Louisiana Tech University
Louisiana Tech Digital Commons

Doctoral Dissertations | Graduate School

Winter 2007

Analysis and prediction of effectiveness for residential HVAC ductwork

Jinson J. Erinjeri
Louisiana Tech University

Follow this and additional works at: https://digitalcommons.latech.edu/dissertations

Part of the Mechanical Engineering Commons

Recommended Citation
Erinjeri, Jinson J., "" (2007). *Dissertation*. 548.
https://digitalcommons.latech.edu/dissertations/548

This Dissertation is brought to you for free and open access by the Graduate School at Louisiana Tech Digital Commons. It has been accepted for inclusion in Doctoral Dissertations by an authorized administrator of Louisiana Tech Digital Commons. For more information, please contact digitalcommons@latech.edu.

ANALYSIS AND PREDICTION OF EFFECTIVENESS FOR RESIDENTIAL HVAC DUCTWORK

by

Jinson J. Erinjeri, M.S.

A Dissertation Presented in Partial Fulfillment
of the Requirement for the Degree of
Doctor of Philosophy

COLLEGE OF ENGINEERING AND SCIENCE
LOUISIANA TECH UNIVERSITY

March 2007

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

UMI Number: 3264695

INFORMATION TO USERS

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleed-through, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

UMI®

UMI Microform 3264695

Copyright 2007 by ProQuest Information and Learning Company. All rights reserved. This microform edition is protected against unauthorized copying under Title 17, United States Code.

ProQuest Information and Learning Company
300 North Zeeb Road
P.O. Box 1346
Ann Arbor, MI 48106-1346

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LOUISIANA TECH UNIVERSITY

THE GRADUATE SCHOOL

January 19, 2007
Date

We hereby recommend that the dissertation prepared under our supervision by Jinson Johnson Erinjeri entitled Analysis and Prediction of Effectiveness for Residential HVAC Ductwork be accepted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy in Engineering

Supervisor of Dissertation Research

Head of Department

Engineering
Department

Recommendation concurred in:

Advisory Committee

Approved:

Director of Graduate Studies

Dean of the College

Approved:

Dean of the Graduate School

GS Form 13
(5/03)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ABSTRACT

An analysis of residential HVAC ductwork has been performed. Ductwork in 55 homes in Northern Louisiana was tested to determine duct leakage by means of using various measurement techniques to determine the differences between the existing methods as well as the revised method developed in this project referred to as Generalized Subtraction Correction Algorithm (GSCA). A protocol to measure and estimate 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™ and a new protocol developed by combining REM/Rate™ and ASHRAE™ 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 $347. 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

APPROVAL FOR SCHOLARLY DISSEMINATION

The author grants to the Prescott Memorial Library of Louisiana Tech University the right to reproduce, by appropriate methods, upon request, any or all portions of this Dissertation. It is understood that "proper request" consists of the agreement, on the part of the requesting party, that said reproduction is for his personal use and that subsequent reproduction will not occur without written approval of the author of this Dissertation. Further, any portions of the Dissertation used in books, papers, and other works must be appropriately referenced to this Dissertation.

Finally, the author of this Dissertation reserves the right to publish freely, in the literature, at any time, any or all portions of this Dissertation.

Author [illegible]

Date February 5, 2007

GS Form 14
(5/03)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

TABLE OF CONTENTS

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LIST OF TABLES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

LIST OF FIGURES

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ACKNOWLEDGMENTS

I would like to acknowledge Dr. Norman Witriol, Dr. Myron Katz and Dr. Raja Nassar for their constant advice and encouragement in both technical and professional aspects of my research work. They have been instrumental in helping me with sound technical advice. I am thankful to members of my advisory committee, Dr. Jun-Ing Ker, Dr. Ray Sterling and Dr. Paul Hale for their valuable advice in my research. I acknowledge the experimental resources made available by the Louisiana Department of Natural Resources, Trenchless Technology Center and the Department of Physics. I also thank all the members of D.K.Shifflet & Associates Ltd. and especially Dr. Nandini Nadkarni for their support during my internship in completing this study. My sincere thanks to Ms. Madhumathy Kodiyappapillai, Mr. Srihari Jaganathan, Mr. Arpan Gurjar, Ms. Shalini Wunnava, Mr. Satish Tahiliani, Mr. Anirbhan Chakraborty, Ms. Prashanthi Vandrangi, Dr. Mangilal Agarwal, Ms. Lalitha Krothapalli, Mr. Mahesh Selvaraj and Mr. Santhana Krishnan for their support during my research. Finally, all this would not have taken place without my family members and I thank my father E.K. Johnson, my mother Mercy Johnson, and my brother Maxon Erinjeri for their lifelong support in achieving my goals.

I sincerely thank the Ruston Community for their participation in this research, without which this study could never have been accomplished.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 1

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], the State of Louisiana ranks second highest among the states in energy consumption by source and total energy consumption per capita. In an earlier study performed by Erinjeri [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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

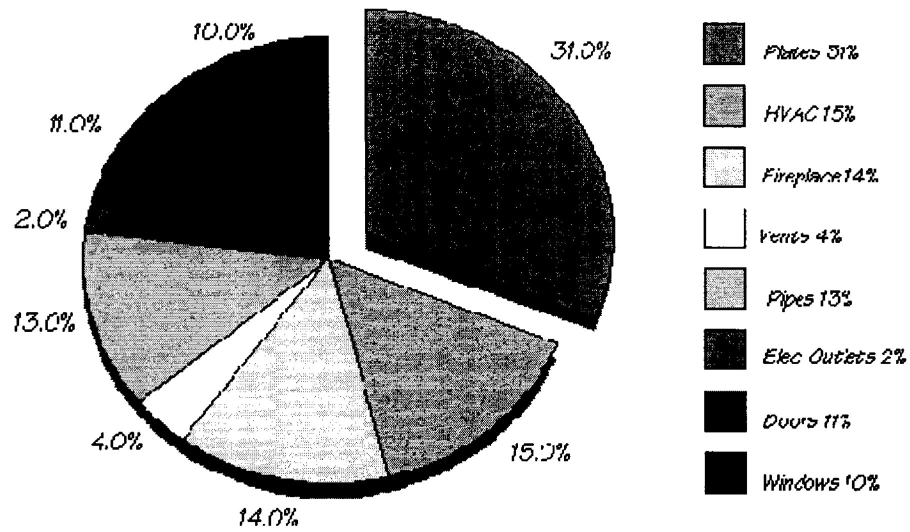


Figure 1.1 Sources of air leakage [3].

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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

4. There was a need to determine the differences between the existing methods which led to the development of new duct leakage methodology, 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.

Fifty-five homes in Northern Louisiana were tested to compare the GSCA with the existing methods. This phase of the project also compared the existing methods statistically to determine how well one method predicts the results of the other methods. This phase of study also attempted to determine an empirical relationship between whole house leakiness and building characteristics. 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 is the development and testing of a new duct-sealing technology in laboratory conditions. The main reason for this study is 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 utilize the duct-leakage database generated in the thesis titled " Testing Ductwork in Residential Buildings" (Erinjeri, 2002) to:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

a. estimate the average duct leakage in residencies in the Northern regions of Louisiana

b. compare the results obtained by utilizing various testing methods for measuring duct leakage, and determine the consistency of these results

c. estimate the total energy cost to Louisiana homeowners caused by duct-leakage

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 determine an empirical relationship between whole-house leakiness and building characteristics
5. 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
6. to develop a methodology for determining the supply leaks at operating pressure
7. to statistically determine whether or not there are differences in the measurements of duct leakage between the pressurized and depressurized conditions
8. to develop and test cost-effective methods to significantly reduce duct-leakage, specifically to:
    a. perform a feasibility study on a new duct-sealing technology in laboratory conditions
    b. measure the actual average effectiveness of the duct-sealing technology in both the supply and the return system of the duct system

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

9. to project the average residential energy savings derived from sealing residential duct leaks
10. 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. Chapter Three gives a statistical analysis of the comparison of duct leakage results provided by automated and manual tests. In Chapter Four, an empirical relationship between the whole-house leakiness and the building characteristics is presented. Chapter Five describes the development of a new algorithm (GSCA) for determining duct leakage. Chapter Six describes a protocol to test and measure return leaks. Chapter Seven provides the data obtained from the actual measurement of duct leakage, taking into account both supply and return leaks. In Chapter Eight, a statistical analysis is presented for determining the differences between pressurized and depressurized conditions on various measurement protocols. Chapter Nine 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 Ten describes a feasibility study on a new duct sealing technology to seal supply and return leaks in laboratory conditions. In Chapter Eleven, the conclusions and outlook for future work in this area is presented.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 2

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 [3, 4, 5]. 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
    - the duct placement outside of conditioned space
    - 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 estimated

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

15 to 30 percent of a home's total heating and cooling energy is lost through leaky ductwork, costing consumers about five billion dollars per year [6].

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 [7]. 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 [7]. Field studies performed in Washington, D.C. and Minnesota revealed that the ducts leaked by about 1300 CFM50 and 2217 CFM50 respectively [8].

According to the Energy Information Administration (EIA) [1], the State of Louisiana ranks second highest among the states in energy consumption by source and total energy consumption per capita. A study by Erinjeri of 55 homes in Northern Louisiana has determined average duct leakage in residential homes in the range of 313 CFM25. However, in Chapter Three, we 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* [9]. In Chapter Nine, 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 Erinjeri in each of the 55 homes tested in North Louisiana were used to determine duct leakage. Many testing procedures were utilized in each home for the following reasons:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

1. The test procedures used in this study were almost precisely identical to tests commonly employed in general practice.
2. There was and is still no standard test procedure that can be used to determine the correct duct leakage value. At the time of the design of these tests, one of the tests we actually performed, a test we call "Combined", was starting to be generally recognized as the standard. It had, in the previous few years, overtaken the older standard, called Modified Subtraction. Erinjeri [2] also performed many common variants of both of these tests in his study.
3. New equipment has made Modified Subtraction with manually collected data increasingly replaced by automated collection methods. Such methods are inherently more accurate because of reduced error in each datum collected and hundreds of times as much data are collected for each test. Moreover, such tests actually require less operator time.
4. There is a continuing debate regarding the best practical method to use.
5. Since these two standard kinds of tests are commonly performed at different pressures, namely direct fan pressurization of ducts is normally performed at 25 Pa, while Modified Subtraction is normally performed at 50 Pa, some rationale is needed to compare these tests.
6. There is a debate about the applicability of these tests to predict duct leakage in an actually running HVAC system.
7. Part of the purpose of this study was to provide some evidence that one test method out performs another in some or most cases.
8. A few modifications in duct-leakage calculations were possible due to the contributions made by researchers in this field mainly;

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 and visa-versa. The details of this study regarding mean duct leakage flow exponent of 0.60 is presented in the Chapter Three.

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

d. Unlike older versions of the Duct Blaster™ 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.

The series of duct leakage tests applied in this study were not only designed to study the relative merit of the commonly used duct-leakage tests but also to check the predictable size in errors in duct-leakage calculation caused by inaccuracies of inherent theoretical assumptions. All the statistical analysis pertaining to this study is presented in Chapter Three of this dissertation.

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 [10]. Duct repairs made on 25 homes in Florida indicated that 14.0% of the house leaks were in the duct system.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Repair of these duct leaks reduced the house ACH50 from 12.30 to 11.13 indicating that 68% of the duct leaks were repaired [11]. 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 [11]. Other effects of duct leaks include the following:

- 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.
- 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.
- 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.
- increased indoor relative humidity the resulting potential for fungus, mold, mildew growth, and condensation on surfaces – threaten human health and building longevity.
- 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, duct sealants, duct sealant application methods, poor workmanship, inadequately sealed original mechanical joint

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 [12]. The repair of 70% of duct leakage in the typical Florida home has been shown, by simulation studies [13, 14] 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 [15].

There has been a continuous encouragement for the use of high-energy efficient HVAC equipments. 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 [16].

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

study by Synertech of Syracuse, New York [8] 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. [8] 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% [17]. HVAC systems having a 15% return leak (from a 120-degree attic) can reduce the effective capacity or, equivalently, Energy Efficiency Ratio (EER) of the system by 50% [9]. 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.

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 [18]. Under these circumstances building material durability is threatened by

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 [19, 20]. 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

- 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 Six. 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 where in the return plenum is depressurized. The basic reasoning behind the differences becomes the foremost issue once we determine that the differences are significant. Chapter Eight 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 [21]. 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 Pascal's) against that envelope [21]. Air-tightness of buildings directly reflects air leakage sites. Air leakage sites include exterior doors, windows, foundations, electrical boxes and plumbing fixtures [22]. Building air-tightness measurements are used for a variety of purposes such as [23]:

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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 [21].

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.) [21].

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 Pascal's" [21].

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 [21]:

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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 create pressures, which increase air leakage in buildings.
5. Door Closure coupled with forced air duct systems: Research has shown (Minneapolis Blower Door™) 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™ test. The Minneapolis Blower Door™, manufactured by the Energy Conservatory is a specialized tool used to measure air-tightness in residential buildings [21]. The Blower Door™ 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Blower Door™ 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 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 softwares in the market to determine the air-tightness values such as TECTITE™ and ZipTest Pro™ [23]. 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 does not adequately seal joints between ducts and has a short life. Researchers at Department of Energy's Lawrence Berkeley National Laboratory have developed aerosol spray sealants [24] 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 [25, 26]. 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 [26]. It is important to note that this

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 [26]. 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 [27] 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 Nine, 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* [9]. We have addressed the ASHRAE™ 152 standard and employed it in conjunction with REM/Rate™ 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™. 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 3

STATISTICAL COMPARISON OF DUCT LEAKAGE TESTS

In this chapter, the analysis of duct leakage in the 55-home sample from the study by Erinjeri [2] was used. The mean (average) duct leakage as estimated by various test methods is summarized. After an extensive discussion of sources of error that may explain their differences, Automated Performance Testing (APT) and Manual test results are compared. Combined duct leakage is extrapolated to 50 Pa and a mean of the duct-leakage flow-exponent is calculated.

The study of duct leakage in the 55-home sample included measurements utilizing the three methods, namely:

(1) Subtraction Correction method using a DG-3 gauge and a Manual data collection algorithm

(2) Subtraction Correction method using APT hardware and TECTITE™ software

(3) Duct Blaster™ assisted by Blower Door™ (referred to as "Combined").

On analyzing, it was found that, among Blower-Door™-only methods, the depressurized APT method produced the best data; unless otherwise stated, duct leakage results are derived from this test (DU-2A together with DT-6A). Erinjeri has presented in detail all the notations and explanations of the test procedures in his study [2].

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3.1 Mean Duct Leakage

Mean Duct Leakage is presented in Table 3.1; its rows and columns summarize the source duct leakage measurements found in Appendix A1. For the most part, at each home, duct leakage was measured multiple times by using most of the five tests; the prevalence of each of these tests is listed in the second column of Table 3.1. Mean values are presented on the first five rows of Table 3.1.

Table 3.1 Mean duct-leakage-to-outside.

Tests	Number of Tests	Mean Duct-Leakage-to-Outside (cfm)	Standard Deviation (cfm)
1. APT Depressurized (50 Pa)	42	733	859
2. Manual Depressurized (50 Pa)	43	645	578
3. APT Pressurized (50 Pa)	16	459	261
4. Manual Pressurized (50 Pa)	16	654	334
5. Combined (25 Pa)	43	313	154
6. Combined (50 Pa)	43	474	233
7. Weighted Sum of all tests at 50 Pa	160	604	503
8. Weighted Sum of all tests at 25 Pa	160	399	332

Because the Combined data were entered into Table 3.1 as interpolated to 25 Pa and the other data at 50 Pa, a sixth row was created as follows: an entry in row five was multiplied by $(50/25)^{0.60}$ to obtain the corresponding entry in row six. The seventh row of Table 3.1 presents a weighted sum of duct leakage measurements at 50 Pa. The eighth row presents a weighted sum of the duct leakage measurements at 25 Pa; it was obtained from the seventh row by multiplying by $(25/50)^{0.60}$.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Unlike the directly obtained means (averages) described herein, this chapter also provides a more detailed and complete statistical analyses of the raw data. For example, at the conclusion of this chapter, Table 3.10 displays revised values for the same parameters displayed in Table 3.1; i.e., the means were recalculated using subsets of original samples after outliers were removed.

3.2 Relationships of Depressurized APT and Manual Methods' Measured Results

The relationships in measurements of duct leakage CFM50 between the APT and Manual methods are examined.

The Line of Equality plot and other statistical tests facilitate the distinction between two kinds of data: data probably a product of the common and intended testing environment, and outliers, data probably undermined by errant conditions. It is possible to perform statistical tests on a preferred subset within the sample that avoids outliers. These techniques are explained in the book titled *Introduction to Linear Regression Analysis* by Douglas C. Montgomery, Elizabeth A. Peck and G. Geoffrey Vining.

Duct leakage by Manual vs. APT methods for pressurized and depressurized tests are compared via Line of Equality graphs in Figures 3.1 and 3.2, respectively. Since most of the points lie near or along the 45-degree line, APT and Manual testing methods are in general agreement. Moreover, because most of the data are clustered in the graph, the data probably conform to a relatively consistent testing environment.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

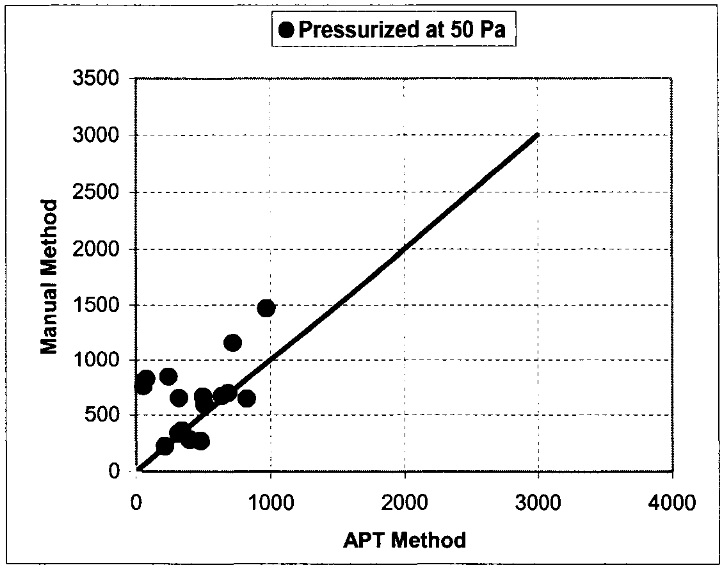


Figure 3.1 Line of equality plot: Manual vs. pressurized APT.

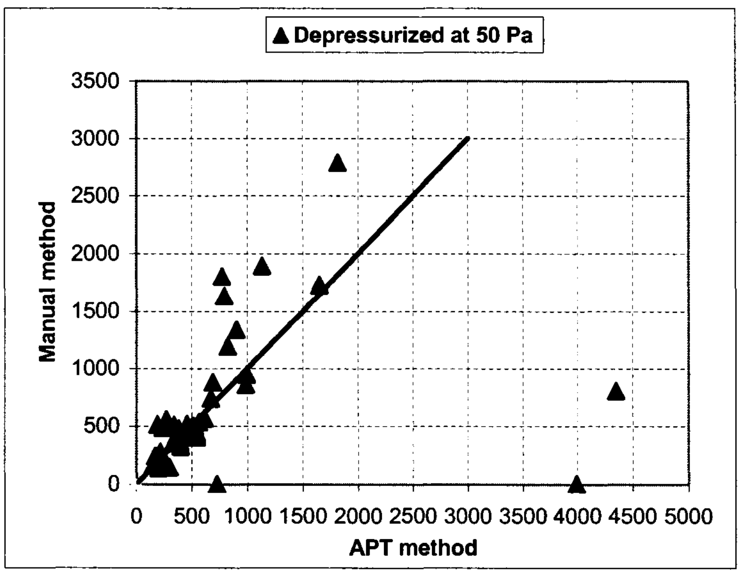


Figure 3.2 Line of equality plot: Manual vs. depressurized APT.

3.3 Sources of Error that Distinguish APT from Manual Measurements

Both here and in Section 3.5, various sources of error that affect duct leakage measurements is discussed. Although these discussions are extensive, we note that we may still not have listed all of the causes of error. While in some cases the consequences

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

of these errors are suggested, in general attempted to comprehensively estimate the magnitudes of their effects. However, beyond these two discussions, the investigations of these sources of error are beyond the scope of this report.

Sources of errors in measurements can be caused by a combination of categories, including:

a. Human error, (e.g., error in setting up the experiment, misreading or untimely reading of the meters, failure to notice defective experimental conditions, inconsistent implementation of procedures)
b. Unanticipated variations in the testing environment, (e.g., changes in wind speed, seals falling off taped registers, opening/closing of air valves in the building envelope)
c. Insufficient or inconsistent accuracy in the test equipment, (e.g., accuracy depends upon magnitude, sensitivity to temperature, zeroing of gauges that may not be automatic)
d. Deficiencies in the data collection algorithm, (e.g., lack of redundancies in the tests that if present would minimize the magnitude of measurement and subsequent calculation errors or, alternatively, help alert the tester to changes in the test environment; inadequate tests at initial steady-state conditions; inadequate procedures to insure dynamic steady-state conditions)
e. Inaccurate to incomplete theoretical models, (e.g., using the wrong flow exponent for the whole-house leakiness, using the wrong flow exponent for duct-leakage to outside, assuming that no valves in the building envelope that can change position within and between various tests, assuming that attic pressure will not change during any test that depressurizes a home)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

In Section 3.3, the experimental problems that tend to cause APT and Manual measurements to differ are discussed. We focus upon the reasons for the outliers in the Line of Equality Plots in Figures 3.1 and 3.2.

1. The use of the "Can't Reach Fifty Factor" is a source of error of types d and e. When a home cannot reach 50 Pa during a Manual test, the flow at 50 is extrapolated from the measured flow at the measured pressure. The procedure is to look up a "Can't Reach Fifty Factor" from the row on the table corresponding to the pressure where the flow measurement was taken; the factor is then multiplied by the measured flow to extrapolate the flow at 50 Pa. The derivation of the "Can't Reach Fifty Factor" table is based upon the assumption that the flow exponent of the tested home is 0.65 since this value has been reported to be the mean flow exponent for thousands of homes [12]. However, this procedure introduces an error into the Manual CFM50 reading that will not correspond to an error in an APT CFM50 reading. Unlike the Manual method, which does not collect sufficient data to estimate the flow exponent for the particular home, the APT method calculates that flow exponent from the data it collects and uses it for the extrapolation to 50 Pa. Therefore, we would expect a difference between the Manual and APT duct leakage calculations for homes where the Blower Door™ could not take the home to 50 Pa and the APT calculates a flow exponent different from 0.65. The greater the difference in attained house pressure from 50 Pa and the flow exponent from 0.65, the greater is the difference in APT and Manual values. Even if the home's APT calculated whole-house leakiness flow exponent is 0.65 during the untaped test, the APT whole-house leakiness calculated flow exponent will most likely be different from 0.65 during the taped

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

test. This difference in flow exponent invariably happens because the characteristic shape and size of the average infiltration hole of the home will shift with the exclusion of some of the duct leaks, thereby changing the flow exponent.

2. Measurements taken at dynamic, non-steady-state flow conditions are sources of error of categories a and d. All of the measurements presume that the readings of the manometers will occur when the home has reached pressure for a time period sufficient for steady-state flows. A Manual test may not have sufficient safeguards to assure steady state. In a Manual test, the operator of the fan speed controller is instructed to begin each test with the fan off and increase the fan speed until 50 Pa is reached and then takes a reading. In fact, the fan speed and the house pressure are both returned to zero three times during a sequence of three readings. However, the home's pressure reading almost always exceeds 50 Pa during the adjustment period just before the measurement is recorded and in response the operator lowers the fan speed. In fact, the fan speed operator may often cycle through several lowering and raising adjustments before the desired stability in the manometer reading is attained, at which time the measurement is taken. However, the steady-state condition may not have been reached. It may be that left with the fan speed kept at the current setting, waiting an extra five to ten seconds would result in few Pa change in the house pressure. In such a case, the reading was taken within non-steady-state conditions and should therefore be more appropriately assigned to a different pressure than 50 Pa. (As explained two paragraphs below, a two Pa error can be expected to be associated with more than a 100 CFM error.) However, the Manual algorithm does not require this idling test to assure steady state, so there is no indication to the fan speed

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

operator that the manometer measurement was taken too early. In the case that the Manual reading is made for the sole purpose of measuring CFM50 for whole-house leakiness, the resulting error may be insignificant. However, since this report is devoted primarily to measuring duct leakage, which depends upon the difference between two such readings, this error can be very significant. APT measurements are far more resilient against this kind of error since 100 data are collected at each of a series of eight decreasing house pressures over five minutes all the while the fan speed is kept on or near the target test pressure; i.e., there are no intermediate trips to zero Pa. Although the initial (first five or ten at each pressure) flow measurements in the automated test may be inappropriately assigned, because steady state may not have been reached, to the simultaneously measured pressure, the mere fact that 100 readings are taken at each target pressure provide significantly more assurance that the average value of each of these flow readings is very close to the true steady-state flow at the averaged measured pressure. Thus, each APT whole-house leakiness CFM50 measurement can be expected to be much less affected by a non-steady state flow error than a Manual measurement, and the corresponding duct-leakage calculation – derived from a difference in two such readings – will correspondingly be subject to significantly less error.

3. The ratio of the magnitudes of whole-house leakiness to duct leakiness for a home is a source of error primarily of categories c and d. The larger this ratio, the greater is this source of error. To appreciate this error, one should recognize that in the Manual test, the Blower Door™ operator uses a digital manometer calibrated against the average Blower Door™ to create a single unified

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

(manometer/Blower Door™) instrument that has decreasing sensitivity with larger flow readings. This setup cannot be expected to have the same $\pm$ 0.1 Pa (95% confidence interval) accuracy, published for the manometer alone, at every flow reading regardless of the magnitude of the measured flow. Again, for the purpose of ascertaining whole-house leakiness, the calibration of the manometer to the Blower Door™ can be more than adequate, but for the purpose of measuring duct leakage via subtraction, this error can be quite substantial. Here again, the APT measurement is significantly less affected by the decreasing accuracy at higher readings inherent in the manometer/Blower Door™ calibration used. The APT CFM50 extrapolated flow is more accurate because it is derived from a regression on eight data – each of which was the average of 100 (or more) measurements made with the manometer/ Blower Door™ device.

4. Failing to record or take into account the pressure in the home when the Blower Door™ fan is off is a source of error of types d and e. Even without a Blower Door™ in operation, the home may be under a persistent negative (or much less common, positive) pressure of a few Pascals; often caused by stack effects or exhaust fans operating within the home or attic. Even more commonly, very modest changes in wind conditions can generate variations in the home's pressure greater than 1 Pa during a one-minute test. Consider the following example: if the home has a normal –two Pa steady-state pressure when the Blower Door™ fan is off, a measured depressurized flow at 50 Pa should be assigned to 48 Pa. If such a home's actual CFM50 were near 5000, then the error associated with ignoring the home's initial pressure, is roughly 131 CFM ($393.2 = 5000/50^{0.65}$; $393.2 * 48^{0.65} = 4869$; $5000 - 4869 = 131$). One could argue that

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

this error in whole-house leakiness will not affect the subtraction algorithm for duct leakage, because this superfluous flow would be the same in taped and untaped cases and thus be subtracted away. However, a home's tendency to have a persistent negative pressure is frequently associated with a persistent negative pressure in the attic. If duct leakage enhances the connection between the attic and home, the attic is better connected to the home with the duct registers untaped than taped; in that case, the error made by ignoring the initial house pressure will not subtract away. Another scenario is the potential change in exterior pressure fields on the home associated with changing wind conditions during the time between the taped and untaped tests. Here too, the Manual test is far more sensitive to this error than the APT test because the Manual test algorithm does not record the pressure in the home when the Blower Door™ fan is off, while the APT test includes measuring 100 data before and after the 800 data are collected, during which time the Blower Door™ fan is off and the fan is covered.

5. Failure to zero the manometer between readings is a source of error of type c. If the manometer has not been reset to zero, it may display a value against a misinterpreted reference. There is no provision for this resetting in the Manual test algorithm, but auto-zeroing occurs eight or more times during the APT test.
6. Failure to account for air temperature is a source of error of type c and e. Flow through the fan is measured as a drop in pressure across the fan, and the manometer's calibration to the Blower Door™ uses this pressure drop to calculate the flow. However, this calibration depends upon the density of the air

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

that in turn is affected by temperature. Unlike the APT tests that collect and use temperature information, Manual tests do not record or use this information.

7. Failure to restart a test when a duct register's seal opens, exterior door opens or exterior fan starts up during the test is a source of error of type a and d. Because the Manual test is actually a redundant one-point test, little information in the resulting data indicates a defect in the test environment. However, an APT test collects data for roughly five minutes, and displays the results graphically during the testing. The computer operator of an APT test soon learns from experience that the quality of an APT test increases, as the displayed graph's data points are more collinear. If a change in the test environment happens during this time, the gathered data will usually show a large change or fluctuation away from linearity. This error probably did not plague our data since when such an event occurred both tests were repeated after the environmental problem was repaired. However, in normal practice when only a Manual test is performed, the resulting error caused by this type of event could be very large.

8. Using the wrong mean whole-house leakiness flow exponent and the way it is used in the data collection algorithms are a source of error of categories a, b, d and e. Unlike error one which tends to cause an extrapolated CFM50 Manual reading to diverge from the true value for a particular home, the use of the mean exponent can make a reported APT reading diverge from an actual, measured CFM50 reading in a particular home for a quite different reason. When the TECTITE™ software performs the regression analysis at the end of the collection of a thousand or more data, the correlation coefficient is calculated and compared to a minimum acceptable value; when this value is not attained, the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

regression is ignored, and instead, all of the data is averaged to a single point and 0.65 is the assumed flow exponent. The reason for this step is associated with the most common use of the APT-TECTITE™ algorithm, for extrapolating CFM4, namely the flow at four Pa. However, for our use, the reported value of CFM50 is consequently affected by this calculation procedure and it therefore depends upon the choice of mean flow exponent. To a very limited extent, this error may have been smaller if 0.64 were used instead. To avoid this error, the tester should always, if practical, repeat or adjust, as necessary, the test conditions to insure that TECTITE™ actually calculates a flow exponent for that home. Subsequent to the data collections of this experiment, we have found that that in all but very rare circumstances, sufficient care and skill in the APT data collection procedures will allow the TECTITE™ regression analysis to calculate a correlation coefficient greater than 99%; however, precautions needed to insure this level of accuracy were not taken during the data collections for this report.

9. The opening or closing of valves during a test can cause errors of categories b, d and e. Although this problem is more easily observed in Section 3.4 below wherein the Combined data are analyzed, this source of error will also cause the APT results to diverge from the Manual. Valves opening or closing during a test will result in a change in the flow exponent. Therefore, a single steady-state measurement at 50 Pa will only experience a single set of open or closed valves, as in the Manual test. However, during the APT test, which takes measurements at a series of pressures, the home may exhibit changes in the flow exponent. This may, in fact, be the reason why the correlation coefficient may be inexplicably low for some homes, despite the care and skill of the equipment operator. In

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

such situations, one would expect the APT test to report a CFM50 different from the value actually measured. Note that this scenario can happen even when the reported correlation coefficient (because it is not small) and the flow exponent of that home are used in the extrapolation. These valves could behave quite differently at different pressure differences and even in a different way when performing depressurized vs. pressurized measurements. For these reasons, this source of error is revisited in Section 3.5 because the Combined tests are pressurized tests, at pressures between 15 and 35 Pa, while the tests under discussion in Section 3.4 are both depressurized tests focused on measurements near 50 Pa.

The explanations of three additional sources of error regarding Blower-Door™-only tests are delayed to Section 3.5 because these kinds of errors do not tend to cause the APT and Manual results to diverge from each other. Instead, these errors cause the APT and Manual results to similarly diverge from accurately measuring duct leakage to outside. Therefore, they tend to cause the Blower-Door™-only test results to diverge from the Combined results.

The following is not a source of error but a comment about the unusual importance of duct leakage testing accuracy in Louisiana. The reader should consider that although a single duct leakage measurement on a single home may have a 50 to 200 CFM error in a Manual test and a much smaller error in an APT test, the real importance of this difference in error comes into play in Louisiana wherein the HERO (Home Energy Rebate Option) program requires duct leakage tests to be performed at least twice on homes with existing duct systems. Because the goal of this program is to promote energy efficiency, which in turn is significantly compromised by duct leakage

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

greater than 50 CFM25, the HERO program would be best served by a duct leakage measuring algorithm capable of confirming changes in duct leakages significantly smaller than 50 CFM25. For example, if the second duct leakage measurement finds no decrease after known repairs were done, it will create unresolved complaints, unsatisfied customers and frustrated AC contractors. Conversely, if the duct leakage test were sufficiently accurate, this same opportunity would measure the slight improvement and enhance the customer's confidence in the rater's competence as well as the ability of the customer to demand higher quality work from the AC contractor. Thus, the accuracy of a duct leakage test can actually play a larger role in Louisiana than it does in many, if not all, other states.

3.4 Combined Duct Leakage

Combined duct leakage measurements provide a unique opportunity to more directly measure duct leakage (to outside) than the Blower-Door™-only methods otherwise used in this report. Many researchers and practitioners believe that the Combined method is the best and most reliable test for duct leakage to outside. For this reason, predictions of Combined from both Depressurized APT and, independently, Depressurized Manual data are analyzed statistically in Sections 3.6.1 and 3.7.1, respectively.

In each home, the Combined measurement of duct leakage flow, F_{15}, was attempted at P_{15} = 15 Pa, F_{25} at P_{25} = 25 Pa, and F_{35} at P_{35} = 35 Pa, respectively. Unlike the APT measurements, the Combined data were only collected utilizing pressures well below 50 Pa. Therefore, to have comparable data, it was necessary to extrapolate the Combined data to 50 Pa. The extrapolation was accomplished using one of the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

following two algorithms; however, both rely upon the following relationship between pressure and flow.

The pressure-flow equation is

$$F = C\Delta P^{n}$$

(3.1)

where F is airflow, C is the leakage coefficient, ΔP is the pressure difference and n is the flow exponent.

Eq. 3.1 was used to determine the airflow at 50 Pa (F_{50}). When all three data, F_{15}, F_{25} and F_{35}, were present for a particular home, the best method for determining n and C was to perform a two-dimensional regression analysis on the logarithm of the flow data, i.e., log(Flow) vs. Pressure. Among the outputs of the regression analysis is the line of best fit. The y-intercept and slope of this line can each be exponentiated to obtain C and n of Eq. 3.1, respectively. Extrapolating the Combined reading to 50 Pa is then reduced to substituting these values into Eq. 3.1.

When only two flow readings are known, a method based upon simultaneous equations was employed, (see flowchart in Figure 3.3). Requiring only F_{15} and F_{25}, this algorithm extrapolates Combined measurements to 50 Pa after it first establishes values of C and n. (The same method could also be performed using any pair of data, e.g., at 25 and 35 Pa as well.) This method was employed for homes where the maximum attainable pressure was 25 Pa.

In summary, for each home in the sample, both algorithms first establish C and n; these parameters are calculated using regression if possible or simultaneous equations when only two data are known; in either case, C and n are used within Eq. 3.1 to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

extrapolate the airflow to 50 Pa. Each home will get have its own duct-leakage flow exponent and flow coefficient calculated, and the extrapolation to CFM50 (as well as, interpolation to CFM25) is more accurate for that home. The results of this work are presented in the 33 rows of data in Table 3.2. In a few homes, flow readings at 35 Pa were not possible and the corresponding cells are left blank.

