression models from the data, the model with response variable CFM50 had a higher predictive power than ELA and EqLA.
2. A test protocol to determine return leaks was developed and tested. Effective means of blocking the airflow to the supply during pressurization/ depressurization was presented in Chapter Five.
3. The weighted flow exponent of return leaks was determined to be 0.55. This value is slightly different from the flow exponent for total duct system flow exponent determined by our measurements to be 0.60.
4. The procedure for estimating supply leaks at operating pressure was presented in Chapter Six. Duct leakage as well as return leakages were used as inputs to measure the supply leaks at operating pressure. In addition, a comparative analysis of duct leakage at operating pressure, and at 25 Pa was made. Statistical tests on the small data set did not reveal any differences between them.

11.1.2 Policy Conclusions

1. Modeling discrepancies were found between the assumptions of the derivation of the subtraction correction algorithm as found in the Minnesota Blower Door^{TM} Manual and the conditions commonly found in homes in Louisiana. For example, the derivation of this algorithm assumes that the attic pressure will remain 50 Pa with respect to outside during the test; but that is seldom the case. To correct this discrepancy, an enhanced and generalized subtraction correction algorithm was derived and presented in Chapter Four.
2. Comparisons of GSCA and MSA for two geographic regions–in this case North Louisiana and New Orleans shows that homes in New Orleans have pressure-coupling ratio lower than that of North Louisiana. In addition, the SCF averaged about two in the case of North Louisiana whereas SCF varied over a range between one and ten.
3. The clusters analysis performed on data from 83 homes (North Louisiana and New Orleans) concluded that homes constructed before 1990 and maximum conditioned area of 4148 sq. ft. generally have higher whole house leakiness than other groups.
4. The weighted average return leakage over all homes tested was determined to be 115cfm at operating pressure. In terms of Equivalent Orifice Leakage Area, the average area was determined to be 28.5 sq. in. Considering the weighted average return leak at 25 Pa and the capacity of the HVAC unit, it was determined that 26% of the total duct leakage was due to

return leaks.

5. Results from Chapter Seven suggest that both Combined Duct Leakage (CDL) and Combined Returned Leakage (CRL) readings differ statistically between the pressurized and the depressurized conditions. These two tests involve both Blower Door^{TM} and Duct Blaster^{TM}. However, it is important to note that tests with Duct Blaster^{TM} only (TDL and TRL) do not show any statistical difference between the pressurized and depressurized conditions.
6. There are significant differences between the output results of REM/Rate^{TM} and the combined REM/Rate^{TM}-ASHRAE^{TM} 152 results as presented in Chapter Eight. The simulations for a simple test case show the inadequacy of the REM/Rate^{TM} model to determine the cost associated with duct leakage. As described in detail in Chapter Eight, at average 17% duct leakage, the average % energy wastage due to duct leakage was determined to be 30% with associated annual cost equal to $280.
7. The conclusions on the feasibility study of sealing duct leaks are as follows:
    a) The return plenums, made of wood, can be cost-effectively sealed using this sealing technology, in addition to sealing the larger holes by conventional methodologies.
    b) The metal ducts can be sealed externally and hence can be used to seal the ducts at joints, seams, turns and register boots after the ductwork has been laid and prior to insulating the ducts.
    c) The metal ducts can also be sealed internally at common points of leaks such as joints, seams, turns and register boots.
    d) The sealant is effective for sealing gaps less than 0.325” (3/8”), and for sealing holes less than 0.5” (1/2”) diameter.
    e) The sealant is safe to use, and, when dry, does not contain organic compounds, thus it cannot support the growth of mold.
    f) However full scale testing of spraying the compound in actual conditions showed significant problems due to dripping of the compound and comparatively long drying times.
    a) Mastic, a well known compound for externally sealing ducts, was considered. This material could not be sprayed, but it did not have the problems associated with the previously explored compound. A method of internally sealing cylindrical ducts internally via applying mastic was devised. Essentially the recommendation for the final solution is to utilize a brush-applied, duct-mastic. The preferred application method would be a rotating brush, configured to rotate at a specified angle. Preliminary studies showed this to be an effective methodology.

11.2 FUTURE WORK

1. The main leakage sites in buildings are exterior doors, windows, foundations, electrical boxes and plumbing fixtures. Therefore, to enhance the model we can include variables such as the number of windows and number of exterior doors. However, this inclusion might limit the usefulness of the model, as physical presence at a respective home might be needed to

collect additional data. The model can be developed in this regard in order to compare to the model developed in this report. This kind of regression model can be developed for other air-tightness parameters such as Air changes per hour (ACH50) and Normalized Leakage Areas (NLA). The model developed should incorporate a variable to account for homes, which are rehabilitated. Air-tightness estimates for the rehabilitated homes based on the developed model may not be a reasonable one since we consider age of the house as a significant factor. A larger sample for the cluster analysis is recommended to obtain accurate segmentation by which homes can be categorized distinctly based on age, conditioned area, and other significant factors.

2. Studies are needed to determine and quantify the symbiotic effects of duct leakage and mold growth. We propose to measure the actual flow through HVAC systems to determine if they consistently conform to the industry standard of 400 cfm per ton. When the flow is found to be significantly below this level, evaporator coil inspections should be performed to look for evidence of blockage that may be associated with mold growth. During a large percentage of the year Louisiana and its sister southern states are hot and very humid. HVAC systems are designed to not only cool the air, but as importantly, to dehumidify the air. If HVAC systems are not leak-free, not well designed, or well serviced (using quality air filters and changing them periodically, or cleaning them when they are dirty/clogged), then the area in the vicinity of the cooling coils may not dry out over a period of over 24 hours. In such cases mold can grow and, along with particular matter in the air, clog the coil, thereby exasperating the situation and aiding the growth of more mold. Some people are allergic to various strains of mold, and these strains may very adversely affect the health of these individuals. There are several cases where homes have been intentionally burned down because of mold infestations. Quantitative data is needed to describe the extent of this problem; namely homes should be inspected for mold in their HVAC systems. Leaks in the supply plenum involve cold air from leaky ducts mixing with hot humid air in unconditioned space, an ideal combination for condensation, and thus possible locations of mold growth. In addition, studies are needed on fabricating sensors for continuing monitoring the need of HVAC systems for servicing to retain efficiency and to thereby prevent the growth of mold as well as reducing the repair costs caused by clogged coils.
3. The results from Chapter Seven show that the interchangeability aspects of the pressurized and depressurized tests are questionable. Therefore, the reasons for the above differences need to be addressed in the future.
4. Discrepancies involved in REM/Rate^{TM} in regards to determining costs associated with duct leakage need to be further investigated.
5. The results from chapter 10 indicate that a brush-applied, duct-mastic material is a practical solution for the inner sealing of ductworks in residential housing. The preferred application method would be a rotating brush configured to rotate at an angle. The limited testing conducted as part of this project suggested this configuration could effectively perform the task of sealing the various leak locations within an 8 inch circular duct with 90° fittings.

APPENDIX A

SAS^{TM} PROGRAMS, INPUT AND OUTPUT

Table A-1. Air-tightness data for 66 homes

Test #	Place	Year Built	Area	Volume	ELA	CFM50	NOS	NOB	Eq.la
			sq.ft.	Cu.ft.	sq.in.	CFM			sq.in.
1	Ruston	1920	1445.0	13005.0	310	5318.0	1.0	3	571
2	Ruston	1980	2100.0	17208.0	168	3212.1	2.0	3	321
3	Ruston	1972	2296.0	18368.0	197	3512.2	1.0	3	367
4	Ruston	1930	3190.0	25968.0	367	7579.7	1.0	2	722
5	Ruston	1985	1230.0	9984.0	88	1697.6	1.0	2	169
6	Calhoun	1990	1216.0	9968.0	99	1744.6	1.0	3	184
8	Dubach	1982	2985.0	28130.0	412	6812.1	2.0	4	747
11	Ruston	1975	1920.0	15360.0	240	4233.3	1.0	3	447
12	Ruston	1990	1370.0	12380.0	67	1156.2	1.5	3	124
13	Ruston	1964	1847.0	14766.0	221	3790.0	1.0	4	407
14	Ruston	1990	3866.0	34794.0	340	5602.1	1.0	4	616
16	Dubach	1987	1500.0	12000.0	96	1651.4	1.0	2	177
18	Ruston	1970	2486.0	19468.0	374	5927.8	2.0	4	669
19	Ruston	1984	3474.0	31748.0	371	6723.2	1.0	4	697
20	Ruston	1970	2276.0	18540.0	215	4160.8	2.0	3	414
21	Dubach	1970	1296.0	10368.0	136	2798.4	1.0	3	267
26	Ruston	1981	1360.0	11212.0	84	1506.3	1.0	3	157
27	Ruston	1977	1041.6	8332.8	133	2177.2	1.0	3	241
28	Ruston	1979	1526.0	12759.0	100	1723.2	1.0	3	184
29	Ruston	1975	2118.0	18474.0	167	3443.9	1.0	3	329
30	Monroe	1950	1595.0	12760.0	193	3201.6	1.0	3	351
31	Ruston	1987	2703.0	20934.0	420	7033.8	2.0	5	766
33	Ruston	1975	2143.0	17144.0	218	3855.6	1.0	3	406
34	Ruston	1970	1688.0	13864.0	112	2003.0	1.0	3	209
35	Choudrant	1976	1850.5	14804.0	180	3263.8	1.0	3	338
36	Ruston	1971	1888.0	15664.0	154	3168.0	1.0	3	303
37	Simsboro	1958	1806.5	14452.0	153	3163.6	1.0	3	301
38	Ruston	1970	2254.8	18038.0	174	3066.0	1.0	4	324
39	Ruston	1989	1458.0	12474.0	138	2468.4	1.0	3	258
40	Ruston	1999	1702.0	13999.9	83	1495.0	1.0	4	156
42	Ruston	1980	1154.0	9232.0	85	1496.4	1.0	2	158
43	Ruston	1973	2544.8	22866.0	219	3885.9	1.0	2	407
44	Ruston	1977	2592.0	20736.0	149	3258.2	2.0	4	300
45	Ruston	1961	2373.0	18984.0	203	3524.8	1.0	3	376
46	Ruston	1927	2284.8	22848.0	349	10057.4	1.0	3	775
47	Ruston	1925	1706.5	17065.0	334	5846.7	1.0	3	619
48	Ruston	1970	2477.0	26094.0	261	8173.4	1.5	3	597

Test #	Place	Year Built	Area	Volume	ELA	CFM50	NOS	NOB	Eq.la
			sq.ft.	Cu.ft.	sq.in.	CFM			sq.in.
51	Ruston	1968	2402.0	20366.0	333	5237.4	2.0	3	594
52	Ruston	1965	1439.0	11514.0	149	2242.5	1.0	3	262
53	Ruston	1984	2686.0	25466.0	283	4891.2	2.0	4	523
54	Ruston	1977	2343.0	18746.0	258	3827.9	1.5	4	451
55	Ruston	1994	2899.0	28985.0	166	3029.2	1.0	3	313
56	Ruston	1985	2388.0	19104.0	182	3372.0	1.0	4	344
57	Ruston	1980	2205.0	17640.0	124	3396.0	1.0	3	271
58	Ruston	1993	1333.0	10664.0	81	747.0	1.0	3	119
59	Ruston	1975	2160.0	17280.0	119	5087.0	1.0	3	305
60	Ruston	2004	1648.0	16480.0	121	2110.0	1.0	2	224
61	Ruston	1970	2250.0	18000.0	461	7332.0	1.0	3	825
62	Ruston	1997	1789.0	14585.0	117	1876.0	1.0	3	210
63	Ruston	1995	2300.0	18400.0	134	2808.0	1.0	3	265
64	Ruston	2001	2458.0	24580.0	133	2915.0	1.0	3	267
65	Ruston	1994	2100.0	16800.0	152	2526.0	1.0	3	271
66	Ruston	1995	2275.0	21000.0	150	2226.0	1.5	2	262
67	Ruston	1955	2200.0	19800.0	312	5432.0	1.0	2	577
68	Ruston	1990	2143.0	17144.0	202	3339.0	1.0	2	503
69	Ruston	1985	1600.0	12800.0	119	2072.0	1.0	3	220
70	Ruston	1957	1550.0	12400.0	165	2664.0	1.0	2	297
71	Ruston	1988	2500.0	21875.0	208	4087.0	1.0	3	402
72	Ruston	2000	2800.0	25200.0	130	1803.0	1.0	3	230
73	Arcadia	1975	2070.0	16560.0	376	5499.0	1.0	3	653
74	Ruston	1970	2200.0	18700.0	105	3015.0	1.0	3	233
75	Ruston	2004	2200.0	23100.0	122	2502.0	1.0	3	239
76	Ruston	1972	1700.0	14025.0	489	5889.0	1.0	3	792
77	Ruston	1983	1350.0	11070.0	136	2155.0	1.0	2	244
78	Ruston	1995	2200.0	20240.0	143	2447.0	1.0	4	263
79	Ruston	1991	1950.0	17050.0	140	2997.0	1.0	2	279

Figure A-1. SAS program for modeling air-tightness using multiple regression

```
                  /*********************************************************************/

/* COMMENTS                      NAME                       DATE MODIFIED
 Initial Version            Jinson Erinjeri                 10/15/2005
 Multiple regression analysis on 3 air tightness
 parameters(ELA,Eqla,CFM50)with respect to year
 built, area,number of storeys and number of bedrooms.
/*********************************************************************/

/* MODIFYING ALREADY IMPORTED DATA FROM EXCEL*/
DATA ESTIMATE;
 SET work.all;
 DROP TestNo Place Volume;
 RENAME YEARBUILT=YB;
/*CREATING DUMMY VARIABLES FOR VARAIBLES BEDROOMS AND STOREYS*/
 S1 = 0;
 S2 = 0;
 B2 = 0;
 B3 = 0;
 IF NOS=1 THEN S1=1;
 IF NOS=1.5 THEN S2=1;
 IF NOB=2 THEN B2=1;
 IF NOB=3 THEN B3=1;
PROC PRINT DATA=ESTIMATE;
RUN;
/*MACRO FOR RUNNING REGRESSION WITH ALL THE INDEPENDENT VARIABLES*/
%LET IV = YB AREA /*S1 S2 B2 B3*/;
%MACRO REGR(AT);
 PROC REG DATA=ESTIMATE;
 MODEL &AT = &IV /SELECTION=STEPWISE SLE=.05 SLS=.10 VIF;
 RUN;
%MEND;
%REGR(EqLA)
%REGR(ELA)
%REGR(CFM50)
/*MACRO FOR RUNNING REGRESSION WITH SIGNIFICANT INDEPENDENT VARIABLES*/
/* RAT IS THE ARGUMENT FOR THE MACRO REGR*/
%LET VAR=YB AREA /*S1;*/;
%MACRO REGR(RAT);
 %IF &RAT=CFM50 %THEN %DO;
 PROC REG DATA=ESTIMATE;
 MODEL &RAT=%SUBSTR(&VAR,1,7)/ALPHA=0.05 CLB CLM CLI INFLUENCE;
      OUTPUT OUT=NEW H=LEVERAGE P=PREDICTED COOKD=COOKS DFFITS=DFFI
      R=RESIDUALS RSTUDENT=RSTD;
 proc univariate data=new normal;
 var residuals;
 probplot;
 %END;
 %IF &RAT=ELA %THEN %DO;

proc univariate data=new normal;
 var residuals;
         probplot;
PROC REG DATA=ESTIMATE;
 MODEL &RAT=&VAR/ALPHA=0.05 CLB CLM CLI INFLUENCE;
      OUTPUT OUT=NEW H=LEVERAGE P=PREDICTED COOKD=COOKS DFFITS=DFFI
              R=RESIDUALS RSTUDENT=RSTD;\
        %END;
 %IF &RAT= EqLA %THEN %DO;
```

```
 PROC REG DATA=ESTIMATE;
 MODEL &RAT = &VAR/ALPHA=0.05 CLB CLM CLI INFLUENCE;
      OUTPUT OUT=NEW H=LEVERAGE P=PREDICTED COOKD=COOKS DFFITS=DFFI
      R=RESIDUALS RSTUDENT=RSTD;
 proc univariate data=new normal;
 var residuals;
 probplot;
 %END;
 RUN;
%MEND;
%REGR(CFM50);
%REGR(ELA);
%REGR(EqLA);
/*MACRO FOR PLOTTING DEPENDENT VARIABLES WITH INDEPENDENT VARIABLES*/
%LET V=YB AREA;
%LET ATS=ELA EqLA CFM50;
%MACRO PLOTS;
%DO J=1 %TO 3;
%DO I=1 %TO 2;
PROC PLOT DATA=ESTIMATE;
PLOT %SCAN(&ATS,&J)*%SCAN(&V,&I)='*';
%END;
%END;
RUN;
%MEND;
%PLOTS
```

Figure A-1. SAS program for modeling air-tightness using multiple regression

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
                 The SAS System       17:38 Thursday, October 26, 2006  38

                                    The REG Procedure
                                      Model: MODEL1
                                Dependent Variable: Eqla Eqla


                                Summary of Stepwise Selection

                Variable    Variable              Number    Partial     Model
 Step   Entered     Removed     Label       Vars In   R-Square   R-Square    C(p)     F Value   Pr
                                                > F

   1    Area                    Area           1      0.5029     0.5029    49.7899     44.52
                                              <.0001
   2    YB                     Year Built       2      0.2228     0.7257    10.6565     34.92
                                              <.0001
   3    S1                                     3      0.0483     0.7739     3.7462      8.96
                                              0.0046
                 The SAS System       17:38 Thursday, October 26, 2006  39