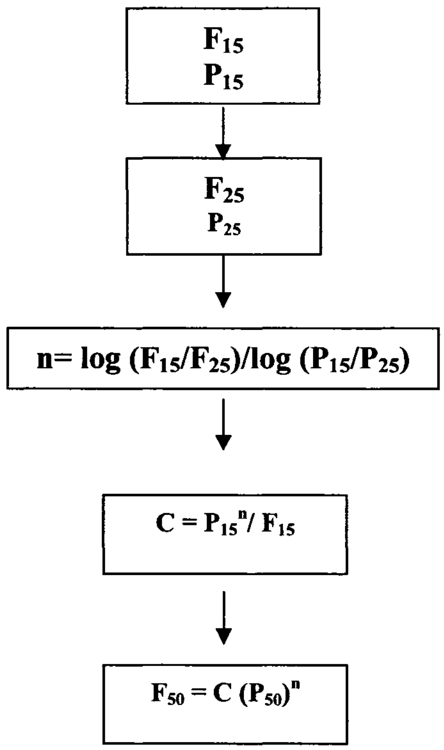


Figure 3.3 Flow chart for calculating duct leakage parameters via simultaneous equations.

3.4.1 Mean Combined Duct Leakage and Mean Flow Exponent

At the beginning of this chapter, Mean Combined Duct Leakage was estimated in Table 3.1 using the flow exponent 0.60. However, the best way to obtain this value is to treat each home independently, as explained previously in this section. Following this methodology, we independently obtain both:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Mean Combined Duct Leakage = 312 CFM25 and,

Mean Combined Duct Leakage = 473 CFM50.

Table 3.2 Combined duct leakage flow data and parameters.

Home No.	Flow at 15 Pa	Flow at 25 Pa	Flow at 35 Pa	Flow Expone-nt	Flow Coefficie-nt	Flow Interpol-ated to 25 Pa	Flow Extrap-olated to 50 Pa
3	368	551	636	0.657	63.32	525	828
4	449	651		0.727	62.66	651	1078
5	212	285	350	0.590	42.86	286	431
6	115	153	195	0.618	21.39	156	240
7	420	529	642	0.497	108.67	538	759
8	234	316	387	0.592	47.00	317	477
9	571	729		0.478	156.39	729	1016
11	144	204	258	0.688	22.34	204	329
12	121	160	187	0.516	30.01	158	226
13	299	387	497	0.592	59.42	400	602
14	337	486	584	0.654	57.79	475	748
15	161	246	278	0.660	27.64	231	365
16	92	132	154	0.616	17.58	128	196
17	234	307	380	0.570	49.74	311	462
18	395	478	625	0.528	92.48	506	729
19	129	172		0.563	28.07	172	254
20	163	235	300	0.719	23.28	235	387
21	162	214	268	0.590	32.56	218	328
22	264	362		0.618	49.52	362	555
25	91	111	136	0.467	25.38	114	158
26	115	173	208	0.709	17.08	167	274
27	77	93	100	0.310	33.53	91	113
28	95	121	159	0.599	18.43	127	192
29	140	211	245	0.671	23.20	201	320
30	248	325	393	0.543	56.88	327	476
31	243	340	422	0.653	41.52	339	534
32	149	201	269	0.691	22.57	209	337
33	309	409	497	0.561	67.60	411	606
34	260	377	448	0.650	45.25	366	575
35	109	148	183	0.610	20.83	149	227
36	315	427	517	0.586	64.59	425	638
37	218	315	364	0.614	41.92	303	464
38	261	325	415	0.537	60.03	338	490
39	171	259	298	0.669	28.49	246	391

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

43	290	391		0.585	59.48	391	586
46	407	524		0.495	106.62	524	738
48	240	308	390	0.566	51.23	317	469
49	86	131	204	1.002	5.56	140	280
50	111	170	198	0.694	17.31	161	261
51	388	490	558	0.431	121.17	485	654
52	178	256	315	0.678	28.54	253	405
53	338	491	590	0.663	56.61	479	759
55	160	233		0.736	21.82	233	388

The mean flow exponent was found to be 0.60914. Using t-statistics, it was determined that the 95% confidence for the mean value of the exponent ranged between 0.5773 and 0.6410. The calculated mean value and its confidence interval agree with 0.60 – the value provided by Gary Nelson [28].

3.5 Sources of Error that Distinguish APT and Manual from Combined Measurements

In this section and in Section 3.3, various sources of error that affect duct leakage measurements are discussed. It is important to note that all the plausible causes of error may not have been listed nor the estimated magnitudes of the effects of these listed errors. However, beyond these two discussions, the investigations of these sources or errors are beyond the scope of this thesis.

As stated in Section 3.3, sources of errors in measurements can be caused by a combination of categories, including

a. Human error,

b. Unanticipated variations in the testing environment,

c. Insufficient or inconsistent accuracy in the test equipment,

d. Deficiencies in the data collection algorithm,

e. Inaccurate to incomplete theoretical models,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

This section describes the problems that tend to cause APT and Manual measurements to differ from Combined results, as well as general sources of error of Combined tests that decrease their accuracy.

1. The opening or closing of valves during a test can cause errors of types b, d and e (Section 3.3 and Section 3.4). It is important to note that, the flow exponent (n) has limiting values of 0.50 and 1.00 for fully developed turbulent and laminar flow respectively [30]. However in Table 3.2, the flow exponent for home 49 is greater than 1.00, and the respective flow exponents for homes 7, 9, 25, 27, 46 and 51 are less than 0.50. One possible reason for this discrepancy is the opening and/or closing of air valves at different pressurizations, namely that in a given home we may not be looking at airflow through equivalent openings between pressure changes. In addressing the decision of whether to accept, to reject, or to alter these values, it is important to note that there is no evidence that similar changes might not be occurring in some, or in all of the other homes measured. Thus, this study has decided to retain all the values in our analysis, while pointing out a possible flaw in the assumption of the applicability of the flow equation to this problem; namely it may give acceptable results, but its physical assumptions may not always be satisfied.

   This last paragraph points to another error that can help explain the discrepancy between the mean duct leakage CFM50 for Manual or APT versus CFM50 for Combined. The fact that seven out of 33 homes exhibit flow exponents outside of the theoretical range (ignoring the existence of valves that open or close under varying pressures) strongly suggests that this phenomenon is probably a common occurrence. That we do not see it in the data of the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

remaining homes simply indicates that it does not produce a large enough average change in the exponent to put it outside of the acceptable range. However, this change in the home parameters means that this can be a very significant source of error for a particular home. Moreover, the set of valves will probably be quite different in a pressurized test (e.g. Combined) than in a depressurized test (e.g. APT and Manual).

As mentioned in Section 3.3, three additional sources of error regarding Blower-Door^{TM}-only tests were delayed to this section because these kinds of errors do not tend to cause the APT and Manual results to diverge from each other. Instead, these errors cause the APT and Manual results to diverge from accurately measuring duct-leakage-to-outside in a similar manner. However, they do tend to cause the Blower-Door^{TM}-only test results to diverge from the Combined results.

2. Incorrectly assuming that the attic pressure remains constant and at 50 Pa during both taped and untaped measurements of whole-house leakiness is a source of error of categories b, d and e. Our tests demonstrate that this assumption is seldom verified in practice and will definitely affect the resulting measurements; it will tend to affect the Manual and APT tests in the same manner but it may have a very different affect upon the Combined tests. This source of error will change the meaning of the reading; in fact: ignoring attic pressure will cause the flow readings to be assigned to a higher pressure than it was actually tested at, resulting in an underestimate of the measured CFM25 flow. Because the APT and Manual tests occur at different pressures and opposite pressurization direction from a Combined test, we should expect a significantly different effect

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

on attic pressures. This result may account for the significantly lower CFM50 mean of the Combined measurements as compared with either the APT or Manual measurements.

3. Incorrectly assuming that the pressure in the ducts when the registers are untaped is the same as that in the house leakiness is a source of error of types b, d and e. This source of error will tend to affect the APT and Manual tests the same way. Although this error does not tend to distinguish the APT and Manual tests from each other, it will cause APT and Manual tests to be more unlike the Combined test.
4. Incorrectly assuming that the average duct leakage flow exponent is 0.65 is a source of error of type e. Although this error does not tend to distinguish the APT and Manual tests from each other, it will cause APT and Manual tests to be more unlike the Combined test.
5. Combined duct leakage measurements are susceptible to an inherent error in addition to those discussed above in reference to the Manual and APT tests. In (apparently) rare situations, airflow short-circuits can be set up between the Duct Blaster™ and some hole between the ducts and the house. The measured flow assigned to duct-leakage-to-outside will then incorrectly contain this short-circuit flow, and thus the Combined measurement will be an overestimate of duct leakage-to-outside. To investigate this concern, special tests (not otherwise described in this report) were devised and implemented in a few homes. However, in the few homes where these specialized tests were performed, we found no evidence of short-circuits. When this kind of error occurs it would be

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

of types b, d and e. Tests performed by Blower-Door™-only methods would not be susceptible to this error.

It should be pointed out that when the evaporator coil is significantly blocked and short-circuiting is possible, a Duct Blaster™ assisted by Blower Door™ test; i.e., Combined test, would be much more likely to overestimate duct leakage than a Blower-Door™-only test. In the former case, the test must pass adequate air through the evaporator coil to pressurize the ducts to a given pressure. However, a Blower-Door™-only test may not even develop a pressure across the evaporator coil. The barrier to airflow provided by the coil, in this case, is not in the theoretical model of measuring duct leakage via subtraction.

3.6 Statistical Comparisons: Depressurized APT vs. Depressurized Manual

Depressurization measurements were obtained at 50 Pa using the APT and Manual methods. From the 55-home sample, only 42 could be used for comparing the APT and the Manual methods. The reduction was caused by a variety of experimental difficulties. Most of the excluded homes had acoustical ceilings that precluded depressurization tests. These data can be found in Appendix A1.

The 42-home sample of depressurized APT and Manual tests were statistically analyzed in two ways. In Section 3.6.1, the two samples are compared on a home-by-home basis to determine how well a single Manual measurement can predict the corresponding APT measurement; Line of Equality and Regression Analysis were used. The means of the Manual and APT measurements are statistically compared in Section 3.6.2 using the Paired t-test and a Non-Parametric test.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3.6.1 Predicting Depressurized APT from Manual Measurements

3.6.1.1 Line of equality

Figure 3.4 shows the Line of Equality associating APT vs. Manual methods within the 42-home sample. It shows that the APT and Manual methods are in reasonable agreement when the duct leakage is below 1000 CFM but there are more outliers for higher values.

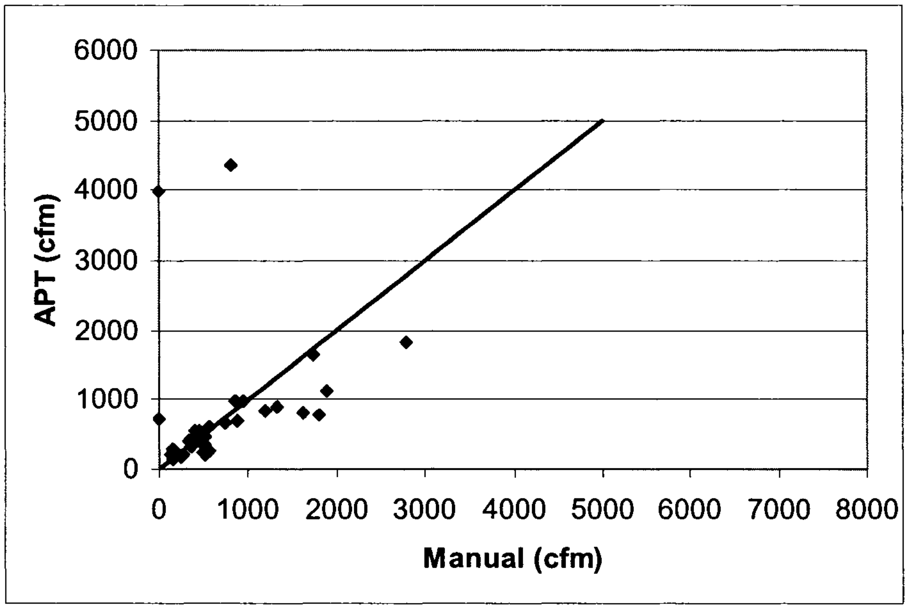


Figure 3.4 Line of equality: APT vs. Manual.

The causes for these abnormal variations may be attributed to errant conditions, such as: unusual wind speed, untimely changes in other building environmental parameters, human errors, as well as, test conditions that may have resulted in the inconsistent opening/closing of building airflow valves. A more complete list of sources of error can be found in Section 3.4.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3.6.1.2 Regression analysis

A simple regression analysis was used to investigate and model the relationship between APT and Manual methods. Figure 3.7 demonstrates a regression analysis for the preferred subset of the sample data. This analysis is presented in Section 3.6.1.6 after outliers are removed. The resulting regression provides a 95% confidence interval in addition to the comparison parameters.

3.6.1.3 Determining outliers using standardized residuals

Using the results of regression technique, data associated with standardized residuals with magnitude above two were removed and this procedure was repeated until all such outliers were removed. Using this procedure, 11 outliers were removed and the sample size decreased from 42 to 31.

A regression analysis provides a prediction. However, to obtain a quantitative confidence interval, namely an interval in which there is a defined probability (normally taken to be 95%) of being correct, Independence of Errors and Normality must be established. Confirmations of these assumptions were ascertained via Figure 3.5 for Independence of Errors and Figure 3.6 for Normality.

3.6.1.4 Independence of errors

The observation order of the data is the home numbers (experiment number) after outliers are removed. The residual plot indicates that the residuals are random, thereby supporting independence of errors.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

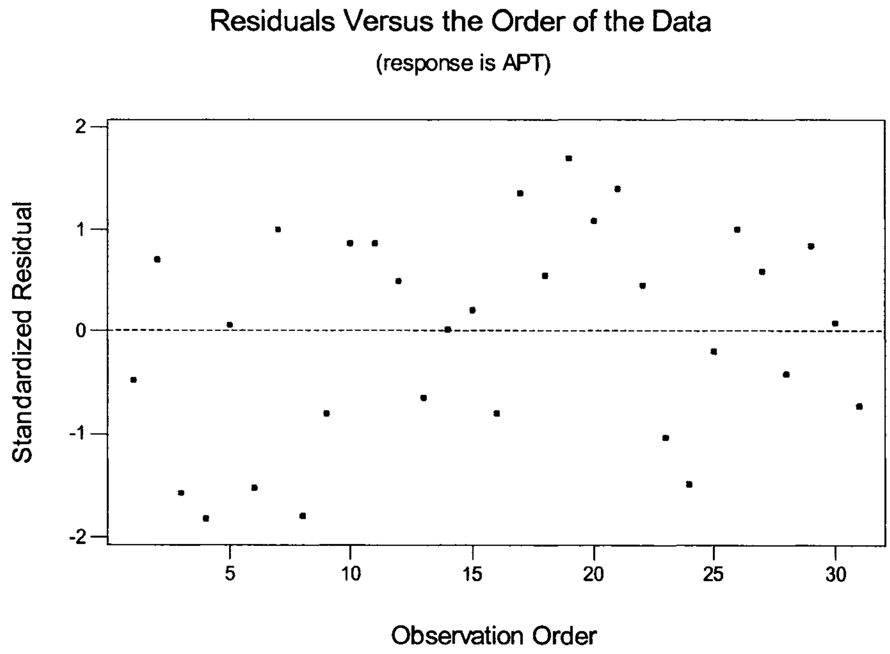


Figure 3.5 Standardized residuals' plot: APT vs. Manual.

3.6.1.5 Normality

The residuals were tested for normality using an Anderson-Darling test [31][32]. Figure 3.6 displays an Anderson Darling P-value of 0.230 confirming the 95% confidence in normality.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

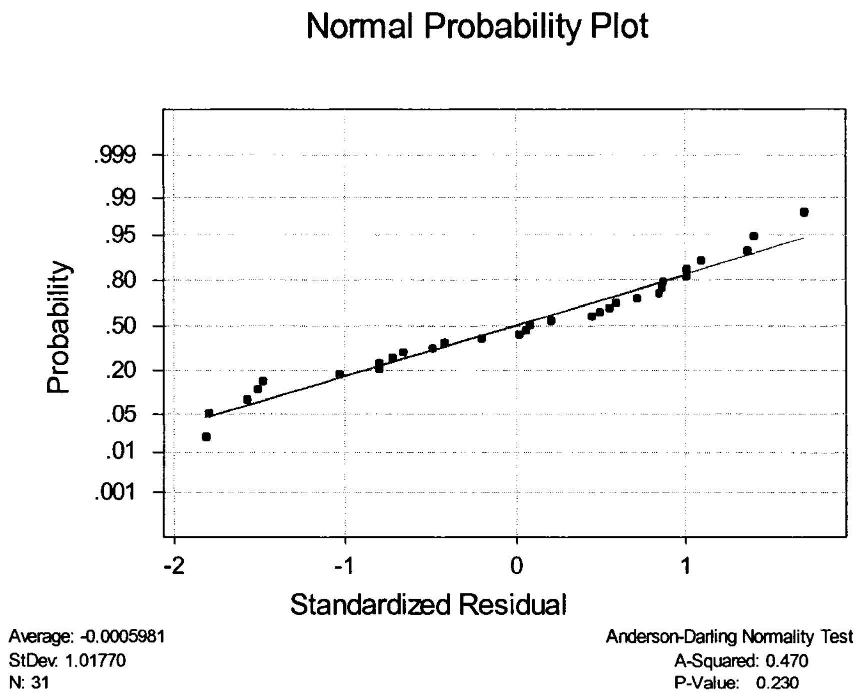


Figure 3.6 Normal probability plot of standardized residuals: APT vs. Manual.

To summarize, 11 outliers were removed from the data, leaving a 31-home sample (all residuals data that lie between +/-2 standard deviations of the mean). To validate the two assumptions needed for producing a 95% prediction interval within the regression model, Independence of Errors and Normality were confirmed. The 31-home sample was used for the plot of Standardized Residuals vs. Observation Order (Figure 3.5) and the Normal Probability Plot of Residuals (Figure 3.6). The scatter of the data in Figure 3.5 suggests that the errors are independent. The normal probability plot (Figure 3.6) and its analysis using the Anderson-Darling normality test established the closeness of the revised data set to a normal distribution. Therefore, a 95% Prediction Interval is justified. Statistical calculation details are presented in Appendix A2.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3.6.1.6 Regression analysis and 95% prediction interval

The regression analysis (Figure 3.7) performed on the 31-home sample illustrates the 95% prediction interval for the data.

The regression equation is

$$APT = 176.552 + 0.574620 \text{ Manual} \quad (3.2)$$

Namely, the value of the APT reading can be predicted from the Manual reading using Eq. 3.2. For a given manual value, the dashed lines in Figure 3.7 give the interval that includes the true APT value with probability of 0.95.

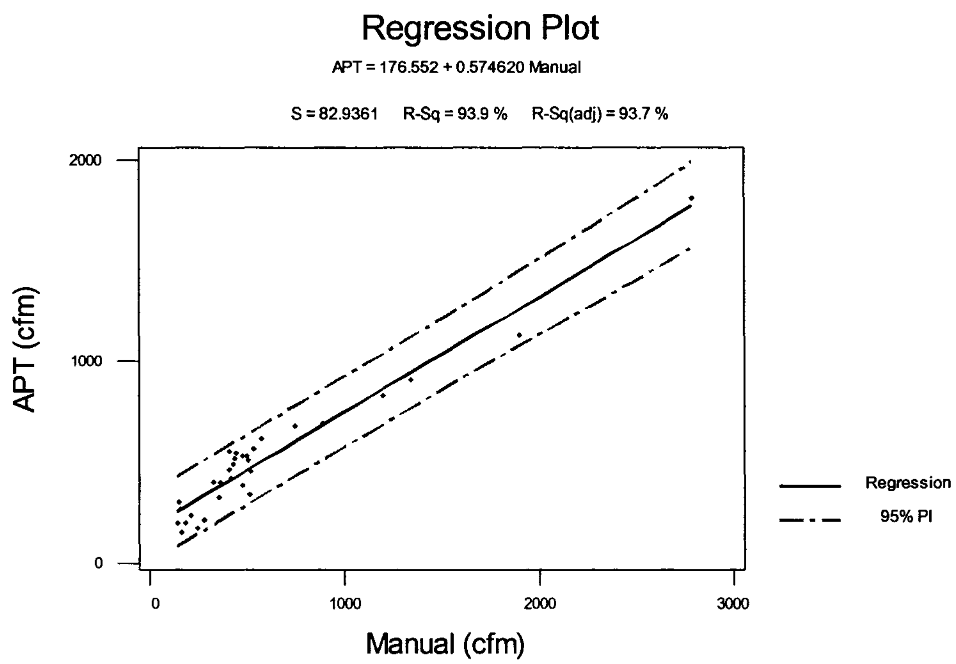


Figure 3.7 Regression plot with 95% confidence interval: APT vs. Manual.

Also displayed in the MINITAB™ output is the coefficient of determination, r^2, with a value of 0.939; thus indicating a high correlation between the two measuring methods (the correlation coefficient r = 0.97).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3.3 shows the predicted APT values for each Manual reading and their 95% prediction intervals; namely a predicted APT value, given in column four, has a 0.95 probability of being within the prediction interval; the prediction interval is bounded by the values in columns five and six, centered about the predicted APT value, given in column four.

Table 3.3 95% Prediction interval for duct leakage values: APT vs. Manual.

Observation/(Home Number)	Manual (cfm)	APT (cfm)	Predicted (cfm)	95% Prediction Interval	
1 (03)	1337.90	907.00	697.73	524.44	871.02
2 (04)	2789.20	1818.00	1221.44	1035.83	1407.05
3 (05)	508.40	340.30	372.09	199.23	544.96
4 (06)	245.50	170.10	274.29	100.44	448.15
5 (11)	418.70	421.80	418.93	246.36	591.49
6 (12)	166.70	149.70	262.57	88.56	436.58
7 (13)	474.10	530.80	481.56	309.20	653.92
8 (14)	1895.60	1134.00	828.06	652.99	1003.12
9 (16)	209.60	232.50	310.15	136.72	483.58
10 (18)	742.50	674.00	563.85	391.43	736.26
11 (20)	427.60	492.40	459.49	287.09	631.90
12 (21)	148.00	301.50	349.80	176.76	522.84
13 (26)	354.50	326.80	364.34	191.41	537.26
14 (28)	153.80	266.30	329.57	156.34	502.81
15 (29)	361.10	400.50	406.69	234.05	579.32
16 (30)	477.30	385.38	398.00	225.31	570.68
17 (33)	569.60	615.30	530.12	357.77	702.46
18 (34)	502.30	510.10	469.67	297.28	642.05
19 (36)	408.40	549.80	492.48	320.13	664.82
20 (37)	438.30	517.40	473.86	301.49	646.23
21 (38)	445.30	546.60	490.64	318.29	662.99
22 (39)	327.20	401.10	407.03	234.40	579.66
23 (40)	182.80	198.20	290.44	116.78	464.10
24 (42)	278.30	216.10	300.73	127.19	474.27
25 (43)	517.00	457.40	439.38	266.91	611.86
26 (45)	535.00	566.20	501.90	329.56	674.24
27 (47)	409.00	459.40	440.53	268.06	613.00

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

28 (51)	1192.00	828.30	652.51	479.63	825.39
29 (53)	496.50	530.50	481.39	309.03	653.75
30 (54)	883.30	690.40	573.27	400.83	745.71
31 (55)	140.90	199.10	290.96	117.31	464.61

3.6.2 Comparing the APT Mean to the Manual Mean

To confirm that the two methods tend to measure the same duct leakage, a comparison of the means was performed using the Paired t-test. The Paired t-test was performed on the 42-home sample using the MINITAB™ software and the detailed results are presented in Appendix A2.

3.6.2.1 Paired t-test application

The 95% confidence interval, Δ, for the mean difference between APT and Manual was determined to be between –197 cfm and 360 cfm; since this range includes zero, the test indicates that there is no statistically significant difference in the average measured readings of the APT and the Manual method. A Non-Parametric test was also performed because an assumption of the Paired t-test was violated, namely: the set of paired differences (APT – Manual) failed a normality test (presented in Appendix A2).

3.6.2.2 Non-Parametric test application

The Wilcoxon signed-rank test was used to compare the means of the APT and Manual measurements. This test utilizes both direction and magnitude of the differences between the two measured values of duct leakage. The 95% confidence interval for the difference between the means of the APT and Manual methods is bounded by –118 cfm and 39 cfm. Since this range includes zero, we can conclude that on average the APT and Manual methods measure the same amount of duct leakage. The conclusion of the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Parametric test (Paired t-test) was similar to that of the Non-Parametric test (Wilcoxon signed-rank test) even though the Paired t-test was not formally applicable since the data did not follow a normal distribution. The agreement in these conclusions derives from the robustness of the Paired t-test against relatively small deviations from normality.

3.7 Statistical Comparisons: Combined vs. Depressurized APT

Measurements obtained at 50 Pa in the depressurized state for APT and the Combined methods produced two experimental data sets. These sets were statistically compared in two ways. In Section 3.7.1, the two samples are compared on a home-by-home basis to ultimately determine how well a single APT measurement can predict the corresponding Combined measurement. These sets were analyzed with Line of Equality and Regression Analysis. In Section 3.7.2, the mean of the set of APT measurements is compared to the mean of the set of Combined measurements. These two values were compared with a Paired t-test and a Non-Parametric test.

3.7.1 Choosing a Suitable Sample

3.7.1.1 Extrapolating combined data to 50 Pa

Unlike the APT measurements, the Combined data were only collected utilizing pressures well below 50 Pa. Therefore, to have comparable data, it was necessary to extrapolate the Combined data to 50 Pa. The extrapolation is explained in Section 3.4.

3.7.1.2 Finding a suitable sample and line of equality

Although it was originally a 55-home sample, only 34 homes had sufficient data to compare the APT and Combined methods. Some of the excluded homes had missing APT data, but most had missing Combined data.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Figure 3.8 illustrates the Line of Equality for Combined vs. APT for the resulting 34-home sample. While running the regression analysis we checked for outliers in the data. Using the standardized-residual methodology, 7 outliers were removed leaving a 27-home sample for the final regression model. Section 3.5 provides a list of possible sources of error.

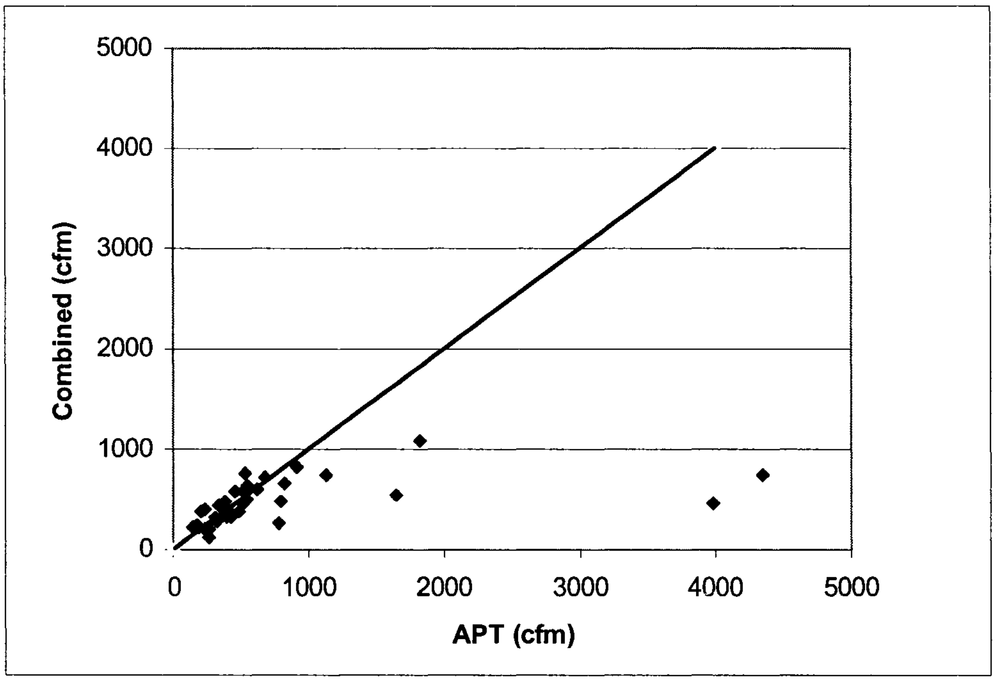


Figure 3.8 Line of equality: Combined vs. APT.

3.7.1.3 <u>Independence of errors</u>

Assumptions of Independence of Errors and Normality were confirmed via Figure 3.9 and Figure 3.10, respectively. Standardized Residuals vs. Observation Order is graphed in Figure 3.9. All the standardized residuals are within +/-2 and the scatter indicates that the errors are independent.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

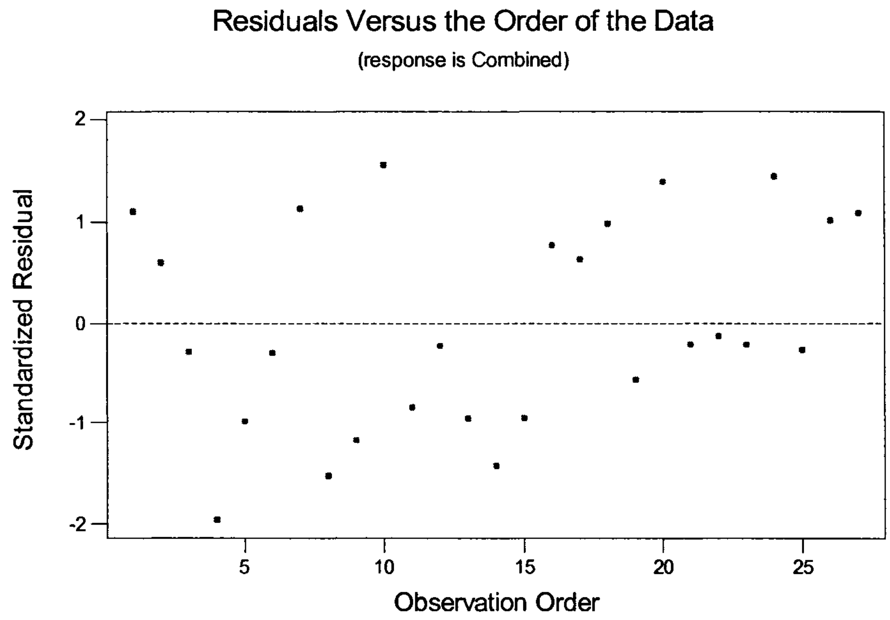


Figure 3.9 Standardized residuals' plot: Combined vs. APT.

3.7.1.4 Normality

Normality was confirmed using an Anderson-Darling test presented in Figure 3.10. The results of the statistical output can be found in Appendix A2. A P-value of 0.100 of the Anderson-Darling test indicates that the revised data follows a normal distribution.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

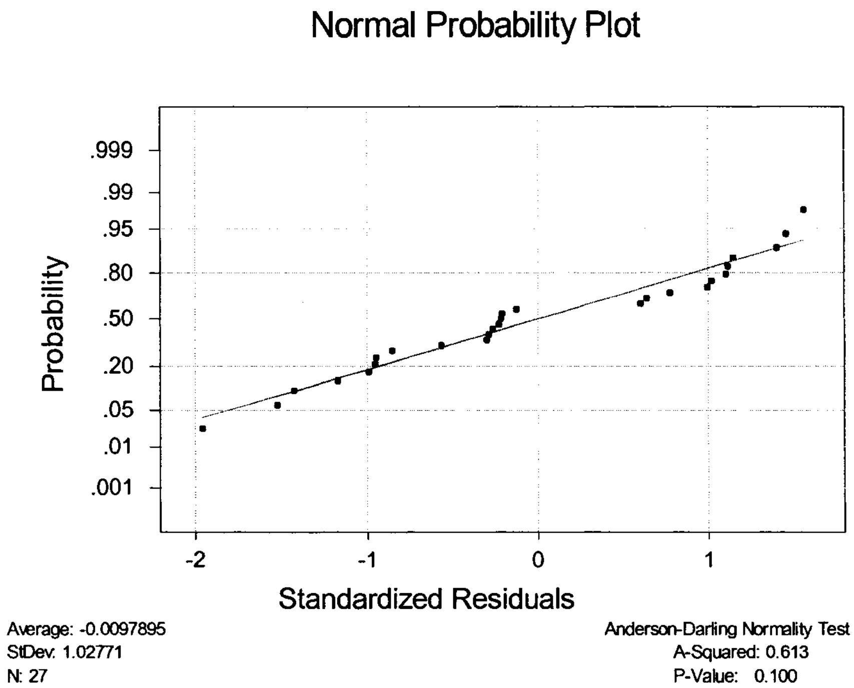


Figure 3.10 Normal probability plot of standardized residuals: Combined vs. APT.

3.7.1.5 Regression analysis and 95% prediction interval

The response variable is taken to be Combined and the predictor is taken to be APT data. The regression analysis was performed on the revised 25-home sample (Figure 3.11). This figure illustrates the 95% prediction interval. The regression equation was determined to be:

Combined = 160.535 + 0.625714 APT (3.3)

Using Eq. 3.3 and the indicated, dashed line confidence interval, the Combined reading is predicted from the APT reading with a probability of 0.95. The r^2 value of 0.715 indicates a moderate correlation (r = 0.846) between the two measuring methods. The output for regression analysis can be found in Appendix A3.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

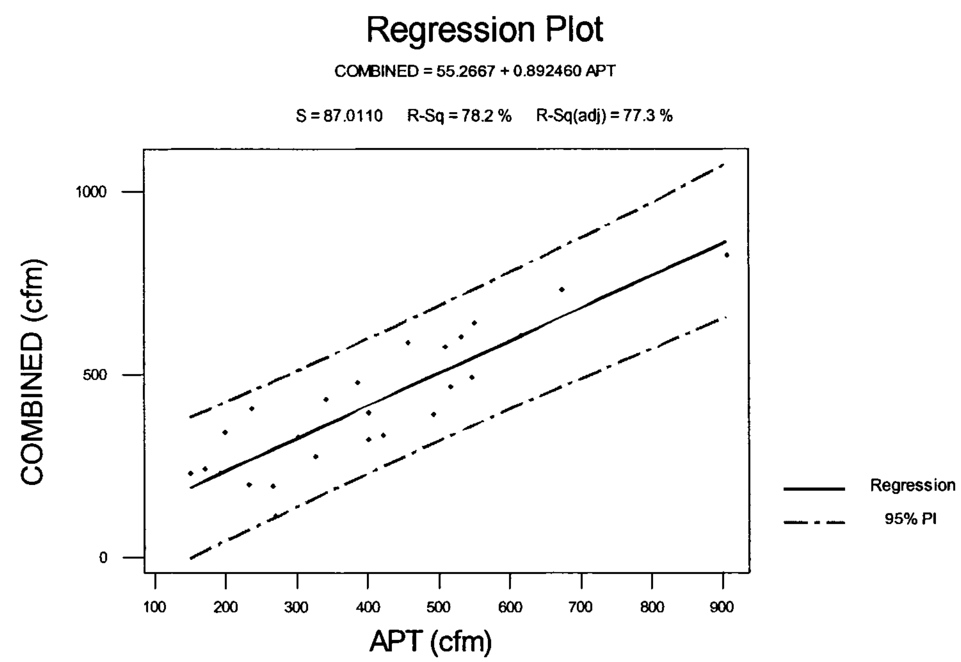


Figure 3.11 Regression plot with 95% confidence interval: Combined vs. APT.

Table 3.4 shows the predicted Combined values for each APT reading and their 95% prediction intervals. A predicted Combined value, from an observed APT reading, falls within its prediction interval with probability 0.95.

Table 3.4 95% Prediction interval for duct leakage: Combined vs. APT.