                                    The REG Procedure
                                      Model: MODEL1
                                Dependent Variable: Eqla Eqla

                           Number of Observations Read          46
                           Number of Observations Used          46


                                    Analysis of Variance

                                    Sum of           Mean
         Source                  DF        Squares         Square    F Value    Pr > F

         Model                     3        1242169         414056      47.93    <.0001
                  Error                      42         362854     8639.36944
                         Corrected Total          45        1605023


                      Root MSE             92.94821    R-Square     0.7739
                      Dependent Mean      383.39130    Adj R-Sq     0.7578
                                 Coeff Var            24.24369


                                   Parameter Estimates

                 Parameter       Standard                                  Variance
 Variable     Label        DF       Estimate           Error    t Value    Pr > |t|      Inflation

 Intercept    Intercept     1          10732      1568.26130       6.84      <.0001              0
YB           Year Built     1        -5.40497         0.79127      -6.83      <.0001         1.02668
 Area         Area          1        0.19059         0.02285       8.34      <.0001        1.10548
 S1                         1     -102.39724        34.20000      -2.99      0.0046        1.13311


                 The SAS System       17:38 Thursday, October 26, 2006  42

                                    The REG Procedure
                                      Model: MODEL1
                                 Dependent Variable: ELA ELA


                                Summary of Stepwise Selection
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
                Variable    Variable                Number    Partial     Model
Step   Entered     Removed     Label        Vars In   R-Square   R-Square    C(p)      F Value   Pr
                                                > F

   1    Area                   Area            1      0.4914     0.4914    41.6032     42.52
                                             <.0001
   2    YB                     YearBuilt       2      0.1828     0.6743    13.5485     24.13
                                             <.0001
   3    S1                                     3      0.0544     0.7286     6.6134      8.41
                                             0.0059
                     The SAS System        17:38 Thursday, October 26, 2006  43

                                          The REG Procedure
                                            Model: MODEL1
                                    Dependent Variable: ELA ELA

                              Number of Observations Read          46
                              Number of Observations Used          46


                                         Analysis of Variance

                                         Sum of           Mean
         Source                   DF        Squares         Square    F Value    Pr > F

         Model                     3         327534         109178      37.59    <.0001
                   Error                     42         122002     2904.80032
                          Corrected Total          45         449535


                        Root MSE             53.89620    R-Square     0.7286
                        Dependent Mean      202.28261    Adj R-Sq     0.7092
                                   Coeff Var            26.64401


                                         Parameter Estimates

                 Parameter       Standard                                      Variance
Variable     Label        DF       Estimate          Error    t Value    Pr > |t|      Inflation

Intercept    Intercept     1     5217.08412      909.35937       5.74      <.0001              0
YB           YearBuilt     1       -2.62279        0.45882      -5.72      <.0001        1.02668
Area         Area          1        0.09882        0.01325       7.46      <.0001        1.10548
S1                         1      -57.51555       19.83093      -2.90      0.0059        1.13311


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                                          The REG Procedure
                                            Model: MODEL1
                                  Dependent Variable: CFM50 CFM50


                                    Summary of Stepwise Selection

                Variable    Variable                Number    Partial     Model
Step   Entered     Removed     Label        Vars In   R-Square   R-Square    C(p)      F Value   Pr
                                                > F

   1    Area                   Area            1      0.4449     0.4449    42.6889     35.27
                                             <.0001
   2    YB                     YearBuilt       2      0.2635     0.7085     4.4778     38.88
                                             <.0001
   3    S1                                     3      0.0334     0.7419     1.3806      5.44
                                             0.0246
                     The SAS System        17:38 Thursday, October 26, 2006  47

                                          The REG Procedure
                                            Model: MODEL1
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
                                 Dependent Variable: CFM50 CFM50

                             Number of Observations Read          46
                             Number of Observations Used          46


                                      Analysis of Variance

                                      Sum of           Mean
         Source                   DF        Squares         Square    F Value    Pr > F

         Model                     3      137121869       45707290      40.24    <.0001
                    Error                    42       47703706        1135803
                           Corrected Total          45      184825575


                      Root MSE           1065.74037    R-Square     0.7419
                      Dependent Mean     3816.56304    Adj R-Sq     0.7235
                                  Coeff Var            27.92409


                                       Parameter Estimates

                 Parameter       Standard                              Variance
Variable     Label        DF       Estimate          Error    t Value    Pr > |t|      Inflation

Intercept    Intercept     1         122899          17982       6.83      <.0001              0
YB           YearBuilt     1      -62.04287        9.07269      -6.84      <.0001        1.02668
Area         Area          1        1.95090        0.26205       7.44      <.0001        1.10548
S1                         1     -914.29358      392.13575      -2.33      0.0246        1.13311




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                                        The REG Procedure
                                          Model: MODEL1
                                 Dependent Variable: CFM50 CFM50

                             Number of Observations Read          46
                             Number of Observations Used          46


                                      Analysis of Variance

                                      Sum of           Mean
         Source                   DF        Squares         Square    F Value    Pr > F

         Model                     2      130947376       65473688      52.25    <.0001
                    Error                    43       53878199        1252981
                           Corrected Total          45      184825575


                      Root MSE           1119.36651    R-Square     0.7085
                      Dependent Mean     3816.56304    Adj R-Sq     0.6949
                                  Coeff Var            29.32918


                                       Parameter Estimates

                                     Parameter     Standard
 Variable   Label      DF     Estimate        Error  t Value  Pr > |t|    95% Confidence Limits

Intercept  Intercept   1       115105        18557     6.20    <.0001        77681       152529
YB         YearBuilt   1    -58.64132      9.40520    -6.23    <.0001    -77.60872    -39.67393
Area       Area        1      2.13951      0.26179     8.17    <.0001      1.61156      2.66746
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
                                        The REG Procedure
                                          Model: MODEL1
                                  Dependent Variable: Eqla Eqla

                             Number of Observations Read          46
                             Number of Observations Used          46


                                      Analysis of Variance

                                      Sum of           Mean
         Source                   DF        Squares         Square    F Value    Pr > F

         Model                     2        1164722         582361      56.87    <.0001
                    Error                    43         440301          10240
                           Corrected Total          45        1605023


                      Root MSE            101.19068    R-Square     0.7257
                      Dependent Mean      383.39130    Adj R-Sq     0.7129
                                  Coeff Var            26.39358


                                       Parameter Estimates

                 Parameter       Standard                              Variance
Variable     Label        DF       Estimate          Error    t Value    Pr > |t|      Inflation

Intercept    Intercept     1     9859.40436     1677.56832       5.88      <.0001              0
YB           YearBuilt     1       -5.02401        0.85023      -5.91      <.0001        1.00013
              Area         Area          1        0.21172        0.02367       8.95


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                                        The REG Procedure
                                          Model: MODEL1
                                   Dependent Variable: ELA ELA

                             Number of Observations Read          46
                             Number of Observations Used          46


                                      Analysis of Variance

                                      Sum of           Mean
         Source                   DF        Squares         Square    F Value    Pr > F

         Model                     2         303099         151550      44.50    <.0001
                    Error                    43         146436     3405.48719
                           Corrected Total          45         449535


                      Root MSE             58.35655    R-Square     0.6743
                      Dependent Mean      202.28261    Adj R-Sq     0.6591
                                  Coeff Var            28.84902


                                       Parameter Estimates

                 Parameter       Standard                              Variance
Variable     Label        DF       Estimate          Error    t Value    Pr > |t|      Inflation

Intercept    Intercept     1     4726.76957      967.45173       4.89      <.0001              0
YB           YearBuilt     1       -2.40881        0.49033      -4.91      <.0001        1.00013
Area         Area          1        0.11069        0.01365       8.11      <.0001        1.00013
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
                   The SAS System        17:38 Thursday, October 26, 2006  82

                                        The REG Procedure
                                          Model: MODEL1
                                 Dependent Variable: CFM50 CFM50

                             Number of Observations Read          46
                             Number of Observations Used          46


                                      Analysis of Variance

                                      Sum of           Mean
         Source                   DF        Squares         Square    F Value    Pr > F

         Model                     2      130947376       65473688      52.25    <.0001
                    Error                    43       53878199        1252981
                           Corrected Total          45      184825575


                      Root MSE           1119.36651    R-Square     0.7085
                      Dependent Mean     3816.56304    Adj R-Sq     0.6949
                                  Coeff Var            29.32918

                                       Parameter Estimates

                                     Parameter     Standard
 Variable   Label      DF     Estimate        Error  t Value  Pr > |t|    95% Confidence Limits

Intercept   Intercept   1       115105        18557     6.20    <.0001         77681       152529
YB          YearBuilt   1    -58.64132      9.40520    -6.23    <.0001     -77.60872    -39.67393
Area        Area        1      2.13951      0.26179     8.17    <.0001       1.61156      2.66746

                                          Model: MODEL1
                                 Dependent Variable: CFM50 CFM50

                                        Output Statistics
                                Dependent Predicted    Std Error
Obs  Variable     Value Mean Predict     95% CL Mean        95% CL Predict    Residual  RStudent

  1      5318      5605     545.8209      4504      6706      3094      8117 -287.1385   -0.2907
  2      3212      3488     178.6082      3128      3848      1202      5774 -275.9369   -0.2470
  3      3512      4377     176.7130      4020      4733      2091      6662 -864.3111   -0.7784
  4      7580      8752     529.3515      7685      9820      6255     11249     -1172   -1.1947
  5      1698      1333     296.2808  735.9511      1931     -1002      3669  364.1418    0.3338
  6      1745      1010     320.3288  364.2938      1656     -1338      3358  734.3016    0.6803
  7      6812      5264     305.3376      4648      5880      2924      7604      1548    1.4559
  8      4233      3396     170.1720      3053      3739      1113      5679  837.1679    0.7529
  9      1156      1340     293.8291  747.2198      1932 -994.1122      3674 -183.5827   -0.1680
 10      3790      3885     192.4702      3497      4273      1594      6176  -95.0025   -0.0852
 11      5602      6680     525.2270      5621      7739      4186      9174     -1078   -1.0929
 12      1651      1794     258.2899      1273      2315 -522.8926      4111 -142.4427   -0.1293
 13      5928      4900     201.5723      4494      5307      2607      7194      1027    0.9318
 14      6723      6193     418.3413      5349      7037      3783      8603  530.0441    0.5061
 15      4161      4451     176.8319      4094      4808      2166      6736 -290.2036   -0.2597
 16      2798      2354     259.8169      1830      2878   36.8560      4672  444.1144    0.4039
 17      1506      1846     258.3767      1325      2367 -470.6151      4163 -339.8595   -0.3087
 18      2177      1400     315.7057  762.8243      2036 -945.9791      3745  777.6946    0.7201
 19      1723      2319     223.8626      1867      2770   16.4814      4621 -595.4005   -0.5384
 20      3444      3820     167.0476      3483      4157      1537      6102 -375.8547   -0.3361
 21      3202      4167     295.5572      3571      4763      1832      6502 -965.2250   -0.8919
 22      7034      4368     270.3668      3822      4913      2045      6690      2666    2.6160
 23      3856      3873     167.7914      3535      4212      1591      6156  -17.6424   -0.0158
 24      2003      3193     192.9092      2804      3582  902.2774      5484     -1190   -1.0813
 25      3264      3189     176.3157      2833      3544  903.5449      5474   75.0051    0.0671
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
 26      3168      3562    171.6737      3216      3908       1278      5846 -394.2331   -0.3528
 27      3164      4150    225.3231      3696      4605       1848      6453 -986.6004   -0.8978
 28      3066      4406    175.1009      4053      4759       2121      6691     -1340   -1.2185
 29      2468      1587    274.7931      1033      2141 -737.7438      3911  881.6993    0.8093
 30      1495      1522    311.4454  894.2380      2150 -820.8394      3865  -27.3275   -0.0251
 31      1496      1464    296.7014  865.7069      2062 -871.3101      3799   32.3378    0.0296
 32      3886      4850    208.6845      4429      5271       2554      7146 -964.2794   -0.8744
 33      3258      4717    219.7156      4274      5160       2416      7017     -1458   -1.3410
 34      3525      5186    216.0292      4751      5622       2887      7485     -1662   -1.5365
 35     10057      6991    465.9968      6052      7931       4546      9437      3066    3.3519
 36      5847      5871    486.8654      4890      6853       3410      8333  -24.7133   -0.0242
 37      8173      4881    200.2653      4477      5285       2588      7174      3292    3.3196
 38      5237      4838    193.7889      4447      5229       2547      7129  399.5357    0.3587
 39      2243      2953    241.9730      2465      3441  643.8826      5263 -710.9419   -0.6461
 40      4891      4507    254.9636      3993      5021       2192      6822  383.9766    0.3487
 41      3828      4184    185.2591      3810      4557       1896      6472 -355.9614   -0.3191
 42      3029      4377    338.3554      3694      5059       2018      6735     -1347   -1.2718
 43      3372      3811    218.2484      3371      4251       1511      6111 -439.0087   -0.3959
 44      3396      3713    182.3013      3345      4080       1426      6000 -316.6853   -0.2837
 45  747.0000      1085    316.2012  447.0164      1722      -1261      3430 -337.6969   -0.3112
                   The SAS System        17:38 Thursday, October 26, 2006  84

                                    The REG Procedure
                                     Model: MODEL1
                               Dependent Variable: CFM50 CFM50

                                    Output Statistics

              Hat Diag         Cov              -------------DFBETAS-------------
            Obs        H       Ratio      DFFITS    Intercept          YB        Area

              1   0.2378      1.3994     -0.1623      -0.1490      0.1472      0.0459
              2   0.0255      1.0964     -0.0399       0.0148     -0.0151     -0.0023
              3   0.0249      1.0543     -0.1244      -0.0057      0.0060     -0.0441
              4   0.2236      1.2504     -0.6412      -0.4831      0.4920     -0.3649
              5   0.0701      1.1449      0.0916      -0.0338      0.0362     -0.0674
              6   0.0819      1.1311      0.2032      -0.0990      0.1041     -0.1408
              7   0.0744      1.0002      0.4128      -0.1204      0.1129      0.3271
              8   0.0231      1.0552      0.1158      -0.0125      0.0142     -0.0246
              9   0.0689      1.1502     -0.0457       0.0244     -0.0255      0.0283
             10   0.0296      1.1053     -0.0149      -0.0066      0.0064      0.0042
             11   0.2202      1.2651     -0.5807       0.1861     -0.1726     -0.5216
             12   0.0532      1.1321     -0.0307       0.0153     -0.0160      0.0175
             13   0.0324      1.0431      0.1706       0.0221     -0.0236      0.0953
             14   0.1397      1.2248      0.2039      -0.0537      0.0491      0.1802
             15   0.0250      1.0953     -0.0415      -0.0064      0.0064     -0.0135
             16   0.0539      1.1211      0.0964       0.0117     -0.0090     -0.0738
             17   0.0533      1.1259     -0.0732       0.0205     -0.0224      0.0520
             18   0.0795      1.1237      0.2117      -0.0222      0.0284     -0.1785
             19   0.0400      1.0950     -0.1099       0.0266     -0.0293      0.0686
             20   0.0223      1.0888     -0.0507       0.0058     -0.0062      0.0048
             21   0.0697      1.0904     -0.2442      -0.1802      0.1762      0.0979
             22   0.0583      0.7246      0.6511      -0.3245      0.3164      0.4036
             23   0.0225      1.0978     -0.0024       0.0003     -0.0003     -0.0003
             24   0.0297      1.0185     -0.1892      -0.0292      0.0250      0.0944
             25   0.0248      1.1001      0.0107      -0.0017      0.0018     -0.0033
             26   0.0235      1.0893     -0.0547      -0.0062      0.0053      0.0140
             27   0.0405      1.0565     -0.1845      -0.1163      0.1136      0.0524
             28   0.0245      0.9912     -0.1930      -0.0299      0.0300     -0.0574
             29   0.0603      1.0902      0.2049      -0.1103      0.1148     -0.1182
             30   0.0774      1.1631     -0.0073       0.0057     -0.0058      0.0022
             31   0.0703      1.1542      0.0081      -0.0017      0.0019     -0.0065
             32   0.0348      1.0532     -0.1659       0.0019     -0.0001     -0.1015
             33   0.0385      0.9842     -0.2684       0.0491     -0.0460     -0.1706
             34   0.0372      0.9460     -0.3022      -0.1556      0.1569     -0.1175
             35   0.1733      0.6375      1.5347       1.4202     -1.4217      0.2128
             36   0.1892      1.3235     -0.0117      -0.0109      0.0108      0.0021
             37   0.0320      0.5511      0.6036       0.0787     -0.0839      0.3324
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
            38   0.0300      1.0962      0.0631       0.0147      -0.0151       0.0296
            39   0.0467      1.0928     -0.1430      -0.0460       0.0424       0.0951
            40   0.0519      1.1221      0.0816      -0.0341       0.0330       0.0523
            41   0.0274      1.0954     -0.0535       0.0113      -0.0111      -0.0215
            42   0.0914      1.0545     -0.4033       0.2401      -0.2343      -0.2600
            43   0.0380      1.1032     -0.0787       0.0413      -0.0409      -0.0308
            44   0.0265      1.0961     -0.0468       0.0171      -0.0172      -0.0098
            45   0.0798      1.1582     -0.0916       0.0536      -0.0556       0.0556

                   The SAS System        17:38 Thursday, October 26, 2006  85

                                        The REG Procedure
                                          Model: MODEL1
                                 Dependent Variable: CFM50 CFM50