Observation /(Home Number)	APT (cfm)	Combined (cfm)	Predicted (cfm)	95% Prediction Interval (cfm)	
1 (03)	907.00	827.510	728.058	510.824	945.29
2 (05)	340.30	430.572	373.466	167.424	579.51
3 (06)	170.10	239.942	266.969	56.364	477.57
4 (08)	795.00	477.234	657.978	446.071	869.88
5 (11)	421.80	329.296	424.462	219.312	629.61
6 (12)	149.70	226.339	254.205	42.816	465.59
7 (13)	530.80	602.188	492.664	287.369	697.96
8 (14)	1133.80	747.740	869.970	637.900	1102.04
9 (16)	232.50	195.717	306.014	97.498	514.53
10 (18)	674.00	729.215	582.267	374.464	790.07

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

11 (20)	492.40	387.048	468.637	263.568	673.71
12 (21)	301.50	327.508	349.188	142.424	555.95
13 (26)	326.80	273.639	365.019	158.747	571.29
14 (28)	266.30	191.863	327.163	119.579	534.75
15 (29)	400.50	320.037	411.134	205.834	616.43
16 (30)	385.38	475.915	401.673	196.230	607.12
17 (33)	615.30	605.803	545.537	339.077	752.00
18 (34)	510.10	574.981	479.712	274.562	684.86
19 (35)	190.90	226.931	279.984	70.128	489.84
20 (36)	549.80	638.490	504.553	299.075	710.03
21 (37)	517.40	463.917	484.280	279.085	689.47
22 (38)	546.60	490.459	502.551	297.107	707.99
23 (39)	401.10	390.903	411.509	206.214	616.80
24 (43)	457.40	586.000	446.737	241.709	651.77
25 (51)	828.30	654.462	678.814	465.472	892.16
26 (52)	236.60	404.510	308.579	100.184	516.98
27 (55)	199.10	388.019	285.115	75.539	494.69

3.7.2 Statistical Comparison of Means: Combined vs. APT

To confirm that the two methods tend to measure the same duct leakage, a comparison of the means was performed using the Paired t-test on the 34-home sample.

3.7.2.1 Paired t-test application

The 95% confidence interval, Δ, for the mean difference between APT and Manual was determined to be between –16 cfm and 594 cfm; since this range includes zero, the test indicates that there is no statistically significant difference in the average measured readings of APT and Combined method. However, Non-Parametric tests give more reliable results when normality conditions are not satisfied, as in this case.

3.7.2.2 Non-Parametric test

Non-Parametric tests are distribution-free methods are used when the assumption of normality cannot be justified. The Wilcoxon signed-rank test mentioned in Section 3.6.2 was performed on the data. The 95% confidence interval for the mean difference

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

between APT and Combined ranged between -14 cfm and 185 cfm. Because this range includes zero, we can conclude that on average the APT and Combined methods measure the same quantity of duct leakage. The details of the Wilcoxon signed-rank test MINITAB™ software are presented in Appendix A3.

3.8 Statistical Comparisons: Combined vs. Depressurized Manual

Measurements obtained at 50 Pa in the depressurized state for Manual and Combined produced two data sets. These sets were statistically compared in two ways. In Section 3.8.1, the two samples are compared on a home-by-home basis to ultimately determine how well a single Manual measurement can predict the corresponding Combined measurement. These data were analyzed with Line of Equality (Figure 3.12) and Regression Analysis techniques. In Section 3.8.2, the mean of the set of Manual measurements is compared to the mean of the set of Combined measurements. These two values were analyzed with Paired t-test and Non-Parametric tests.

3.8.1 Assembling the Airflow Data

For comparing them with Manual readings at 50 Pa, Combined measurements were extrapolated to 50 Pa (as explained in Section 4.9).

3.8.2 Finding a Suitable Sample and Line of Equality

From the 55-home sample, only 35 could be used for comparing the Manual and Combined methods. These data given can be found in Appendix A4. Figure 3.12 illustrates the Line of Equality for Combined vs. Manual for the resulting 35-home sample.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

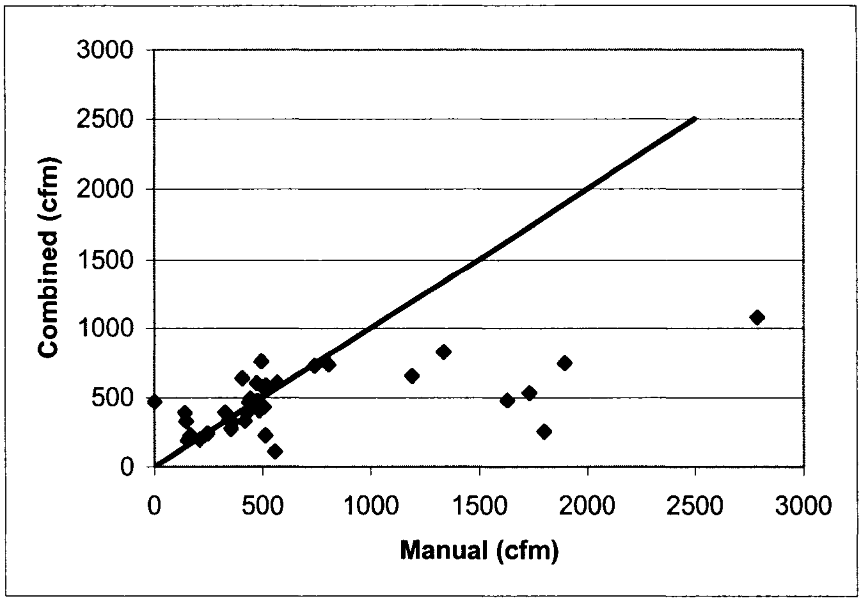


Figure 3.12 Line of equality: Combined vs. Manual.

3.8.2.1 Removing outliers

While running the regression analysis we checked for outliers in the data. Using the standardized residuals > 2 test, three outliers were removed – leaving a 32-home sample for the final regression model. Section 3.5 provides a list of possible sources of error.

A regression analysis can be performed on any data; however, to produce a 95% confidence interval it is important to verify Independence of Errors and Normality assumptions. The normality test was performed on the residuals using Anderson-Darling tests to verify the validity of the model.

3.8.2.2 Independence of errors

Assumptions of Independence of Errors and Normality were confirmed via Figure 3.13 and Figure 3.14, respectively. Normality was confirmed using an Anderson-Darling test.The Residuals vs. Observation Order is shown in Figure 3.13. All the

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

standardized residuals are within +/- 2 and the scatter indicates that the errors are independent.

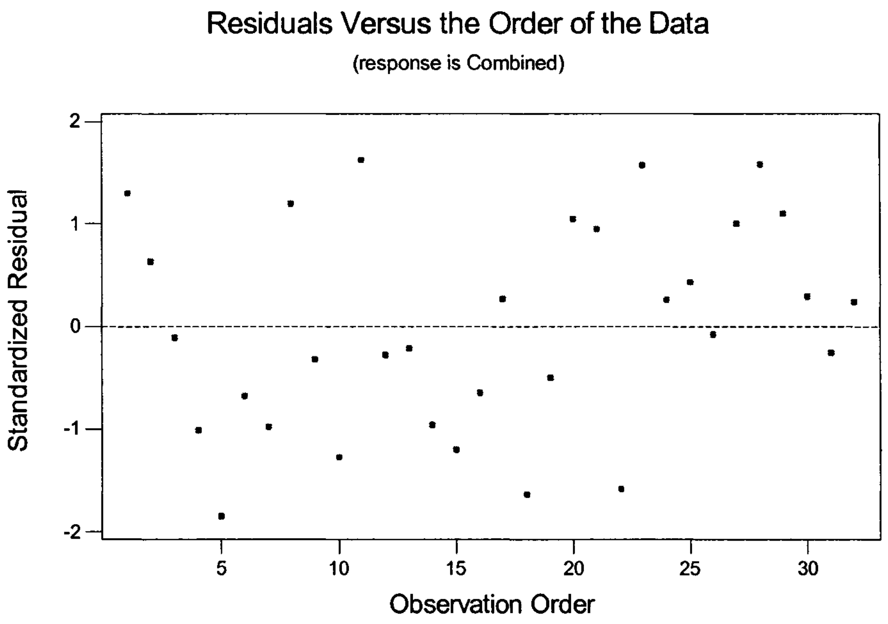


Figure 3.13 Standardized residuals' plot: Combined vs. Manual.

3.8.2.3 Normality

A P-value of 0.552 for the Anderson-Darling test, illustrated in Figure 3.14, indicates that the 32-home sample follows a normal distribution. The details are in Appendix A4.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

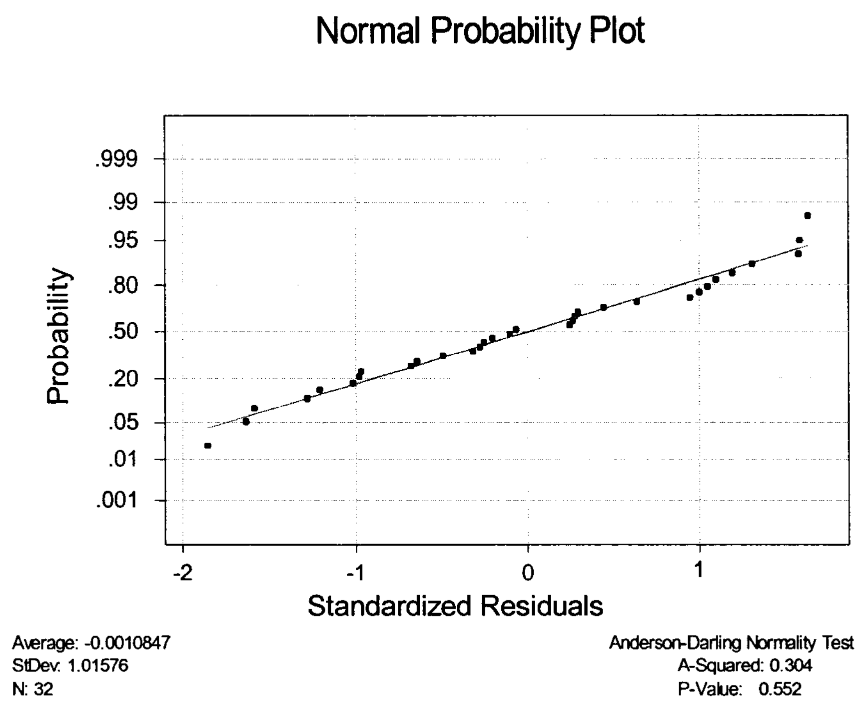


Figure 3.14 Normal probability plot of standardized residuals: Combined vs. Manual.

3.8.2.4 Regression analysis and 95% confidence interval

In this analysis the response variable was taken to be the Combined method and the predictor variable was duct leakage by the Manual method.

The regression analysis, performed on the 32-home sample, is shown in Figure 3.15. This figure illustrates the 95% prediction interval. The regression equation is:

$$\text{Combined} = 319.411 + 0.247518 \text{ Manual} \tag{3.4}$$

Namely using Eq. 3.4, the value of the Combined reading can be predicted from the Manual reading and the r^2 value of 0.545 indicates a moderate correlation ($r = 0.738$) between the two measuring methods.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

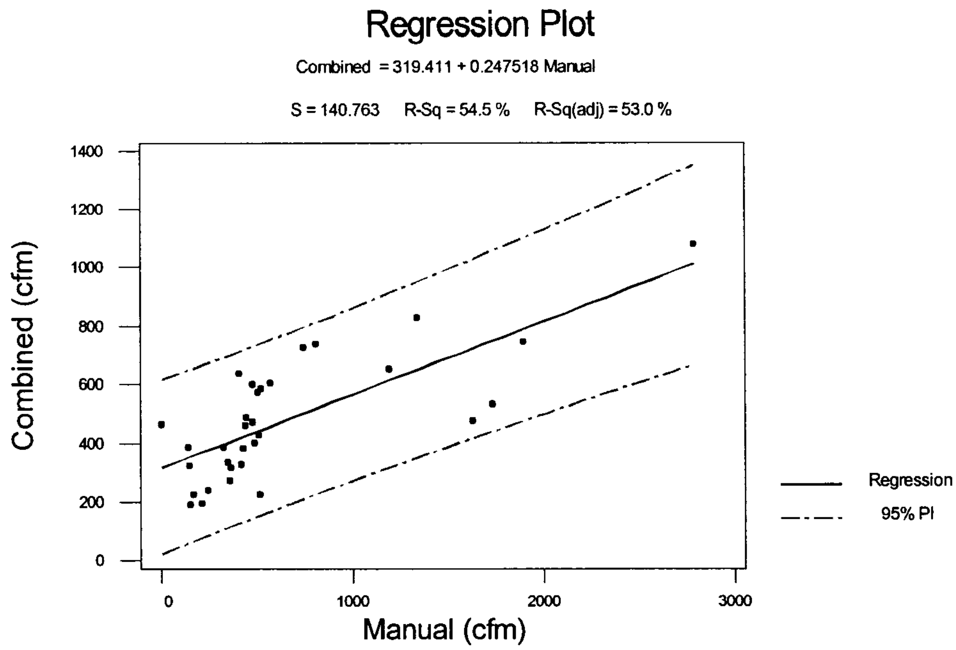


Figure 3.15 Regression plot with 95% confidence interval: Combined vs. Manual.

Table 3.5 shows the predicted Combined values for each Manual reading and their 95% prediction intervals. A predicted Combined value, from an observed Manual value, falls within its prediction interval with a probability of 0.95.

Table 3.5 95% Prediction interval for duct leakage values: Combined vs. Manual.

Observation/ (Home Number)	Manual (cfm)	APT (cfm)	Predicted (cfm)	95% Prediction Interval	
1 (03)	1337.9	827.51	650.57	352.905	948.23
2 (04)	2789.2	1077.70	1009.79	666.554	1353.02
3 (05)	508.4	430.57	445.25	153.074	737.42
4 (06)	245.5	239.94	380.18	86.265	674.09
5 (08)	1630.5	477.23	722.99	419.545	1026.43
6 (11)	418.7	329.30	423.05	130.467	715.63
7 (12)	166.7	226.34	360.67	65.917	655.43
8 (13)	474.1	602.19	436.76	144.452	729.07
9 (14)	1895.6	747.74	788.61	478.315	1098.90
10 (16)	209.6	195.72	371.29	77.013	665.57

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

11 (18)	742.5	729.22	503.19	211.152	795.23
12 (20)	427.6	387.05	425.25	132.719	717.78
13 (21)	148.0	327.51	356.04	61.067	651.02
14 (26)	354.5	273.64	407.16	114.167	700.14
15 (28)	153.8	191.86	357.48	62.572	652.39
16 (29)	361.1	320.04	408.79	115.847	701.73
17 (30)	477.3	475.92	437.55	145.258	729.84
18 (31)	1732.0	533.57	748.11	442.222	1054.00
19 (32)	345.1	336.82	404.83	111.772	697.89
20 (33)	569.6	605.80	460.40	168.386	752.41
21 (34)	502.3	574.98	443.74	151.543	735.94
22 (35)	515.2	226.93	446.93	154.780	739.08
23 (36)	408.4	638.49	420.50	127.858	713.14
24 (37)	438.3	463.92	427.90	135.423	720.37
25 (38)	445.3	490.46	429.63	137.191	722.07
26 (39)	327.2	390.90	400.40	107.205	693.59
27 (43)	517.0	586.00	447.38	155.231	739.52
28 (46)	807.0	738.30	519.16	226.920	811.40
29 (48)	1.4	469.15	319.76	22.757	616.76
30 (51)	1192.0	654.46	614.45	318.948	909.96
31 (52)	486.0	404.51	439.70	147.447	731.96
32 (55)	140.9	388.02	354.29	59.223	649.35

3.8.3 Statistical Comparison of Means: Combined vs. Manual

To confirm that the two methods tend to measure the same duct leakage, a comparison of the means was performed using the Paired t- test on the 35-home sample test.

3.8.3.1 Paired t-test application

The 95% confidence interval, Δ, for the mean difference between APT and Manual was determined to lie between 24 cfm and 384 cfm; Because this range does not include zero, the test indicates that a statistically significant difference in the average measured readings of APT and Combined method. However, it is necessary to test the results with a distribution-free method since the conditions of normality are unsatisfied.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3.8.3.2 Non-Parametric test

Non-Parametric tests are distribution-free methods that are used when the assumptions of normality cannot be justified, as in this case. The Wilcoxon signed-rank test was then performed. The 95% confidence interval for the difference between Manual and Combined ranged between -23 cfm and 264 cfm. Since this range includes zero, we can conclude that on an average the two methods measure the same amount of duct leakage.

3.9 Mean Duct-Leakage-to-Outside Following Statistical Analyses

Table 3.6 displays the statistically revised, mean values of the duct leakage methods, i.e., as discussed in Sections 3.6.2, 3.7.2, and 3.8.2; compare it to Table 3.1 where all of the original data was used. There are no differences between the two tables in the pressurized rows. However, the two sub-rows of the Combined row (fifth row) highlight the fact that the statistical analysis of the mean of the Combined data was against the APT in Section 3.7.2 and, in another analysis, against the Manual data in Section 3.8.2, because the comparison was different so was the set of outliers. The weighted sum of the two sub-rows is used to calculate the sixth row. The seventh row is a weighted sum of rows 1-4 together with the sixth row. The eighth row is the conversion of the weighted sum to 25 Pa. The ninth row is a conversion of the sixth row to 25 Pa.

Combined test results have a standard deviation that is less than half of either the APT or Manual data.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 3.6 Mean duct-leakage-to-outside.

Test	Number of Outliers	Number of Tests	Mean Duct Leakage to Outside (cfm)	Standard Deviation (cfm)
1. **APT Depressurized (50 Pa)**	11	31	511	330
2. **Manual Depressurized (50 Pa)**	11	31	582	556
3. **APT Pressurized (50 Pa)**	n/a	16	459	261
4. **Manual Pressurized (50 Pa)**	n/a	16	654	334
5. **Combined (50 Pa) (vs. APT)** **Combined (50 Pa) (vs. Manual)**	7 3	34 32	452 480	179 205
6. **Combined (50 Pa) Weighted Sum**	n/a	33	466	192
7. **All tests (50 Pa) Weighted Sum**	n/a	127	528	341
8. **All tests (25 Pa) Weighted Sum**	n/a	127	348	225
9. **Combined (25 Pa)**	n/a	33	307	127

The sets of APT results have lower standard deviations than the Manual results. The lower standard deviations strongly imply that the Manual measurements were less consistent than the APT measurements. It is important to note that the higher consistency of APT measurements does not necessarily indicate that the target value is more accurately being measured.

If we assume that the average AC size of the various samples was near three tons, then the expected mean percent duct leakage would be 348/1200 = 29%.

In comparison with the last two rows of Table 3.10, after outliers are removed the weighted sum of all tests decreased about 15%. This decrease in weighted sum implies that outliers are dominated by relatively large readings.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

3.10 Projecting Energy Waste Associated with Duct Leakage

From the database of 55 homes we calculate average duct leakage. Projecting the energy waste in the homes of our study requires some assumptions; they will be highlighted in bold in this section.

Duct leakage CFM25 should be used to characterize what is happening in real-world conditions [29, 9]. In the real world, the pressure in a duct system typically varies from roughly –50 Pa in the return plenum to 30 Pa in the supply plenum, but it drops to values much closer to zero near the registers. For this reason, duct leakage CFM50 is not as good an estimate of real-world duct leakage as CFM25. Table 3.6 shows that for the homes in our database, about 348 CFM25 is the average duct leakage to outside.

If we assume that **three tons is the average size of the cooling systems** of our homes, then we can calculate the average % duct leakage. Because the standard assumption is that an HVAC moves an average of 400 cfm per ton of cooling, a 3-ton unit moves an average of 1200 cfm. Therefore, the average duct leakage is roughly 350/1200 or 29% duct leakage. Assuming that **% loss of HVAC efficiency = 2.5 times % duct leakage**, we can conclude that efficiency would drop by 2.5 * 29% = 73%. The value of 2.5 is obtained from the graph published in HVAC efficiency tables published by Jeffrey S. Tiller's book titled *Builders Guide to Energy Efficient Homes in Louisiana* [9] assume 65% replacement air from outside.

Assuming that the **average efficiency of the AC is 9 SEER**, then the resulting efficiency after losses associated with duct leakage would be (100% - 73%) x 9 SEER = 2.4 SEER. Because (9 – 2.4) / 2.4 = 6.6 / 2.4 = 2.7, it can be noted that more than 2.5 times as much energy is lost by the ducts than is actually delivered to our homes.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

In Chapter Nine, the actual energy lost due to duct leaks has been presented. The energy lost obtained in Chapter Nine is more realistic as it does not include the assumptions considered in this section. Note that this loss of energy calculated was based completely on certain assumptions as highlighted.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 4

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 [21]. 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 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.

4.1 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 [33]. Air-tightness of buildings directly reflects air leakage sites. Air leakage sites include exterior doors, windows, foundations, electrical boxes and plumbing fixtures [34].

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

There are a number of standardized formats for measuring air-tightness as described in Minneapolis Blower Door^{TM} Operation Manual [21]. 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 [21]. 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 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 be applicable to Northern Louisiana only, 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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" [35]. 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 [36] 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 [37]. 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 [38]. 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

natural air leakage and/or continuously operating ventilation. We have not developed a model with ACH in this report but recommended it as a part of future study.

Blower doors™ 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 [38, 39]. 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 4.4.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

4.2 Sampling and Data Collection

The primary data were collected performing additional Blower Door™ 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 4.1. From Figure 4.1, we can see 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 where in the data set is split into model building and prediction sets [41]. 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 Appendix B1. The detail of the validation process is described in Section 4.7.

The data for this study were collected by performing Blower Door™ tests in sixty-six homes in the Northern part of Louisiana. The details of the testing procedure using Blower Door™ 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 ™ 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™ software and run the process.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

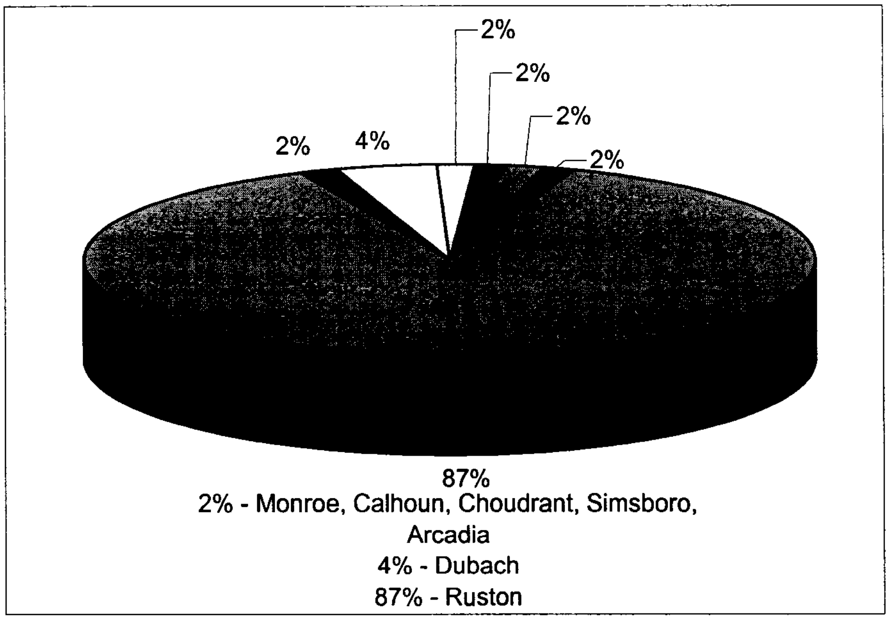


Figure 4.1 % Location of residential houses sampled.

In default mode of the TECTITE™ 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.

4.3 Response Variables - CFM50, ELA and EqLA

The three response variables or the dependent variables – CFM50, ELA and EqLA measured using Blower Door™ were compared against each other and the plots between these two variables are shown in Figures 4.2, 4.3 and 4.4. From Figure 4.2, we can see that as ELA increases CFM50 also increases. However, the relationship between

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

ELA and CFM50 widens beyond the 250 sq. in. and 4000 CFM mark. Considering the line of equality, a 45-degree line from the origin, we can see a few points lie away from the line of equality.

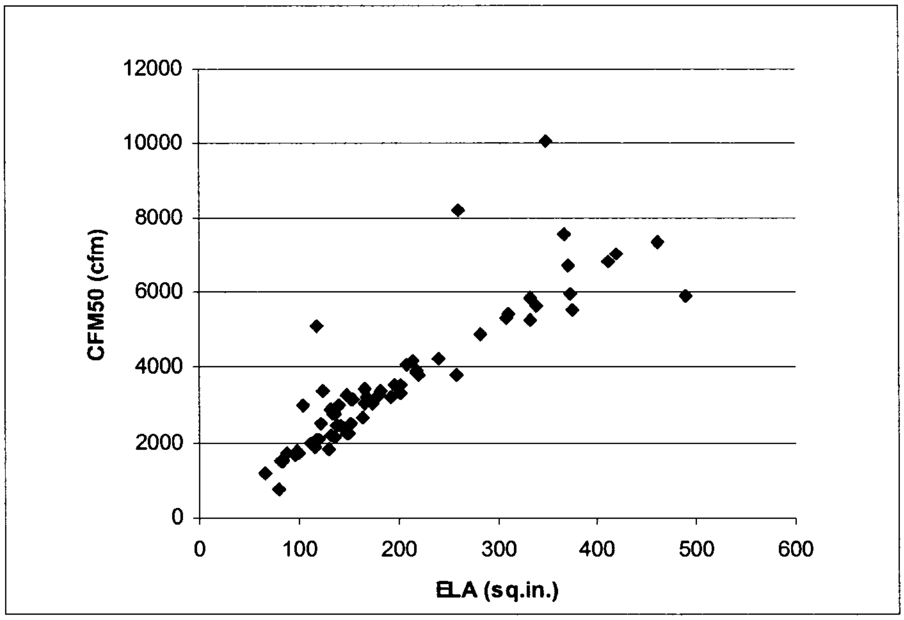


Figure 4.2 Plot of CFM50 vs. ELA.

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 [42].

The relationship between ELA and CFM50 [12]: is given by:

ELA = 0.055 x CFM50 (4.1)

Equation 4.1 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 4.3. 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™ Manual [21], which states that the calculated EqLA will typically be about two times as large as the ELA.

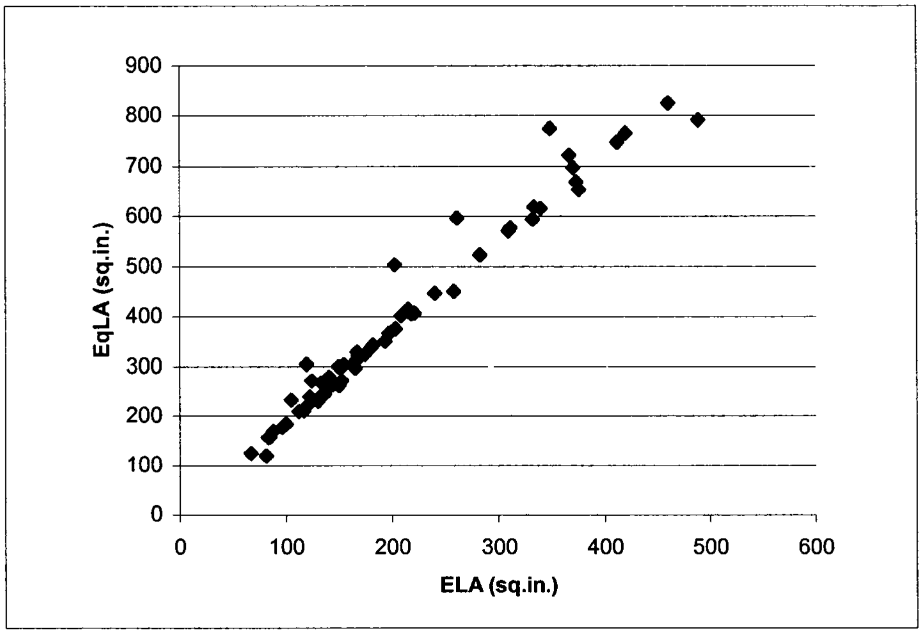


Figure 4.3 Plot of EqLA vs. ELA.

Figure 4.4 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

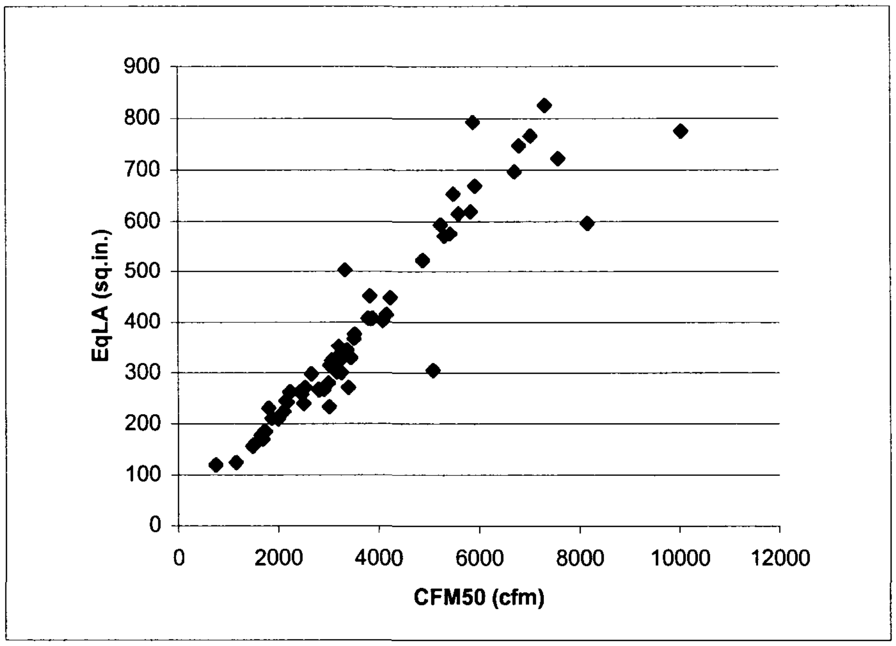


Figure 4.4 Plot of EqLA vs. CFM50.

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.

4.4 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 4.1 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 [34]. Tables 4.2 and 4.3 show the levels of the indicator variables for NOS and NOB.

Table 4.1 Predictor details.

Predictors	**Units**	**Range**	**House Parameters**
Year Built	Numerical Value	1920 – 2004	X_1
Floor Area	Square Feet	1041 - 3866	X_2
Number of Stories	Numerical Value	1, 1.5 or 2	X_3
Number of Bedroom	Numerical Value	2, 3, 4 or 5	X_4

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.2 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 4.3 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 4.1 was categorized as X_{41} and X_{42} as shown in Table 4.2. The house parameter NOB, X_5 was similarly categorized as X_{51} and X_{52} as shown in Table 4.3. The response for the above model was the air-tightness measure of CFM50 or ELA or EqLA. The independent variables considered in Tables 4.1, 4.2 and 4.3 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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™ 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 [41]. 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™ program and the output of the above result are presented in Appendix B2 and B3 respectively. The outputs of the SAS™ 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 4.4, 4.5 and 4.6. The detailed results of these runs using SAS™ is presented in Appendix B3. From Table 4.4, the included predictor variables in the model ELA are Area, YB and S1. Therefore

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

the regression equation for the response ELA becomes

$$Y_{ELA} = B_0 + B_1 X_1 + B_2 X_2 + B_{31} X_{31} + e \quad (4.2)$$

Incorporating the parameter estimates we obtain the following regression Eq. 4.3

$$Y_{ELA} = 5217.08 - 2.63 X_1 + 0.10 X_2 - 57.52 X_{31} + e \quad (4.3)$$

Table 4.4 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	YearBuilt	2	0.1828	0.6743	13.5485	24.13	<.0001
3	S1		3	0.0544	0.7286	6.6134	8.41	0.0059

Table 4.5 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	<.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

From Table 4.5, the included predictor variables in the CFM50 model are YB and Area. Therefore the regression equation for the response CFM50 becomes

$$Y_{CFM50} = B_0 + B_1 X_1 + B_2 X_2 + e \quad (4.4)$$

Incorporating the parameter estimates we obtain the following regression Eq. 4.5

$$Y_{CFM50} = 115105 - 58.64 X_1 + 2.14 X_2 + e \quad (4.5)$$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The summary of Stepwise regression for EqLA as the response variable is presented in Table 4.6 with significant predictor variables YB, Area and S1.

Table 4.6. 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	<.0001
2	YB	YearBuilt	2	0.2228	0.7257	10.6565	34.92	<.0001
3	S1		3	0.0483	0.7739	3.7462	8.96	0.0046

The regression equation for the response EqLA is

$$Y_{EqLA} = B_0 + B_1 X_1 + B_2 X_2 + B_{31} X_{31} + e \qquad (4.6)$$

Incorporating the parameter values, we obtain the Eq. 4.7

$$Y_{EqLA} = 10732 - 5.40 X_1 + 0.19 X_2 - 102.40 X_{31} + e \qquad (4.7)$$

Both EqLA and ELA have the same predictor variables significant as seen from Eqs. (4.2) and (4.6). 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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. (4.3), (4.5), (4.7) for ELA, CFM50 and EqLA are obtained for the new model respectively. The detailed multiple regression for this analysis are presented in Appendix B3.

$$Y_{EqLA} = 9859.40 - 5.02\ X_1 + 0.21\ X_2\ + e \tag{4.8}$$

$$Y_{CFM50} = 115105 - 58.64\ X_1 + 2.14\ X_2\ + e \tag{4.9}$$

$$Y_{ELA} = 4726.77 - 2.41\ X_1 + 0.11\ X_2\ + e \tag{4.10}$$

Eqs (4.8), (4.9) and (4.10) are the models considering only Area and the Year Built as independent variables. Eq. (4.9) is the same as Eq. (4.5) 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.

4.5 Aptness of the Regression Model

The regression models for CFM50, ELA and EqLA (Eqs. (4.8), (4.9) and (4.10)) were checked for aptness in order to verify the major assumptions behind the regression analysis. The major assumptions behind the regression analysis are [43]:

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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

4.5.1 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 B4 (Figures B4.1 to B4.6) 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 B5 (Figures B5.1 to B5.3). 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 4.7.

4.5.2 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 B5.

4.5.3 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 [43]. The error terms are expected to fall approximately along a straight line if the normality assumption is satisfied. The normal probability plots in Figures 4.5, 4.6 and 4.7 shows that the resulting points lie approximately on a straight line (except for few outliers) verifying the assumptions of normality.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

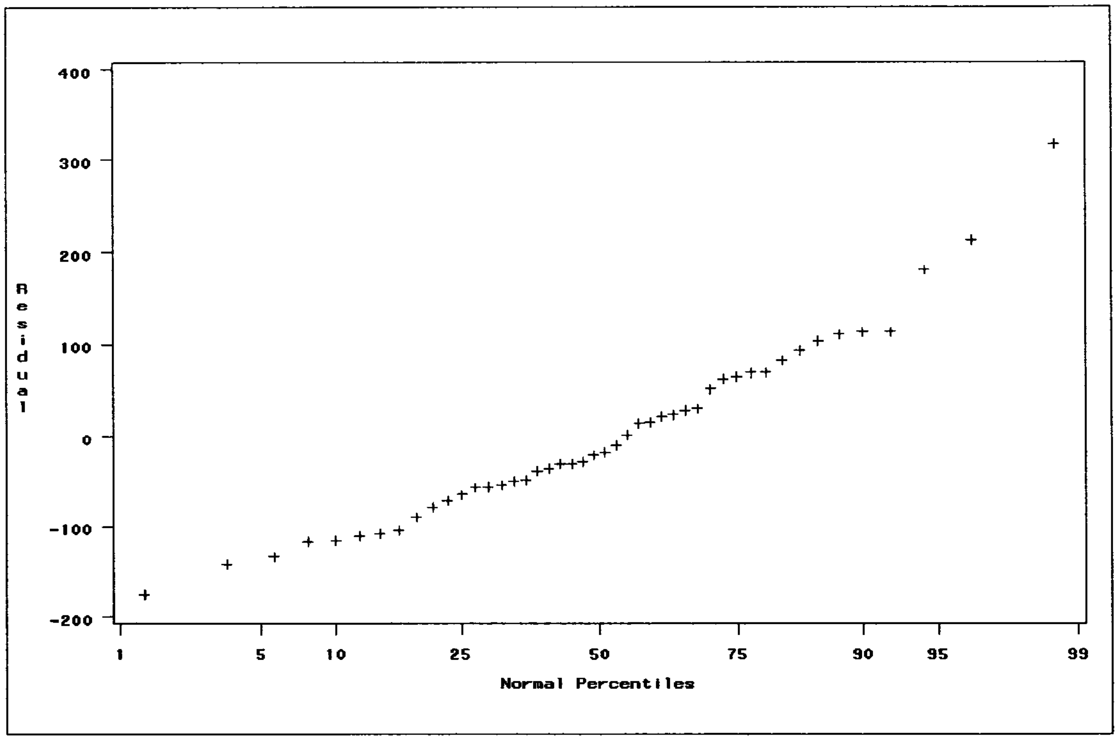


Figure 4.5 Normal plot for error terms of CFM50.