                                        Output Statistics

                                Dependent Predicted    Std Error
Obs  Variable     Value Mean Predict     95% CL Mean        95% CL Predict    Residual  RStudent

 46      5087      3910     168.4406      3570      4249      1627      6192      1177    1.0656

                                        Output Statistics

              Hat Diag         Cov                -------------DFBETAS-------------
            Obs        H       Ratio      DFFITS    Intercept          YB        Area

            46   0.0226      1.0136      0.1622      -0.0187       0.0194       0.0258


                          Sum of Residuals                           0
                          Sum of Squared Residuals            53878199
                          Predicted Residual SS (PRESS)       64100927
                   The SAS System        17:38 Thursday, October 26, 2006  86

                                    The UNIVARIATE Procedure
                                Variable:  RESIDUALS  (Residual)

                                             Moments

                 N                          46    Sum Weights                 46
                 Mean                        0    Sum Observations             0
                 Std Deviation      1094.20899    Variance            1197293.32
                 Skewness           1.25796034    Kurtosis            2.01091922
                 Uncorrected SS     53878199.2    Corrected SS        53878199.2
                 Coeff Variation             .    Std Error Mean      161.332314


                                   Basic Statistical Measures

                             Location                    Variability

                      Mean        0.000     Std Deviation               1094
                      Median   -229.760     Variance                 1197293
                      Mode           .      Range                       4954
                                Interquartile Range         1155


                                    Tests for Location: Mu0=0

                        Test           -Statistic-    -----p Value------

                        Student's t    t         0    Pr > |t|    1.0000
                        Sign           M        -6    Pr >= |M|   0.1038
                        Signed Rank    S     -73.5    Pr >= |S|   0.4280


                                      Tests for Normality
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
          Test                  --Statistic---    -----p Value------

          Shapiro-Wilk          W     0.901766    Pr < W      0.0009
          Kolmogorov-Smirnov    D     0.146588    Pr > D      0.0145
          Cramer-von Mises      W-Sq  0.182336    Pr > W-Sq   0.0086
          Anderson-Darling      A-Sq  1.217376    Pr > A-Sq  <0.0050

                           Quantiles (Definition 5)

                           Quantile       Estimate

                           100% Max       3292.355
                           99%            3292.355
                           95%            2666.129
                           90%            1177.386
                           75% Q3          444.114
                           50% Median     -229.760
                           25% Q1         -710.942
                           10%           -1189.973
          The SAS System        17:38 Thursday, October 26, 2006  87

                           The UNIVARIATE Procedure
                       Variable:  RESIDUALS  (Residual)

                           Quantiles (Definition 5)

                           Quantile       Estimate

                           5%            -1347.325
                           1%            -1661.508
                           0% Min        -1661.508

                             Extreme Observations

                  ------Lowest-----        -----Highest-----

                    Value      Obs           Value      Obs

                  -1661.51      34          1177.39      46
                  -1458.40      33          1547.88       7
                  -1347.33      42          2666.13      22
                  -1339.65      28          3065.99      35
                  -1189.97      24          3292.36      37
          The SAS System        17:38 Thursday, October 26, 2006  88



                              The REG Procedure
                                Model: MODEL1
                         Dependent Variable: ELA ELA

                   Number of Observations Read          46
                   Number of Observations Used          46


                             Analysis of Variance

                            Sum of           Mean
Source                   DF        Squares         Square    F Value    Pr > F

Model                     2         303099         151550      44.50    <.0001
          Error                    43         146436     3405.48719
                  Corrected Total          45         449535


             Root MSE             58.35655    R-Square     0.6743
             Dependent Mean      202.28261    Adj R-Sq     0.6591
                        Coeff Var            28.84902
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
                                     Parameter Estimates

                                  Parameter     Standard
 Variable    Label      DF     Estimate        Error  t Value   Pr > |t|    95% Confidence Limits

 Intercept   Intercept   1   4726.76957    967.45173     4.89     <.0001   2775.71721   6677.82193
 YB          YearBuilt   1     -2.40881      0.49033    -4.91     <.0001     -3.39765     -1.41997
 Area        Area        1      0.11069      0.01365     8.11     <.0001      0.08316      0.13821
                   The SAS System       17:38 Thursday, October 26, 2006  89
                                      The REG Procedure
                                        Model: MODEL1
                                 Dependent Variable: ELA ELA

                                      Output Statistics

                              Dependent Predicted    Std Error
Obs  Variable     Value Mean Predict     95% CL Mean        95% CL Predict    Residual  RStudent

 1  310.0000  261.7987      28.4556  204.4125  319.1848  130.8657  392.7317   48.2013    0.9449
 2  168.0000  189.7700       9.3115  170.9916  208.5484   70.5940  308.9459  -21.7700   -0.3741
 3  197.0000  230.7350       9.2127  212.1559  249.3142  111.5903  349.8798  -33.7350   -0.5809
 4  367.0000  430.8590      27.5970  375.2044  486.5136  300.6756  561.0424  -63.8590   -1.2500
 5   88.0000   81.4285      15.4462   50.2783  112.5786  -40.3115  203.1684    6.5715    0.1154
 6   99.0000   67.8348      16.6999   34.1563  101.5133  -54.5765  190.2461   31.1652    0.5528
 7  412.0000  282.9101      15.9183  250.8077  315.0125  160.9231  404.8972  129.0899    2.4264
 8  240.0000  181.8904       8.8717  163.9990  199.7818   62.8510  300.9298   58.1096    1.0077
 9   67.0000   84.8806      15.3184   53.9882  115.7730  -36.7937  206.5548  -17.8806   -0.3142
10  221.0000  200.3072      10.0342  180.0714  220.5430   80.8929  319.7214   20.6928    0.3563
11  340.0000  361.1547      27.3820  305.9337  416.3756  231.1561  491.1533  -21.1547   -0.4065
12   96.0000  106.4963      13.4656   79.3404  133.6522  -14.2834  227.2759  -10.4963   -0.1828
13  374.0000  256.5831      10.5087  235.3904  277.7759  137.0030  376.1633  117.4169    2.1277
14  371.0000  332.2183      21.8096  288.2350  376.2016  206.5807  457.8559   38.7817    0.7124
15  215.0000  233.3389       9.2189  214.7473  251.9306  114.1923  352.4856  -18.3389   -0.3149
16  136.0000  124.8659      13.5452   97.5495  152.1824    4.0501  245.6818   11.1341    0.1939
17   84.0000  105.4530      13.4701   78.2879  132.6180  -15.3287  226.2347  -21.4530   -0.3740
18  133.0000   79.8456      16.4589   46.6531  113.0380  -42.4329  202.1240   53.1544    0.9483
19  100.0000  128.6446      11.6708  105.1083  152.1809    8.6269  248.6622  -28.6446   -0.4966
20  167.0000  203.8064       8.7088  186.2434  221.3693   84.8159  322.7969  -36.8064   -0.6334
21  193.0000  206.1374      15.4084  175.0633  237.2115   84.4169  327.8579  -13.1374   -0.2308
22  420.0000  239.6524      14.0952  211.2268  268.0781  118.5810  360.7239  180.3476    3.6007
23  218.0000  206.5735       8.7476  188.9324  224.2147   87.5715  325.5756   11.4265    0.1958
24  112.0000  168.2551      10.0570  147.9732  188.5371   48.8330  287.6772  -56.2551   -0.9781
25  180.0000  171.7889       9.1920  153.2515  190.3262   52.6507  290.9271    8.2111    0.1409
26  154.0000  187.9837       8.9500  169.9344  206.0330   68.9204  307.0469  -33.9837   -0.5848
27  153.0000  210.2772      11.7469  186.5873  233.9671   90.2294  330.3251  -57.2772   -1.0021
28  174.0000  230.9924       9.1286  212.5827  249.4020  111.8740  350.1108  -56.9924   -0.9885
29  138.0000   97.0298      14.3259   68.1388  125.9208  -24.1517  218.2114   40.9702    0.7202
30   83.0000   99.9493      16.2368   67.2047  132.6938  -22.2083  222.1069  -16.9493   -0.2992
31   85.0000   85.0603      15.4681   53.8659  116.2547  -36.6909  206.8116   -0.0603 -0.001059
32  219.0000  255.8651      10.8795  233.9246  277.8056  136.1502  375.5800  -36.8651   -0.6386
33  149.0000  251.4543      11.4546  228.3540  274.5546  131.5214  371.3872 -102.4543   -1.8394
34  203.0000  265.7548      11.2624  243.0421  288.4676  145.8960  385.6137  -62.7548   -1.0986
35  349.0000  337.8918      24.2941  288.8981  386.8854  210.4137  465.3698   11.1082    0.2070
36  334.0000  278.6992      25.3820  227.5115  329.8870  150.3619  407.0365   55.3008    1.0537
37  261.0000  255.5870      10.4405  234.5316  276.6423  136.0311  375.1428    5.4130    0.0932
38  333.0000  252.1031      10.1029  231.7286  272.4775  132.6652  371.5409   80.8969    1.4242
39  149.0000  152.7382      12.6149  127.2978  178.1786   32.3326  273.1437   -3.7382   -0.0648
40  283.0000  244.9972      13.2922  218.1910  271.8034  124.2957  365.6987   38.0028    0.6644
41  258.0000  223.8933       9.6582  204.4156  243.3709  104.6052  343.1814   34.1067    0.5881
42  166.0000  244.4854      17.6397  208.9116  280.0591  121.5391  367.4316  -78.4854   -1.4279
43  182.0000  209.6037      11.3781  186.6577  232.5498   89.7004  329.5070  -27.6037   -0.4779
44  124.0000  201.3921       9.5040  182.2254  220.5588   82.1543  320.6298  -77.3921   -1.3572
45   81.0000   73.5587      16.4847   40.3142  106.8033  -48.7339  195.8513    7.4413    0.1314
                   The SAS System       17:38 Thursday, October 26, 2006  90

                                      The REG Procedure
                                        Model: MODEL1
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
                                 Dependent Variable: ELA ELA

                                      Output Statistics

              Hat Diag         Cov                  -------------DFBETAS-------------
            Obs        H       Ratio      DFFITS    Intercept           YB        Area

              1   0.2378      1.3218      0.5277       0.4843      -0.4786     -0.1494
              2   0.0255      1.0902     -0.0605       0.0224      -0.0228     -0.0036
              3   0.0249      1.0745     -0.0929      -0.0043       0.0045     -0.0329
              4   0.2236      1.2388     -0.6709      -0.5055       0.5148     -0.3818
              5   0.0701      1.1529      0.0317      -0.0117       0.0125     -0.0233
              6   0.0819      1.1437      0.1651      -0.0805       0.0846     -0.1144
              7   0.0744      0.7822      0.6880      -0.2006       0.1881      0.5452
              8   0.0231      1.0226      0.1550      -0.0167       0.0190     -0.0329
              9   0.0689      1.1445     -0.0855       0.0456      -0.0476      0.0529
             10   0.0296      1.0959      0.0622       0.0276      -0.0266     -0.0174
             11   0.2202      1.3600     -0.2160       0.0692      -0.0642     -0.1940
             12   0.0532      1.1308     -0.0433       0.0217      -0.0227      0.0247
             13   0.0324      0.8158      0.3895       0.0504      -0.0539      0.2177
             14   0.1397      1.2032      0.2870      -0.0755       0.0692      0.2537
             15   0.0250      1.0929     -0.0504      -0.0077       0.0078     -0.0164
             16   0.0539      1.1312      0.0463       0.0056      -0.0043     -0.0354
             17   0.0533      1.1223     -0.0887       0.0248      -0.0271      0.0630
             18   0.0795      1.0941      0.2788      -0.0292       0.0374     -0.2351
             19   0.0400      1.0984     -0.1014       0.0245      -0.0270      0.0632
             20   0.0223      1.0667     -0.0956       0.0110      -0.0116     -0.0090
             21   0.0697      1.1492     -0.0632      -0.0466       0.0456      0.0253
             22   0.0583      0.5085      0.8962      -0.4466       0.4354      0.5556
             23   0.0225      1.0948      0.0297      -0.0034       0.0036      0.0039
             24   0.0297      1.0337     -0.1711      -0.0264       0.0226      0.0854
             25   0.0248      1.0989      0.0225      -0.0035       0.0039     -0.0069
             26   0.0235      1.0726     -0.0908      -0.0103       0.0088      0.0233
             27   0.0405      1.0419     -0.2059      -0.1298       0.1267      0.0584
             28   0.0245      1.0267     -0.1566      -0.0243       0.0243     -0.0466
             29   0.0603      1.1007      0.1824      -0.0981       0.1022     -0.1052
             30   0.0774      1.1558     -0.0867       0.0676      -0.0688      0.0266
             31   0.0703      1.1542     -0.0003       0.0001      -0.0001      0.0002
             32   0.0348      1.0800     -0.1212       0.0014      -0.0001     -0.0741
             33   0.0385      0.8847     -0.3682       0.0674      -0.0631     -0.2340
             34   0.0372      1.0238     -0.2161      -0.1112       0.1122     -0.0840
             35   0.1733      1.2942      0.0948       0.0877      -0.0878      0.0131
             36   0.1892      1.2239      0.5090       0.4733      -0.4692     -0.0905
             37   0.0320      1.1079      0.0169       0.0022      -0.0024      0.0093
             38   0.0300      0.9603      0.2503       0.0585      -0.0600      0.1174
             39   0.0467      1.1254     -0.0144      -0.0046       0.0043      0.0095
             40   0.0519      1.0969      0.1554      -0.0649       0.0629      0.0997
             41   0.0274      1.0766      0.0987      -0.0208       0.0205      0.0397
             42   0.0914      1.0245     -0.4528       0.2696      -0.2631     -0.2919
             43   0.0380      1.0975     -0.0950       0.0498      -0.0494     -0.0372
             44   0.0265      0.9692     -0.2240       0.0819      -0.0824     -0.0467
             45   0.0798      1.1648      0.0387      -0.0226       0.0235     -0.0235
                    The SAS System        17:38 Thursday, October 26, 2006  91
                                      The REG Procedure
                                        Model: MODEL1
                                 Dependent Variable: ELA ELA

                                      Output Statistics

                               Dependent Predicted    Std Error
 Obs  Variable     Value Mean Predict     95% CL Mean         95% CL Predict    Residual  RStudent

  46  119.0000  208.4552       8.7814  190.7458  226.1646   89.4430  327.4674  -89.4552   -1.5772



                                      Output Statistics
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
   Hat Diag         Cov                -------------DFBETAS-------------
 Obs        H       Ratio      DFFITS    Intercept          YB        Area

 46   0.0226      0.9239     -0.2401       0.0277     -0.0287     -0.0381


               Sum of Residuals                           0
               Sum of Squared Residuals              146436
               Predicted Residual SS (PRESS)         167396
        The SAS System        17:38 Thursday, October 26, 2006  92

                         The UNIVARIATE Procedure
                     Variable:  RESIDUALS  (Residual)

                                 Moments

      N                          46    Sum Weights                 46
      Mean                        0    Sum Observations             0
      Std Deviation      57.0450016    Variance            3254.13221
      Skewness           0.87484829    Kurtosis            1.42297708
      Uncorrected SS     146435.949    Corrected SS        146435.949
      Coeff Variation             .    Std Error Mean      8.41082662


                        Basic Statistical Measures

                  Location                    Variability

          Mean      0.00000     Std Deviation           57.04500
          Median   -7.11722     Variance                    3254
          Mode       .          Range                  282.80186
                     Interquartile Range     68.09039


                         Tests for Location: Mu0=0

             Test           -Statistic-    -----p Value------

             Student's t    t         0    Pr > |t|    1.0000
             Sign           M        -2    Pr >= |M|   0.6587
             Signed Rank    S     -46.5    Pr >= |S|   0.6168


                            Tests for Normality

        Test                  --Statistic---    -----p Value------

        Shapiro-Wilk          W       0.9541    Pr < W      0.0676
        Kolmogorov-Smirnov    D     0.116273    Pr > D      0.1193
        Cramer-von Mises      W-Sq  0.078042    Pr > W-Sq   0.2212
        Anderson-Darling      A-Sq  0.535167    Pr > A-Sq   0.1682



                         Quantiles (Definition 5)

                         Quantile        Estimate

                         100% Max       180.34758
                         99%            180.34758
                         95%            117.41685
                         90%             58.10959
                         75% Q3          34.10672
                         50% Median      -7.11722
                         25% Q1         -33.98367
                         10%            -63.85897
        The SAS System        17:38 Thursday, October 26, 2006  93
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
                                    The UNIVARIATE Procedure
                                Variable:  RESIDUALS  (Residual)

                                    Quantiles (Definition 5)

                                    Quantile        Estimate

                                    5%              -78.48536
                                    1%             -102.45428
                                    0% Min         -102.45428


                                      Extreme Observations

                          ------Lowest------        ------Highest-----

                            Value      Obs            Value      Obs

                          -102.4543       33          58.1096        8
                           -89.4552       46          80.8969       38
                           -78.4854       42         117.4169       13
                           -77.3921       44         129.0899        7
                           -63.8590        4         180.3476       22
                   The SAS System        17:38 Thursday, October 26, 2006  94

                                       The REG Procedure
                                         Model: MODEL1
                                 Dependent Variable: Eqla Eqla

                             Number of Observations Read          46
                             Number of Observations Used          46


                                      Analysis of Variance

                                      Sum of           Mean
         Source                  DF        Squares         Square    F Value    Pr > F

         Model                    2        1164722         582361      56.87    <.0001
                    Error                   43        440301          10240
                           Corrected Total          45        1605023