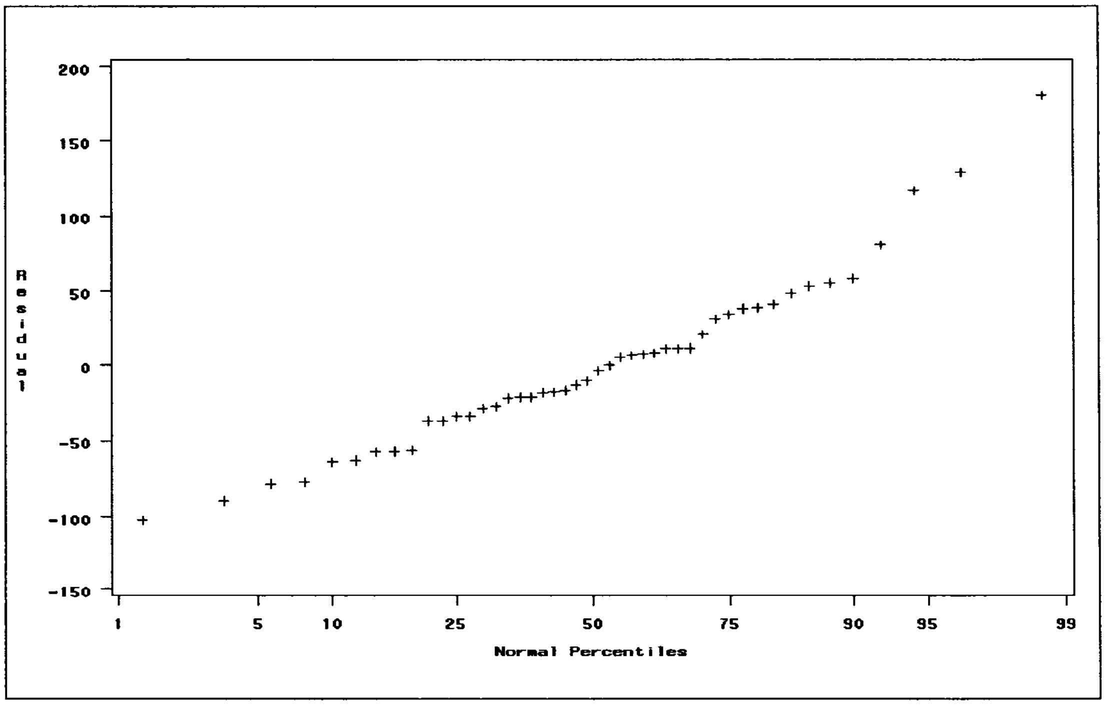


Figure 4.6 Normal plot for error terms of ELA.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

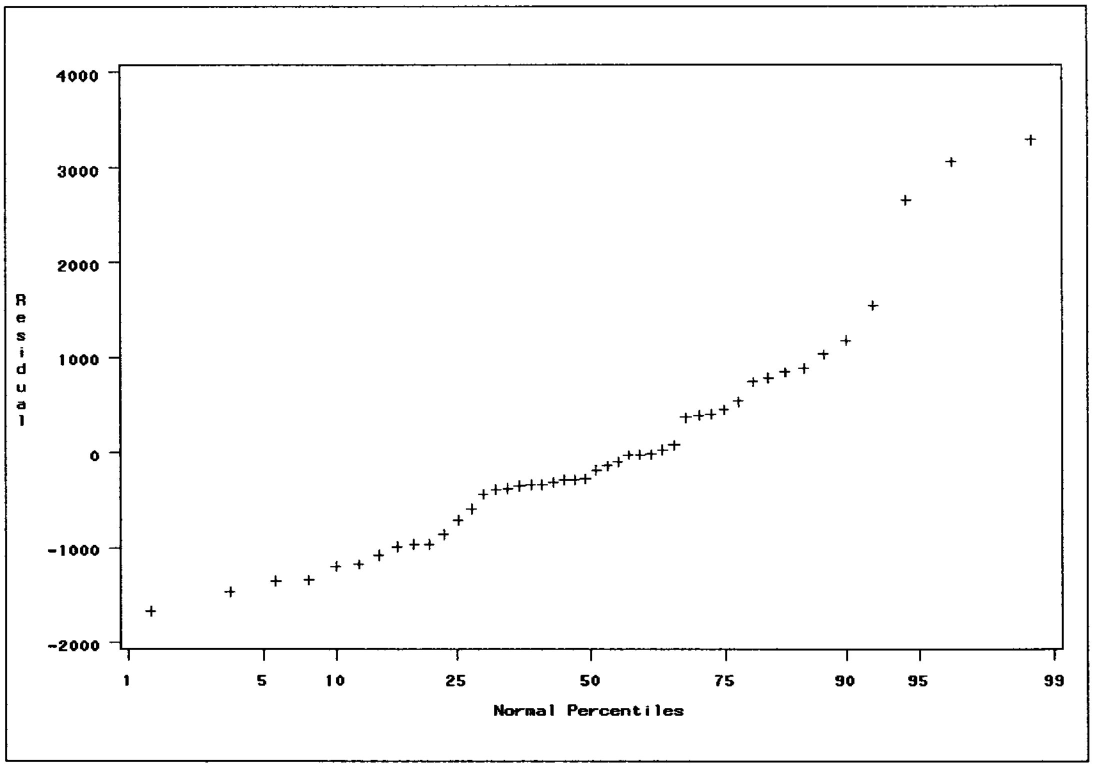


Figure 4.7 Normal plot for error terms of EqLA.

4.5.4 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 B5 show the plot of residual vs. the predicted values for the three models. The graphs do not show dependence of error terms.

4.6 Outliers

The outliers for the data under study were investigated and are presented in Sections 4.6.1, 4.6.2, 4.6.3, and 4.6.4.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

4.6.1 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 Appendix B3.

4.6.2 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 B3.

4.6.3 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 B3 respectively.

4.6.4 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 4.7.

4.7 Model Validation and Predictive Power

The air-tightness model for EqLA, CFM50, and ELA was given in Eqs. (4.8), (4.9) and (4.10) 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 [41] 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 [41]. 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).

$$MSPR = \frac{\sum_{i=1}^{n^*} (Y_i - Y_i^{\wedge})^2}{n^*} \qquad (4.11)$$

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 4.7, 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.

Table 4.7 Validation results.

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

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 [44, 45]. One

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 [46] and Root-Mean-Square Percent Error (RMSPE) [47] to determine the predictive power of the two regression models.

Theil's Statistic is given by

$$U = \sqrt{\sum_i (Y_i - Y_i^{\wedge})^2 / \sum_i Y_i^2} \tag{4.12}$$

whereas RMSPE is defined as

$$RMSPE = \frac{1}{n^*} \sum_{i=1}^{n^*} \left(\frac{Y_i - Y_i^{\wedge}}{Y_i^{\wedge}}\right)^2 \tag{4.13}$$

In both Theil's Statistic and RMSPE, Y_i and $Y_i^{\wedge}$ represents the actual and the predicted response value for the i^{th} observation respectively. Table 4.8 shows the predictive power of the competing models with respect to Theil's Statistic and RMSPE.

Table 4.8 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 4.8, 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.

4.8 Air-tightness Classification of Residential Homes

In Section 4.7, 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 4.4.

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 [48]. There are basically two methods of clustering, hierarchical and non-hierarchical clustering methods [49]. In this study, we have used the non-hierarchical method to cluster the data into meaningful structures. We have used SAS™ software to perform cluster analysis. The SAS's™ FASTCLUS procedure was used to perform a disjoint cluster analysis on the basis of distances computed from one or more quantitative variables [50]. 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 [51] provides an excellent discussion on the types of basis variables and the need for careful forethought when selecting basis variables for use in cluster

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

identification algorithms. In this case, we select the base variables as CFM50, Year Built and Floor Area as per the conclusions obtained in Sections 4.4 and 4.7.

The SAS™ program and the detailed output using the PROC FASTCLUS are presented in the Appendix B6. 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 4.9 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.9 Run1 results from PROC FASTCLUS procedure.

Cluster Summary

Cluster	Frequency	RMS Std Deviation	Maximum Distance from Seed to Observation	Radius Exceeded	Nearest Cluster	Distance Between 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 4.8. 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

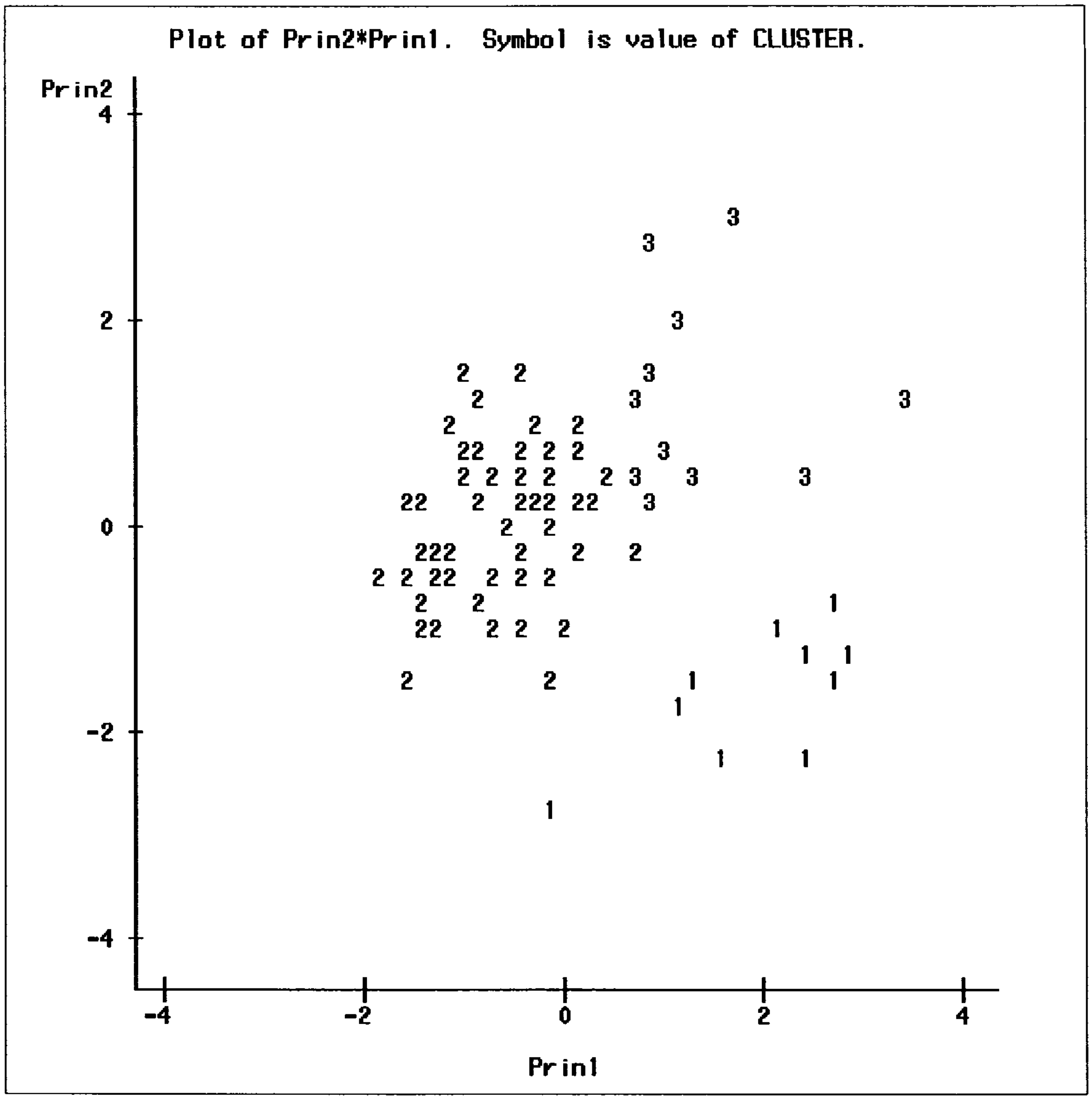


Figure 4.8 Plot of the clusters using run1.

The cluster means on the original data from Run1 is presented in Table 4.10. 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.10 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	2284.80
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

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 [49].

The Beale's pseudo F-statistic is given by

$$F^* = J \times (U) \times (L)^{-1} \quad (4.14)$$

where,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 Appendix B7. Table 4.11 shows the results obtained from Run2 of PROC FASTCLUS. Run2 has produced four clusters.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 4.11 Run2 results from PROC FASTCLUS procedure.

Cluster Summary

Cluster	Frequency	RMS Std Deviation	Maximum Distance from Seed to Observation	Radius Exceeded	Nearest Cluster	Distance Between 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 4.10, 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 4.4.

4.9 Conclusions

Three models (CFM50, ELA and EqLA) to determine air-tightness based on the age of the home and conditioned area was developed using multiple regression analysis (Eqs. (4.9), (4.10) and (4.11)). 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 4.8 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 5

GENERALIZED SUBTRACTION ALGORITHM

The Subtraction Method measures duct-leakage-to-outside (hereinafter referred to as "duct-leakage") by subtracting Blower Door ™ 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" [34]. Since these measurements involve changes in a variety of environmental parameters, duct-leakage is often underestimated. To correct for these differences [22], 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

study on 55 homes in North Louisiana provided in Chapter Five 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 [53, 54], 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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.

5.1 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.

5.2 Data Collection Procedure

1. Perform a depressurization test with a Blower Door™ to depressurize the house to P.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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™ 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, P_D. This procedure calculates duct-leakage but the pressure between the ducts and the attic, P_D, 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™ is taken to be, as a first approximation, the duct-leakage (to outside the conditioned space) at some

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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*.

5.3 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 5.1 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

$$Q = Q_{nvd} + Q_{vd} \tag{5.1}$$

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

$$= Q_{vr} + Q_{vdbnr} \tag{5.2}$$

Q_{nvd} = flow not via ducts

= flow not via attic + flow via attic but not ducts

$$= Q_{nva} + Q_{vabnd} \tag{5.3}$$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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.

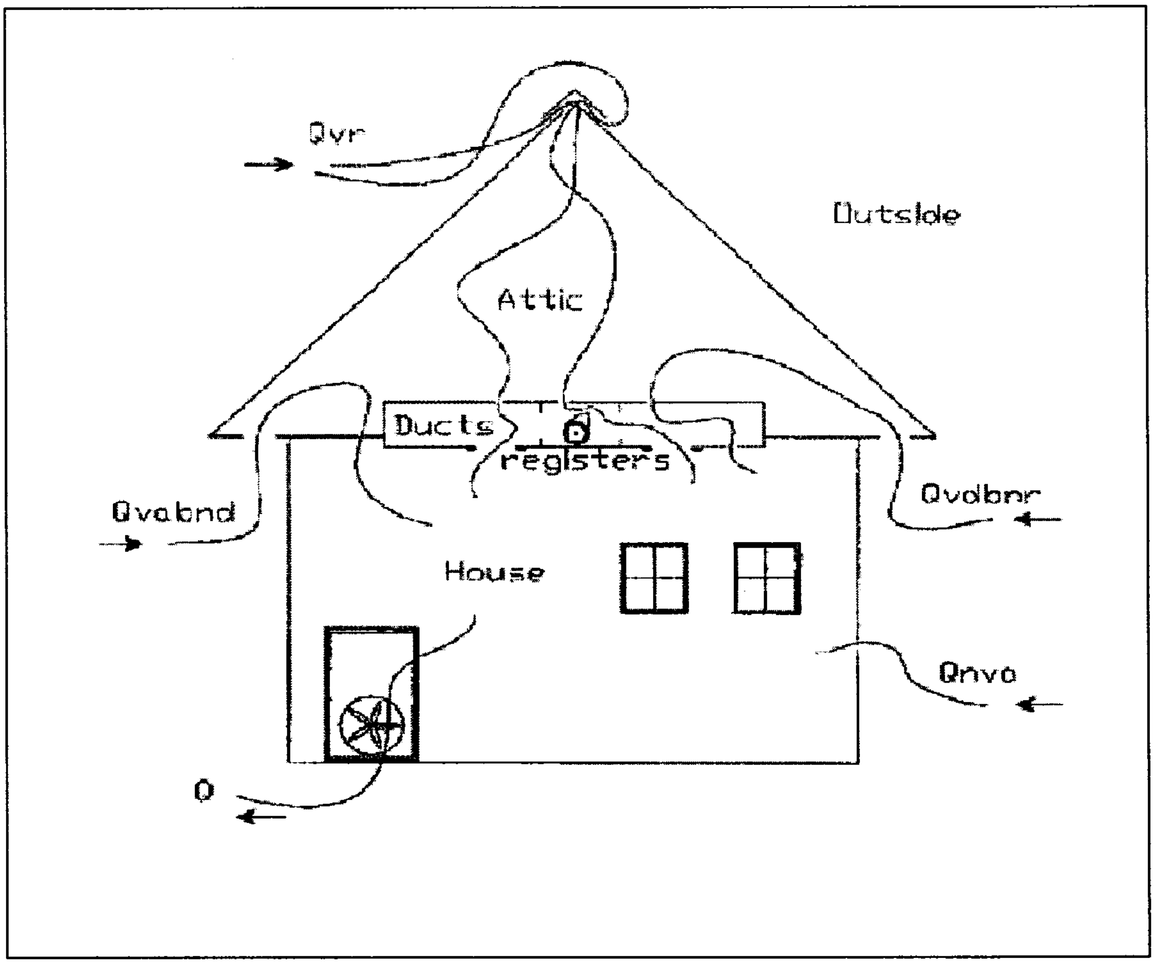


Figure 5.1 Airflows generated by using a Blower Door™ to depressurize a home.

Thus:

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

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

$$Q_{dlo} = \text{duct-leakage (to outside)}$$

$$= \text{flow into the ducts from the attic}$$

Therefore,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

$$Q_{dlo} = Q_{vr} + Q_{vdbnr} \tag{5.4}$$

Thus:

$$Q = Q_{nvd} + Q_{dlo} \tag{5.5}$$

Empirically it has been found [31] 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

$$Q = \kappa P^{n} \tag{5.6}$$

Experience from alternative testing methods [56, 34] has confirmed that the same power-law relationship applies to duct-leakage, namely

$$Q_{dlo} = \kappa_D P_D^{\ m} \tag{5.7}$$

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 [56, 34].

We define

Q' = the flow with the registers taped.

$$Q' = Q'_{nvd} + Q'_{vr} + Q'_{vdbnr} \tag{5.8}$$

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

$$Q' = Q'_{nvd} + Q'_{vdbnr} \tag{5.9}$$

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

$$Q'_{dlo} = Q'_{vdbnr} = \kappa'_D P'^{m'}_D \tag{5.10}$$

$$Q' = Q'_{nvd} + Q'_{dlo} \tag{5.11}$$

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. (5.10) 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. (5.5) and Eq. (5.11) we obtain

$$Q - Q' = (Q_{nvd} + Q_{dlo}) - (Q'_{nvd} + Q'_{dlo}) \tag{5.12}$$

Assuming house-leakiness to be independent of the change in the flow through the ducts, $Q_{nvd} = Q'_{nvd}$ (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

$$Q - Q' = Q_{dlo} - Q'_{dlo}$$

Substituting Eq. (5.10) into this equation, we obtain

$$Q - Q' = \kappa_D P_D^{m} - \kappa'_D P'^{m'}_D \tag{5.13}$$

By definition

$$SCF = \text{duct-leakage} \;/\; [\,Q - Q'\,] \tag{5.14}$$

Thus

$$SCF = \kappa_D P_D^{m} \;/\; [\,\kappa_D P_D^{m} - \kappa'_D P'^{m'}_D\,] \tag{5.15}$$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

We now assume that $\kappa_D = \kappa'_D$. 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

$$SCF = P_D^m / [P_D^m - P_D'^m] \quad (5.16)$$

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, $m = 0.60$ [56, 34] (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

$$SCF = P_D^{0.6} / [P_D^{0.6} - P_D'^{0.6}] \quad (5.17)$$

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 P_D and 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

$$P_D = K * P \quad (5.18)$$

$$P'_D = K' * P \quad (5.19)$$

for some constants K and K'.

Then, substituting Eqs. (5.17) and (5.18) into Eq. (5.15)

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

$$= \quad K^{0.6} \quad / \quad [\, K^{0.6} \quad - \quad K^{0.6} \,] \qquad (5.20)$$

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. (5.10), assuming the same exponent, m, for all duct-leakage flows

$$\kappa_{dh}\,(P_d - P_h)^m = \kappa_{ad}\,(P_a - P_d)^m \qquad (5.21)$$

Therefore, solving for P_h

$$P_h = \{[1 + (\kappa_{ad}/\kappa_{ah})]^{1/m}\}P_d \; - \; (\kappa_{ad}/\kappa_{ah})^{1/m}P_a \qquad (5.22)$$

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

$$Q_{oa} \quad = \quad Q_{vabnd} \; + \quad Q_{vd}$$

Utilizing Eq. (5.6) and assuming all the exponents are the same (to within a reasonable approximation; see the *Choice of Flow Exponent* comment)

$$\kappa_{oa}\,(P_a)^m \quad = \quad \kappa_{vabnd}\,(P_h - P_a)^m \quad + \quad \kappa_{vd}\,(P_d - P_a)^m \qquad (5.23)$$

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.

$$\kappa_{vabnd}\,(P_h - P_a)^m >> \kappa_{vd}\,(P_d - P_a)^m \qquad (5.24)$$

Eq. (5.24) becomes

$$\kappa_{oa} P_a^{\ m} \simeq \kappa_{vabnd}\,(P_h - P_a)^m \qquad (5.25)$$

Thus, for homes satisfying the approximation of Eq. (5.25), 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 (5.22), 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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.

$$Q - Q' = \kappa P^{n} - \kappa' P^{n'} \qquad (5.26)$$

From Eq. (5.8), 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.

$$\text{Duct-leakage at 25 Pa} = SCF\,\{\kappa[25\,(25/P_{D25})]^{n} - \kappa'[25\,(25/P_{D25})]^{n'}\} \qquad (5.27)$$

<u>GSCA Generalizes Modified Subtraction</u>

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.

5.4 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

system [60] 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. (5.2) [60]. 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 [56], 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 [34]. 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 [57]. This same issue has also been considered significant by Sherman and Palmiter [58].

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 [57]. 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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™ [59].

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 [34]. 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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, $m = 0.60$ [55, 56]. 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.

5.5 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 CFM = 4.72 x 10^{-4} m^3/s). The first of these, CFM50 (the flow through a Blower Door™ 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 [60]. 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,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 5.1. Table 5.1 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 5.1 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 5.1 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 5.2 shows the comparison of duct leakage obtained using GSCA as well as MSA for the 55 homes sampled in Northern Louisiana. From Figure 5.2, 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 5.1, the duct leakage was found to be comparatively high in homes with low coupling ratios. Figure 5.3 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

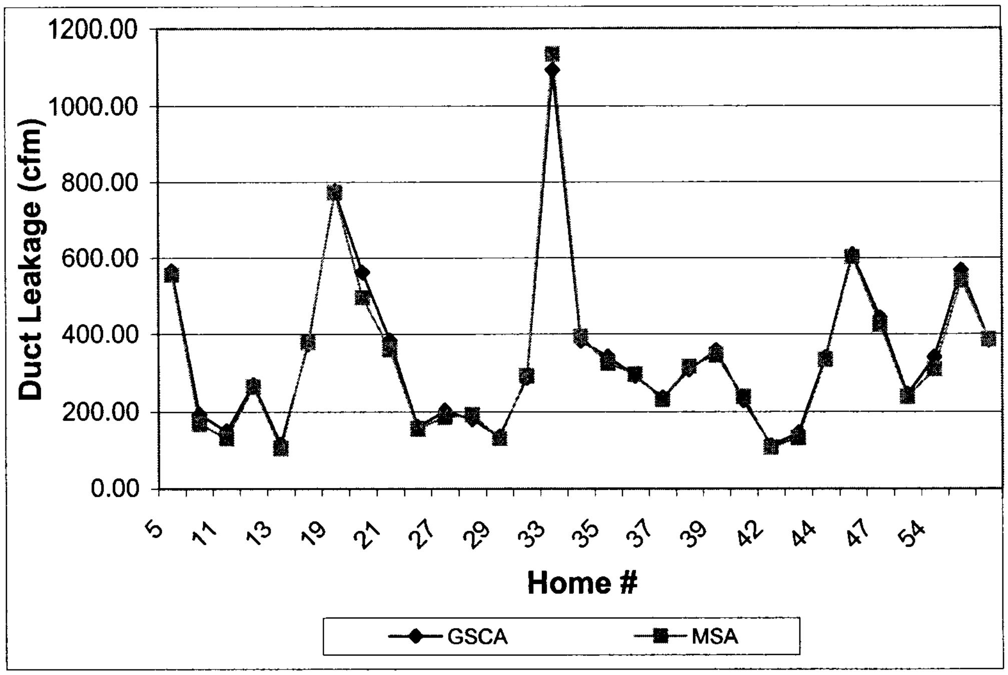


Figure 5.2 Duct leakage comparison of GSCA vs. MSA – North Louisiana.

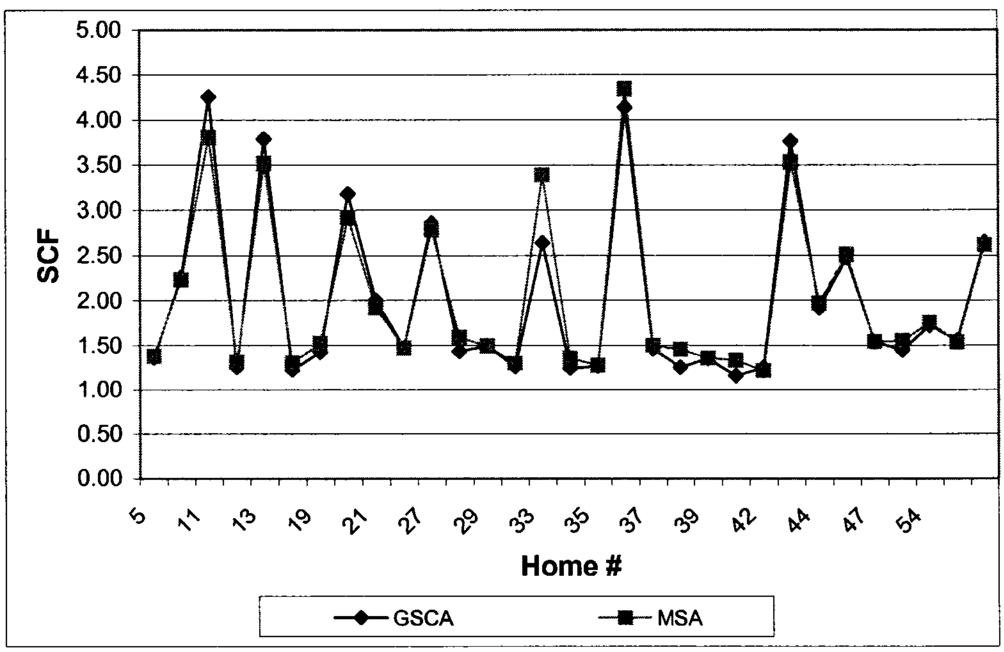


Figure 5.3 SCF comparison of GSCA vs. MSA – North Louisiana.

A plot of the difference in duct leakage values between the GSCA and MSA is presented in Figure 5.4. From Figure 5.4, the differences between the duct leakage

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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™ program and the output is presented in Appendices B11 and B12 respectively.

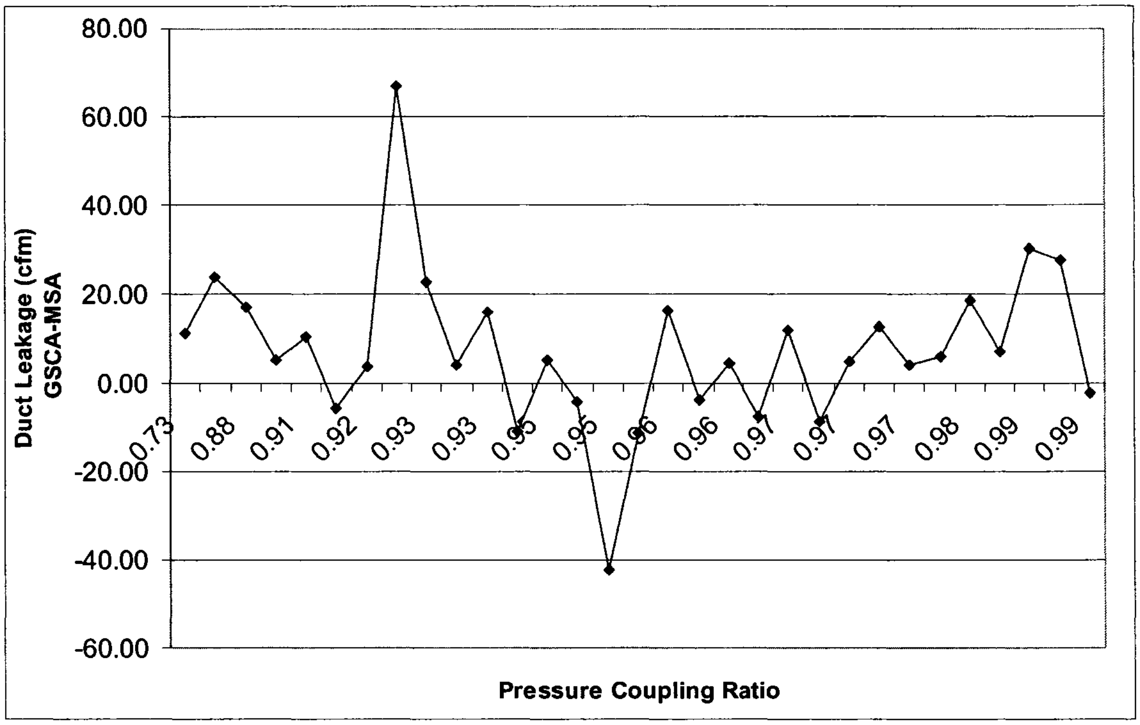


Figure 5.4 Plot of (GSCA-MSA) and pressure coupling ratio – North Louisiana.

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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 5.2 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 then 0.90, which is the reverse of the coupling ratios in Northern Louisiana where they are generally higher than 0.90.

Table 5.2 GSCA vs. MSA of homes tested in South Louisiana.

Home #	Coupling Ratio (P_A/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 5.5, we see that the duct leakage obtained from GSCA and MSA are similar, differences appear only for high values of duct leakage. From Figure 5.6, the difference between the *SCF's* of MSA and GSCA is not high except for homes with low pressure coupling ratios.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

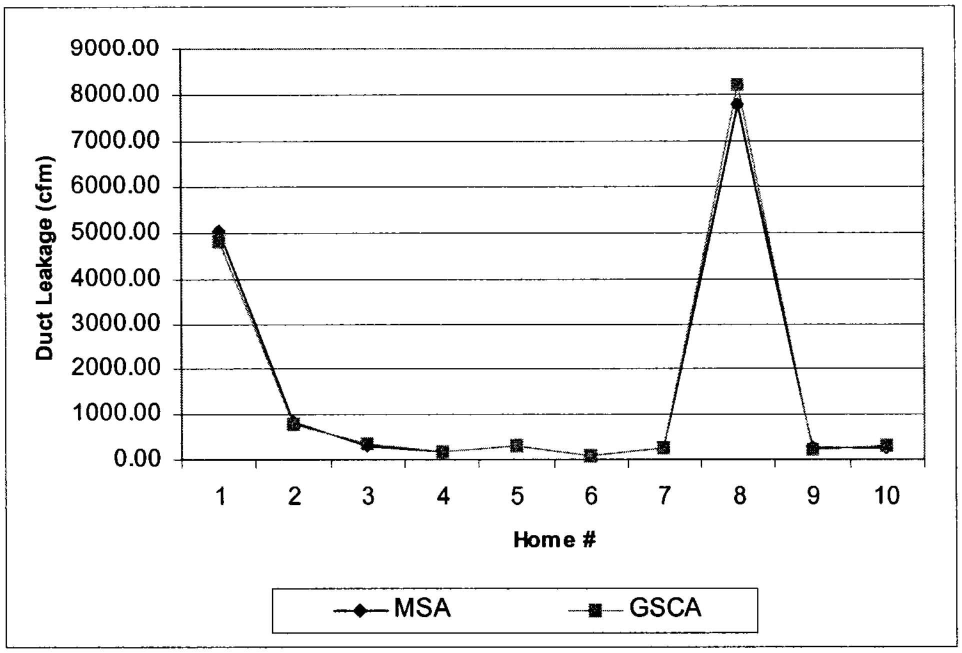


Figure 5.5 Duct leakage comparison of GSCA vs. MSA – South Louisiana.

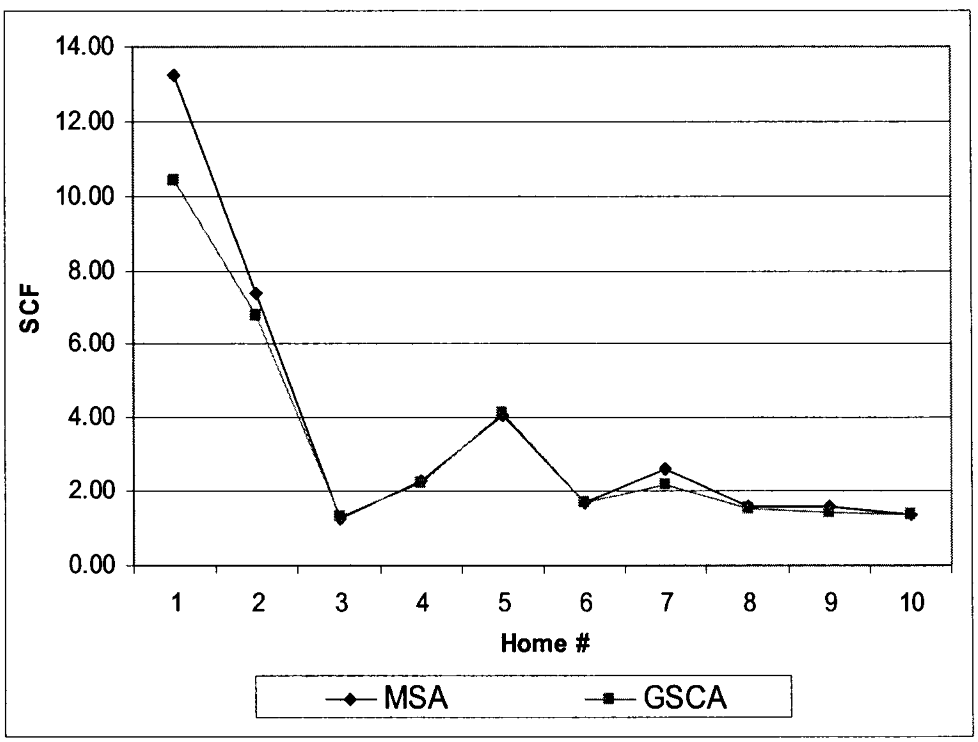


Figure 5.6 SCF comparison of GSCA vs. MSA – South Louisiana.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

A plot of the difference in duct leakage values between the GSCA and MSA in Figure 5.7 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.