                      Root MSE            101.19068    R-Square     0.7257
                      Dependent Mean      383.39130    Adj R-Sq     0.7129
                                 Coeff Var            26.39358


                                       Parameter Estimates
                                     Parameter     Standard
 Variable   Label      DF     Estimate        Error  t Value  Pr > |t|    95% Confidence Limits

 Intercept  Intercept   1   9859.40436   1677.56832     5.88    <.0001   6476.26542        13243
 YB         YearBuilt   1     -5.02401      0.85023    -5.91    <.0001     -6.73866     -3.30936
 Area       Area        1      0.21172      0.02367     8.95    <.0001      0.16399      0.25944


                   The SAS System        17:38 Thursday, October 26, 2006  95

                                       The REG Procedure
                                         Model: MODEL1
                                 Dependent Variable: Eqla Eqla
                                       Output Statistics
                                Dependent Predicted    Std Error
Obs  Variable     Value Mean Predict     95% CL Mean        95% CL Predict    Residual  RStudent

  1  571.0000  519.2364      49.3422  419.7284  618.7444  292.1976  746.2751   51.7636    0.5814
  2  321.0000  356.4694      16.1462  323.9075  389.0312  149.8174  563.1213  -35.4694   -0.3514
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
 3 367.0000  438.1576       15.9748  405.9413  470.3740  231.5598  644.7554  -71.1576    -0.7080
 4 722.0000  838.4395       47.8534  741.9340  934.9449  612.7005      1064 -116.4395    -1.3171
 5 169.0000  147.1570       26.7838   93.1424  201.1716  -63.9409  358.2550   21.8430     0.2214
 6 184.0000  119.0730       28.9577   60.6742  177.4718  -93.1891  331.3350   64.9270     0.6653
 7 747.0000  533.7894       27.6025  478.1236  589.4551  322.2629  745.3158  213.2106     2.2963
 8 447.0000  343.4807       15.3835  312.4568  374.5045  137.0655  549.8959  103.5193     1.0359
 9 124.0000  151.6771       26.5621   98.1095  205.2448  -59.3069  362.6611  -27.6771    -0.2804
10  407.0000  383.2895       17.3993  348.2005  418.3786  176.2243  590.3547   23.7105     0.2352
11  616.0000  680.1185       47.4805  584.3649  775.8720  454.7000  905.5370  -64.1185    -0.7134
12  177.0000  194.2721       23.3494  147.1836  241.3607  -15.1606  403.7049  -17.2721    -0.1734
13  669.0000  488.4316       18.2221  451.6831  525.1800  281.0787  695.7844  180.5684     1.8657
14  697.0000  627.2701       37.8180  551.0028  703.5375  409.4136  845.1266   69.7299     0.7390
15  414.0000  443.9713       15.9856  411.7333  476.2094  237.3702  650.5725  -29.9713    -0.2968
16  267.0000  236.4904       23.4874  189.1234  283.8573   26.9948  445.9859   30.5096     0.3067
17  157.0000  194.7761       23.3572  147.6717  241.8804  -14.6603  404.2124  -37.7761    -0.3798
18  241.0000  147.4619       28.5398   89.9060  205.0179  -64.5698  359.4936   93.5381     0.9627
19  184.0000  239.9688       20.2372  199.1567  280.7809   31.8573  448.0803  -55.9688    -0.5600
20  329.0000  385.4003       15.1011  354.9460  415.8545  179.0699  591.7306  -56.4003    -0.5592
21  351.0000  400.2734       26.7184  346.3907  454.1561  189.2092  611.3376  -49.2734    -0.5004
22  766.0000  448.9656       24.4411  399.6753  498.2559  239.0269  658.9044  317.0344     3.6660
23  406.0000  390.6932       15.1683  360.1033  421.2830  184.3428  597.0436   15.3068     0.1512
24  209.0000  319.4828       17.4390  284.3137  354.6518  112.4040  526.5615 -110.4828    -1.1114
25  338.0000  323.7424       15.9389  291.5985  355.8864  117.1559  530.3290   14.2576     0.1410
26  303.0000  356.8018       15.5193  325.5042  388.0994  150.3453  563.2583  -53.8018    -0.5336
27  301.0000  404.8591       20.3692  363.7807  445.9375  196.6953  613.0230 -103.8591    -1.0490
28  324.0000  439.4830       15.8291  407.5605  471.4054  232.9308  646.0351 -115.4830    -1.1601
29  258.0000  175.3321       24.8413  125.2349  225.4293  -34.7976  385.4618   82.6679     0.8398
30  156.0000  176.7505       28.1547  119.9713  233.5298  -35.0717  388.5727  -20.7505    -0.2111
31  158.0000  156.1867       26.8218  102.0954  210.2780  -54.9308  367.3043    1.8133     0.0184
32  407.0000  485.8084       18.8651  447.7633  523.8534  278.2218  693.3949  -78.8084    -0.7892
33  300.0000  475.7053       19.8623  435.6492  515.7614  267.7408  683.6698 -175.7053    -1.8176
34  376.0000  509.7238       19.5290  470.3398  549.1078  301.8877  717.5599 -133.7238    -1.3601
35  775.0000  661.8668       42.1261  576.9115  746.8222  440.8189  882.9147  113.1332     1.2372
36  619.0000  549.4799       44.0126  460.7200  638.2398  326.9421  772.0177   69.5201     0.7592
37  597.0000  486.5261       18.1040  450.0160  523.0363  279.2154  693.8369  110.4739     1.1127
38  594.0000  480.6955       17.5185  445.3660  516.0249  273.5894  687.8016  113.3045     1.1409
39  262.0000  291.8857       21.8743  247.7719  335.9995   83.1016  500.6698  -29.8857    -0.2993
40  523.0000  460.4385       23.0487  413.9563  506.9206  251.1412  669.7357   62.5615     0.6305
41  451.0000  422.9882       16.7474  389.2138  456.7626  216.1417  629.8347   28.0118     0.2777
42  313.0000  455.2938       30.5873  393.6086  516.9789  242.1041  668.4834 -142.2938    -1.4963
43  344.0000  392.3233       19.7296  352.5347  432.1119  184.4102  600.2365  -48.3233    -0.4825
44  271.0000  378.6995       16.4800  345.4643  411.9346  171.9404  585.4586 -107.6995    -1.0808
45  119.0000  128.7716       28.5846   71.1253  186.4179  -83.2846  340.8279   -9.7716    -0.0995
                   The SAS System        17:38 Thursday, October 26, 2006  96
                                        The REG Procedure
                                          Model: MODEL1
                                  Dependent Variable: Eqla Eqla
                                        Output Statistics
               Hat Diag         Cov                -------------DFBETAS------------
            Obs        H       Ratio      DFFITS    Intercept          YB        Area

             1   0.2378      1.3744       0.3247       0.2980     -0.2945     -0.0919
             2   0.0255      1.0915      -0.0568       0.0210     -0.0214     -0.0033
             3   0.0249      1.0621      -0.1132      -0.0052      0.0054     -0.0401
             4   0.2236      1.2242      -0.7069      -0.5326      0.5424     -0.4023
             5   0.0701      1.1500       0.0608      -0.0224      0.0240     -0.0447
             6   0.0819      1.1327       0.1987      -0.0968      0.1018     -0.1377
             7   0.0744      0.8131       0.6511      -0.1898      0.1780      0.5159
             8   0.0231      1.0185       0.1593      -0.0172      0.0195     -0.0338
             9   0.0689      1.1461      -0.0763       0.0407     -0.0425      0.0472
            10    0.0296      1.1015       0.0411       0.0182     -0.0176     -0.0115
            11    0.2202      1.3273      -0.3791       0.1215     -0.1126     -0.3405
            12    0.0532      1.1311      -0.0411       0.0206     -0.0215      0.0235
            13    0.0324      0.8734       0.3416       0.0442     -0.0472      0.1909
            14    0.1397      1.1999       0.2978      -0.0783      0.0718      0.2632
            15    0.0250      1.0937      -0.0475      -0.0073      0.0073     -0.0155
            16    0.0539      1.1267       0.0732       0.0089     -0.0068     -0.0560
            17    0.0533      1.1219      -0.0901       0.0252     -0.0275      0.0639
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
          18   0.0795     1.0920     0.2830     -0.0297     0.0379    -0.2387
          19   0.0400     1.0932    -0.1143      0.0276    -0.0305     0.0713
          20   0.0223     1.0734    -0.0844      0.0097    -0.0102    -0.0080
          21   0.0697     1.1332    -0.1370     -0.1011     0.0989     0.0549
          22   0.0583     0.4955     0.9125     -0.4548     0.4434     0.5657
          23   0.0225     1.0960     0.0229     -0.0026     0.0028     0.0030
          24   0.0297     1.0139    -0.1945     -0.0300     0.0257     0.0970
          25   0.0248     1.0989     0.0225     -0.0035     0.0039    -0.0069
          26   0.0235     1.0769    -0.0828     -0.0094     0.0080     0.0212
          27   0.0405     1.0350    -0.2156     -0.1359     0.1327     0.0612
          28   0.0245     1.0007    -0.1837     -0.0285     0.0285    -0.0547
          29   0.0603     1.0863     0.2127     -0.1144     0.1191    -0.1227
          30   0.0774     1.1595    -0.0612      0.0477    -0.0485     0.0188
          31   0.0703     1.1542     0.0050     -0.0011     0.0012    -0.0040
          32   0.0348     1.0638    -0.1498      0.0017    -0.0001    -0.0916
          33   0.0385     0.8893    -0.3639      0.0666    -0.0623    -0.2312
          34   0.0372     0.9795    -0.2675     -0.1377     0.1389    -0.1040
          35   0.1733     1.1659     0.5665      0.5242    -0.5248     0.0785
          36   0.1892     1.2705     0.3667      0.3410    -0.3380    -0.0652
          37   0.0320     1.0161     0.2023      0.0264    -0.0281     0.1114
          38   0.0300     1.0095     0.2005      0.0468    -0.0480     0.0940
          39   0.0467     1.1186    -0.0663     -0.0213     0.0196     0.0441
          40   0.0519     1.1003     0.1475     -0.0616     0.0597     0.0946
          41   0.0274     1.0973     0.0466     -0.0098     0.0097     0.0187
          42   0.0914     1.0107    -0.4745      0.2825    -0.2757    -0.3059

          43   0.0380     1.0972    -0.0959      0.0503    -0.0499    -0.0375
          44   0.0265     1.0153    -0.1784      0.0652    -0.0656    -0.0372
          45   0.0798     1.1654    -0.0293      0.0171    -0.0178     0.0178
                The SAS System        17:38 Thursday, October 26, 2006  97

                                    The REG Procedure
                                      Model: MODEL1
                              Dependent Variable: Eqla Eqla

                                    Output Statistics

                             Dependent Predicted    Std Error
 Obs  Variable     Value Mean Predict     95% CL Mean        95% CL Predict    Residual  RStudent

  46  305.0000  394.2923      15.2270  363.5841  425.0005  187.9243  600.6603  -89.2923   -0.8904

                                    Output Statistics

             Hat Diag         Cov               -------------DFBETAS-------------
          Obs        H       Ratio      DFFITS    Intercept          YB        Area

          46   0.0226      1.0381     -0.1355       0.0156     -0.0162     -0.0215


                       Sum of Residuals                        0
                       Sum of Squared Residuals           440301
                       Predicted Residual SS (PRESS)      506811
                The SAS System        17:38 Thursday, October 26, 2006  98

                                 The UNIVARIATE Procedure
                              Variable:  RESIDUALS  (Residual)

                                         Moments

                N                          46    Sum Weights                 46
                Mean                        0    Sum Observations             0
                Std Deviation      98.9164464    Variance            9784.46337
                Skewness            0.8476179    Kurtosis            1.21126023
                Uncorrected SS     440300.852    Corrected SS        440300.852
                Coeff Variation             .    Std Error Mean      14.5844344
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

```
                Basic Statistical Measures

          Location                    Variability

  Mean       0.0000     Std Deviation           98.91645
  Median   -19.0113     Variance                    9784
  Mode        .         Range                  492.73969
             Interquartile Range    129.04549


                 Tests for Location: Mu0=0

     Test           -Statistic-    -----p Value------

     Student's t    t         0    Pr > |t|    1.0000
     Sign           M        -2    Pr >= |M|   0.6587
     Signed Rank    S     -42.5    Pr >= |S|   0.6475


                    Tests for Normality

Test                  --Statistic---    -----p Value------

Shapiro-Wilk          W     0.958064    Pr < W      0.0964
Kolmogorov-Smirnov    D     0.091047    Pr > D     >0.1500
Cramer-von Mises      W-Sq  0.063547    Pr > W-Sq  >0.2500
Anderson-Darling      A-Sq  0.444115    Pr > A-Sq  >0.2500


                 Quantiles (Definition 5)

                  Quantile       Estimate

                  100% Max       317.0344
                  99%            317.0344
                  95%            180.5684
                  90%            113.1332
                  75% Q3          64.9270
                  50% Median     -19.0113
                  25% Q1         -64.1185
                  10%           -115.4830
The SAS System        17:38 Thursday, October 26, 2006  99

                 The UNIVARIATE Procedure
             Variable:  RESIDUALS  (Residual)

                 Quantiles (Definition 5)

                  Quantile       Estimate

                  5%            -133.7238
                  1%            -175.7053
                  0% Min        -175.7053

                   Extreme Observations

        ------Lowest-----        -----Highest-----

          Value      Obs           Value      Obs

        -175.705      33         113.133       35
        -142.294      42         113.305       38
        -133.724      34         180.568       13
        -116.439       4         213.211        7
        -115.483      28         317.034       22
```

Figure A-2. SAS output for modeling air-tightness using multiple regression

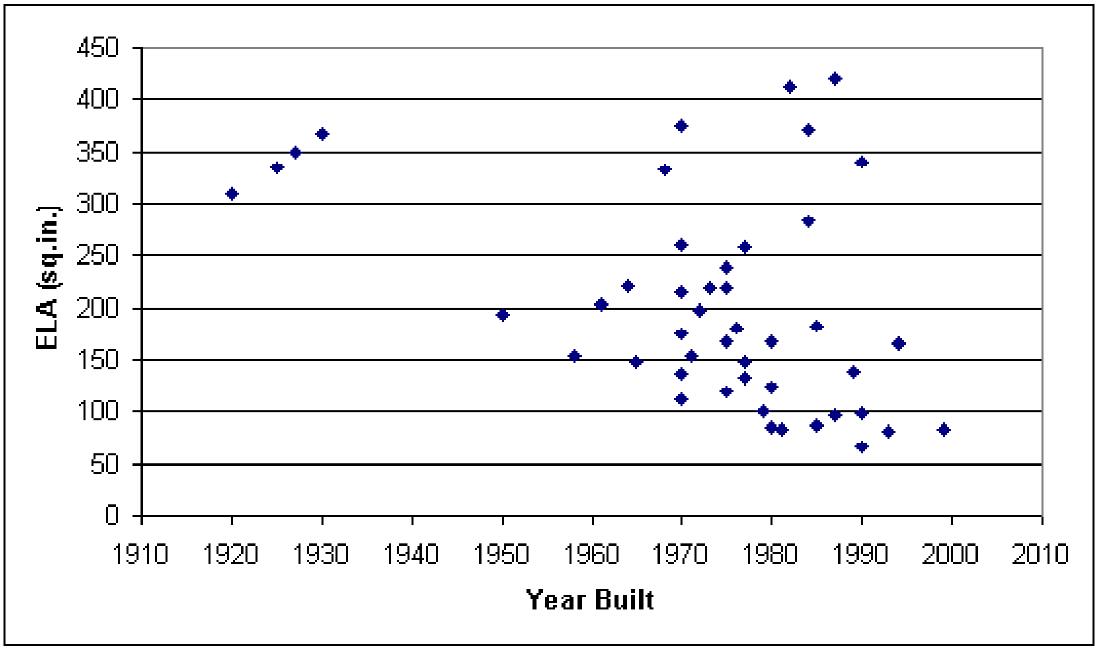

Figure A-3. Plot of Year Built vs. ELA.

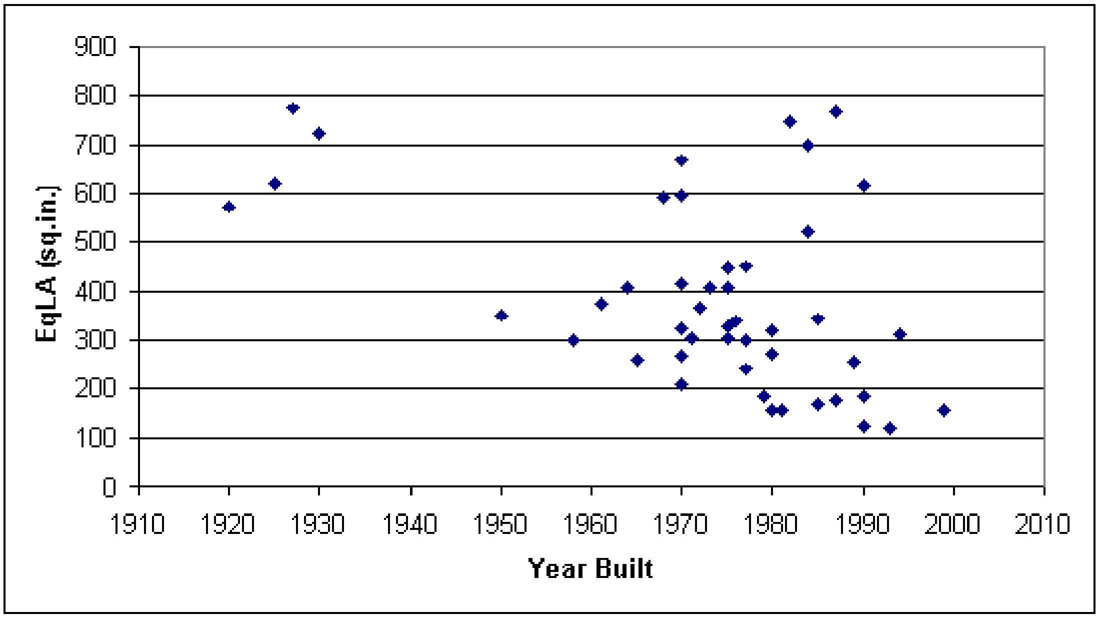

Figure A-4. Plot of Area vs. ELA.