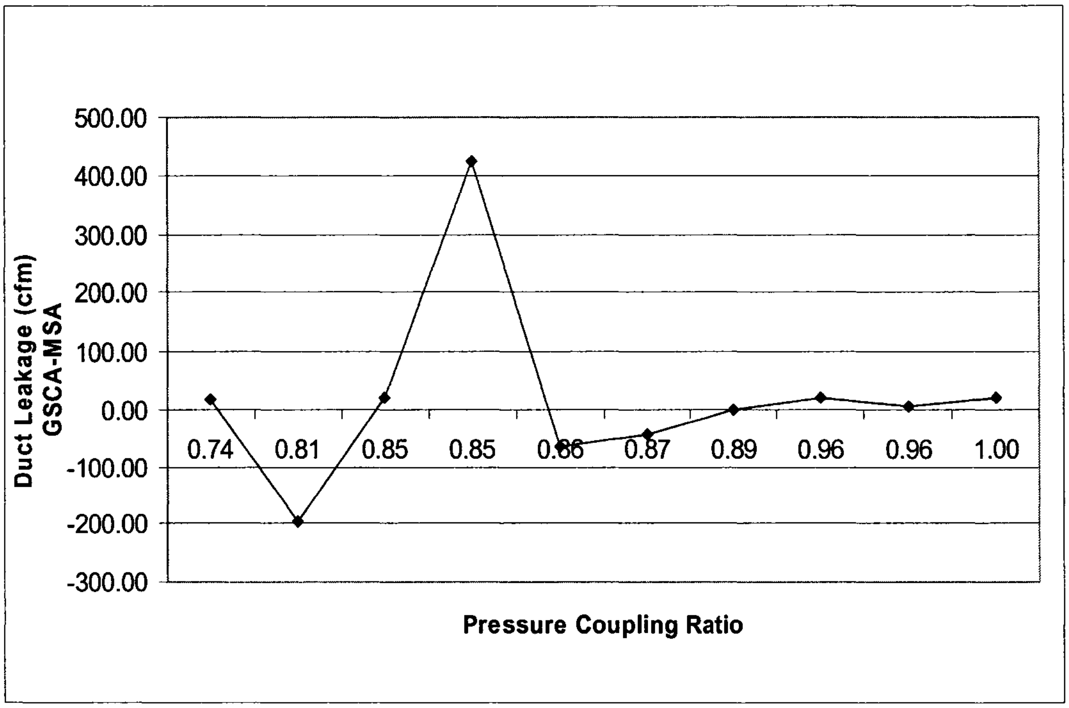


Figure 5.7 Plot of (GSCA-MSA) and pressure coupling ratio – South Louisiana.

Figure 5.8 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 5.7 by the scatter of individual data points.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

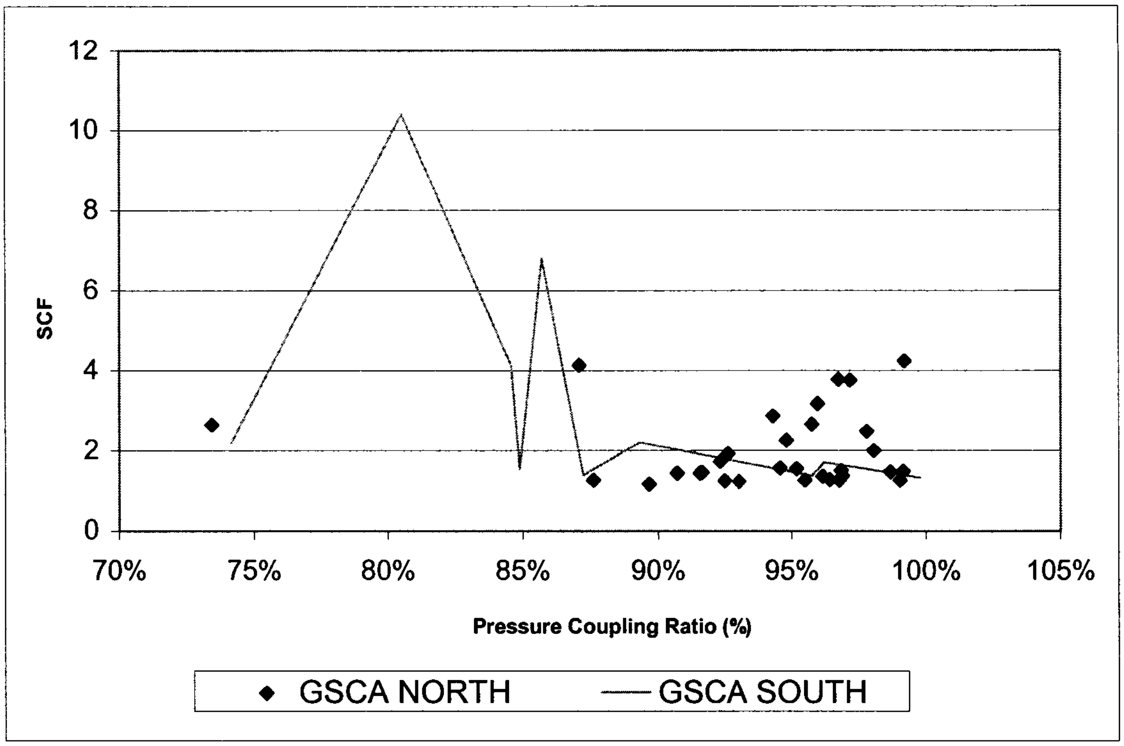


Figure 5.8 Comparison of North and South Louisiana in regards to SCF of GSCA and pressure coupling ratio.

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 [30].

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 6

RETURN LEAK MEASUREMENT

Duct leakage can occur both at the supply side as well as the return side of the duct system. Figure 6.1 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 6.2 shows some of the common sources of return leaks.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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™ 152 [60] 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 Seven.
3. statistically analyze the differences between pressurization and depressurization measurements as presented in Chapter Eight.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

4. incorporate the measured return leakage to determine energy losses for a given home as presented in Chapter Nine.

Figure 6.1 shows the components of the duct system. In the overall view of the duct system in Figure 6.1, the return side components of the duct system mainly comprises of return grille, return plenum and air filter. The source of Figure 6.1 is http://www.mbmairduct.com/ images/design03.jpg [61].

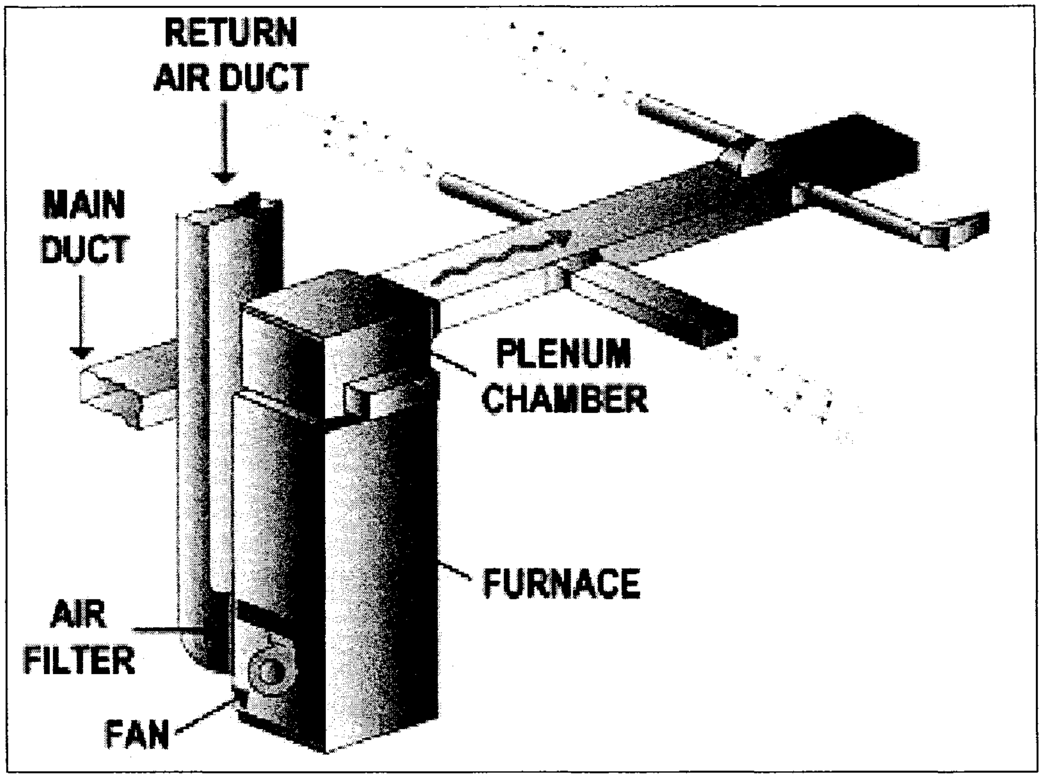


Figure 6.1 Typical components of duct system.

6.1 Testing Return Leaks

Testing return leaks involves two stages, namely measurement of return leakage and detection of return leaks. Figure 6.2 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 [62].

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

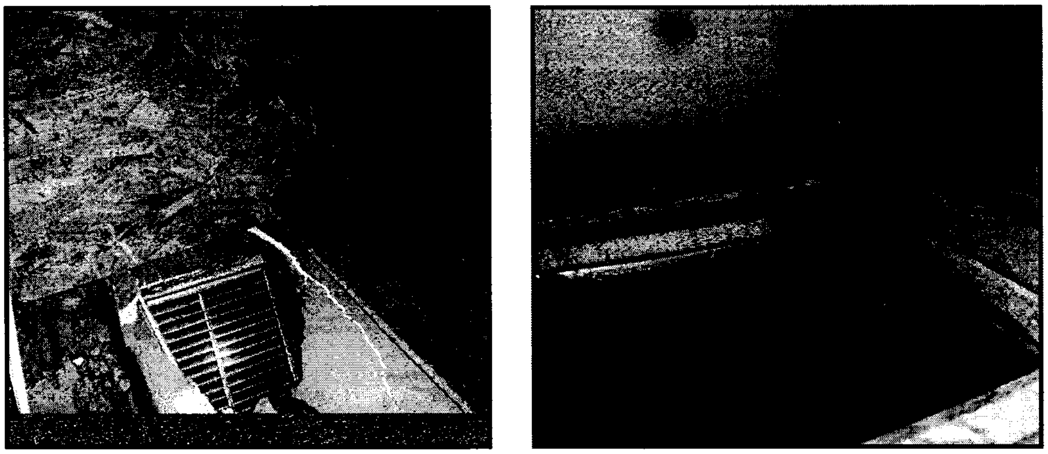


Figure 6.2 Common spots of return leaks.

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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

From now on, 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™: 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™ to measure the flow.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

From now on, we will term the second approach as the True Flow Meter™ approach (TFM). The theory behind the testing procedure for both the testing approaches is described below. Figure 6.3 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 6.3, the Blower Door™ used to pressurize/depressurize the house; the flow is given by F_1. The Duct Blaster™ 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 6.3. The detail of this blockage is described in detail in Section 6.3.

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

Notationally,

F_1 = flow from the Blower Door™

F_2 = flow reading measured using Duct Blaster™

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

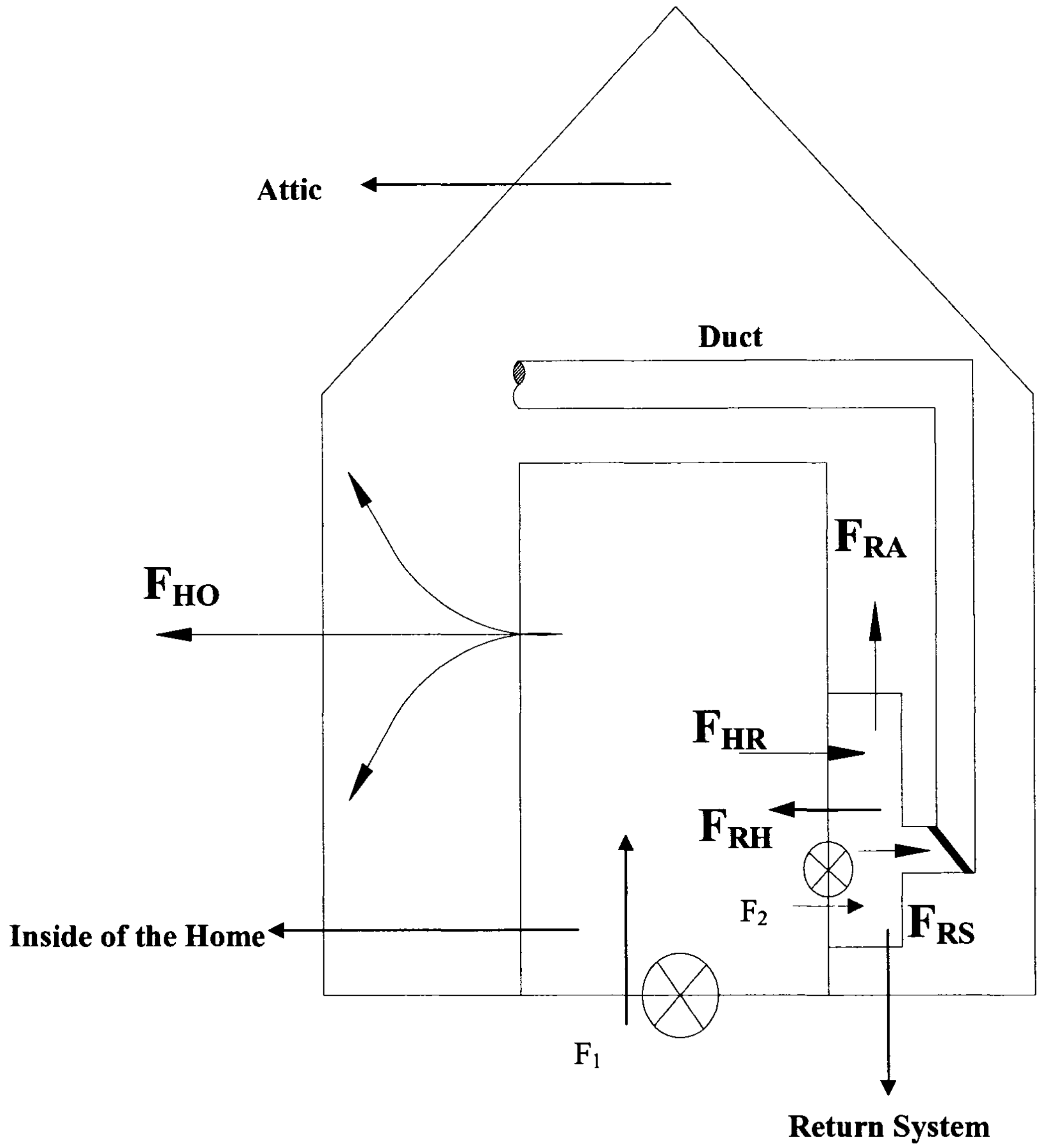


Figure 6.3 Two-dimensional view of a typical home with ducts in attic.

In a combined operation of both Blower Door™ and Duct Blaster™, the actual flow recorded at the Duct Blaster™ 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.

$$F_2 = (F_{RA} + F_{RS} + F_{RH}) - F_{HR} \tag{6.1}$$

Since the flow to the supply is blocked,

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

$$F_{RS} = 0 \tag{6.2}$$

Therefore Eq. (6.1) becomes

$$F_2 = F_{RA} + F_{RH} - F_{HR} \tag{6.3}$$

Considering the Blower Door™ we have,

$$F_1 = F_{HR} + F_{HO} \tag{6.4}$$

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,

$$F_{HR} = F_{RH} \tag{6.5}$$

Therefore substituting Eq.(6.5) in Eq.(6.3), we have

$$F_2 = F_{RA} \tag{6.6}$$

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™. 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™, 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 two more additional pressure points.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

6.3 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 6.4. The arrows indicate that the blockage can be placed above or below the return box.

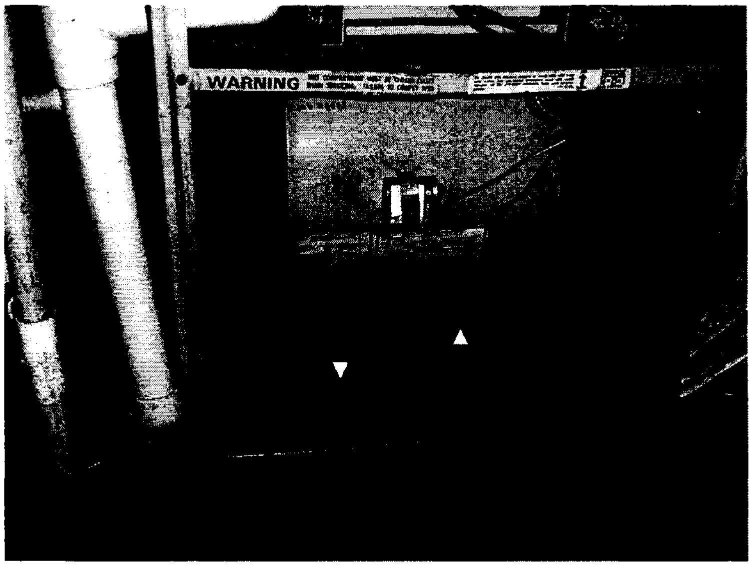


Figure 6.4 Placement of blockage to seal of the supply side.

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 6.4. Figure 6.5 shows a design of a flexible blockage system, which can be used in most homes but is not sufficient.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

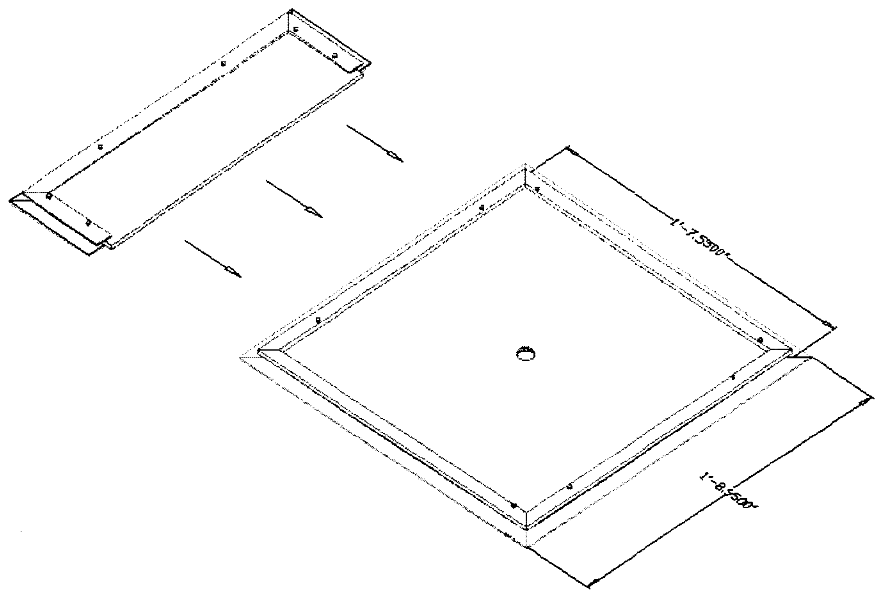


Figure 6.5 Blocking above the return box (BARB).

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™ 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 6.5, 6.6 and 6.7. Figure 6.6 also shows the direction of fit of the spacers to the main plate.

Figure 6.6 Side view of BARB.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

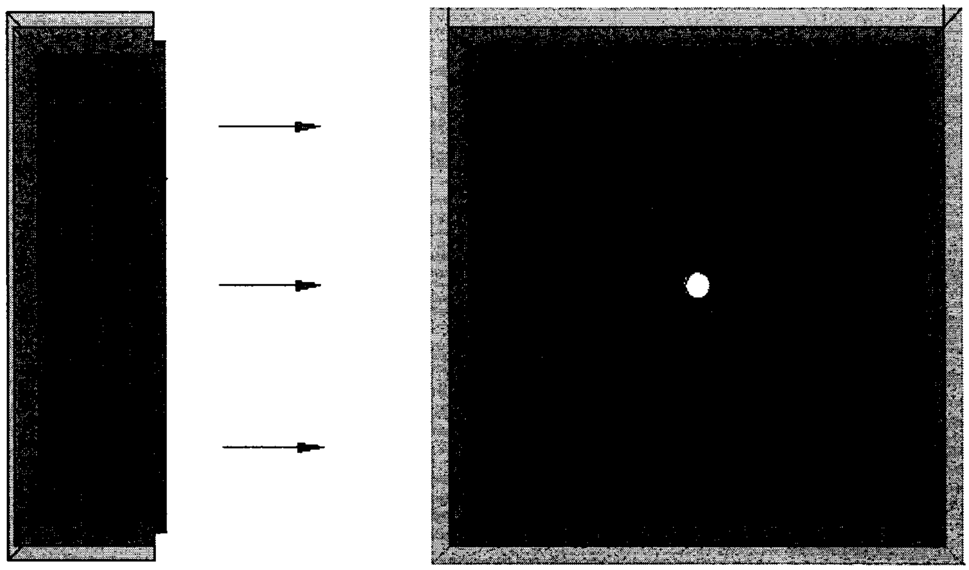


Figure 6.7 Top view of BARB.

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™. 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 6.4 and 6.6 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 6.4. The design of this blockage system BBRB

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

is presented in Figure 6.8. 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 pitot tube, as in the case of BARB, can be introduced by drilling a hole.

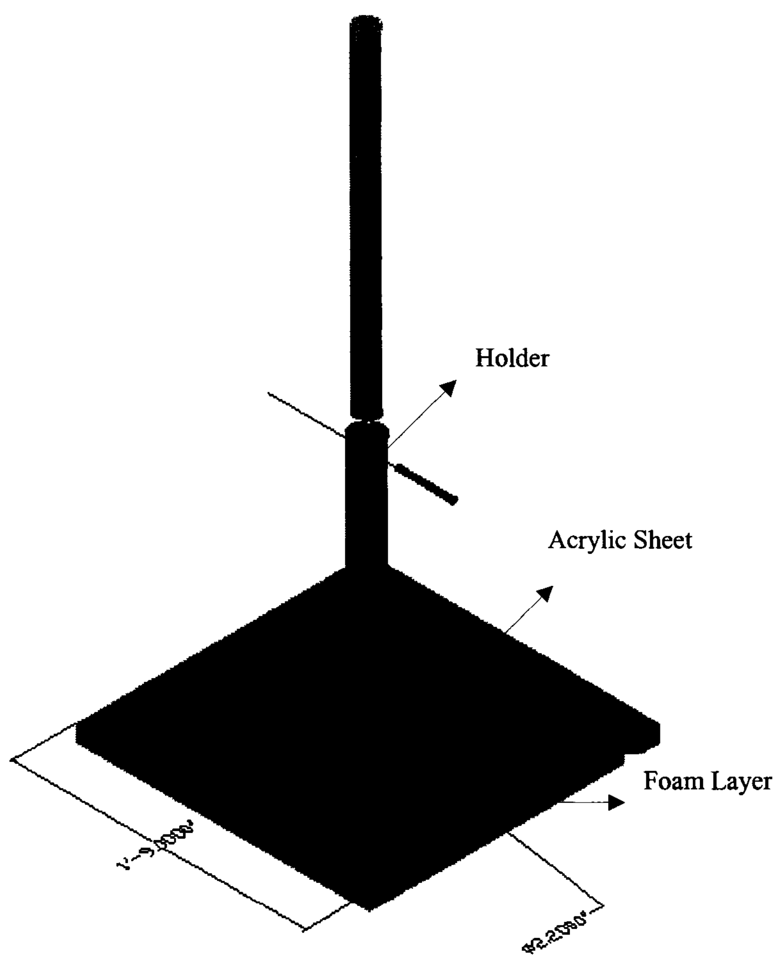


Figure 6.8 Blocking below the return box (BBRB).

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 6.9 and 6.10 show situations where the BBRB system is inapplicable.

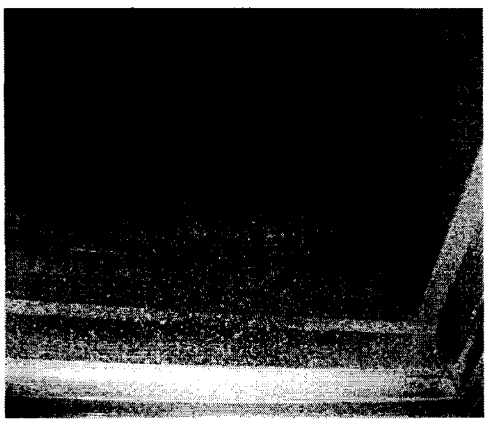


Figure 6.9 Non-standardized return chase.

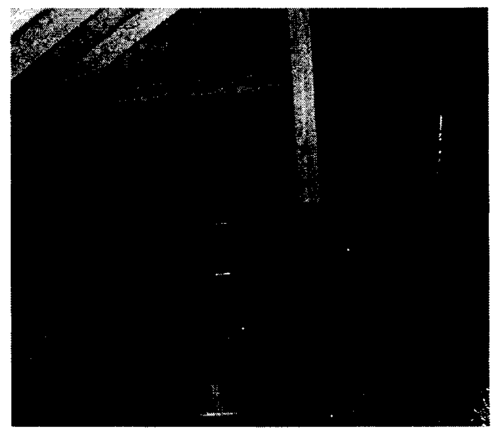


Figure 6.10 HVAC unit in attic.

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.

6.4 <u>Measurement of Return Leaks</u>

In this study, we have employed two techniques to measure return leaks. The first method uses Blower Door™, Duct Blaster™ and APT hardware (BDDB) where as the second method uses True Flow Meter™ (TFM) as described in Section 6.2. The detailed procedure of these two methods is described in Section 6.4. The BDDB and TFM are

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

used to determine return leakage to the attic. In addition, we also measured total return leakage using the Duct Blaster™ 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:

<u>Total Return Leakage (TRL) – Pressurized (TRL+) and Depressurized (TRL-):</u>

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™ 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™ 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

9. Pressurize/Depressurize the return duct system to 15 Pa. using the Duct Blaster™.
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™ and Duct Blaster™ respectively to 15 Pa. The Blower Door™ maintains the home at a given pressure with respect to the outside while the Duct Blaster™ 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™ 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™ manual.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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™.
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™ pressure tubes using the DG-3 gauge.
6. Normalize these values as described in the True Flow Meter™ Manual to obtain a reading, R1
7. Replace the filter below the blower of the HVAC unit with the True Flow Meter™.
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.

6.5 Comparison of CRL with BARB and BBRB

For comparison purposes, we used the True Flow Meter™ plates and covered it with polythene sheet. Table 6.1 shows the results of the comparison of using BARB and BBRB as blocking media.

From Table 6.1, 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 6.1 BBRB 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**

6.6 Analysis of Return Leak Exponents

We have proved from Eq. (6.6) that leaks in the return plenum are airflows from the attic to the return plenum as described in Section 6.2. Rewriting Eq.(6.6) as

$$F_{\mathrm{HR}} = F_{\mathrm{RA}} \tag{6.7}$$

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™ (F_2) during simultaneous pressurization of home and return plenum as described in Section 6.2.

Relation of Flow and Pressure is given by

$$F = CP^n \tag{6.8}$$

(Power Law Equation)

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

C=leakage coefficient

P=pressure in Pascal (Pa)

n=flow exponent

From Eqs. (6.7, 6.8), we have

$$C_{HR}P_{HR}^{n}{}_{HR} = C_{RA}P_{RA}^{n}{}_{RA} \quad (6.9)$$

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™ readings. If we measure the respective P_{RA} at pressures P_1 and P_2 then

$$C_{HR1}P_{HR1}^{n}{}_{HR1} = C_{RA2}P_{RA2}^{n}{}_{RA2} \quad (6.10)$$

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.

$$n_{RA} = \log(F_{HR1} / F_{HR2}) \ / \ \log(P_{RA1} / P_{RA2}) \quad (6.11)$$

The flow coefficient values of C_{RA} can also be determined by substituting the values of n_{RA} shown in Eq. (6.12.)

$$C_{RA} = F_{HR1} \ / \ P^{n}{}_{RA} \quad (6.12)$$

Similarly, we can find the values of the n_{HR} and C_{HR} using the Eqs. (6.10, 6.11 and 6.12).

Tables 6.2 to 6.5 are all the readings collected from the sample of 43 homes. Values of flow exponent and leakage coefficients are obtained from Eqs. (6.11) and (6.12) 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 6.2 to 6.5, the following variables are abbreviated as,

a. Exponent – EXP

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

b. Leakage Coefficient – COE

c. Operating Pressure in Pascal – OPP

d. Return Leaks at Operating Pressure in cubic feet per minute – RLOP

Table 6.2 Return leaks and parameters for combined return leaks (P_{RA}).

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 6.3 Return leaks and parameters for total return leaks (P_{RA}).

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**

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 6.4 Return leaks and parameters for combined return leaks (P_{HR}).

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+.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6.5 Return leaks and parameters for total return leaks (P_{HR}).

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 >

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

|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 6.6.

Table 6.6 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 [30]. 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™ method, as described in Section 6.4. 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

True Flow Meter™ 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.

6.7 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™ Manual can be used to calculate the Equivalent Orifice Leakage Area (EOLA).

EOLA is given by

$$\text{EOLA (sq. in.)} = (\text{Return System Leakage Rate})/1.06 \times (\text{Return Duct System Pressure})^{0.5} \quad (6.13)$$

where,

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

Return Duct System Pressure = operating pressure of return duct system

Table 6.7 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 Four.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 6.7 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**

6.8 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 6.8. 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 6.8 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. [64]. 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

In Chapter Three, we determined the duct leakage to outside to be about 348 cfm. 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 Seven.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 7

SUPPLY LEAK MEASUREMENT

Return leak measurements were treated in detail in Chapter Six. 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 Six, 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 6.1 in Chapter Six 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 Six and Section 7.2.

7.1 Testing Supply Leaks

Supply leaks are generally measured using the same measuring equipment as used in measuring the return leakage described in Section 6.2. 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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™.

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 7.1 shows some common sources of supply leaks in residential homes.

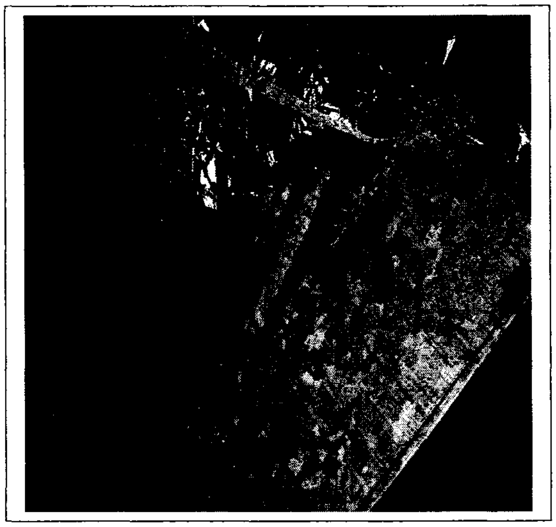


Figure 7.1 Common sources of supply duct leakage.

Combined Return Leakage (CRL):

Follow the test procedure as described in Section 6.4 of Chapter Six 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 6.3 and 6.4 of Chapter Six. For

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 7.2.

7.2 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

are necessary to obtain any result, and in most cases, accurately approximate the actual system.

The relation of flow and pressure is given by

$$F = CP^{n} \tag{7.1}$$

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 P_1 and P_2 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.

$$CDL = CRL + CSL \tag{7.2}$$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Therefore,

$$CSL = CDL - CRL \tag{7.3}$$

Assuming two pressure points 35 and 25 Pa and using Eq. 7.1, we have

$$CRL_{35} = C_{RL}P_{35}^{n_{RL}} \tag{7.4}$$

$$CRL_{25} = C_{RL}P_{25}^{n_{RL}} \tag{7.5}$$

Dividing Eq. 7.4 by Eq. 7.5 we get,

$$CRL_{35}\ P_{25}^{n_{RL}} = CRL_{25}\ P_{35}^{n_{RL}} \tag{7.6}$$

$$n_{RL} = \log(CRL_{35} / CRL_{25})\ /\ \log(P_{35} / P_{25}) \tag{7.7}$$

$$C_{RL} = CRL_{35} /\ P_{35}^{n_{RL}} \tag{7.8}$$

Similarly Eqs. (7.6), (7.7), (7.8) can be used to determine n_{DL}, C_{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™ and Duct Blaster™ at these pressures.

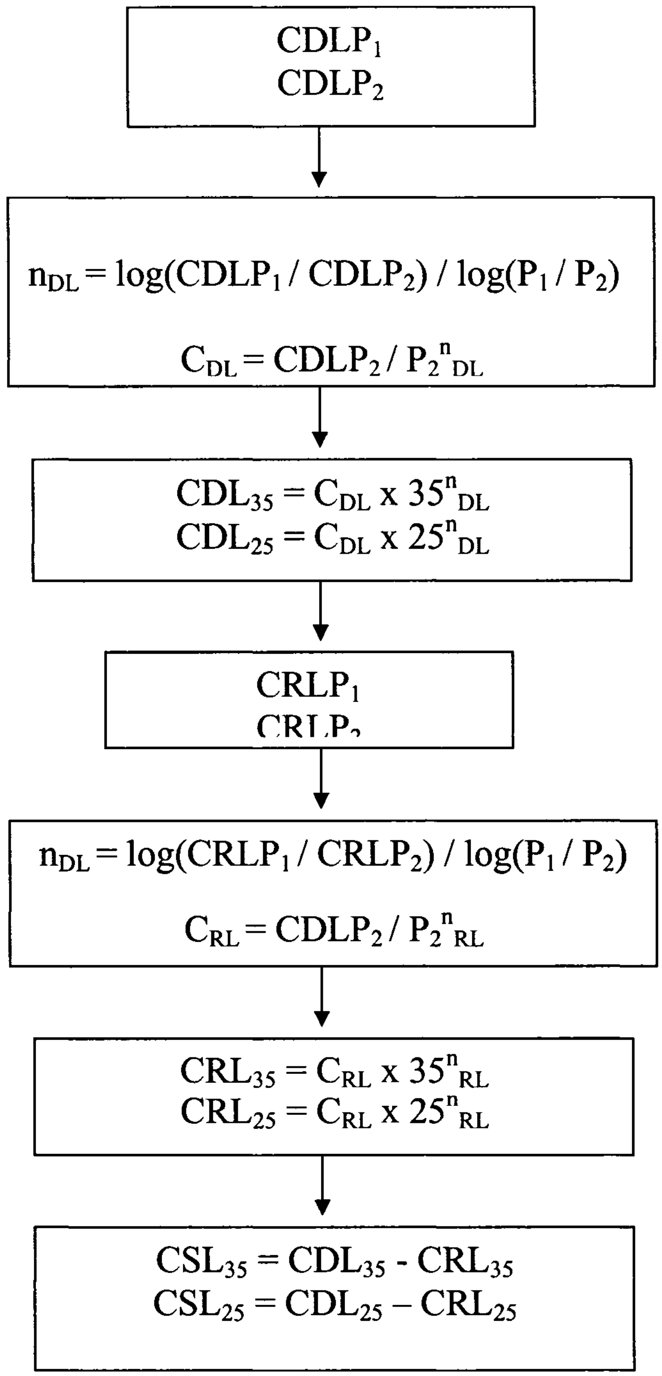
However, our objective is to determine the duct leakage at the actual operating pressure, obtained through our measurements. It is important to note that the return plenum and the supply plenum operate at different pressures. Therefore, it becomes critical to measure the operating pressure both in the 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. (7.2) and (7.3) 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. (7.1) to obtain the supply leakage at the operating pressure *OPS*.

$$CSL_{OP} = C_{SL}\ OPS^{n_{SL}} \tag{7.9}$$

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

To obtain the combined duct leakage at the actual operating condition we use Eq. (7.2). 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 in Figure 7.2.



Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

$$n_{SL} = \log(CSL_{35} / CSL_{25}) / \log(P_{35} / P_{25})$$

$$C_{SL} = CSL_{35} / P_{35}^{n_{SL}}$$

$$CSL_{OP} = C_{SL} \times OPS^{n_{SL}}$$

$$CRL_{OP} = C_{RL} \times OPR^{n_{RL}}$$

$$CDL_{OP} = CSL_{OP} + CRL_{OP}$$

Figure 7.2 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 7.2 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 7.2) is presented in Tables 7.1, 7.2, 7.3 and 7.4.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 7.1 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 7.1, n_{DL} (=0.73) and C_{DL} (=16.88). Using the equations given in the flow chart (Figure 7.2) we obtain CDL_{35} (=228.17 cfm) and CDL_{25} (=178.33 cfm).

The data n_{RL} and C_{RL} from Table 7.2 is used with Eq. (7.4) 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 7.2 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 7.3 gives the combined supply leakage at the operating pressure in the supply plenum. For example, for home number 15 using Eq. (7.3), we determine CSL_{35} to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

be 161.21 cfm. The *OPS* is measured as described in Section 7.1. These values are then substituted into the power law equation, Eq. (7.1) to obtain the supply leaks at operating pressure as described in the flow chart (Figure 7.2). For home number 15, the *OPS* was determined to be 45.67 Pa which using Eq. (7.9) gives the combined supply leakage at operating pressure of 200.96 cfm. As discussed in Chapter Six, Section 6.8, 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 7.3 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 7.4 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:

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 Six.
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 7.4 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

7.3 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 25Pa. Table 7.5 shows the comparison of duct leakage values both with 25 Pa and 35 Pa. From Table 7.5, 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 7.5 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 Eight 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 8

STATISTICAL ANALYSIS OF PRESSURIZED AND DEPRESSURIZED CONDITIONS

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

$$F = C\Delta P \tag{8.1}$$

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 [65]. 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 [33, 55].

The Eq. (8.1) 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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™ only whereas both CDL and CRL involve both Duct Blaster™ as well as Blower Door™ as described in Chapter Three. All the statistical tests were performed using SAS™ and the detailed output is presented in Appendices B13 and B14.

8.1 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 8.1.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 8.1 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 8.1 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 B14.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

8.2 Combined Duct Leakage (CDL)

The CDL is performed using both Blower Door™ and Duct Blaster™ 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 8.2 show that the distribution is not normal as all the p-values for normality tests are less than 0.05.

Table 8.2 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 Appendix B14. The % difference in readings between the pressurized and depressurized conditions is shown in Table 8.3. The depressurized reading on an average is about 20% higher than the pressurized readings.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 8.3 % Difference in measurements between pressurized vs. depressurized.

House #	Pressure (Pa)	Flow Depressurized (cfm)	Flow Pressurized (cfm)	%Difference
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%

8.3 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

normal distribution, as the p-values for all the normality tests are less than 0.05 as shown in Table 8.4.

Table 8.4 Non-Parametric and normality test for TRL.

Tests for Location: Mu0=0

<table>
<tr><th>Test</th><th colspan="2">-Statistic-</th><th colspan="2">-----p Value------</th></tr>
<tr><td>Student's t</td><td>t</td><td>0.706342</td><td>Pr > |t|</td><td>0.4935</td></tr>
<tr><td>Signed Rank</td><td>S</td><td>-21.5</td><td>Pr >= |S|</td><td>0.1421</td></tr>
</table>

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

We note there were limited data due to the limitations as described in Chapter Six. 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 Appendix B14.

8.4 Combined Return Leakage (CRL)

The CRL is performed using Blower Door™ and Duct Blaster™ to determine return leaks to the outside. Chapter Six 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 8.5 indicate that the small sample data do not follow a normal

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 Appendix B14. Table 8.6 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 8.5 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 8.6 % 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%

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

8.5 Conclusions of Pressurized Vs. Depressurized Conditions

Results of Sections 8.1 to 8.4 suggest that CDL and CRL readings differ statistically between the pressurized and the depressurized conditions. These two tests involve both Blower Door™ and Duct Blaster™. However, it is important to note that tests with Duct Blaster™ 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™ 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™ 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™, for pressurizing/depressurizing the whole house. Another factor, which may contribute to this difference, is the sensitivity of the Blower Door™ to the environmental changes in contrast to the Duct Blaster™. All these factors mentioned in the preceding lines may also interact to give variations in readings between the pressurized and depressurized conditions.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 9

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 [10]. 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

as much as 0.5 kilowatts (kW) of electricity during peak cooling periods [66]. It is estimated that each year, U.S. residential ductwork leakage costs consumers $5 billion [67].

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 [68]. 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™ 152 standard for determining distribution system efficiency and REM/Rate™ software developed by Architectural Energy Corporation for determining the cooling/heating load in each of the 43 homes tested.

REM/Rate™ 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™ is Department of Energy (DOE)-approved for Weatherization Assistance Programs in all states [69].

In Chapter Three, Section 3.10, 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 9.1 is the reproduced chart that shows the efficiency losses due to attic return and supply leaks.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

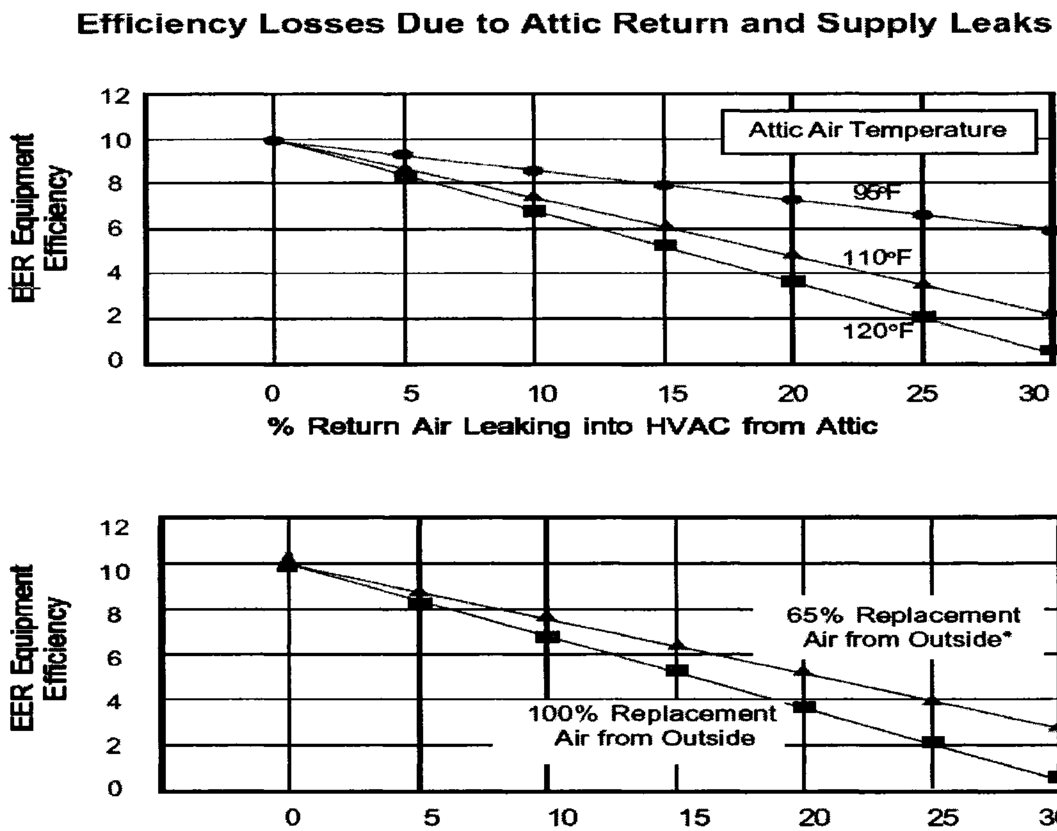


Figure 9.1 Energy losses due to attic return and supply leaks.

There are many drawbacks to adopting this chart, shown in Figure 9.1, 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 9.1 [70].

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™ software along with ASHRAE™ 152 standard to estimate energy losses due to duct leakage rather than using the chart presented in Figure 9.1. In the next two sections, we discuss REM/Rate™ and ASHRAE™ 152 in relation to this study, highlighting the significance of this study and its implications.

9.1 REM/Rate™ Inputs

REM/Rate™ 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

and energy cost data. REM/Rate™ is U.S Department of Energy (DOE)-approved software for Weatherization Assistance Programs in all states [69]. 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 [9]. 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™ 152 standard whereas REM/Rate™ was used to determine the cooling load/heating load for the home. The output from REM/Rate™ was used in conjunction with the results from the ASHRAE™ 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Slab Depth Below Grade, Type of Infiltration, and Measured Infiltration Rate estimated from the Blower Door™ 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-

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 Six. For those homes, the return leakage was estimated by multiplying the duct

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 9.1 presents the data of the energy use of the 43 homes tested using REM/Rate^{TM} following the above 11 steps. Table 9.2 shows the energy wastage due to duct leakage.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 9.1 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 9.2, we observe that the % cooling and heating energy wastage from duct leakage (100 x (Energy Use with Measured Duct Leakage in $ - Energy Use with

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 [71] and [72].

Table 9.2 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					
House #	Heating	Cooling	Total Energy Use	Heating	Cooling	Total Energy Use			
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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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
Average								**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 9.1 the % energy loss due to duct leakage should be much greater than the % duct leakage. This expectation is not satisfied in Table 9.2.

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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" [73]. 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™ 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™ 12, with that given by REM/Rate™ 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 Six, 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" [74]. The study in Mississippi showed that when the outside temperature was 95 degrees F, the attic temperature was at 129.2 degrees F. However the outside temperature varies throughout the day. Thus, we will use an average temperature, conservatively taken to be 86 degrees, wherein the attic temperature can then, from the above quoted study, be taken to be 104 degrees.

We will assume that the air conditioner is running when the outside air is 77 degrees or greater. The study titled "Roof Temperature Histories in Matched Attics in

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 degrees Fahrenheit respectively. The number of hours corresponding to outside temperatures 77, 86, and 104 degree 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 degree 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 degrees Fahrenheit from the above study in Mississippi was for 639 + 494 + 507 + 398 + 130 + 2 = 2143 hours. Table 9.3 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 9.3. 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 9.4 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

air (Table 9.4). At 0% duct leakage, by this definition we have 100% air conditioning distribution efficiency, which is presented as 1 in Table 9.4.

Table 9.4 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 degrees F for the heating season. Therefore, it is reasonable to consider the average heating temperature to be near 50 degree F. Since

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 degree F.

Tables 9.5 and 9.6 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 9.5 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 9.6 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The air conditioning distribution efficiency and heating distribution efficiency for the respective % duct leakage values are presented in Tables 9.4 and 9.6. 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 9.4 and 9.6, 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™, we see that the numbers are much smaller than expected. This small difference suggests that there is an inherent error in REM/Rate™'s calculation of energy wastage as it does not appropriately account for temperature and humidity. Table 9.7 depicts the comparison results for the first four homes.

In Table 9.7, the drop in air conditioning distribution efficiency and heating distribution efficiency for the respective % duct leakage values are obtained from Tables 9.4 and 9.6 (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 9.4 and 9.6. 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™) from Table 9.2. For home number one, the cooling cost is obtained my multiplying, 1.77 by 420 (cooling cost at zero duct leakage from Table 9.2), 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 9.7 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™ is also presented in Table 9.7. From Table 9.7, 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™'s calculation of energy costs.

We further investigated the results obtained from REM/Rate™ 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 9.8.

Table 9.8 REM/Rate™ results for varying supply and return leaks.

Supply	Return	Duct Leakage	Heating	Cooling	Heating	Cooling	%Change in Energy		Remarks	Capacity	%Leakage	
cfm			*MMBTU/yr*		*$*		*Heating*	*Cooling*			*Supply*	*Return*
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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 9.2 and 9.3 show the plots for the % supply leakage and return leakage with % change in energy consumption respectively. From Figure 9.2, 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.

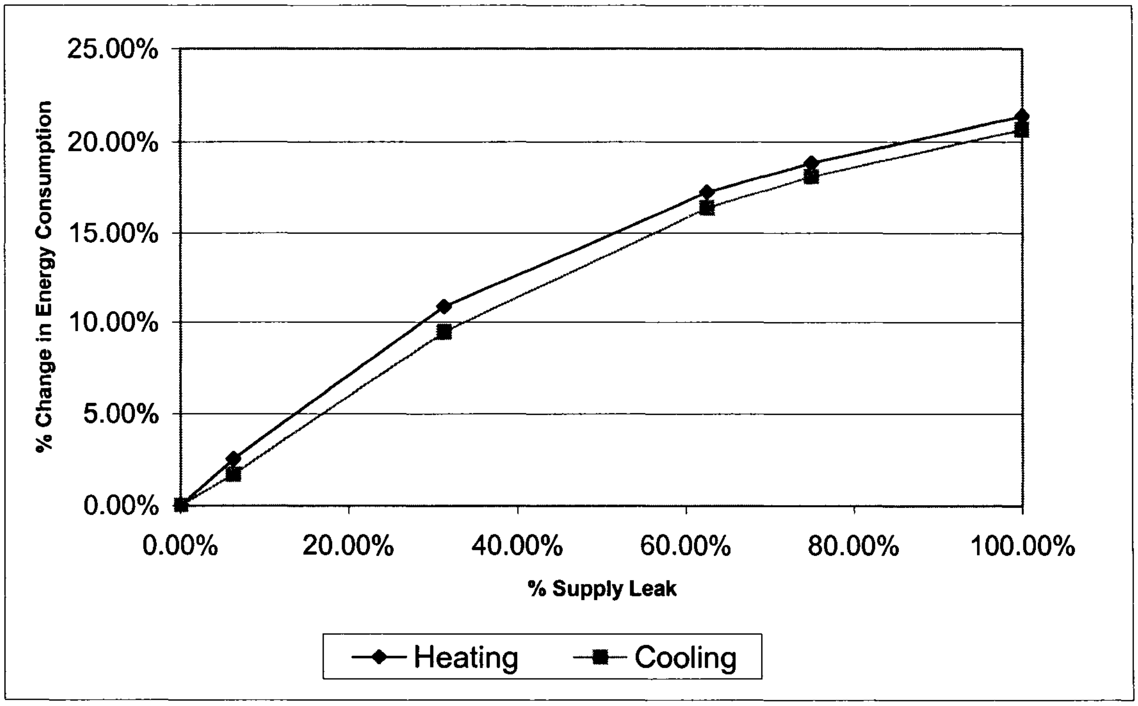


Figure 9.2 % Supply leak vs. % change in energy consumption.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

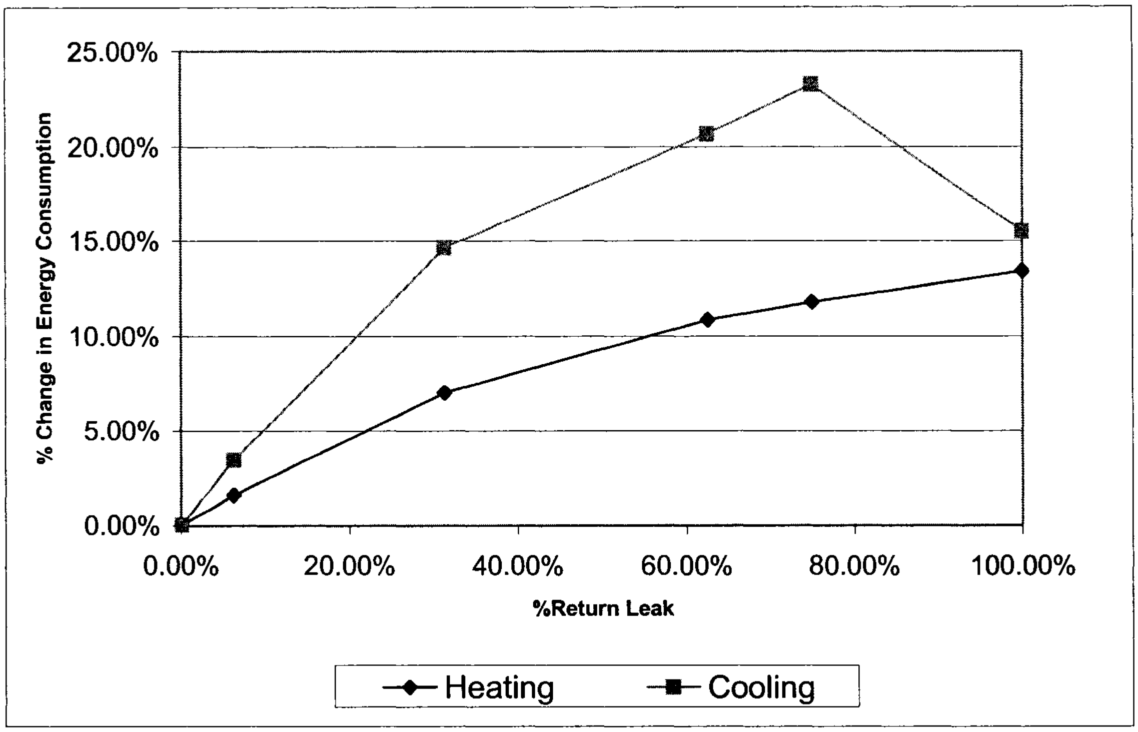


Figure 9.3 % Return leak vs. % change in energy consumption.

In the case of return leaks, from Figure 9.3 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 degrees 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 9.3, 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™ outputs a warning message in certain cases as shown

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

in Table 9.3. 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™ 152 standard in combination with REM/Rate™, which is described in Section 9.2.

9.2 ASHRAE™ 152 Standard

The ASHRAE™ 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 [68]. The standard quantifies how much energy and HVAC equipment capacity duct leaks actually waste [69]. The main objective of our study is to determine the dollar energy wastage due to duct leakage.

ASHRAE™ 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™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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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. Distribution 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 [60].

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 [60].

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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 Seven.

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 Six.

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.

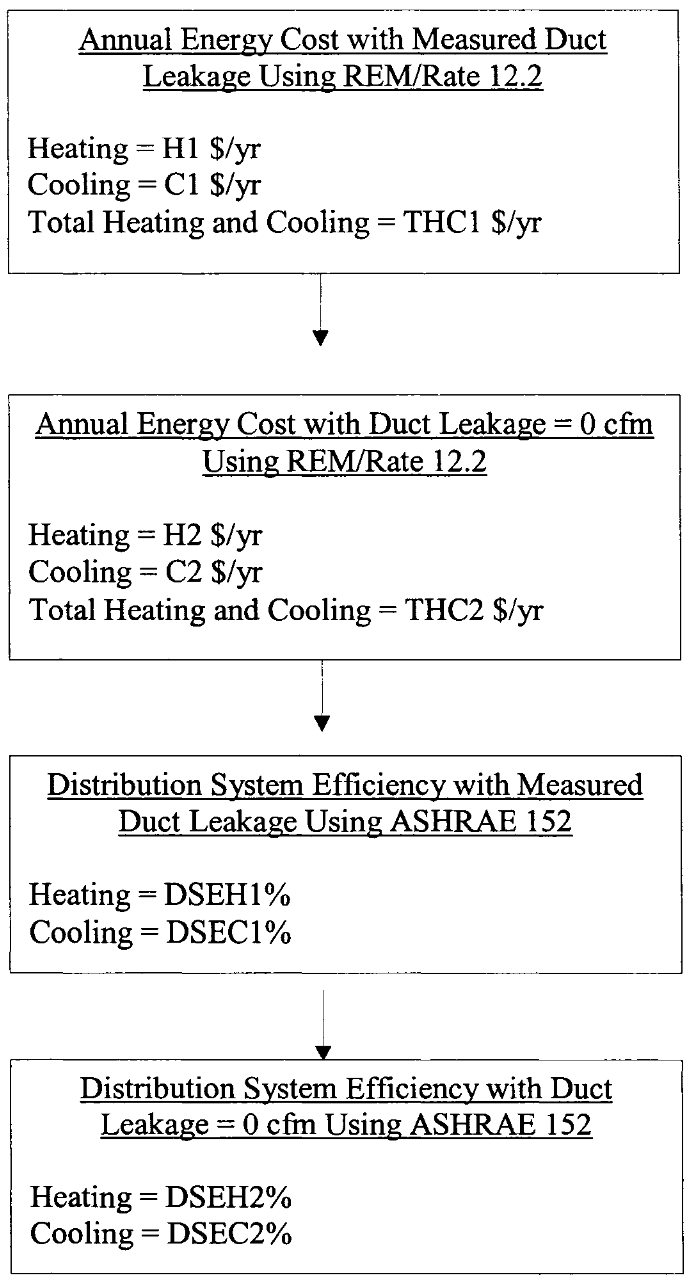
The output includes DE and DSE for both heating and cooling modes. Our objective was to determine the unnecessary wastage associated with duct leakage. Therefore, the distribution system efficiency is the relevant output in our study as it measures the ratio between the energy consumption by the equipment 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.

9.3 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 9.4 shows the methodology involved in estimating the unnecessary cost associated with duct leakage. The calculation involves the combined use of REM/Rate™ and the ASHRAE™ 152 standard.



Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Annual Energy Cost with Measured Duct Leakage Using ASHRAE 152

Heating = H3 $/yr = H2 x DSEH2% / DSEH1%

Cooling = H4 $/yr = C2 x DSEC2% / DSEC1%

Total Heating and Cooling = THC3 $/yr = THC2 – (H2+C2) +(H3+H4)

↓

% Total Cooling and Heating Energy Wastage from Duct Leakage

REM/Design
%Wastage = ((H1+C1) – (H2+C2))/(H2+C2)

REM/Design and ASHRAE 152
%Wastage = ((H3+C3) – (H2+C2))/(H2+C2)

Figure 9.4 Flow chart for calculating % energy wastage from duct leakage.

The calculated values using the methodology described in Figure 9.4 is presented in Table 9.9. From Table 9.2, the average % cooling and heating energy waste for an individual home from duct leakage obtained from REM/Rate^{TM} is 5% with an average annual duct leakage associated cost equal to $52.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 9.9 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					
House #	Heating	Cooling	Total Energy Use	Heating	Cooling	Total Energy Use			
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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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™ 152 as described in flow chart (Figure 9.4), with energy cost at duct leakage equal to zero obtained from REM/Rate™, 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 9.2 and 9.8, there is no doubt that there are significant differences between the output results of REM/Rate™ and ASHRAE™ 152 results. However, ASHRAE™ 152 standard is the presently accepted standard in the HVAC industry [73]. The accuracy of ASHRAE™ 152 standard lies in the fact that it determines the distribution efficiency, which is directly related to duct leaks. Duct leaks affects the distribution efficiency – higher the duct leaks lower the distribution efficiency.

9.4 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 9.10.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 9.10 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					
House #	Heating	Cooling	Total Energy Use	Heating	Cooling	Total Energy Use			
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 9.9 and 9.10, 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 9.10.

From Table 9.11, 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 9.11 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%	-	-	-

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

The census data for Louisiana indicates that there are 1,656,053 households in Louisiana [75]. 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 [1] 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 9.12 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 9.12. This average value of $280 was obtained from Table 9.9. 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 9.12.was determined to be $263,383,306.

Table 9.12 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-

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

effectively is very important especially for the State of Louisiana, which has hot and humid summers. Chapter Ten presents the feasibility tests of one such sealing technique for sealing duct leaks in laboratory conditions.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 10

PROPOSED RESIDENTIAL DUCT SEALING TECHNOLOGY – A FEASIBILITY STUDY

10.1 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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.

10.2 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 Six 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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.

10.3 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™ following the application of the sealant. The results of these tests are shown in the following sections.

10.3.1 External Sealing of Wooden Box

A wooden box was constructed with a register as shown in Figures 10.1 to 10.4. Holes of varying diameters 0.078", 0.104", 0.144", 0.193", 0.201" and 0.228" were drilled as shown in Figure 10.1. In addition, gaps of less than 0.25" were made along the edges of the wooden box as shown in Figure 10.2. These holes and gaps were introduced to check the effectiveness of the sealant technology. The leaks prior to sealing were

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

measured using the Duct Blaster™. After measuring the leakage rate, the sealing methodology was applied as shown in Figures 10.1 to 10.4. The final reading after the application was again measured using the Duct Blaster™. The difference between these initial and final readings is used to determine the efficacy of this methodology. Figures 10.3 and 10.4 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 10.1.

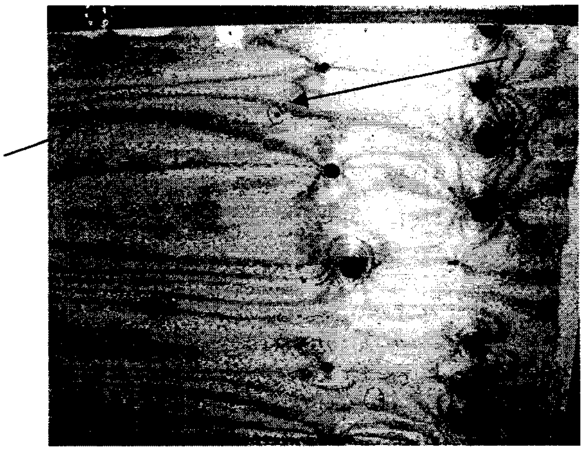


Figure 10.1 Drilled holes.

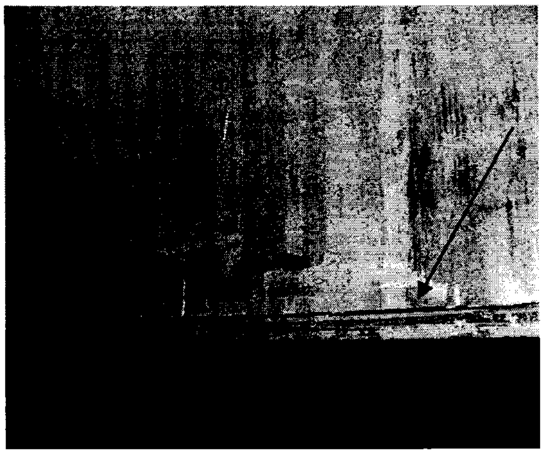


Figure 10. 2 Gap along the edge.

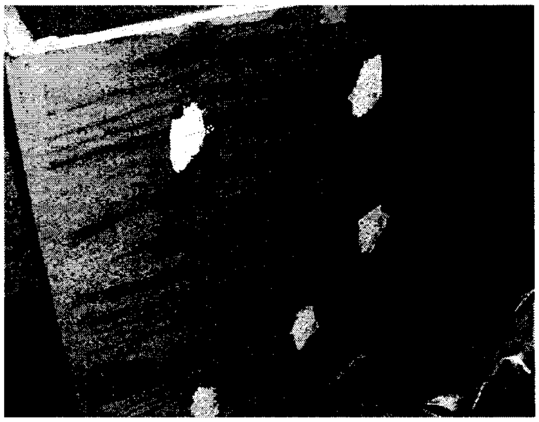


Figure 10. 3 Sealant applied on drilled holes.

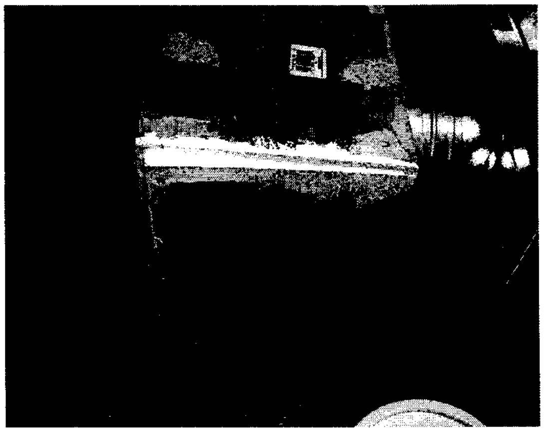


Figure 10. 4 Sealant applied along the edges.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 10.1 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.

10.3.2 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 10.3.1. The only difference was that readings were measured separately at the registers, joints and seam.

10.3.2.1 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 10.5 and 10.6 point to

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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.

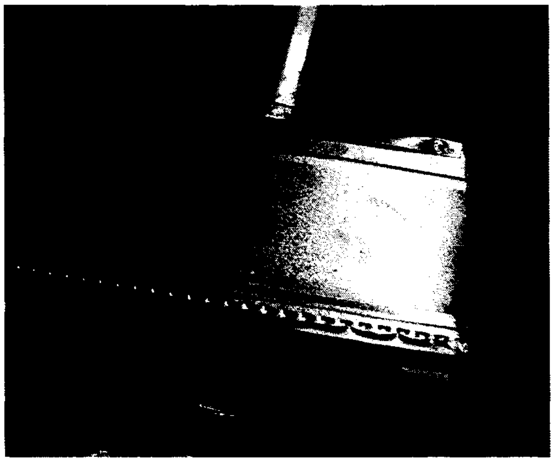


Figure 10.5 Leaks at register boot.

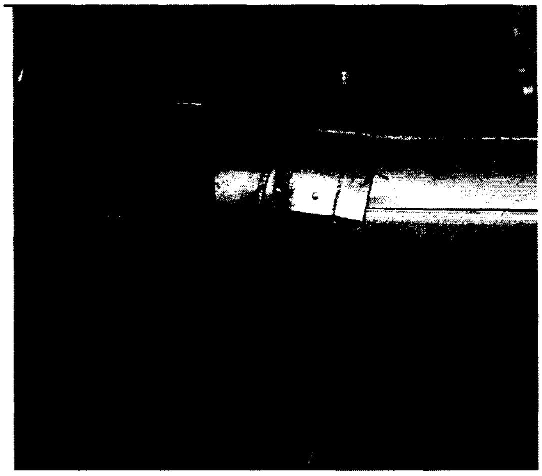


Figure 10.6 Leaks at register boot.

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 10.7; Figure 10.8 shows the sealant applied on the register.

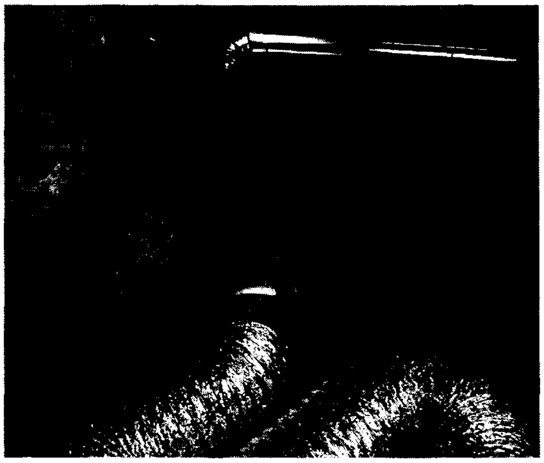


Figure 10.7 Experimental set up.

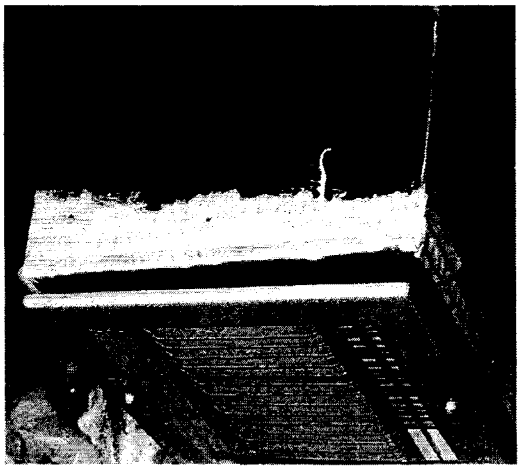


Figure 10.8 Sealant applied on the register boot.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 10.2, 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 10.2 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

10.3.2.2 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 10.3.1; the only difference being that the sealant was externally applied over the joints. The procedure followed was the same as that used in Section 10.3.1, and the results are presented in Table 10.3. Figures 10.9 and 10.10 depict the joints sealed using this sealing technology.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Figure 10.9 Sealant applied at joints with turns

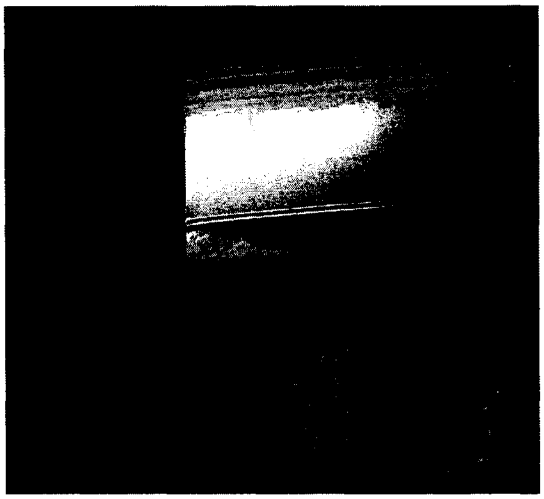


Figure 10.10 Sealant applied at joints with registers

From Table 10.3, 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 10.9 and 10.10.

Table 10.3 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

10.3.2.3 **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 10.3.1; the only difference

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

being that the sealant was applied externally over the seam. Figure 10.11 shows the seam whereas Figure 10.12 shows the sealant applied over the seam.

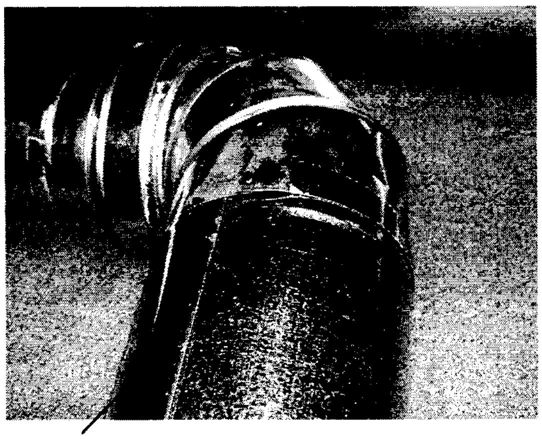


Figure 10.11 Seam of the duct system.

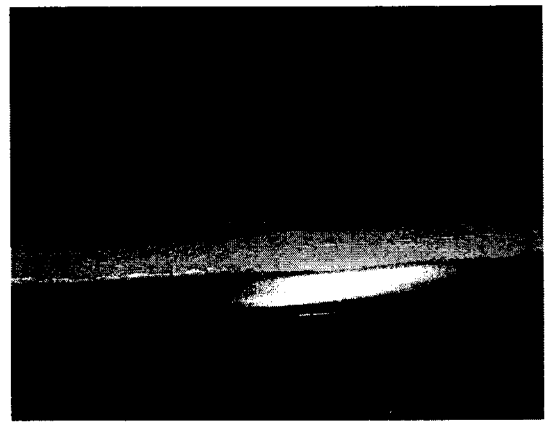


Figure 10.12 Sealant applied on the seam.

The results of leakage rates using Duct Blaster™ after sealing the seam is presented in Table 10.4. 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 10.4 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

10.3.3 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 10.3.2. 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.

10.3.3.1 Sealing turn/joint

A 6' duct system was constructed with a 10" diameter duct with a register boot at one end. The experimental set up is shown in Figure 10.13 where as Figure 10.14. shows the sealant applied on the joints.

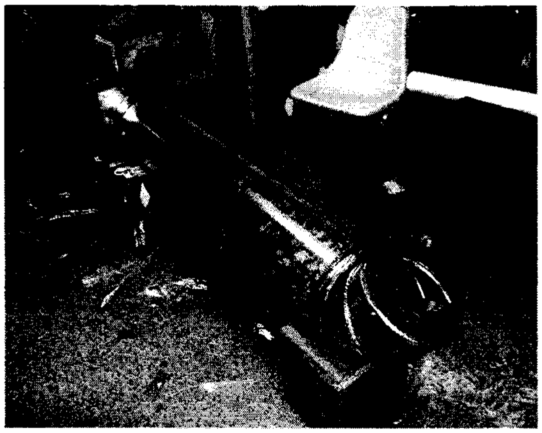


Figure 10.13 Experimental set up.

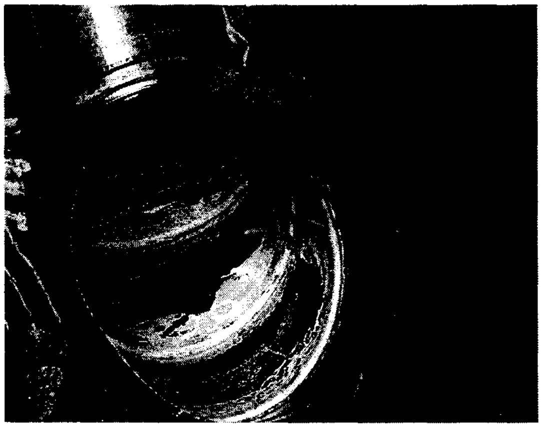


Figure 10.14 Sealant applied on turns/joints.

The sealing procedure followed the same steps as followed in Section 10.3.1, the only difference being that the sealant was applied internally to the duct system. Figure 10.15 shows the application of the sealant internally in the ducts. Figure 10.16 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Figure 10.15 Sealant applied on turns/joints.