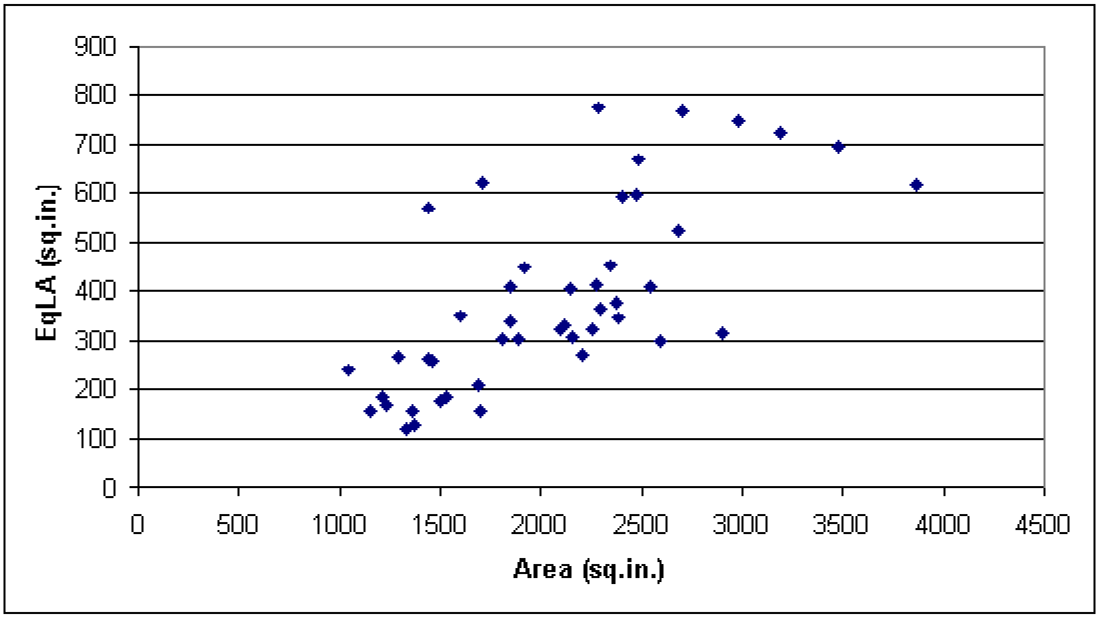

Figure A-5. Plot of Year Built vs. EqLA.

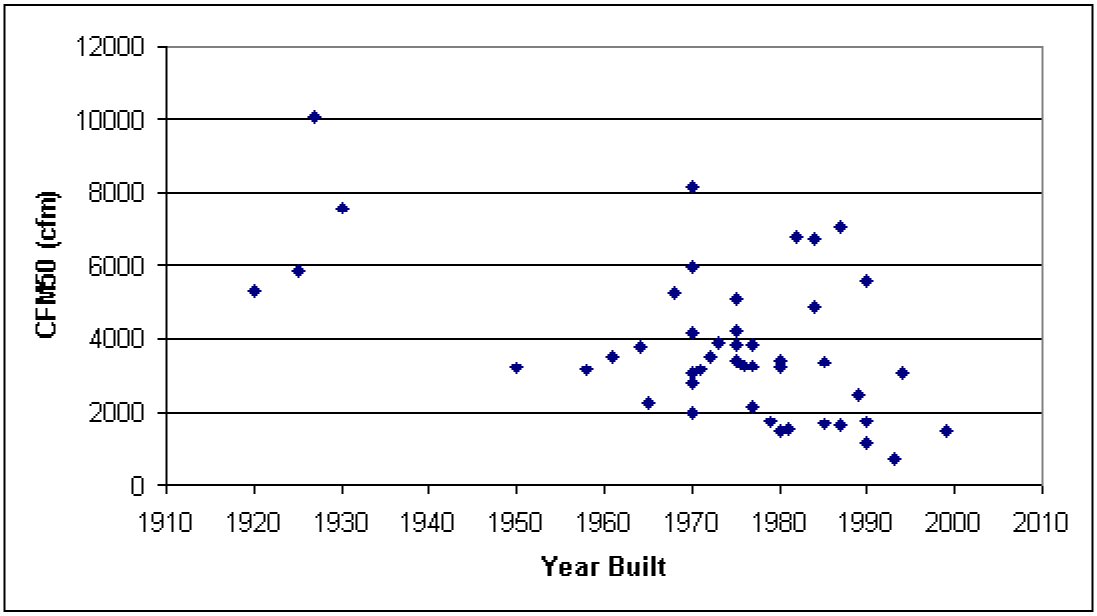

Figure A-6. Plot of Area vs. EqLA.

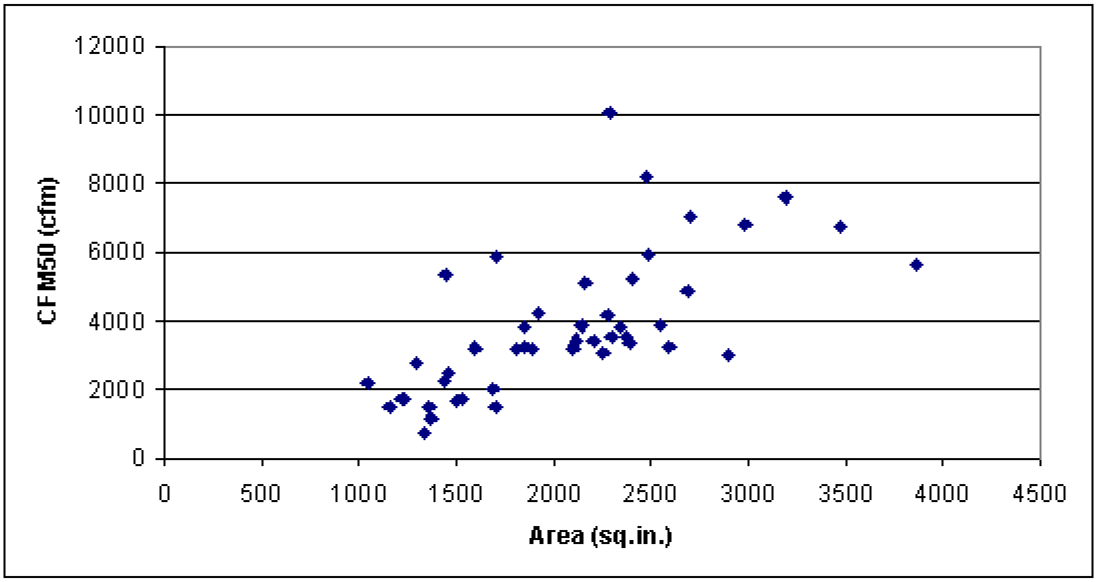

Figure A-7. Plot of Year Built vs. CFM50.

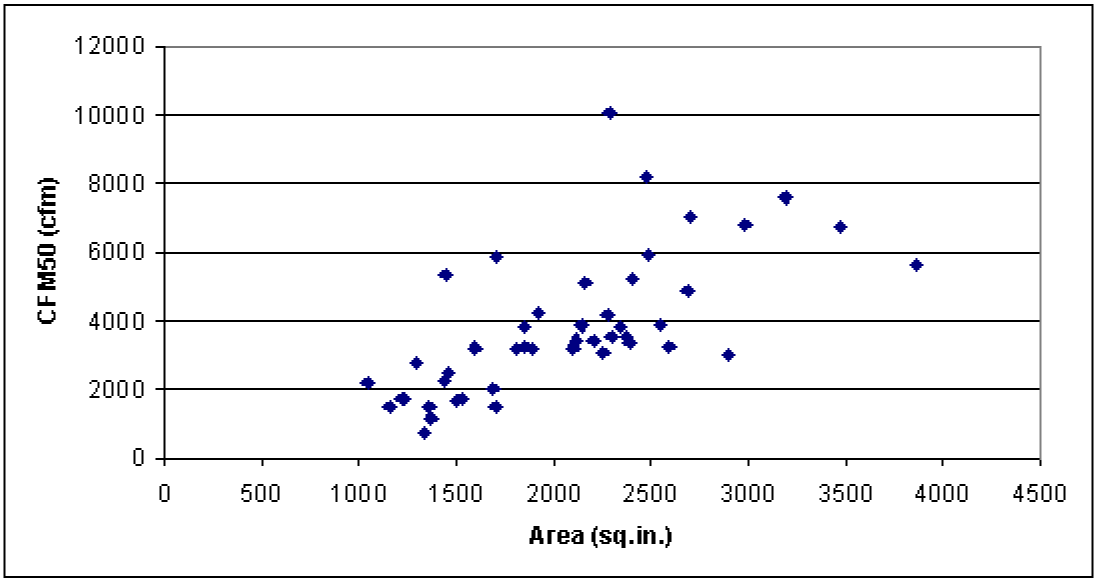

Figure A-8. Plot of Area vs. CFM50.

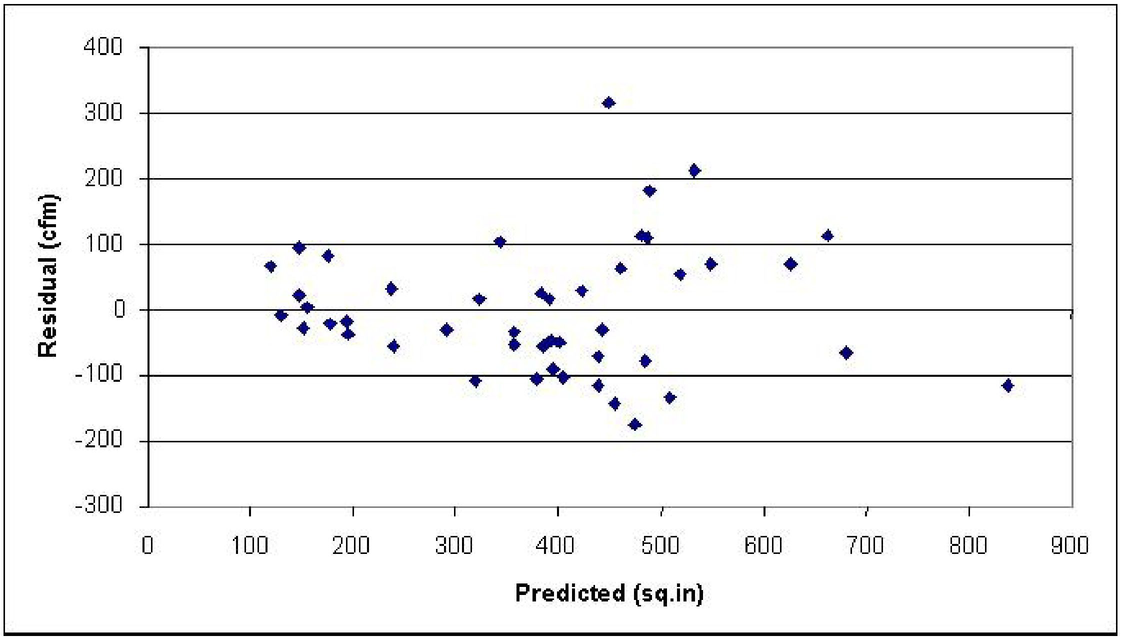

Figure A-9. Plot of predicted vs. residual for ELA.

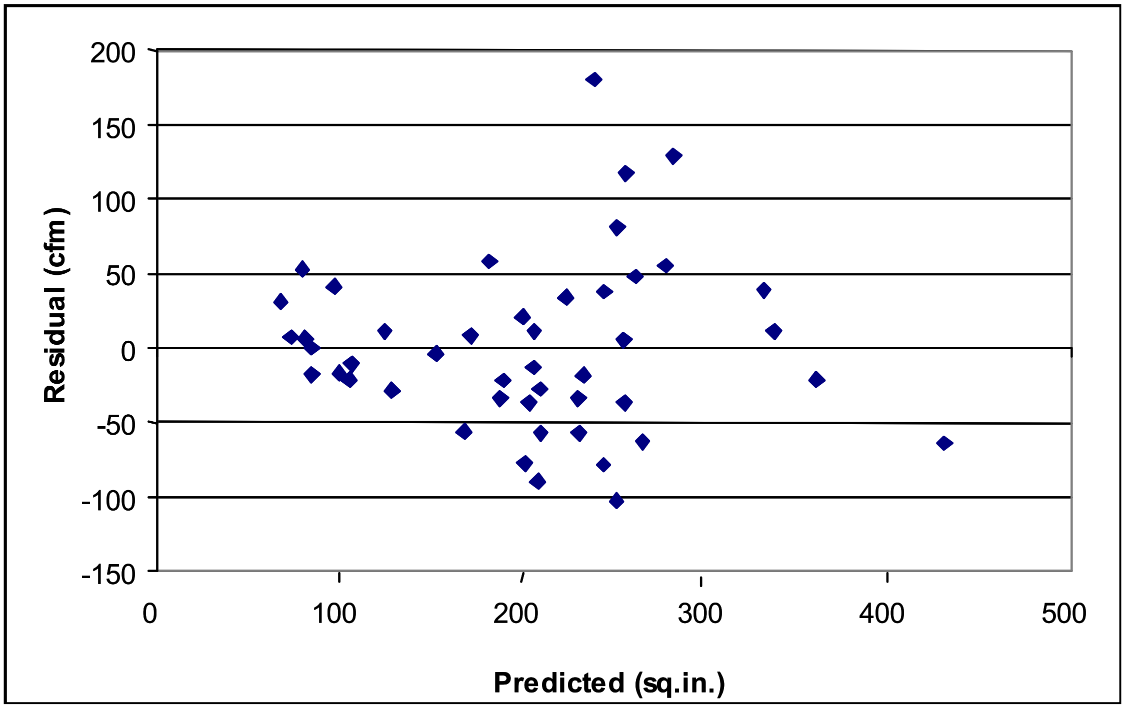

Figure A-10. Plot of predicted vs. residual for EqLA.

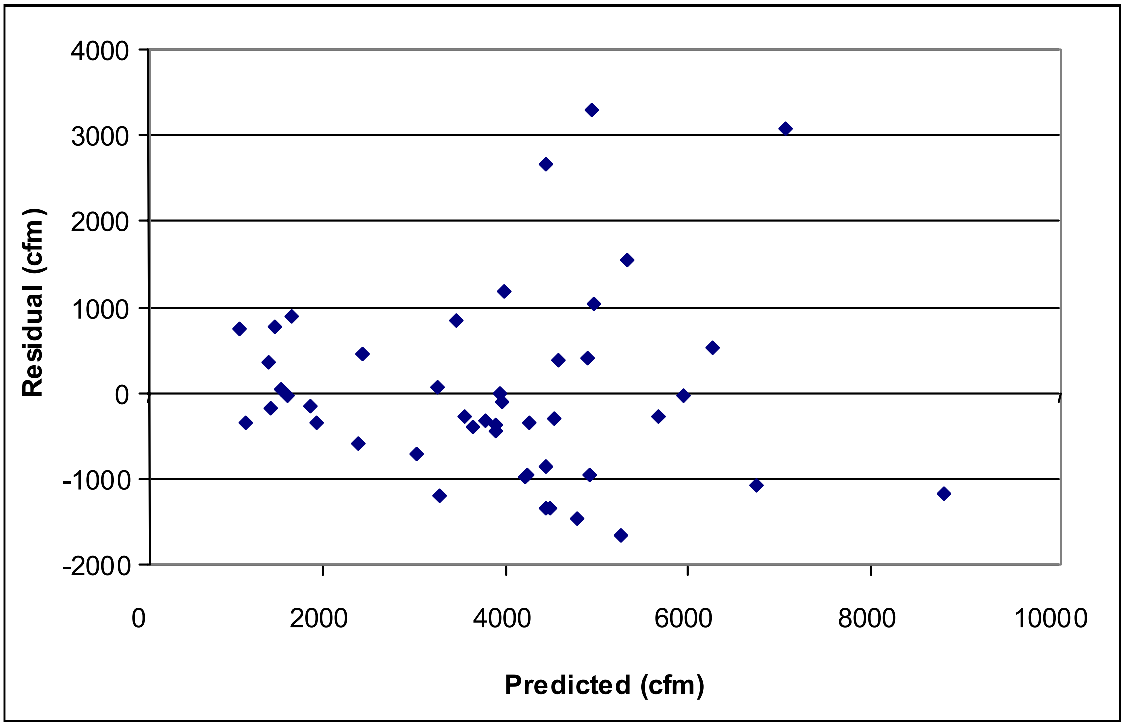

Figure A-11. Plot of predicted vs. residual for CFM50.