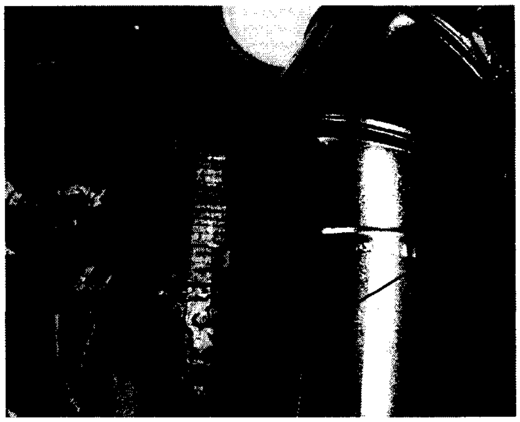


Figure 10.16 Flow of sealant to the outside.

The results of leakage rates measured using Duct Blaster™ are presented in Table 10.5. The results from Table 10.5 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 10.5 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

10.3.3.2 Sealing register/joint

The steps for sealing the joint at the register are similar to that mentioned in Section 10.3.1. The results of the leakage rates are presented in Table 10.6. From Table 10.6, the results show that about 80% of the existing leaks at the joints can be sealed at the joints.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table 10.6 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 10.17 shows the joint prior to sealing where as Figure 10.18 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 10.17 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.

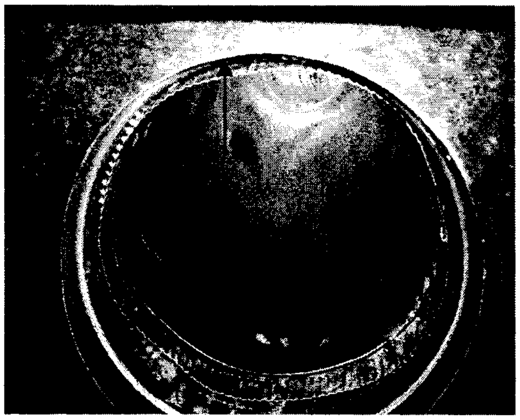


Figure 10.17 Leakage spot prior to sealing.

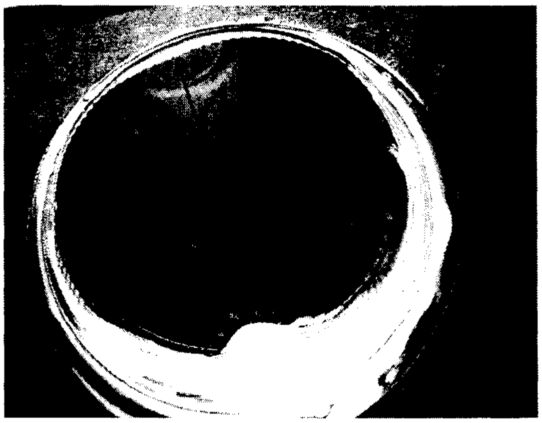


Figure 10.18 Leakage spot after applying sealant.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

10.3.3.3 Sealing register boots

The register boot was sealed internally with the sealant as shown in Figures 10.19 and 10.20. The sealing methodology was similar to that followed in sealing the registers externally as described in Section 10.3.1. 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.

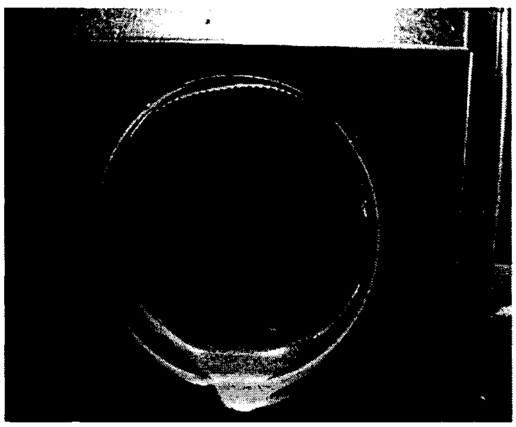


Figure 10.19 Source of leaks in register.

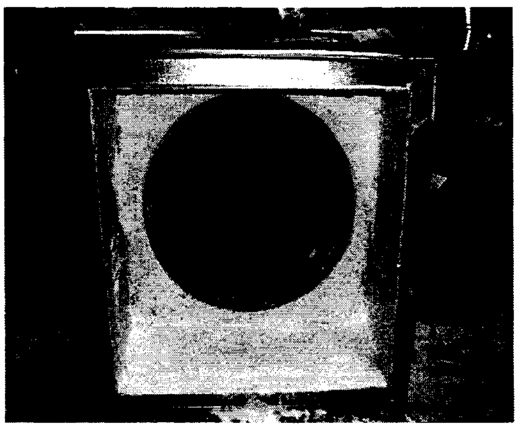


Figure 10.20 Sealant applied on the register.

The arrowheads in Figure 10.19 shows the source of leaks in the register boot whereas Figure 10.20 shows the sealant over the insulation. The results of the leak tests using the Duct Blaster™ are presented in Table 10.7. 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 10.7 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

10.3.3.4 Sealing seams

Seams were sealed internally with the help of a cotton mop. The sealing methodology followed was similar to that described in Section 10.3.3. The results presented in Table 10.8, 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 10.3.3. However, this result may not always be the case.

Table 10.8 Results of sealing seam 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

10.4 Tests in Progress

There are various other tests in progress to check for the applicability of this new duct sealing technology. Tests on flex ducts are in progress to determine the feasibility of using the sealant at the registers and joints. Also, the feasibility study has not

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

considered sealing leaks in ducts of larger size. In addition, it has to be tested in actual residential homes, with multiple size ducts, joints, registers and seams.

10.5 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

CHAPTER 11

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. A statistical analysis on the results on various measurements indicate that the Automated Performance Testing (APT) Method and the Manual method for implementing the Subtraction Correction Algorithm (described in Chapter Three), as well as, the Duct Blaster™ assisted by Blower Door™ method can be used interchangeably for finding the mean duct leakage averaged over a large sample of homes. Although these three approaches for finding the mean duct leakage will provide statistically indistinguishable results, this apparent agreement is more a consequence of the large standard deviation in each of these data sets rather than to the proximity of their independently calculated means. In other words, while the average in a large sample of homes can be used interchangeably, the results for individual homes can differ.
2. For any particular home, an APT test result can be predicted from a Manual test within a fixed diameter confidence interval. Although the prediction

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

model is quite useful for confirming large duct leakage, the prediction's confidence interval, being independent of the size of the reading, undermines the most important predictions, namely the ability to definitively confirm low duct leakage. Chapter Three presents an extensive statistical explanation of the confidence in relying on the output of one test to predict the results of the other. In addition, nine potential sources of error that that may cause the differences in the data obtained from the Manual and APT tests are presented in Chapter Three. Similarly, Chapter Three presents five potential sources of error that may cause the differences in the data obtained from the Combined and the Blower-Door™ - only, APT and Manual tests.

3. Including all the data, Chapter Three shows that mean duct leakage measured with Blower-Door™-only methods were found to be more than 25% higher than duct leakage measured with a Duct Blaster™ assisted by Blower Door™. However, with outliers removed, this disparity decreased to less than 15%. Simultaneously, i.e., with outliers removed, mean duct leakage over all datasets decreased by about 15% from 399 CFM25 to 348 CFM25.
4. 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

5. 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 Six.
6. 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.
7. The procedure for estimating supply leaks at operating pressure was presented in Chapter Seven. Duct leakage as well return leakages were used as input 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™ 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 Five.
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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 Eight suggest that both Combined Duct Leakage (CDL) and Combined Duct Leakage (CRL) readings differ statistically between the pressurized and the depressurized conditions. These two tests involve both Blower Door™ and Duct Blaster™. However, it is important to note that tests with Duct Blaster™ 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™ and the combined REM/Rate™-ASHRAE™ 152 results as presented in Chapter Nine. The simulations for a simple test case show the inadequacy of the REM/Rate™ model to determine the cost associated with duct leakage. As described in detail in Chapter Nine, 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.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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 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.

11.2 Future Work

1. Many of the sources of error discussed in Chapter Three should be more thoroughly analyzed and tested to determine the causes of the tests' differences and to provide guidance in developing methods to improve the accuracy of these tests.
2. 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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.

3. 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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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.

4. The results from Chapter Eight 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.
5. Discrepancies involved in REM/Rate™ in regards to determining costs associated with duct leakage need to be further investigated.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

APPENDIX A

MINITAB^{TM} INPUT AND OUTPUT

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

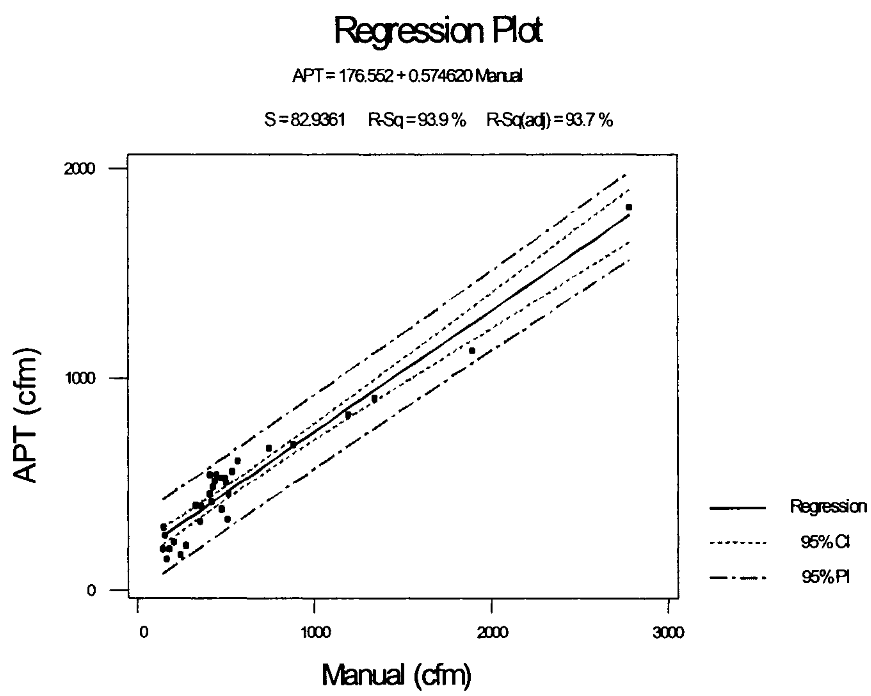
Table A.1 Duct leakage results.

Home Number	Depressurization (50 Pa) Using Blower door		Pressurization (50 Pa) Using Blower door		Combined test (25Pa) Using Duct blaster and Blower door
	APT (cfm)	Manual (cfm)	APT (cfm)	Manual (cfm)	Combined (cfm)
1	726.6	0.00			
2	987.20	861.00			
3	907.00	1337.90			551.00
4	1818.40	2789.20			651.00
5	340.30	508.40			285.00
6	170.10	245.50			153.00
7					529.00
8	795.00	1630.50			316.00
9					729.00
10					
11	421.80	418.70			204.00
12	149.70	166.70			160.00
13	530.80	474.10			387.00
14	1133.80	1895.60			486.00
15					246.00
16	232.50	209.60			132.00
17					307.00
18	674.00	742.50			478.00
19	775.70	1800.80			172.00
20	492.40	427.60			235.00
21	301.50	148.00			214.00
22					362.00
23					
24					
25					111.00
26	326.80	354.50			173.00
27	270.60	559.40			93.00
28	266.30	153.80			121.00
29	400.50	361.10			211.00
30	385.38	477.30			325.00
31	1647.90	1732.00			340.00
32		345.10			201.30
33	615.30	569.60			409.00
34	510.10	502.30			377.00
35	190.90	515.20			148.00
36	549.80	408.40			427.00
37	517.40	438.30	482.6	269.1	315.00

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

38	546.60	445.30	513.6	592	325.00
39	401.10	327.20	319.8	338.6	259.00
40	198.20	182.80	215.6	223.6	
42	216.10	278.30			
43	457.40	517.00	324.1	653.2	391.00
44	994.50	950.20	825.5	648.3	
45	566.20	535.00	687.5	697.9	
46	4353.00	807.00	974.5	1473.5	524.00
47	459.40	409.00	79.0	826.7	
48	3989.00	1.40	248.3	849.2	308.00
49			57.3	758.2	131.00
50			403	279.9	170.00
51	828.30	1192.00	725.5	1158	490.00
52	236.60	486.00	345.3	360.2	256.00
53	530.50	496.50	501.7	666.9	491.00
54	690.40	883.30	643.1	674.3	
55	199.10	140.90			253.00

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.




```
The regression equation is
APT = 176.552 + 0.574620 Manual

S = 82.9361      R-Sq = 93.9 %      R-Sq(adj) = 93.7 %

Analysis of Variance

Source          DF        SS        MS         F       P
Regression       1   3058609   3058609   444.669   0.000
Error           29    199473      6878
Total           30   3258083


Predicted Values for New Observations

New Obs     Fit     SE Fit       95.0% CI             95.0% PI
1         697.7       17.3   (  662.3,   733.2)  (  524.4,   871.0)
2        1221.4       36.8   ( 1146.1,  1296.8)  ( 1035.8,  1407.0)
3         372.1       16.3   (  338.8,   405.4)  (  199.2,   545.0)
4         274.3       18.6   (  236.2,   312.4)  (  100.4,   448.2)
5         418.9       15.5   (  387.2,   450.7)  (  246.4,   591.5)
6         262.6       19.0   (  223.7,   301.4)  (   88.6,   436.6)
7         481.6       15.0   (  451.0,   512.2)  (  309.2,   653.9)
8         828.1       21.2   (  784.8,   871.4)  (  653.0,  1003.1)
9         310.2       17.7   (  274.0,   346.3)  (  136.7,   483.6)
10        563.8       15.1   (  533.0,   594.7)  (  391.4,   736.3)
11        459.5       15.1   (  428.6,   490.4)  (  287.1,   631.9)
12        349.8       16.7   (  315.6,   384.0)  (  176.8,   522.8)
```

Figure A.1 Regression analysis: APT vs. Manual.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

13	364.3	16.4	(	330.7,	398.0)	(	191.4,	537.3)
14	329.6	17.2	(	294.4,	364.7)	(	156.3,	502.8)
15	406.7	15.7	(	374.6,	438.8)	(	234.1,	579.3)
16	398.0	15.8	(	365.6,	430.4)	(	225.3,	570.7)
17	530.1	14.9	(	499.6,	560.6)	(	357.8,	702.5)
18	469.7	15.0	(	438.9,	500.4)	(	297.3,	642.0)
19	492.5	14.9	(	462.0,	523.0)	(	320.1,	664.8)
20	473.9	15.0	(	443.2,	504.5)	(	301.5,	646.2)
21	490.6	14.9	(	460.1,	521.2)	(	318.3,	663.0)
22	407.0	15.7	(	374.9,	439.1)	(	234.4,	579.7)
23	290.4	18.2	(	253.2,	327.7)	(	116.8,	464.1)
24	300.7	17.9	(	264.1,	337.4)	(	127.2,	474.3)
25	439.4	15.3	(	408.1,	470.6)	(	266.9,	611.9)
26	501.9	14.9	(	471.4,	532.4)	(	329.6,	674.2)
27	440.5	15.3	(	409.3,	471.8)	(	268.1,	613.0)
28	652.5	16.3	(	619.1,	685.9)	(	479.6,	825.4)
29	481.4	15.0	(	450.8,	512.0)	(	309.0,	653.7)
30	573.3	15.2	(	542.2,	604.3)	(	400.8,	745.7)
31	291.0	18.2	(	253.8,	328.1)	(	117.3,	464.6)

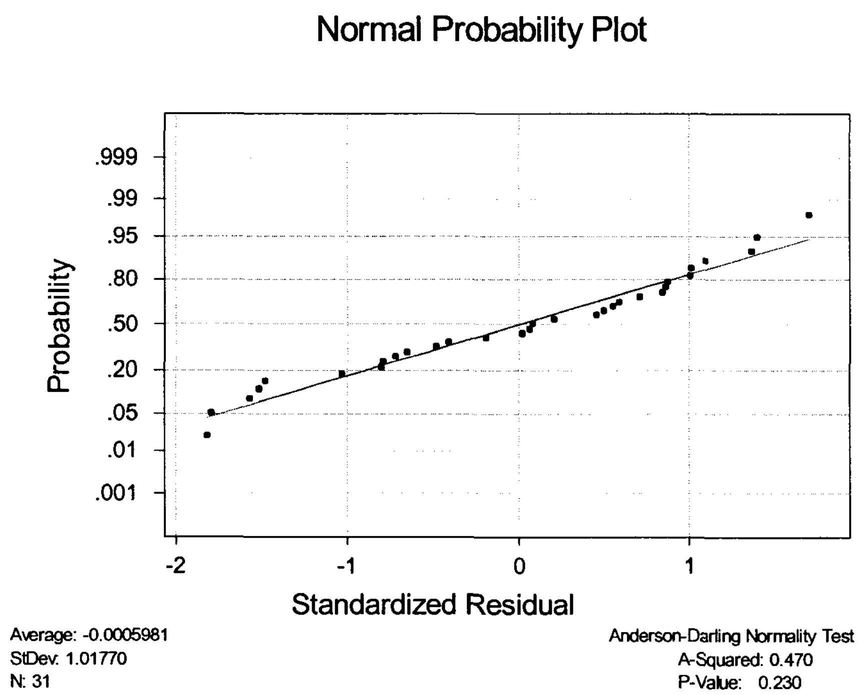
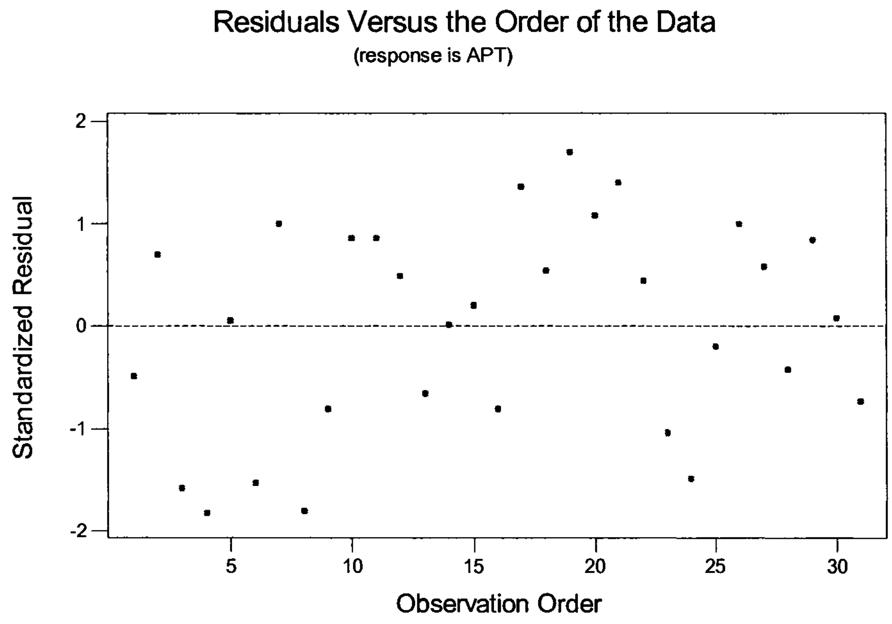


Figure A.1 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.



Paired T-Test and CI: APT, Manual

Paired T for APT - Manual

	N	Mean	StDev	SE Mean
APT	42	733	859	132
Manual	42	652	583	90
Difference	42	82	894	138

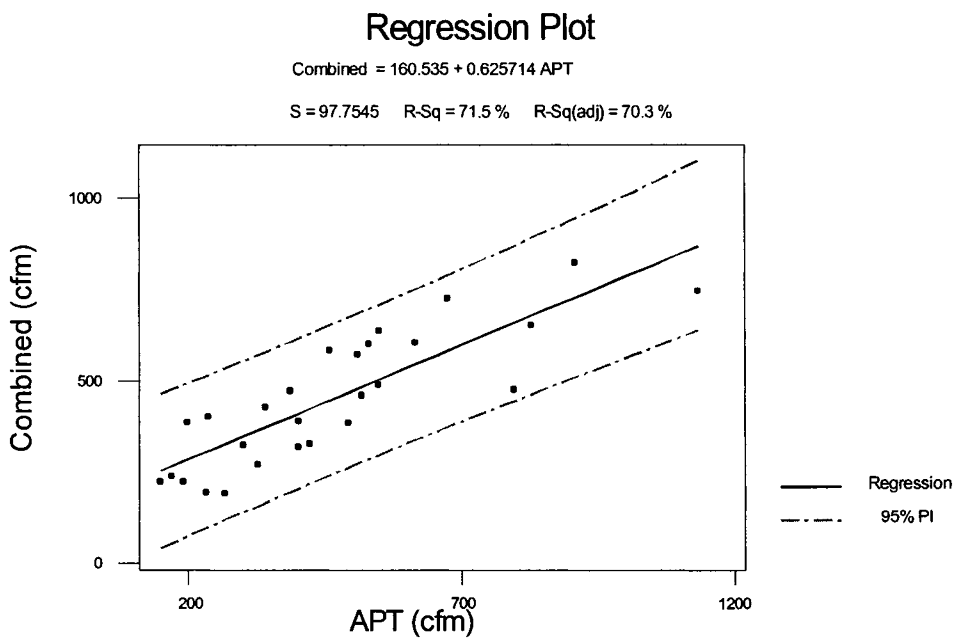
95% CI for mean difference: (-197, 360)
T-Test of mean difference = 0 (vs not = 0): T-Value = 0.59 P-Value = 0.558

Wilcoxon Signed Rank CI: Difference (APT- Manual)

	N	Estimated Median	Achieved Confidence	Confidence Interval
Difference	42	-17	95.0	(-118, 39)

Figure A.1 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.




```
The regression equation is
Combined  = 160.535 + 0.625714 APT (cfm)

S = 97.7545      R-Sq = 71.5 %      R-Sq(adj) = 70.3 %

Analysis of Variance

Source          DF        SS        MS         F       P
Regression       1    598751    598751   62.6575   0.000
Error           25    238899      9556
Total           26    837650


Predicted Values for New Observations

New Obs     Fit    SE Fit        95.0% CI              95.0% PI
1         728.1      39.6   (  646.5,   809.6)  (  510.8,   945.3)
2         373.5      21.3   (  329.7,   417.3)  (  167.4,   579.5)
3         267.0      30.0   (  205.2,   328.8)  (   56.4,   477.6)
4         658.0      32.1   (  591.9,   724.1)  (  446.1,   869.9)
5         424.5      19.1   (  385.1,   463.9)  (  219.3,   629.6)
6         254.2      31.3   (  189.8,   318.6)  (   42.8,   465.6)
7         492.7      19.5   (  452.5,   532.8)  (  287.4,   698.0)
8         870.0      56.0   (  754.5,   985.4)  (  637.9,  1102.0)
9         306.0      26.4   (  251.7,   360.3)  (   97.5,   514.5)
10        582.3      25.0   (  530.8,   633.7)  (  374.5,   790.1)
11        468.6      18.9   (  429.7,   507.6)  (  263.6,   673.7)
12        349.2      22.9   (  302.1,   396.3)  (  142.4,   556.0)
13        365.0      21.8   (  320.1,   409.9)  (  158.7,   571.3)
14        327.2      24.6   (  276.6,   377.7)  (  119.6,   534.7)
```

Figure A.2 Regression analysis: Combined vs. APT.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

15	411.1	19.5	(	370.9,	451.3)	(	205.8,	616.4)
16	401.7	19.9	(	360.8,	442.6)	(	196.2,	607.1)
17	545.5	22.2	(	499.8,	591.3)	(	339.1,	752.0)
18	479.7	19.1	(	440.3,	519.1)	(	274.6,	684.9)
19	280.0	28.8	(	220.8,	339.2)	(	70.1,	489.8)
20	504.6	19.9	(	463.5,	545.6)	(	299.1,	710.0)
21	484.3	19.2	(	444.6,	523.9)	(	279.1,	689.5)
22	502.6	19.9	(	461.6,	543.5)	(	297.1,	708.0)
23	411.5	19.5	(	371.4,	451.7)	(	206.2,	616.8)
24	446.7	18.8	(	408.0,	485.5)	(	241.7,	651.8)
25	678.8	34.3	(	608.2,	749.4)	(	465.5,	892.2)
26	308.6	26.1	(	254.8,	362.4)	(	100.2,	517.0)
27	285.1	28.3	(	226.9,	343.3)	(	75.5,	494.7)

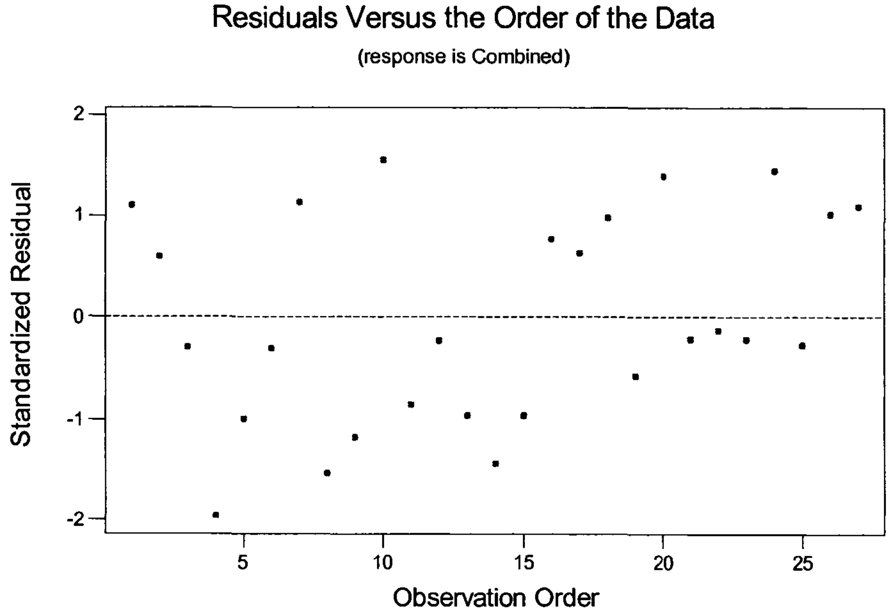
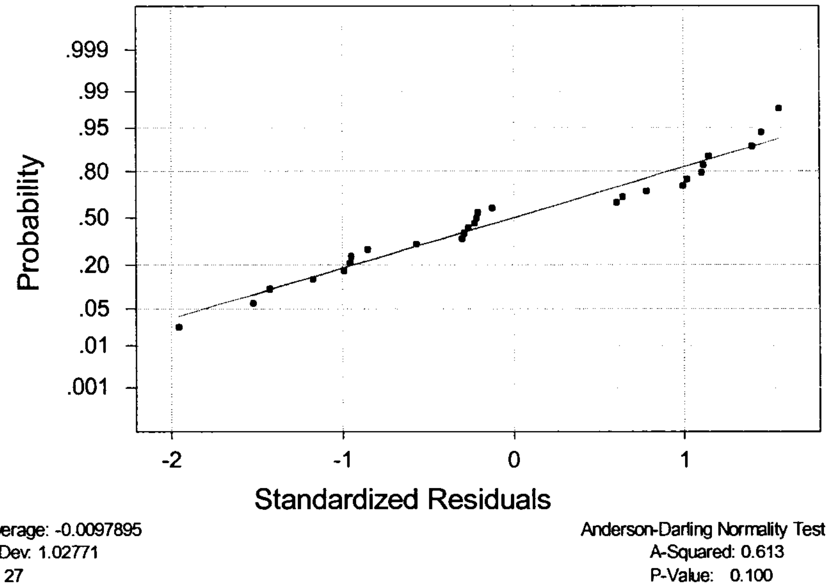


Figure A.2 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Normal Probability Plot



Paired T-Test and CI: APT (cfm), Combined (cfm)

Paired T for APT (cfm) - Combined (cfm)

	N	Mean	StDev	SE Mean
APT (cfm)	34	764	944	162
Combined (cf	34	475	217	37
Difference	34	289	874	150

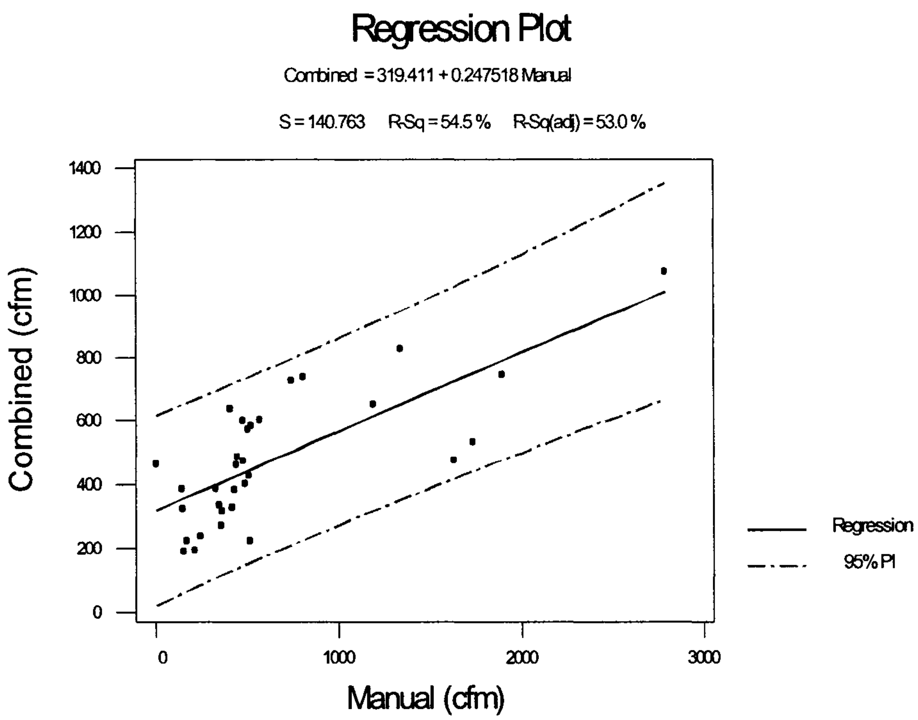
95% CI for mean difference: (-16, 594)
T-Test of mean difference = 0 (vs not = 0): T-Value = 1.93 P-Value = 0.063

Wilcoxon Signed Rank CI: Difference (APT - Combined)

	N	Estimated Median	Achieved Confidence	Confidence Interval
Difference	34	46	95.1	(-14, 185)

Figure A.2 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.




```
The regression equation is
Combined (cf = 319.411 + 0.247518 Manual (cfm)

S = 140.763      R-Sq = 54.5 %      R-Sq(adj) = 53.0 %

Analysis of Variance
```

Source	DF	SS	MS	F	P
Regression	1	711720	711720	35.9196	0.000
Error	30	594428	19814		
Total	31	1306148			

Predicted Values for New Observations

New Obs	Fit	SE Fit	95.0% CI	95.0% PI
1	650.6	37.8	(573.4, 727.8)	(352.9, 948.2)
2	1009.8	91.8	(822.3, 1197.3)	(666.6, 1353.0)
3	445.2	25.6	(393.1, 497.4)	(153.1, 737.4)
4	380.2	29.9	(319.0, 441.3)	(86.3, 674.1)
5	723.0	47.6	(625.9, 820.1)	(419.5, 1026.4)
6	423.0	26.6	(368.6, 477.5)	(130.5, 715.6)
7	360.7	31.9	(295.6, 425.8)	(65.9, 655.4)
8	436.8	25.9	(383.8, 489.7)	(144.5, 729.1)
9	788.6	57.2	(671.8, 905.4)	(478.3, 1098.9)
10	371.3	30.8	(308.4, 434.2)	(77.0, 665.6)
11	503.2	25.2	(451.8, 554.6)	(211.2, 795.2)
12	425.2	26.5	(371.1, 479.4)	(132.7, 717.8)
13	356.0	32.4	(289.9, 422.1)	(61.1, 651.0)
14	407.2	27.7	(350.6, 463.7)	(114.2, 700.1)

Figure A.3 Regression analysis: Combined vs. Manual.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

15	357.5	32.2	(	291.7,	423.3)	(	62.6,	652.4)
16	408.8	27.6	(	352.5,	465.1)	(	115.8,	701.7)
17	437.6	25.9	(	384.7,	490.4)	(	145.3,	729.8)
18	748.1	51.2	(	643.6,	852.6)	(	442.2,	1054.0)
19	404.8	27.9	(	347.9,	461.7)	(	111.8,	697.9)
20	460.4	25.1	(	409.1,	511.7)	(	168.4,	752.4)
21	443.7	25.6	(	391.4,	496.0)	(	151.5,	735.9)
22	446.9	25.5	(	394.9,	499.0)	(	154.8,	739.1)
23	420.5	26.8	(	365.8,	475.2)	(	127.9,	713.1)
24	427.9	26.4	(	374.1,	481.7)	(	135.4,	720.4)
25	429.6	26.3	(	376.0,	483.3)	(	137.2,	722.1)
26	400.4	28.2	(	342.8,	458.0)	(	107.2,	693.6)
27	447.4	25.5	(	395.4,	499.4)	(	155.2,	739.5)
28	519.2	25.7	(	466.6,	571.7)	(	226.9,	811.4)
29	319.8	36.5	(	245.1,	394.4)	(	22.8,	616.8)
30	614.5	33.5	(	546.0,	682.9)	(	318.9,	910.0)
31	439.7	25.8	(	387.1,	492.4)	(	147.4,	732.0)
32	354.3	32.6	(	287.8,	420.8)	(	59.2,	649.3)

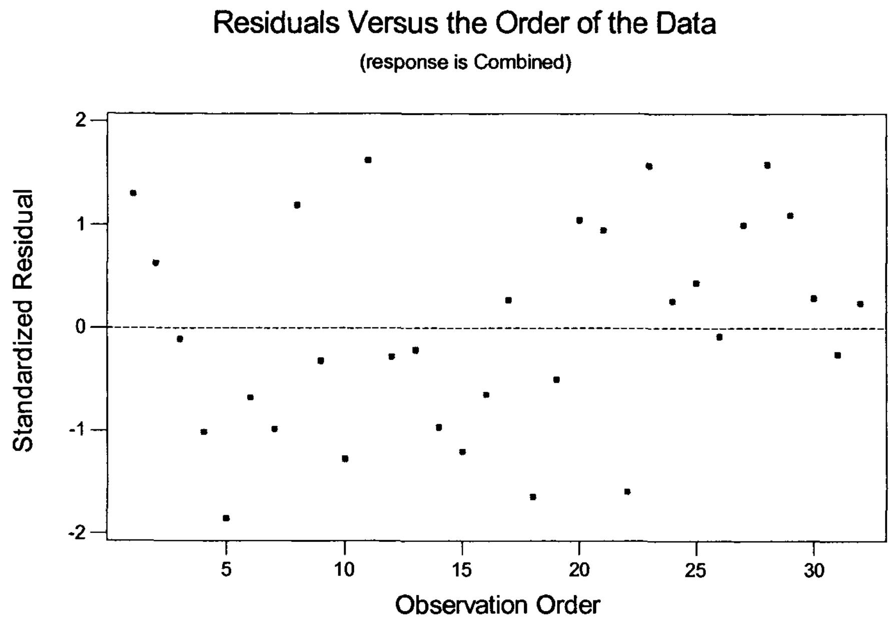
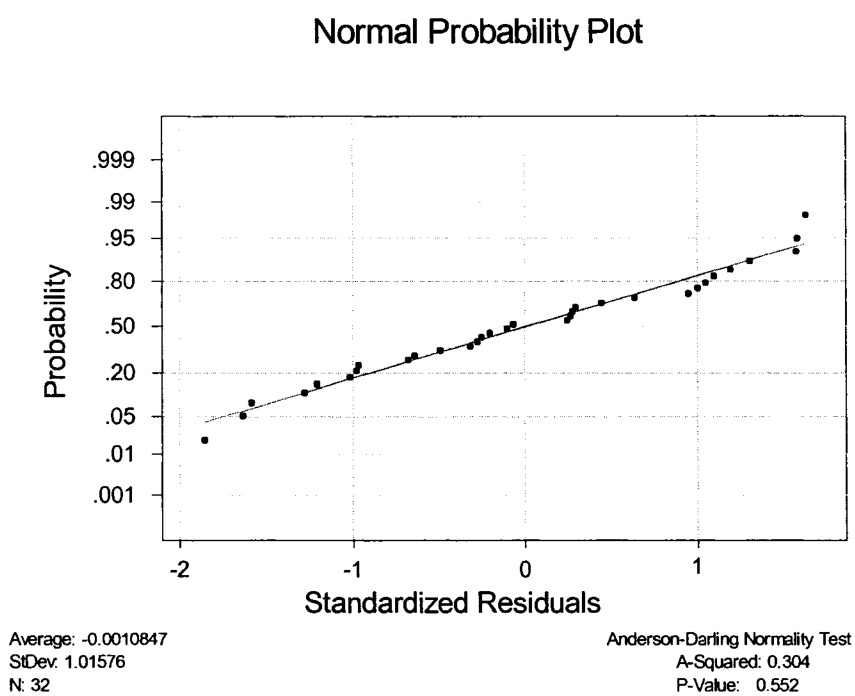


Figure A.3 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.