Figure A-12. SAS program for cluster analysis.

```
/*******************************************************************/
/* COMMENTS                        NAME                        DATE MODIFIED
 Initial Version             Jinson Erinjeri                  10/12/2006
 Cluster Analysis of year built, area and cfm50
/*******************************************************************/

data complete;
input test year area cfm50;
cards;
1 1920 1445 5318
2 1980 2100 3212.1
3 1972 2296 3512.2
4 1930 3190 7579.7
5 1985 1230 1697.6
6 1990 1216 1744.6
8 1982 2985 6812.1
11 1975 1920 4233.3
12 1990 1370 1156.2
13 1964 1847 3790
14 1990 3866 5602.1
16 1987 1500 1651.4
18 1970 2486 5927.8
19 1984 3474 6723.2
20 1970 2276 4160.8
21 1970 1296 2798.4
26 1981 1360 1506.3
27 1977 1041.6 2177.2
28 1979 1526 1723.2
29 1975 2118 3443.9
30 1950 1595 3201.6
31 1987 2703 7033.8
33 1975 2143 3855.6
34 1970 1688 2003
35 1976 1850.5 3263.8
36 1971 1888 3168
37 1958 1806.5 3163.6
38 1970 2254.8 3066
39 1989 1458 2468.4
40 1999 1702 1495
42 1980 1154 1496.4
43 1973 2544.8 3885.9
44 1977 2592 3258.2
45 1961 2373 3524.8
46 1927 2284.8 10057.4
47 1925 1706.5 5846.7
48 1970 2477 8173.4
51 1968 2402 5237.4
52 1965 1439 2242.5
53 1984 2686 4891.2
54 1977 2343 3827.9
55 1994 2899 3029.2
56 1985 2388 3372
57 1980 2205 3396
58 1993 1333 747
59 1975 2160 5087
60 2004 1648 2110
61 1970 2250 7332
62 1997 1789 1876
```

Figure A-12. SAS program for cluster analysis.

```
63 1995 2300 2808
64 2001 2458 2915
65 1994 2100 2526
66 1995 2275 2226
67 1955 2200 5432
68 1990 2143 3339
69 1985 1600 2072
70 1957 1550 2664
71 1988 2500 4087
72 2000 2800 1803
73 1975 2070 5499
74 1970 2200 3015
75 2004 2200 2502
76 1972 1700 5889
77 1983 1350 2155
78 1995 2200 2447
79 1991 1950 2997
2 1930 1458 12060.4
3 1905 3871 12305.8
4 1985 1973 2470.8
5 1900 1458 4825.9
6 1980 2266 3230.3
7 1905 2197 7542.2
8 1915 2193 7250.4
9 1940 3570 11740.2
10 1990 4148 8093.6
11 1930 535 2915.4
12 1930 856 12305.8
15 1930 1630 12558.4
16 1975 1418 2707.3
17 1970 816 809.3
19 1953 2959 4696.1
20 1980 1546 4482.6
22 1940 1437 2104.3
;
proc standard data=complete mean=0 std=1 out=standarddata;
 var year area cfm50;
run;
proc princomp data=standarddata out=scrs;
 var year area cfm50;
proc plot data=scrs;
 plot prin2*prin1='*'/vaxis=-4 to 4 by 2 haxis=-4 to 4 by 2
 vpos=35 hpos=60;
run;
proc fastclus data=standarddata out=cluster1 maxclusters=3 random=2342901 maxiter=3;
 var year area cfm50;
run;

proc princomp data=cluster1 out=scrs1;
 var year area cfm50;
proc plot data=scrs1;
 plot prin2*prin1=cluster /vaxis=-4 to 4 by 2 haxis=-4 to 4 by 2
 vpos=35 hpos=60;
run;


/*To compute Beale's Statistic*/

proc means uss data=cluster1;
 var distance;
run;
```

```
proc sort data=cluster1;
 by test;
run;
proc sort data=complete;
 by test;
run;

  /* To obtain the mean values as in the original data set*/

data avg;
 merge cluster1 complete;
 by test;
run;
proc sort data=avg;
 by cluster;
run;
proc means data=avg;
 var year area cfm50;
 by cluster;
run;
```

Figure A-12. SAS program for cluster analysis.

Figure A-13. SAS output for cluster analysis.

```
  The SAS System          06:08 Sunday, October 29, 2006   1

                    The PRINCOMP Procedure

                   Observations          83
                   Variables              3


                       Simple Statistics

           year              area             cfm50

  Mean       0.000000000       0.000000000       0.000000000
  StD        1.000000000       1.000000000       1.000000000



                      Correlation Matrix

                 year        area       cfm50

           year       1.0000      0.0615      -.6144
           area       0.0615      1.0000      0.4160
           cfm50      -.6144      0.4160      1.0000



            Eigenvalues of the Correlation Matrix

     Eigenvalue    Difference    Proportion    Cumulative

   1    1.71442444    0.65739868        0.5715        0.5715
   2    1.05702576    0.82847597        0.3523        0.9238
   3    0.22854980                      0.0762        1.0000

                         Eigenvectors

               Prin1         Prin2         Prin3

        year       -.587654      0.558395      0.585541
        area       0.368800      0.828991      -.420428
        cfm50      0.720173      0.031118      0.693096

  The SAS System          06:08 Sunday, October 29, 2006   3

                    The FASTCLUS Procedure
Replace=FULL  Radius=0  Maxclusters=3 Maxiter=3  Converge=0.02

                         Initial Seeds

 Cluster              year              area              cfm50

  1         -1.636055009      -1.735501748       2.895507852
  2          0.926068873      -1.042749859      -1.262840225
  3          0.804062974       3.045502901       1.380137149


      Minimum Distance Between Initial Seeds = 4.869705
```

Figure A-13. SAS output for cluster analysis.

```
                                    Iteration History

                            Relative Change in Cluster Seeds
               Iteration    Criterion           1           2           3
                   1       1.0567      0.3770      0.2630      0.3522
                   2       0.6622      0.0552      0.0125      0.0209
                   3       0.6590           0           0           0



                          Convergence criterion is satisfied.


                       Criterion Based on Final Seeds =   0.6590


                                     Cluster Summary

                                    Maximum Distance
        RMS Std           from Seed     Radius     Nearest     Distance Between
      Cluster     Frequency    Deviation      to Observation    Exceeded    Cluster
                                    Cluster Centroids

        1              10       0.9042             2.4190                            3
                                         2.8998
        2              61       0.5596             1.8083                            3
                                         2.5636
        3              12       0.9484             3.1050                            2
                                         2.5636


                                Statistics for Variables

           Variable     Total STD    Within STD      R-Square     RSQ/(1-RSQ)
           year           1.00000       0.64195      0.597954        1.487277
           area           1.00000       0.73546      0.472286        0.894966
           cfm50          1.00000       0.63127      0.611222        1.572160
           OVER-ALL       1.00000       0.67119      0.560487        1.275247


                              Pseudo F Statistic =    51.01
               The SAS System          06:08 Sunday, October 29, 2006   4

                                 The FASTCLUS Procedure
             Replace=FULL  Radius=0  Maxclusters=3 Maxiter=3  Converge=0.02

                   Approximate Expected Over-All R-Squared =   0.47006


                          Cubic Clustering Criterion =    4.206

           WARNING: The two values above are invalid for correlated variables.


                                      Cluster Means

              Cluster              year              area              cfm50

                1         -1.993938979      -0.689359257       1.370949444
                2          0.374708881      -0.205238372      -0.466148561
                3         -0.243154327       1.617761107       1.227130650
```

Figure A-13. SAS output for cluster analysis.

```
                   Cluster Standard Deviations

 Cluster              year              area             cfm50

  1          0.451566322       0.829465929       1.249229775
  2          0.545046910       0.683875529       0.417984165
  3          1.099917200       0.905501775       0.817534890
  The SAS System          06:08 Sunday, October 29, 2006   5



                      The PRINCOMP Procedure

                     Observations          83
                     Variables              3

                        Simple Statistics

           year              area              cfm50

  Mean       0.000000000       0.000000000       0.000000000
  StD        1.000000000       1.000000000       1.000000000


                        Correlation Matrix

                 year        area       cfm50

           year       1.0000      0.0615      -.6144
           area       0.0615      1.0000      0.4160
           cfm50      -.6144      0.4160      1.0000



               Eigenvalues of the Correlation Matrix

     Eigenvalue    Difference    Proportion    Cumulative

   1    1.71442444    0.65739868        0.5715        0.5715
   2    1.05702576    0.82847597        0.3523        0.9238
   3    0.22854980                      0.0762        1.0000

                           Eigenvectors

                Prin1          Prin2          Prin3

        year       -.587654      0.558395      0.585541
        area       0.368800      0.828991      -.420428
        cfm50      0.720173      0.031118      0.693096


  The SAS System          06:08 Sunday, October 29, 2006   7

                       The MEANS Procedure

     Analysis Variable : DISTANCE Distance to Cluster Seed

                               USS
```

Figure A-13. SAS output for cluster analysis.

```
                                      108.1201270

              The SAS System          06:08 Sunday, October 29, 2006   8

--------------------------------------------- Cluster=1 -------------------------------
                                   ----------------

                                  The MEANS Procedure

    Variable     N            Mean         Std Dev         Minimum         Maximum

    year        10         1921.20      11.1035530         1900.00         1930.00
    area        10         1576.33     571.1355746     535.0000000         2284.80
    cfm50       10         8068.10         3472.46         2915.49        12558.48


--------------------------------------------- Cluster=2 -------------------------------
                                   ----------------

    Variable     N            Mean         Std Dev         Minimum         Maximum

    year        61         1979.44      13.4021448         1940.00         2004.00
    area        61         1909.68     470.8881097     816.0000000         2899.00
    cfm50       61         2961.55         1161.86     747.0000000         5889.00



--------------------------------------------- Cluster=3 -------------------------------
                                   ----------------

    Variable     N            Mean         Std Dev         Minimum         Maximum

    year        12         1964.25      27.0458365         1905.00         1990.00
    area        12         3164.92     623.4906806         2250.00         4148.00
    cfm50       12         7668.33         2272.49         4696.09        12305.89

              The SAS System          06:08 Sunday, October 29, 2006   9

                                The PRINCOMP Procedure

                               Observations          83
                               Variables              3

                                   Simple Statistics

                       year              area             cfm50

              Mean       0.000000000       0.000000000       0.000000000
              StD        1.000000000       1.000000000       1.000000000

                                  Correlation Matrix

                             year        area       cfm50

                       year       1.0000      0.0615      -.6144
                       area       0.0615      1.0000      0.4160
                       cfm50      -.6144      0.4160      1.0000


                         Eigenvalues of the Correlation Matrix
```

Figure A-13. SAS output for cluster analysis.

```
              Eigenvalue    Difference    Proportion    Cumulative

         1    1.71442444    0.65739868        0.5715        0.5715
         2    1.05702576    0.82847597        0.3523        0.9238
         3    0.22854980                      0.0762        1.0000

                                Eigenvectors

                      Prin1         Prin2         Prin3

              year       -.587654      0.558395      0.585541
              area       0.368800      0.828991      -.420428
              cfm50      0.720173      0.031118      0.693096

         The SAS System          06:08 Sunday, October 29, 2006  11

                           The FASTCLUS Procedure
       Replace=FULL  Radius=0  Maxclusters=4 Maxiter=3  Converge=0.02

                                Initial Seeds

        Cluster              year              area              cfm50

          1         -1.636055009      -1.735501748       2.895507852
          2         -0.009309687      -1.793594150      -1.240404669
          3          0.804062974       3.045502901       1.380137149
          4         -2.652770835       2.643213020       2.895507852

            Minimum Distance Between Initial Seeds = 3.795772

                              Iteration History

                      Relative Change in Cluster Seeds
   Iteration    Criterion           1           2           3           4

       1       1.1720      0.4837      0.4446      0.5218      0.2993
       2       0.6025      0.0708      0.0150      0.0454           0
       3       0.5974           0     0.00723      0.0217           0


          WARNING: Iteration limit reached without convergence.

                Criterion Based on Final Seeds =   0.5968

                               Cluster Summary

                              Maximum Distance
   RMS Std           from Seed      Radius      Nearest     Distance Between
Cluster     Frequency    Deviation       to Observation    Exceeded    Cluster
                              Cluster Centroids

  1             10       0.9042              2.4190                      4
                                  2.9966
  2             52       0.5173              1.7091                      3
                                  1.7127
  3             18       0.6616              2.2039                      2
                                  1.7127
  4              3       0.7406              1.2003                      1
                                  2.9966
                          Statistics for Variables
```

Figure A-13. SAS output for cluster analysis.

```
Variable     Total STD    Within STD      R-Square     RSQ/(1-RSQ)

year           1.00000       0.53729      0.721886        2.595646
area           1.00000       0.67404      0.562293        1.284633
cfm50          1.00000       0.61553      0.634980        1.739574
OVER-ALL       1.00000       0.61152      0.639720        1.775615
    The SAS System          06:08 Sunday, October 29, 2006  12

                      The FASTCLUS Procedure
  Replace=FULL  Radius=0  Maxclusters=4 Maxiter=3  Converge=0.02

                  Pseudo F Statistic =    46.76

        Approximate Expected Over-All R-Squared =   0.63022

              Cubic Clustering Criterion =    0.504

WARNING: The two values above are invalid for correlated variables.

                          Cluster Means

   Cluster              year              area              cfm50

    1         -1.993938979      -0.689359257       1.370949444
    2          0.375478149      -0.361549421      -0.535725921
    3          0.329595588       1.066149549       0.409193954
    4         -1.839398174       2.167823534       2.260920762


                   Cluster Standard Deviations

   Cluster              year              area              cfm50

    1          0.451566322       0.829465929       1.249229775
    2          0.547789827       0.600557150       0.376878197
    3          0.519690581       0.797586972       0.637937227
    4          0.733164209       0.495619464       0.928492989

    The SAS System          06:08 Sunday, October 29, 2006  13
                      The PRINCOMP Procedure

                     Observations          83
                     Variables              3


                        Simple Statistics

             year              area             cfm50

    Mean       0.000000000       0.000000000       0.000000000
    StD        1.000000000       1.000000000       1.000000000


                        Correlation Matrix

                   year        area       cfm50

             year       1.0000      0.0615      -.6144
             area       0.0615      1.0000      0.4160
             cfm50      -.6144      0.4160      1.0000
```

Figure A-13. SAS output for cluster analysis.

```
                        Eigenvalues of the Correlation Matrix

                 Eigenvalue    Difference    Proportion    Cumulative

              1    1.71442444    0.65739868        0.5715        0.5715
              2    1.05702576    0.82847597        0.3523        0.9238
              3    0.22854980                      0.0762        1.0000

                                     Eigenvectors

                          Prin1         Prin2         Prin3

                   year       -.587654      0.558395      0.585541
                   area       0.368800      0.828991      -.420428
                   cfm50      0.720173      0.031118      0.693096

              The SAS System          06:08 Sunday, October 29, 2006  15

                                 The MEANS Procedure

                Analysis Variable : DISTANCE Distance to Cluster Seed

                                         USS
                                      88.7007288

              The SAS System          06:08 Sunday, October 29, 2006  16
--------------------------------------------- Cluster=1 ------------------------------
                                     -----------

                                 The MEANS Procedure

    Variable     N             Mean          Std Dev          Minimum          Maximum

    year        10          1921.20      11.1035530         1900.00         1930.00
    area        10          1576.33     571.1355746     535.0000000         2284.80
    cfm50       10          8068.10         3472.46         2915.49        12558.48



--------------------------------------------- Cluster=2 ------------------------------
                                   ----------------

    Variable     N             Mean          Std Dev          Minimum          Maximum

    year        52          1979.46      13.4695904         1940.00         2004.00
    area        52          1802.05     413.5185557     816.0000000         2458.00
    cfm50       52          2768.15         1047.60     747.0000000         5889.00



--------------------------------------------- Cluster=3 ------------------------------
                                   ----------------

    Variable     N             Mean          Std Dev          Minimum          Maximum
    year        18          1978.33      12.7786587         1953.00         2000.00
    area        18          2785.10     549.1850572         2160.00         4148.00
    cfm50       18          5394.72         1773.26         1803.00         8173.40
```

Figure A-13. SAS output for cluster analysis.

```
--------------------------------------------- Cluster=4 ------------------------------
                                   ----------------

    Variable      N            Mean          Std Dev          Minimum          Maximum

    year          3         1925.00       18.0277564          1905.00          1940.00
    area          3         3543.67      341.2628508          3190.00          3871.00
    cfm50         3        10541.94          2580.92          7579.70         12305.89
```

Figure A-13. SAS output for cluster analysis.

Table A-2. Untaped data and calculations for GSCA.

APT	Untaped									
Test No.	CFM50	Attic (P_A)	Duct (P_D)	Correlation Coefficient	Pda @50Pa	Pda @25 Pa	Leakage Coeff	Flow Exponent	CFM @25Pa	CFM Corrected @25Pa
3	3513	48.5	0.8	99.81	47.6	23.8	285.00	0.64	2251.00	2323.00
5	1720	47.4	2.9	99.98	44.5	22.3	122.50	0.67	1065.00	1152.00
6	1744	49.6	0.9	99.96	48.7	24.3	143.80	0.64	1121.00	1140.00
11	4241	47.8	2.4	99.92	45.3	22.7	350.30	0.64	2722.00	2897.00
12	1156	48.4	0.3	99.92	48.1	24.0	99.00	0.63	748.10	766.80
13	3791	46.5	1.5	99.97	45.0	22.5	327.40	0.63	2456.00	2624.00
14	5594	45.4	1.2	99.94	44.1	22.1	515.20	0.61	3670.00	3962.00
19	6731	48.0	1.1	99.76	46.9	23.4	532.90	0.65	4291.00	4473.00
20	4166	49.0	1.2	99.82	47.8	23.9	297.90	0.67	2608.00	2687.00
21	2794	49.6	0.7	99.91	48.9	24.4	182.40	0.70	1725.00	1753.00
26	1505	47.2	0.5	99.95	46.7	23.3	120.80	0.65	963.20	1007.00
27	2180	45.8	0.2	99.96	45.6	22.8	201.80	0.61	1428.00	1511.00
28	1720	48.4	0.2	99.96	48.2	24.1	147.70	0.63	1115.00	1141.00
29	3450	48.4	0.4	99.51	48.0	24.0	223.60	0.70	2121.00	2183.00
31	7038	36.7	3.0	99.94	33.7	16.9	629.40	0.62	4586.00	5848.00
33	3857	46.3	0.6	99.89	45.7	22.9	317.80	0.64	2478.00	2624.00
34	2005	48.2	2.5	99.97	45.7	22.9	161.90	0.64	1283.00	1359.00
35	3264	43.5	0.5	99.97	43.0	21.5	258.70	0.65	2083.00	2296.00
36	3163	49.3	0.9	99.28	48.4	24.2	207.30	0.70	1954.00	1999.00
37	3161	43.8	1.9	99.65	41.9	20.9	203.80	0.70	1946.00	2204.00
38	3063	48.1	0.8	99.99	47.3	23.7	254.70	0.64	1973.00	2044.00
39	2467	44.8	1.3	99.80	43.5	21.8	200.30	0.64	1582.00	1730.00
40	1493	49.5	0.3	99.73	49.2	24.6	119.90	0.65	956.10	965.80
42	1498	48.6	0.4	99.97	48.2	24.1	124.80	0.64	963.60	986.20
43	3881	46.3	0.2	99.89	46.1	23.0	317.80	0.64	2494.00	2627.00
44	3253	48.9	0.5	99.57	48.4	24.2	194.10	0.72	1977.00	2025.00
45	3530	47.6	2.5	99.85	45.1	22.5	298.60	0.63	2276.00	2431.00
47	5857	45.8	0.6	99.97	45.2	22.6	487.60	0.64	3765.00	4015.00
53	4898	46.2	2.8	99.88	43.4	21.7	417.60	0.63	3163.00	3458.00
54	3824	47.3	2.3	99.75	45.0	22.5	414.90	0.57	2582.00	2742.00
55	3033	47.9	0.7	99.83	47.2	23.6	237.30	0.65	1929.00	2003.00

Table A-3. Taped data and calculations for GSCA

APT	Taped									
Test No.	CFM50	Attic (P'A)	Duct (P'D)	Correlation Coefficient	Pda @50Pa	Pda @25 Pa	Leakage Coeff	Flow Exponent	CFM @25Pa	CFM Corrected @25Pa
3	2859	48.3	43.1	99.96	5.20	2.60	245.70	0.63	1849.00	1907.00
5	1595	46.7	30.0	99.99	16.80	8.40	124.90	0.64	989.60	1066.00
6	1697	49.9	18.7	99.75	31.10	15.60	135.80	0.65	1086.00	1105.00
11	3904	47.7	44.5	99.91	3.10	1.60	327.50	0.63	2521.00	2682.00
12	1113	49.0	20.1	99.65	28.80	14.40	93.60	0.63	718.10	736.10
13	3384	47.3	44.7	99.93	2.60	1.30	272.40	0.64	2165.00	2318.00
14	4856	46.3	40.4	99.93	5.90	2.90	431.20	0.62	3162.00	3417.00
19	6450	48.8	23.8	99.89	24.90	12.50	511.80	0.65	4121.00	4296.00
20	3908	48.9	33.8	99.79	15.10	7.50	262.60	0.69	2420.00	2496.00
21	2595	48.7	41.3	99.88	7.40	3.70	181.40	0.68	1619.00	1645.00
26	1389	47.6	24.8	99.98	22.80	11.40	117.20	0.63	896.20	936.00
27	2004	45.3	39.1	99.98	6.20	3.10	178.90	0.62	1308.00	1385.00
28	1559	48.6	40.9	99.98	7.70	3.80	148.40	0.60	1027.00	1050.00
29	3137	48.2	44.8	98.16	3.40	1.70	183.90	0.73	1897.00	1954.00
31	6559	36.0	20.8	99.96	15.20	7.60	572.30	0.62	4251.00	5434.00
33	3402	46.6	43.7	99.91	3.00	1.50	281.40	0.64	2187.00	2316.00
34	1603	48.6	45.3	99.98	3.40	1.70	130.60	0.64	1028.00	1089.00
35	3185	43.7	16.6	99.97	27.10	13.60	239.20	0.66	2015.00	2225.00
36	2803	47.9	40.8	99.92	7.10	3.60	230.90	0.64	1800.00	1838.00
37	2809	44.5	41.6	99.94	2.90	1.40	181.60	0.70	1729.00	1957.00
38	2665	48.6	43.6	99.99	5.00	2.50	224.70	0.63	1718.00	1780.00
39	2166	45.6	44.1	99.97	1.50	0.80	186.50	0.63	1403.00	1531.00
40	1331	49.9	46.6	99.82	3.30	1.70	118.20	0.62	866.80	875.30
42	1435	48.9	20.1	99.96	28.80	14.40	121.10	0.63	926.10	947.70
43	3660	46.7	33.2	99.89	13.50	6.80	284.00	0.65	2324.00	2451.00
44	2864	47.5	27.1	99.71	20.40	10.20	170.50	0.72	1736.00	1778.00
45	3154	47.8	40.0	99.81	7.90	3.90	240.70	0.66	2001.00	2143.00
47	5541	46.2	39.8	99.96	6.40	3.20	490.90	0.62	3612.00	3846.00
53	4598	46.6	36.4	99.98	10.20	5.10	405.80	0.62	2986.00	3260.00
54	3378	48.1	40.1	99.97	8.10	4.00	324.40	0.60	2231.00	2377.00
55	2949	47.6	26.2	99.53	21.40	10.70	170.50	0.73	1782.00	1858.00

Table A-4. Duct leakage calculations using GSCA.

APT					
Test No.	SCF (GSCA}	Duct Leakage @25 Pa (GSCA)	SCF (MSA)	Duct Leakage by Normal APT Method @25Pa	P_A/P
3	1.36	565.90	1.38	554.80	96.90%
5	2.26	193.40	2.23	169.60	94.82%
6	4.25	149.30	3.81	132.20	99.20%
11	1.25	269.50	1.31	264.40	95.50%
12	3.78	116.00	3.51	105.60	96.76%
13	1.22	373.70	1.31	379.40	93.04%
14	1.43	776.60	1.52	772.90	90.72%
19	3.17	561.90	2.91	495.00	95.98%
20	2.00	383.30	1.92	360.60	98.06%
21	1.48	160.00	1.47	156.20	99.16%
26	2.86	202.50	2.78	186.50	94.32%
27	1.43	181.10	1.59	191.90	91.56%
28	1.50	136.20	1.49	131.20	96.86%
29	1.26	287.40	1.30	291.60	96.80%
31	2.64	1092.00	3.39	1135.00	73.44%
33	1.24	382.00	1.35	393.40	92.50%
34	1.27	341.40	1.28	324.90	96.44%
35	4.14	292.10	4.34	296.10	87.08%
36	1.46	235.50	1.50	231.00	98.68%
37	1.25	308.70	1.45	316.50	87.60%
38	1.35	357.00	1.36	345.30	96.18%
39	1.15	228.80	1.33	237.70	89.68%
40	1.25	112.80	1.21	108.00	99.04%
42	3.76	144.90	3.53	132.40	97.20%
43	1.92	338.80	1.97	335.00	92.62%
44	2.47	609.10	2.51	603.30	97.82%
45	1.54	442.60	1.54	424.00	95.20%
47	1.45	244.80	1.55	237.80	91.64%
53	1.72	340.90	1.75	310.50	92.34%
54	1.55	567.80	1.54	540.10	94.58%
55	2.65	383.40	2.62	385.70	95.76%

```
/*********************************************************************/
/*   COMMENTS                        NAME            DATE MODIFIED
 Initial Version       Jinson Erinjeri      10/12/2006
 TWO SAMPLE T-TEST FOR PAIRED OBSERVATIONS
 BETWEEN GSCA AND MSA.
 *********************************************************************/

DATA ONE;
       INPUT DIFFNORTH;
       CARDS;
11.13
23.83
17.09
5.10
10.40
-5.70
3.68
66.85
22.71
3.81
16.01
-10.89
4.96
-4.16
-42.34
-11.38
16.58
-4.08
4.46
-7.87
11.71
-8.81
4.82
12.52
3.82
5.83
18.64
6.98
30.31
27.67
-2.34;
PROC PRINT DATA=ONE;
PROC TTEST DATA=ONE;
       VAR DIFFNORTH;
PROC TTEST DATA=TWO;
       VAR DIFFSOUTH;
PROC UNIVARIATE DATA=CODULE NORMAL;
       VAR DIFFNORTH;
RUN;
```

Figure A-14. SAS program for paired observations (GSCA and MSA) using t-test.

```
The SAS System         07:08 Tuesday, October 10, 2006   1

Obs    DIFFNORTH

1       11.13
2       23.83
3       17.09
4        5.10
5       10.40
6       -5.70
7        3.68
8       66.85
9       22.71
10        3.81
11       16.01
12      -10.89
13        4.96
14       -4.16
15      -42.34
16      -11.38
17       16.58
18       -4.08
19        4.46
20       -7.87
21       11.71
22       -8.81
23        4.82
24       12.52
25        3.82
26        5.83
27       18.64
28        6.98
29       30.31
30       27.67
31       -2.34
The TTEST Procedure

Statistics

Lower CL          Upper CL  Lower CL           Upper CL
Variable       N      Mean    Mean      Mean   Std Dev  Std Dev   Std Dev  Std Err
Minimum  Maximum

DIFFNORTH     31    0.8743  7.4626    14.051    14.353   17.961    24.009    3.226   -
42.34    66.85


T-Tests

Variable       DF    t Value    Pr > |t|

DIFFNORTH      30       2.31      0.0277
```

Figure A-15. SAS output for paired observations (GSCA and MSA) using t-test.

```
/*********************************************************************/
/* COMMENTS                    NAME                       DATE MODIFIED
 Initial Version            Jinson Erinjeri                10/15/2005
 TWO SAMPLE T-TEST FOR PAIRED OBSERVATIONS
 BETWEEN PRESSURIZED AND DEPRESSURIZED STATES.
 MACRO FOR FINDING SIGNIFICANT DIFFERENCES BETWEEN
 CDL+VS.CDL-, TDL+VS.TDL-,CRL+VS.CRL- AND TRL+VS.TRL-
/**************************************************************/
%LET PAR=CDL TDL CRL TRL;
%MACRO DIFF;
%DO I=1 %TO 4;
%LET ORDER=%SCAN(&PAR,&I);
DATA CODULE;
SET SASUSER.&ORDER;
DROP HOUSE PRESSURE HOUSE1 PRESSURE1;
RENAME FLOW=DEPRESSFLOW;
RENAME FLOW1=PRESSFLOW;
DIFFERENCE = FLOW-FLOW1;
PROC PRINT DATA=CODULE;
PROC TTEST DATA=CODULE;
VAR DIFFERENCE;
PROC UNIVARIATE DATA=CODULE NORMAL;
VAR DIFFERENCE;
RUN;
%END;
%MEND;
%DIFF;
```

Figure A-16. SAS program for pressurized and depressurized conditions using t-test.

Figure A-17.

SAS output for pressurized and depressurized conditions using t-test.

```
            The SAS System        21:05 Saturday, October 29, 2005  43

                   Obs    DEPRESSFLOW    PRESSFLOW    DIFFERENCE

                     1       143.33        168.67        -25.34
                     2       309.33        282.67         26.66
                     3       282.00        263.33         18.67
                     4       125.00        137.00        -12.00
                     5       339.00        243.67         95.33
                     6       138.67        178.33        -39.66
                     7       257.67        242.33         15.34
                     8       425.33        406.33         19.00
                     9       238.33        249.33        -11.00
                    10       143.33        164.33        -21.00
                    11       339.33        328.00         11.33
                    12       115.53        126.00        -10.47
                    13       152.67        140.67         12.00
                    14       263.00        234.67         28.33
                    15      2096.33        900.00       1196.33
                    16        76.67        109.33        -32.66
                    17       169.00        174.67         -5.67
                    18       254.67        265.67        -11.00
                    19      1195.67        223.67        972.00
                    20       238.33        249.33        -11.00
                    21       181.00        270.00        -89.00
                    22       150.00        201.00        -51.00
                    23       220.00        270.67        -50.67
                    24       331.67        358.67        -27.00
                    25       141.67        179.00        -37.33
                    26       751.00        392.67        358.33

            The SAS System        21:05 Saturday, October 29, 2005  44

                                The TTEST Procedure

                                    Statistics

              Lower CL          Upper CL  Lower CL           Upper CL
Variable        N      Mean    Mean      Mean   Std Dev  Std Dev   Std Dev  Std Err
                                 Minimum  Maximum

DIFFERENCE     26    -34.11  89.174    212.46    239.37   305.22    421.33  59.859
                                   -89   1196.3

                                      T-Tests

                     Variable        DF    t Value    Pr > |t|

                     DIFFERENCE      25       1.49      0.1488

            The SAS System        21:05 Saturday, October 29, 2005  45

                             The UNIVARIATE Procedure
                               Variable:  DIFFERENCE

                                      Moments
```

Figure A-17.
SAS output for pressurized and depressurized conditions using t-test.

```
N                         26    Sum Weights                 26
Mean              89.1738462    Sum Observations       2318.52
Std Deviation     305.223877    Variance            93161.6149
Skewness          3.10088488    Kurtosis            9.02338368
Uncorrected SS    2535791.72    Corrected SS        2329040.37
Coeff Variation   342.279592    Std Error Mean      59.8593271

                   Basic Statistical Measures

            Location                    Variability

     Mean      89.1738     Std Deviation          305.22388
     Median   -10.7350     Variance                   93162
     Mode     -11.0000     Range                       1285
                Interquartile Range     46.00000


                    Tests for Location: Mu0=0

        Test           -Statistic-    -----p Value------

        Student's t    t  1.489723    Pr > |t|    0.1488
        Sign           M        -2    Pr >= |M|   0.5572
        Signed Rank    S        -4    Pr >= |S|   0.9214

                       Tests for Normality

   Test                  --Statistic---    -----p Value------

   Shapiro-Wilk          W      0.47145    Pr < W     <0.0001
   Kolmogorov-Smirnov    D     0.425156    Pr > D     <0.0100
   Cramer-von Mises      W-Sq  1.181899    Pr > W-Sq  <0.0050
   Anderson-Darling      A-Sq  5.928336    Pr > A-Sq  <0.0050


                    Quantiles (Definition 5)

                    Quantile       Estimate

                    100% Max       1196.330
                    99%            1196.330
                    95%             972.000
                    90%             358.330
                    75% Q3           19.000
                    50% Median      -10.735
                    25% Q1          -27.000
                    10%             -50.670

   The SAS System        21:05 Saturday, October 29, 2005  46

                    The UNIVARIATE Procedure
                     Variable:  DIFFERENCE

                    Quantiles (Definition 5)

                    Quantile       Estimate

                    5%              -51.000
                    1%              -89.000
                    0% Min          -89.000
```

Figure A-17.
SAS output for pressurized and depressurized conditions using t-test.

```
                         Extreme Observations

               -----Lowest----        -----Highest-----

                Value      Obs           Value      Obs

               -89.00       21           28.33       14
               -51.00       22           95.33        5
               -50.67       23          358.33       26
               -39.66        6          972.00       19
               -37.33       25         1196.33       15



      The SAS System        21:05 Saturday, October 29, 2005  47

             Obs    DEPRESSFLOW    PRESSFLOW    DIFFERENCE

               1       234.33        426.33       -192.00
               2       237.33        281.00        -43.67
               3       639.33        557.33         82.00
               4       393.33        343.67         49.66
               5       275.33        279.67         -4.34
               6       614.33        501.33        113.00
               7       634.67        492.67        142.00
               8       329.00        279.00         50.00
               9       654.67        468.67        186.00
              10        306.33        307.00         -0.67
              11        558.00        410.33        147.67
              12        654.33        479.00        175.33
              13        293.33        269.00         24.33
              14        319.00        268.33         50.67
              15        380.00        340.33         39.67
              16       1974.00        799.67       1174.33
              17        344.67        319.00         25.67
              18        256.67        246.33         10.34
              19        374.33        339.33         35.00
              20       1093.00        306.00        787.00
              21        360.33        337.67         22.66
              22        329.00        349.00        -20.00
              23        311.67        298.33         13.34
              24        315.67        302.33         13.34
              25        257.67        334.33        -76.66
              26        225.67        216.67          9.00
              27       1209.67        442.00        767.67

      The SAS System        21:05 Saturday, October 29, 2005  48

                          The TTEST Procedure

                              Statistics

           Lower CL          Upper CL  Lower CL          Upper CL
Variable        N      Mean    Mean      Mean   Std Dev  Std Dev    Std Dev  Std Err
                                  Minimum  Maximum

DIFFERENCE     27    15.056  132.64    250.23    234.08   297.24    407.35   57.205
                                    -192   1174.3
```

Figure A-17.
SAS output for pressurized and depressurized conditions using t-test.

```
                            T-Tests

           Variable        DF    t Value    Pr > |t|

           DIFFERENCE      26       2.32      0.0285

  The SAS System        21:05 Saturday, October 29, 2005  49

                    The UNIVARIATE Procedure
                     Variable:  DIFFERENCE

                            Moments

N                             27    Sum Weights                 27
Mean                  132.642222    Sum Observations       3581.34
Std Deviation          297.24426    Variance            88354.1501
Skewness              2.52271384    Kurtosis            6.18159968
Uncorrected SS         2772244.8    Corrected SS         2297207.9
Coeff Variation       224.094753    Std Error Mean      57.2046845


                   Basic Statistical Measures

            Location                   Variability

    Mean     132.6422     Std Deviation          297.24426
    Median    35.0000     Variance                   88354
    Mode      13.3400     Range                       1366
               Interquartile Range    133.00000

                   Tests for Location: Mu0=0

       Test           -Statistic-    -----p Value------

       Student's t    t   2.31873    Pr > |t|    0.0285
       Sign           M       7.5    Pr >= |M|   0.0059
       Signed Rank    S       125    Pr >= |S|   0.0013

                      Tests for Normality

  Test                  --Statistic---    -----p Value------

  Shapiro-Wilk          W     0.628908    Pr < W     <0.0001
  Kolmogorov-Smirnov    D     0.317658    Pr > D     <0.0100
  Cramer-von Mises      W-Sq  0.813075    Pr > W-Sq  <0.0050
  Anderson-Darling      A-Sq  4.196256    Pr > A-Sq  <0.0050


                   Quantiles (Definition 5)

                    Quantile      Estimate

                    100% Max       1174.33
                    99%            1174.33
                    95%             787.00
                    90%             767.67
                    75% Q3          142.00
                    50% Median       35.00
                    25% Q1            9.00
```

Figure A-17.
SAS output for pressurized and depressurized conditions using t-test.

```
                    10%              -43.67
      The SAS System        21:05 Saturday, October 29, 2005  50

                     The UNIVARIATE Procedure
                       Variable:  DIFFERENCE

                     Quantiles (Definition 5)

                      Quantile      Estimate

                      5%              -76.66
                      1%             -192.00
                      0% Min         -192.00


                       Extreme Observations

                -----Lowest-----        -----Highest-----

                 Value      Obs            Value      Obs

                -192.00       1           175.33       12
                 -76.66      25           186.00        9
                 -43.67       2           767.67       27
                 -20.00      22           787.00       20
                  -4.34       5          1174.33       16



      The SAS System        21:05 Saturday, October 29, 2005  51

             Obs    DEPRESSFLOW    PRESSFLOW    DIFFERENCE

               1       144.00        153.67         -9.67
               2       118.67        108.00         10.67
               3        58.67         56.33          2.34
               4        36.00         36.33         -0.33
               5        20.33         54.00        -33.67
               6        94.33        111.33        -17.00
               7       138.33        136.67          1.66
               8       943.67        456.67        487.00
               9        93.67        100.00         -6.33
              10        98.67        120.00        -21.33
              11        50.00         71.33        -21.33
              12       112.00        138.00        -26.00
              13       216.33        229.00        -12.67

      The SAS System        21:05 Saturday, October 29, 2005  52

                        The TTEST Procedure
                            Statistics

              Lower CL          Upper CL  Lower CL          Upper CL
Variable        N      Mean    Mean      Mean    Std Dev  Std Dev   Std Dev  Std Err
                                 Minimum  Maximum

DIFFERENCE     13    -56.66   27.18    111.02      99.49   138.74    229.03    38.48
                                  -33.67      487
                              T-Tests
```

Figure A-17.
SAS output for pressurized and depressurized conditions using t-test.

```
            Variable        DF    t Value    Pr > |t|

            DIFFERENCE      12       0.71      0.4935

   The SAS System        21:05 Saturday, October 29, 2005  53

                     The UNIVARIATE Procedure
                      Variable:  DIFFERENCE

                             Moments
 N                          13    Sum Weights               13
 Mean                    27.18    Sum Observations      353.34
 Std Deviation      138.741402    Variance          19249.1768
 Skewness           3.55207867    Kurtosis          12.7240455
 Uncorrected SS     240593.902    Corrected SS      230990.121
 Coeff Variation    510.454019    Std Error Mean    38.4799416

                     Basic Statistical Measures

           Location                    Variability

     Mean      27.1800     Std Deviation          138.74140
     Median    -9.6700     Variance                   19249
     Mode     -21.3300     Range                  520.67000
                Interquartile Range     22.99000

                     Tests for Location: Mu0=0

        Test           -Statistic-    -----p Value------

        Student's t    t  0.706342    Pr > |t|    0.4935
        Sign           M      -2.5    Pr >= |M|   0.2668
        Signed Rank    S     -21.5    Pr >= |S|   0.1421


                        Tests for Normality

   Test                  --Statistic---    -----p Value------

   Shapiro-Wilk          W     0.397412    Pr < W     <0.0001
   Kolmogorov-Smirnov    D     0.470439    Pr > D     <0.0100
   Cramer-von Mises      W-Sq  0.705757    Pr > W-Sq  <0.0050
   Anderson-Darling      A-Sq  3.530716    Pr > A-Sq  <0.0050

                     Quantiles (Definition 5)

                      Quantile      Estimate

                      100% Max        487.00
                      99%             487.00
                      95%             487.00
                      90%              10.67
                      75% Q3            1.66
                      50% Median       -9.67
                      25% Q1          -21.33
                      10%             -26.00
   The SAS System        21:05 Saturday, October 29, 2005  54

                     The UNIVARIATE Procedure
                      Variable:  DIFFERENCE
```

Figure A-17.
SAS output for pressurized and depressurized conditions using t-test.

```
                             Quantiles (Definition 5)

                              Quantile      Estimate

                              5%              -33.67
                              1%              -33.67
                              0% Min          -33.67

                               Extreme Observations

                      -----Lowest----        -----Highest----

                       Value      Obs          Value      Obs

                      -33.67        5          -0.33        4
                      -26.00       12           1.66        7
                      -21.33       11           2.34        3
                      -21.33       10          10.67        2
                      -17.00        6         487.00        8

             The SAS System        21:05 Saturday, October 29, 2005  55

                   Obs    DEPRESSFLOW    PRESSFLOW    DIFFERENCE

                     1        98.00        152.00        -54.00
                     2       299.67        244.67         55.00
                     3       447.33        376.00         71.33
                     4       297.67        299.00         -1.33
                     5       338.00        328.67          9.33
                     6        66.33         68.33         -2.00
                     7       333.67        282.67         51.00
                     8       351.67        330.33         21.34
                     9      1523.00        769.00        754.00
                    10       151.00        120.00         31.00
                    11       364.67        329.00         35.67
                    12       291.67        258.00         33.67
                    13       122.67        119.33          3.34
                    14       277.67        259.67         18.00
                    15       309.33        299.33         10.00

             The SAS System        21:05 Saturday, October 29, 2005  56

                                The TTEST Procedure

                                    Statistics

              Lower CL          Upper CL  Lower CL           Upper CL
Variable        N      Mean    Mean      Mean   Std Dev  Std Dev   Std Dev  Std Err
                                 Minimum  Maximum

DIFFERENCE     15    -37.11   69.09    175.29     140.4   191.78    302.45  49.516
                                    -54       754
                                      T-Tests

                     Variable        DF    t Value    Pr > |t|

                     DIFFERENCE      14       1.40      0.1847

             The SAS System        21:05 Saturday, October 29, 2005  57
```

Figure A-17.
SAS output for pressurized and depressurized conditions using t-test.

```
                       The UNIVARIATE Procedure
                        Variable:  DIFFERENCE

                               Moments

 N                          15    Sum Weights                 15
 Mean                    69.09    Sum Observations       1036.35
 Std Deviation      191.776457    Variance            36778.2096
 Skewness           3.71151744    Kurtosis            14.1361173
 Uncorrected SS     586496.356    Corrected SS        514894.934
 Coeff Variation    277.574841    Std Error Mean      49.5164684


                      Basic Statistical Measures

            Location                    Variability

     Mean     69.09000     Std Deviation          191.77646
     Median   21.34000     Variance                   36778
     Mode       .          Range                  808.00000
                Interquartile Range     47.66000


                     Tests for Location: Mu0=0

        Test           -Statistic-    -----p Value------

        Student's t    t  1.395293    Pr > |t|    0.1847
        Sign           M       4.5    Pr >= |M|   0.0352
        Signed Rank    S        45    Pr >= |S|   0.0084

                        Tests for Normality

     Test                  --Statistic---    -----p Value------

     Shapiro-Wilk          W     0.428214    Pr < W     <0.0001
     Kolmogorov-Smirnov    D     0.428674    Pr > D     <0.0100
     Cramer-von Mises      W-Sq  0.711134    Pr > W-Sq  <0.0050
     Anderson-Darling      A-Sq  3.625748    Pr > A-Sq  <0.0050


                       Quantiles (Definition 5)

                        Quantile      Estimate


                        100% Max        754.00
                        99%             754.00
                        95%             754.00
                        90%              71.33
                        75% Q3           51.00
                        50% Median       21.34
                        25% Q1            3.34
                        10%              -2.00

     The SAS System        21:05 Saturday, October 29, 2005  58

                       The UNIVARIATE Procedure
                        Variable:  DIFFERENCE
```

```
                      Quantiles (Definition 5)

                       Quantile      Estimate

                       5%              -54.00
                       1%              -54.00
                       0% Min          -54.00


                        Extreme Observations

                -----Lowest----        -----Highest----

                 Value      Obs           Value      Obs

                -54.00        1           35.67       11
                 -2.00        6          51.00        7
                 -1.33        4          55.00        2
                  3.34       13         71.33        3
                  9.33        5        754.00        9
```

Figure A-17. SAS output for pressurized and depressurized conditions using t-test.

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Glossary

ACH50… Air change rate per hour, at a pressure difference of 50 Pa between inside and outside

Air change rate... The rate of replacement of air in a space, usually due to infiltration of outdoor air through cracks around windows and doors. Commonly expressed in air changes per hour.

Air conditioning... the process of treating air to control its temperature, humidity, cleanliness and distribution to meet requirements of the conditioned space.

Air distribution system... includes all building elements (duct systems, air handling units, cavities of the building structure and mechanical closets) through which air is delivered to or from the conditioned spaces.

Air handler... the fan unit of a furnace and the fan-coil unit of a split-system, packaged air conditioner or heat pump.

Air leakage... the uncontrolled flow of air for instance through a component of the building envelope, or the building envelope itself, when a pressure difference is applied across the component.

Air tightness... the relationship between the exchange of inside air in a dwelling, being replaced at a standardized rate of exchange, with fresh outside air measured in cubic feet per minute (CFM).

ASHRAE... American Society of Heating Ventilating and Air-conditioning Engineers http://www.ashrae.org

Blower door... a large calibrated fan that is temporarily mounted in a house door to measure the house leaks and to assist in finding the location of the leaks

Blower door testing ... tests or measurements to determine the air leakage in a dwelling, overall duct leakage in heating distribution ductwork and pinpointing problem areas which are performed using the blower door

Btu (British thermal unit)... the IP standard unit for measuring the amount of energy consumed by a process, the amount of energy transferred from one location to another, or the amount of embodied energy (such as the heat content of fuel); it is the amount of heat energy necessary to raise the temperature of one pound of water one degree Fahrenheit.

Building air tightness... a measurement of a structure's resistance to the uncontrolled leakage of air and the water vapor it contains (see infiltration).

Building envelope... the sections of the building that enclose conditioned or inside spaces through which heat transfer may occur to or from the outside, including the floor, walls, windows, doors, ceiling and roof.

CGSB... Canadian General Standards Board http://www.pwgsc.gc.ca/cgsb

Conditioned space... space within the living area that is heated and cooled (conditioned) by the furnace, air conditioner, heat pump, etc.

Conductance... measurement of how easily heat energy can move through material

Conduction... heat transfer mechanism that occurs when two materials of different temperature are in direct contact or when there is a difference in temperature within a single material- the warmer material or side conducts it's heat to the cooler one.

Duct blaster... a calibrated airflow measurement system designed to test and document the air tightness of forced-air duct systems. Duct Blaster is the trade name of the device manufactured by the Energy Conservatory of Minneapolis, MN. Other competing companies such as Infiltec and Retrotec manufacture similar systems.

Duct leakage... unintentional air loss from or gain to (via holes, cracks etc.) an air distribution system, or the rate at which the unintentional air gain or loss occurs.

Ductwork... Pipes or channels that carry forced-air (cooled or heated) throughout the house, usually made of sheet metal

EER (Energy Efficiency Ratio)... a measure of the efficiency of central and room air conditioners. It measures instantaneous efficiency and is the cooling capacity in Btu/hr divided by the watts of power consumed for a specific outdoor temperature (usually 95°F). In hotter climates, SEER and EER are more important than HSPF

Energy audit... a site inventory and descriptive record of features impacting the energy use in a building; it includes building component descriptions, energy using equipment and appliance descriptions, and all energy features.

Equipment efficiency... the ratio of useful energy output (at the point of use) to the energy input in consistent units for a designated time period, expressed in percent.

Exfiltration... outward flowing air leakage.

Fahrenheit... measurement scale on which under standard atmospheric pressure the boiling point of water is at 212° above the zero of the scale, the freezing point is at 32° above zero.

Forced air systems ... the most common type of home heating and cooling systems. The air is heated in the furnace or cooled in the air conditioner, and distributed through a set of metal or plastic ducts to various areas of the house.

Geopolymers... a class of synthetic aluminosilicate materials with potential to be a large-scale replacement for concrete produced from Portland cement (geoplymers have lower carbon dioxide emissions, greater chemical and thermal resistance and better mechanical properties at both atmospheric and extreme conditions)

Heat energy... the capacity to increase the molecular activity of a substance and thereby increase its temperature

Heat pump... A mechanical refrigeration-cycle system with has been designed to accomplish space heating, water heating or both and, when the evaporator and condenser effects are reverse, may be used for space air conditioning or water chilling.

HERS (Home Energy Rating System)... a standardized system for rating the energy-efficiency of residential buildings. HERS are currently governed by three national industry standards: 1) the National Association of State Energy Officials Technical Guidelines (the methods and procedures for rating a home); 2) the Mortgage Industry HERS Accreditation Procedures (the methods and procedures for the certification of Home Energy Rating System by individual state governments and the national home mortgage industry); and 3) the RESNET Training and Certifying Standards (prescriptive minimum competencies for trainers and certified raters).

House pressure... the difference in air pressure between the indoor air space and outside

HVAC (heating, ventilation and air conditioning)... A term generally applied to the hardware or the industry concerned with the supply of environmental control in buildings.

HVAC system... the equipment, distribution network, and terminals that provide the processes of heating, ventilating and/or air conditioning to a building

Infiltration... inward flowing air leakage

Metakaolin... a dehydroxylated form of the clay mineral kaolinite

Operating pressure... the gauge pressure at which the air system is maintained in normal operation

Orifice... An opening such as a hole or vent. An opening through which air can pass, or a restricted opening placed in a pipeline to provide a means of controlling or measuring flow.

Pascal... a unit of measure for air pressure. 256 pascals equal one inch of water column (IWC)

Plenum... an air compartment or chamber of an air distribution system to which one or more ducts are connected.

Radiation... heat transfer mechanism that occurs when two materials are separated by air or a vacuum-the warmer surface emits or radiates across the air space to the cooler surface

REM/Rate... the software provided to RESNET Certified Raters to use during the home audit. The software has been acknowledged by the IRS to be suitable tool to use in certifying homes to qualify for the builder's tax credit. It can be used to perform simulations of projected energy savings or costs when features are changed within the home being evaluated. It is designed and updated by Architectural Energy Corporation.

RESNET ... Residential Energy Services Network. A national organization dedicated to setting standards of quality for home energy auditors through creating audit guidelines, training auditors, and certifiying auditors to meet their high standards. http://www.natresnet.org

Return air system...a system of ducts that takes air out of the individual rooms of a home and delivers it to the inlet of the furnace or A/C unit so it can exit or come back out as heated/cold air.

Sealant ... any substance that is used to fill or close small gaps and cracks in another material

SEER (Seasonal Energy Efficiency Ratio)... a standard measurement of the seasonal cooling efficiency of an electric air conditioner. Specifically, the estimated total cooling of a central air conditioner in Btu's during its normal usage period for cooling (not to exceed 12 months) divided by the total electric energy input in watt-hours during the same period.

Shading coefficients... coefficients that rate windows and other transparent apertures based on the fraction of solar heat gain that passes through compared to either the incident solar radiation or the transmission of a reference glazing type. They are all given as a decimal value in the range 0-1, however there several different types, each using a different reference measure for comparison. These include the Standard Shading Coefficient (SC), the Solar Heat Gain Coefficient (SHGC) and the G-Value (G). In all cases, the lower the shading coefficient, the less solar heat the object will transmit and the greater its overall shading ability.

SHGC (Solar Heat Gain Coefficient... the fraction of incident solar radiance that entering a home through the windows. The lower the number, the better the window is at blocking heat gain (see Shading coefficients)

Standard pressure... typical pressure that exists in the branches of a residential duct system (25 Pa)

U-Value... a measurement of heat flow through a material. The lower the U-value, the more slowly the material transfers heat in and out of home. The reciprocal of R-value. While R-value is used for measure of resistance to heat flow for individual building materials, U-factor is used as a summary measure for conductive energy measure of building envelopes.

Ventilation... the process of supplying or removing air, by natural or mechanical means, to or from any space. Such air may or may not have been conditioned.

Weatherization... measures applied to a house which help to conserve heat, maintain temperature and provide a safe and healthy living environment

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