Paired T-Test and CI: Manual (cfm), Combined (cfm)

Paired T for Manual (cfm) - Combined (cfm)

	N	Mean	StDev	SE Mean
Manual (cfm)	35	675	617	104
Combined (cf	35	471	215	36
Difference	35	203.9	522.7	88.4

95% CI for mean difference: (24.4, 383.5)
T-Test of mean difference = 0 (vs not = 0): T-Value = 2.31 P-Value = 0.027

Wilcoxon Signed Rank CI: Difference (Manual - Combined)

	N	Estimated Median	Achieved Confidence	Confidence Interval
Difference	35	41	95.0	(-23, 264)

Figure A.3 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

APPENDIX B

SAS™ PROGRAMS, INPUT AND OUTPUT

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table B.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
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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
/********************************************************************/
/* 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;
```

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
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 B.1 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                                               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                        YearBuilt      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           YearBuilt       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
```

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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

                                   The REG Procedure
                                     Model: MODEL1
                              Dependent Variable: ELA ELA


                             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       0.4914      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
```

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                                                   The SAS System       17:38 Thursday, October
26, 2006  46

                                                 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
                                          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
```

Figure B.2 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
The SAS System        17:38 Thursday, October 26, 2006  48

                                           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


                                           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
```

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Parameter Estimates

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

The SAS System 17:38 Thursday, October 26, 2006 78

The REG Procedure
Model: MODEL1
Dependent Variable: ELA ELA

Number of Observations Read 46
Number of Observations Used 46

Analysis of Variance

Source	DF	Sum of Squares	Mean 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

Variable	Label	DF	Parameter Estimate	Standard Error	t Value	Pr > |t|	Variance 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 B.2 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                 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
```

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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
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

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
      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
```

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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							
	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							

Figure B.2 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
 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
```

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Tests for Normality

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

Figure B.2 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                                       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
   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
```

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
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
```

Figure B.2 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
      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
                                       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      -
```

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
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
```

Figure B.2 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                          Output Statistics

               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
```

Figure B.2 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                    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

                      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
```

Figure B.2 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Parameter Estimates

Variable	Label	DF	Parameter Estimate	Standard 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

Obs	Dependent Variable	Predicted Value	Std Error 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
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

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
      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
```

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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
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

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                  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


                                   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
```

Figure B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                 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 B.2 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

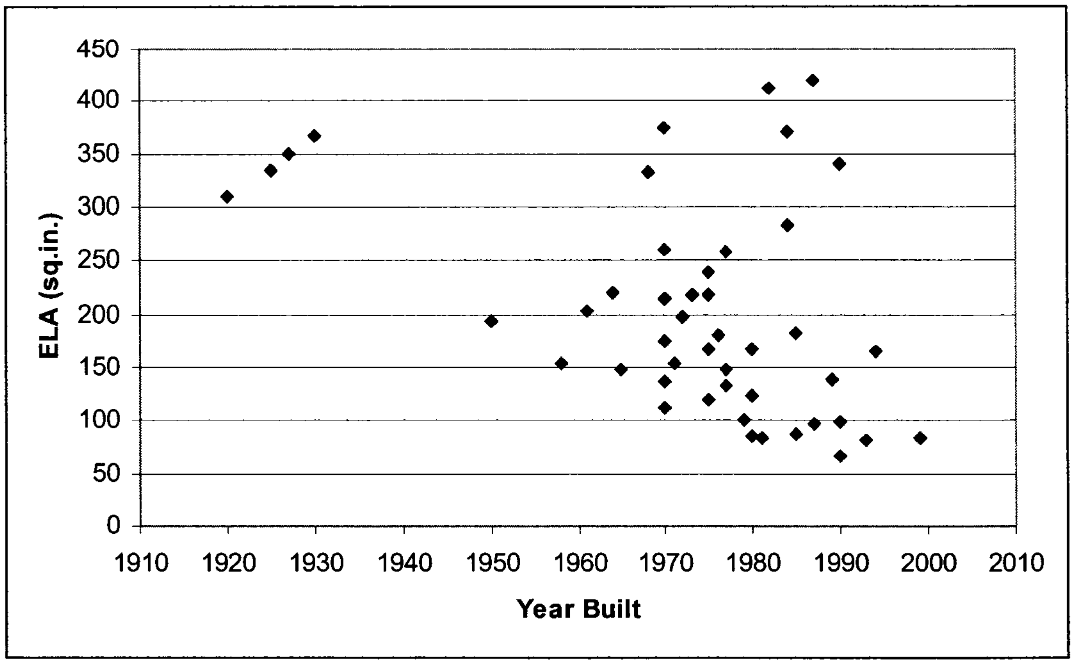


Figure B.3 Plot of Year Built vs. ELA.

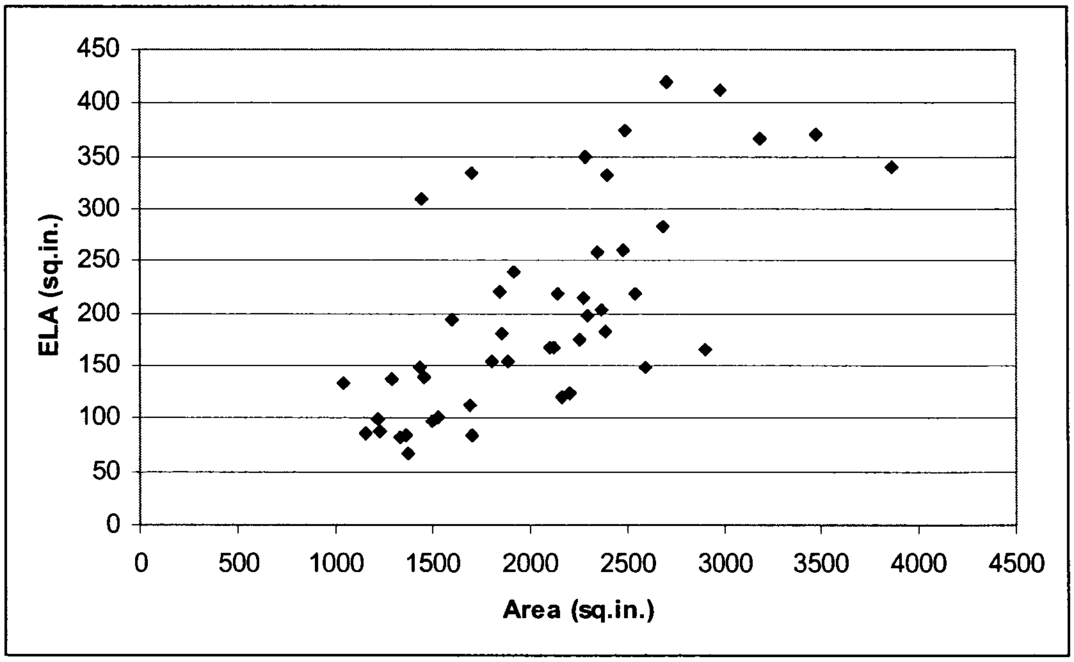


Figure B.4 Plot of Area vs. ELA.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

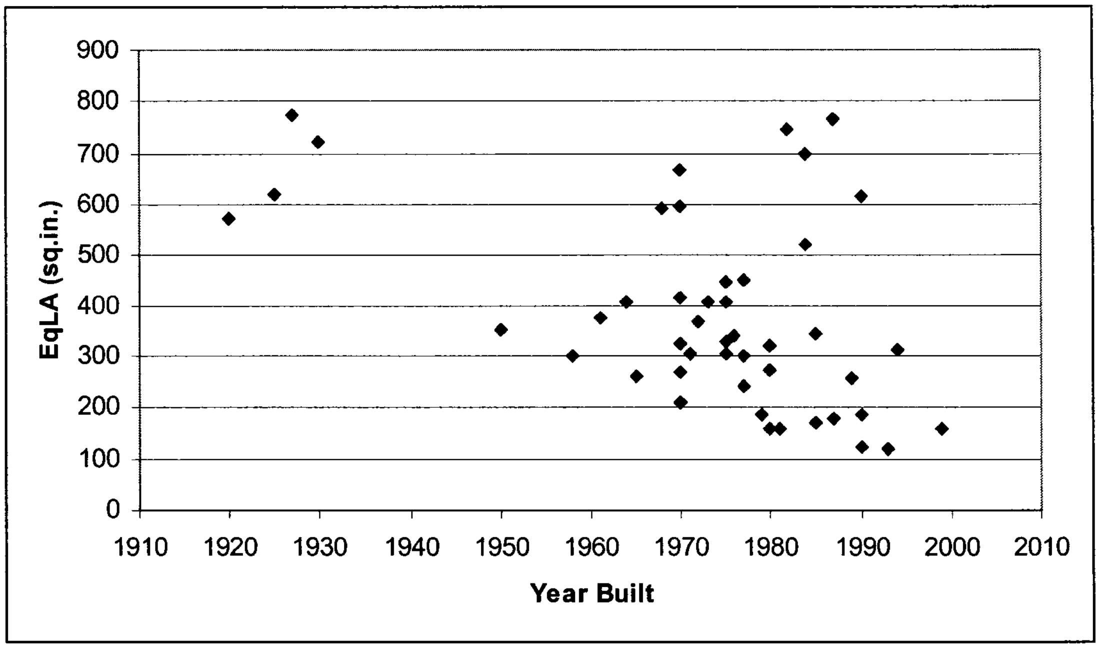


Figure B.5 Plot of Year Built vs. EqLA.

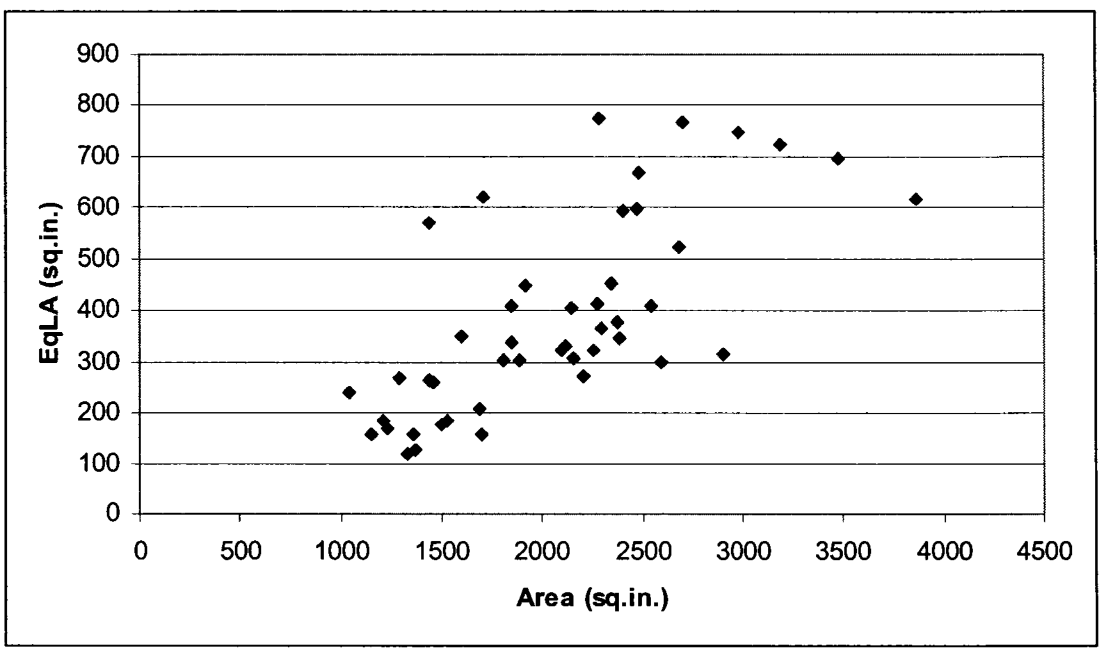


Figure B.6 Plot of Area vs. EqLA.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

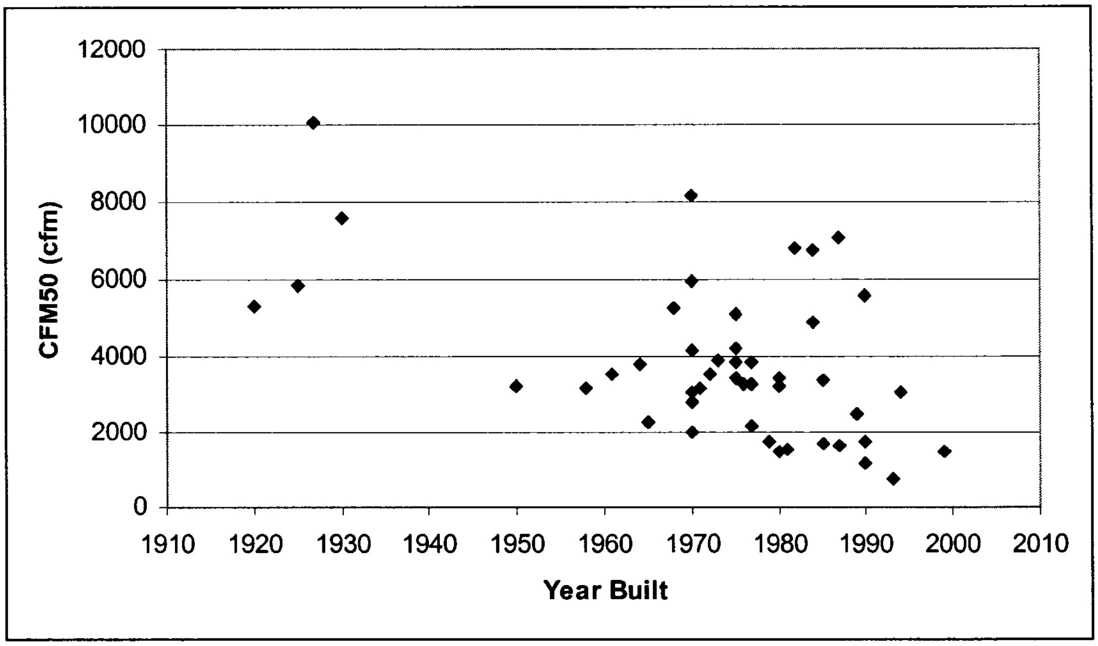


Figure B.7 Plot of Year Built vs. CFM50.

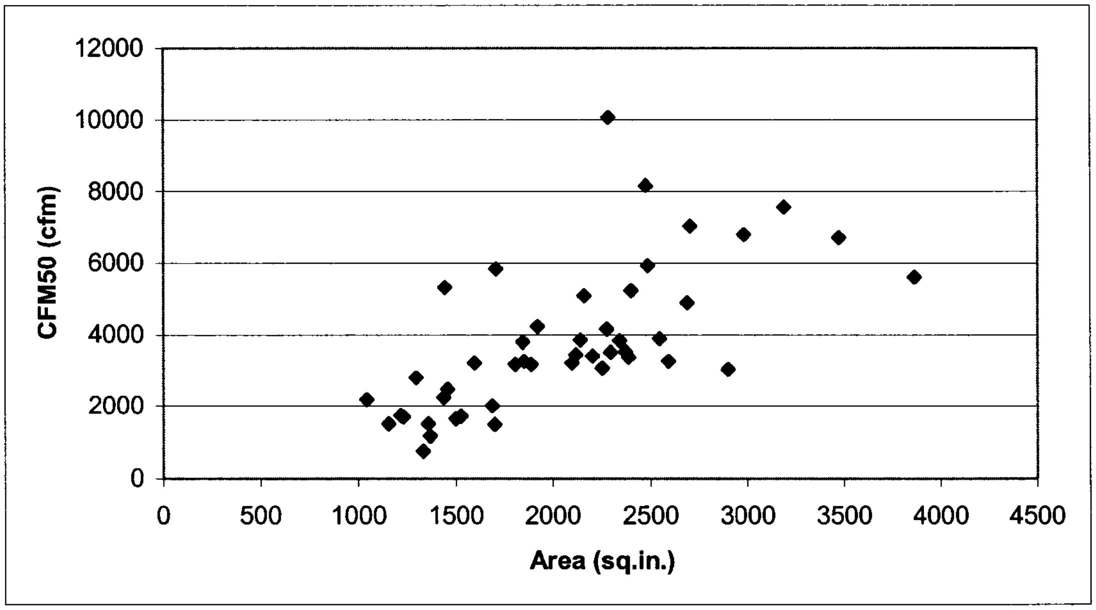


Figure B.8 Plot of Area vs. CFM50.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

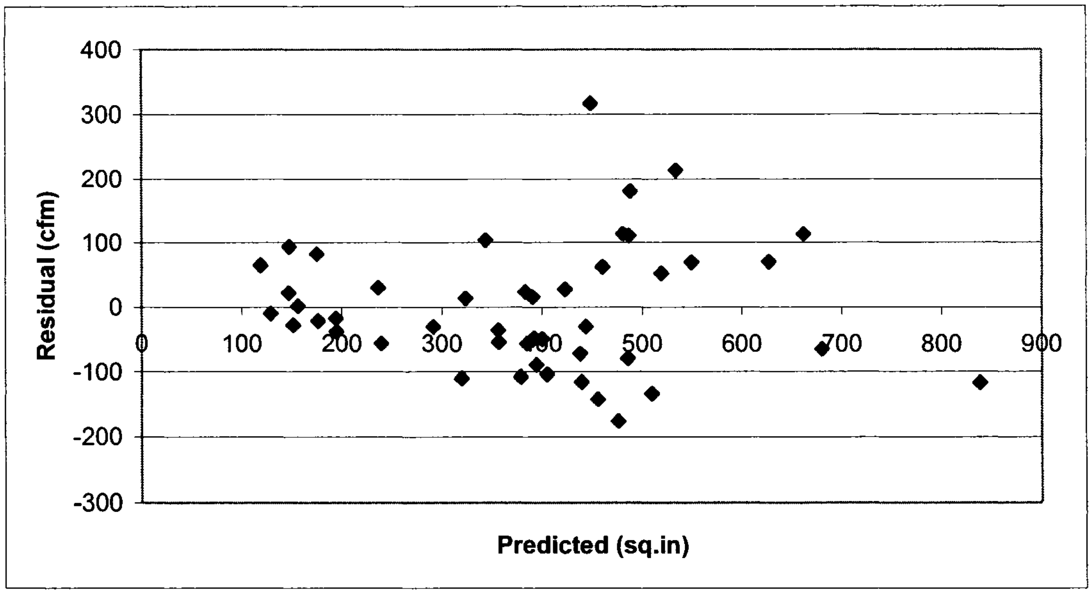


Figure B.9 Plot of predicted vs. residual for ELA.

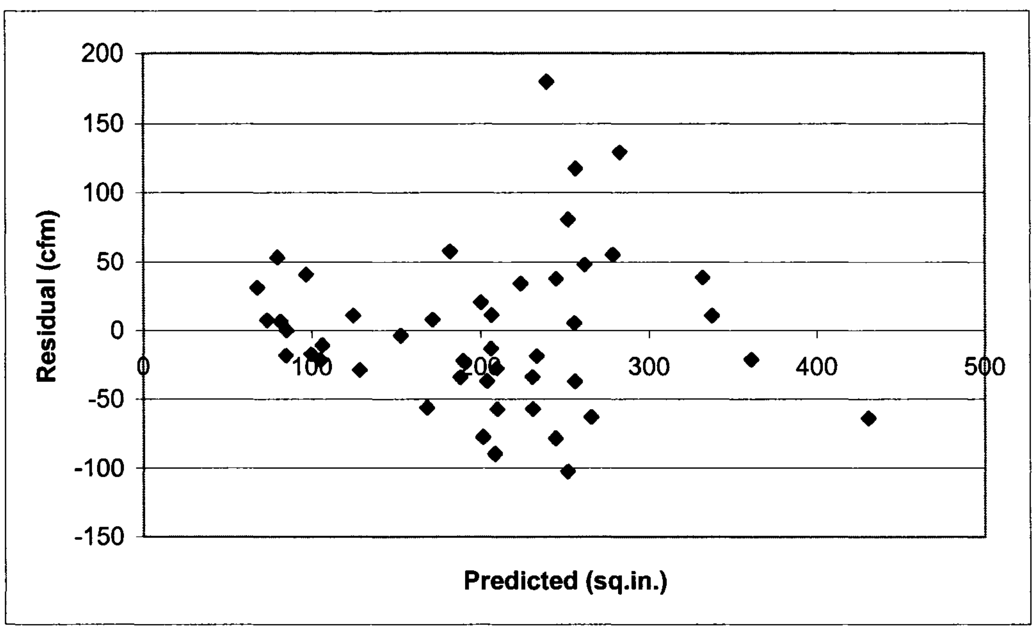


Figure B.10 Plot of predicted vs. residual for EqLA.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

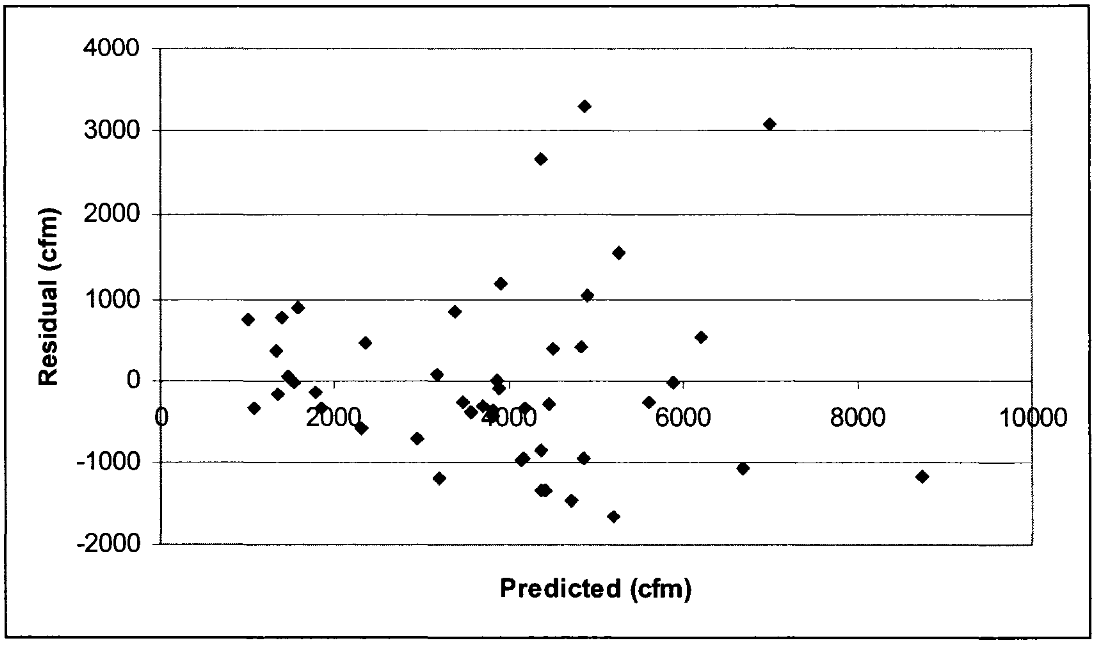


Figure B.11 Plot of predicted vs. residual for CFM50.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

Figure B.12 SAS program for cluster analysis.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
58     1993  1333  747
59     1975  2160  5087
60     2004  1648  2110
61     1970  2250  7332
62     1997  1789  1876
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;
```

Figure B.12 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
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 B.12 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                 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

                            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
```

Figure B.13 SAS output for cluster analysis.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
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


                                     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
```

Figure B.13 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                         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

                                      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
```

Figure B.13 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

-- 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

Figure B.13 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                 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

                      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
```

Figure B.13 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
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

                  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
```

Figure B.13 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                 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


                        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
```

Figure B.13 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Variable	N	Mean	Std Dev	Minimum	Maximum
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

--- 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 B.13 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table B.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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table B.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

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

Table B.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%

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
/**********************************************************************/
/*   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 B.14 SAS program for paired observations (GSCA and MSA) using t-test.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
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 B.15 SAS output for paired observations (GSCA and MSA) using t-test.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
/*********************************************************************/
/* 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 B.16 SAS program for pressurized and depressurized conditions using t-test.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
         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

                   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
```

Figure B.17 SAS output for pressurized and depressurized conditions using t-test.

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                   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


                    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
```

Figure B.17 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

Variable	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev	Std Dev	Upper CL 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

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

Figure B.17 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                    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
                    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
```

Figure B.17 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

Variable	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev	Std Dev	Upper CL 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

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

Figure B.17 continued.....

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

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

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

Figure B.17 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                    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

                                      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
```

Figure B.17 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

```
                    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 B.17 continued…..

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

REFERENCES

1. Energy Information Administration – Official Energy Statistics from the U.S. Government, Washington, D.C. State Energy Data 2000, Table R1. "Energy Consumption by Sector, Ranked by State, 2000." pp. 13-14. http://www.eia.doe.gov/emeu/states/sep_sum/html/pdf/rank_use_all.pdf (10-01-2005).

2. Erinjeri, Jinson J., "Testing Residential Ductwork in Existing Residential Buildings," M.S. thesis, Louisiana Tech University, Ruston, LA, pp. 10-42, (2002).

3. Hales, David, Washington State Energy Code Duct Leakage Study Report, pp. 6-25, (2001).

4. Brown, Evan, "Energy Performance Evaluation of New Homes in Arkansas," Arkansas Energy Office, Arkansas Department of Economic Development, Little Rock, AR, pp. 5-8, (1999).

5. Cummings, James B., Tooley, John J., Jr. and Moyer, Neal, "Duct Doctoring, Diagnosis and Repair of Duct System Leaks", Florida Solar Energy Center, Cocoa, Florida, pp. 2-9, (1993).

6. ToolBase Services. http://www.toolbase.org/index.aspx (01-04-2006).

7. Haskell, T., "Duct Improvement in the Northwest Part I: New Construction and Retrofit" *Home Energy Magazine Online*, Vol. 13, No. 1. (January/February 1996), http://hem.dis.anl.gov/eehem/96/960109.html (02-05-2006).

8. Treidler, B., "The New Monster in the Basement." *Home Energy Magazine Online*, Vol. 10, No. 5. (September/October 1993). http://homeenergy.org/archive/hem.dis.anl.gov/eehem/93/930914.html (03-04 2006).

9. Tiller, J.S., Caldwell, J.C., French, T.M., and Ridgeway, P., "*Builder's Guide to Energy Efficient Homes in Louisiana*", Louisiana Department of Natural Resources, Energy Section, contracted to Southface Energy Institute, pp. 117-120, (2002).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

10. R &D on Heating, Cooling and Commercial Refgrigeration. http://www.eere.energy.gov/buildings/research/hvac/index.cfm#6 (03-05-2006).

11. Cummings, J. B., Tooley, J. J., Moyer, N. A. and Dunsmore, R., "Impacts of Duct Leakage on Infiltration Rates, Space Conditioning Energy Use, and Peak Electrical Demand in Florida Homes," *Proceedings of the ACEEE 1990 Summer Study*, Pacific Grove, CA, pp. 65-76, (August, 1990).

12. Duct Leakage Testing, Energy Conservatory. http://www.energyconservatory.com/applications/applications1.htm (05-15-2006).

13. Parker, D.S., Broman, P.A., Grant, J.B., Gu, L., Anello, M.T., Vieira, R.K., and Henderson, H.I. (1999). "EnergyGauge USA: A Residential Building Energy Simulation Design Tool." *Proceedings of the Sixth International IBPSA Conference Building Simulation 99*, Kyoto, Japan, pp. 73-79, (September, 1999).

14. Parker, D.S., Fairey, P., and Gu, L., "Simulation of the Effect of Duct Leakage and Heat Transfer on Residential Space Cooling Use", *Energy and Buildings*, Elsevier Sequoia, Netherlands, Vol. 20, No. 2, pp. 97-114, (1993).

15. Priorities for Building a New Florida home. http://www.fsec.ucf.edu/bldg/fyh/priority/Index.htm (04-10-2006).

16. Manufactured Home Tests Reveal Duct's Top Problems. http://oikos.com/esb/44/delat.html (08-19-2006).

17. North Carolina Alternative Energy Corporation. "Value of an Energy Efficient Installation," Bel-Red Heating and Air Conditioning, Kirkland, WA, http://www.belred.com/InfoCenter/Wheel_of_Value/install.html (08-19-2006).

18. Rudd, A., Chandra S., and Tooley, J., "Measured Air-Tightness and Thermal Insulation Quality of 11 Industrialized Houses". Presented at the "*1993 EEBA/NESEA Conference on Building Solutions*," Boston, MA, Sponsored by the Energy Efficient Building Association, Minneapolis, MN, (March 3-6, 1993).

19. Chandra, S., Beal, D., and Downing, *Allergy Resistant Housing-Principles and Practice*. Presented at the "Environmental and Economic Balance: The 21st Century Outlook" conference, Miami, FL, Sponsored by the American Institute of Architects, the U.S. Green Building Council and the U.S. Department of Energy, Florida Solar Energy Center, Cocoa, FL, (November 6-9, 1997).

20. Easley, Steve, Tips for managing moisture and air in your home. http://moldinspector.com/house-wrap.htm (01-28-2007).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

21. Minneapolis Blower Door Operation Manual, The Energy Conservatory, Minneapolis, MN, pp. 2-39, (1993). www.EnergyConservatory.com (08-20-2006).

22. Areas of Air Leakage, Building Energy Codes Resource Center. http://resourcecenter.pnl.gov/cocoon/morf/ResourceCenter/article/1385 (07-16-2006).

23. Building Tightness Limits and Ventilations Software for Texas Instruments TI-86,© 2004 WxWare Diagnostics, pp. 2-6, (April 2004). http://www.karg.com/PDF%20files/ZipTest%20Pro2%20Manual/Ti86btl.pdf (8-15-2006).

24. Modera, M.P., Dickerhoff, D.J., Nilssen, O., Duquette, H., and Geyselaers, J., "Residential Field Testing of an Aerosol-Based Technology for Sealing Ductwork." *Proceedings of ACEEE Summer Study*, Lawrence Berkeley Laboratory Report, LBL-38554, Pacific Grove, CA, pp. 169-176, (1996).

25. Heederik, G., "Not Your Daddy's Duct Sealing Method." *Home Energy Magazine Online*, Field Notes, Vol. 15, No. 1, (January/February 1998). http://homeenergy.org/archive/hem.dis.anl.gov/eehem/98/980113.html (06-15-2006).

26. Hamilton, S.D., "Improved Duct Sealing", Emerging Technologies, Copyright ASHRAE, pp. 64-65, (May 2003). http://www.tiax.biz/aboutus/pdfs/ashrae_0501-03.pdf. (08-11-2006)

27. Altman, K., and Linder, R., "Digital Imaging and Pipeline Inspection," *Underground Infrastructure Advanced Technology Conference,* Washington, D.C., (December 3-4, 2001).

28. Nelson, Gary, Principal and President of The Energy Conservatory, Minneapolis, MN, 612-827-1117, www.EnergyConservatory.com, private communication, (2001).

29. Katz, M., Witriol, N., and Erinjeri, J., "The Generalized Subtraction Correction Algorithm for Measuring Duct Leakage Using a Blower Door," *Journal of Testing and Evaluation*, Vol. 32, No. 6, Paper ID JTE 11723, (November 2004).

30. Walker, Iain S., Wilson, David J., and Sherman, Max H., "A comparison of the power law to quadratic formulations for air infiltration calculations," *Energy and Buildings*, Vol. 27, No.3, pp. 293-299, (June 1997).

31. Walpole, Ronald E., Myers, Raymond H., and Myers, Sharon L., Probability *and Statistics for Engineers and Scientists*, 6th edition, Prentice Hall Inc., New Jersey, (1998).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

32. *MINITAB User's Guide for Data Analysis and Quality Tools*, Minitab Inc., pp. 2-1 to 2-58, (1998).

33. Witriol, N., Erinjeri, J., Katz, M, Mc Kim, R., and Nassar, R., Report on "*Testing HVAC Duct Leakage in Existing Residential Buildings in North Louisiana*," Trenchless Technology Center, Louisiana Tech University, Ruston, LA, pp. 66-69, (2003).

34. "Areas of Air leakage," Building Energy Codes Resource Center. http://resourcecenter.pnl.gov/cocoon/morf/ResourceCenter/article/1385 (08-02-2006)

35. Green, Richard R., "Clearing the air", *Commercial Investment Real Estate Journal*, Chicago: Fall 1995, Vol. 14, No. 4, pp. 3-15, (1995).

36. Energy Star Homes – Massachusetts and Rhode Island, "Getting Started". http://www.energystarhomes.com/ESHController.aspx?homebuyers_getting_started (08-02-2006).

37. Instructions for Building Tightness Limits and Ventilation Calculations for Acceptable Indoor Air Quality, pp. 2-6, (April 2004). http://www.karg.com/PDF%20files/ZipTest%20Pro2%20Manual/Ti86btl.pdf (09- 27-2006).

38. Tsongas, George, "Building Tightness Guidelines: When is a house too tight?, "*Home Energy Magazine Online*, Vol. 10, No. 2, (March/April 1993). http://homeenergy.org/archive/hem.dis.anl.gov/eehem/93/930309.html (07-09-2006)

39. Meier, Alan, "Infiltration: Just ACH50 divided by 20," "*Home Energy Magazine Online*, Vol.11, No. 1, (January/February 1994). http://homeenergy.org/archive/hem.dis.anl.gov/eehem/94/940111.html (05-05-2006)

40. Sherman, Max, "Estimation of Infiltration for Leakage and Climate Indicators," *Energy and Buildings,* Vol. 10, No. 1, p.81, (1987).

41. Kutner, Michael H., Nachtsheim, Christopher J., Neter, John, and Li, William, *Applied Linear Statistical Models* (5^{th} edition), McGraw-Hill, New York, (2004).

42. Martin, Bland J., and Altman, Douglas G., Statistical methods for assessing agreement between two methods of clinical measurement, *Lancet*, i, pp. 307-310, (1986).

43. Montgomery, Douglas C., Peck, Elizabeth A., and Vining, Geoffrey G., *Introduction to Linear Regression Analysis*, (3^{rd} edition), John Wiley and Sons, New York, (2001).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

44. SAS OnlineDoc, version 8, SAS Institute, NC, (1999). http://v8doc.sas.com/sashtml/ (05-10-2006).

45. Phillippe, Cattin, Estimation of the Predictive Power of a Regression Model, *Journal of Applied Psychology*, Vol. 65, No. 4, pp. 407-414, (1980).

46. Richards, Timothy J., Ispelen, Pieter V., and Kagan, Al, Forecasting Retail-Farm Margins for Fresh Tomatoes, Econometric vs. Neural Networks, NCR-134 Conference, Chicago, Illinois, (April 1997).

47. Mesak, Hani I., and Darrat, Ali F., On Comparing Alternative Advertising Policies of Pulsation, *Decision Sciences*, Vol. 23, No. 3, pp. 541-564, (1992).

48. www.statsoft.nl/textbook/stcluan.html (9-27-2006).

49. Johnson, Dallas E., "*Applied Multivariate Methods for Data Analysts*", Duxbury Press, California, (1998).

50. http://www.asu.edu/sas/sasdoc/sashtml/stat/chap27/sect2.htm (9-29-2006).

51. Myers, James H., "Segmentation and Positioning for Strategic Marketing Decisions", *American Marketing Association*, Chicago, (1996).

52. ANSI/ASHRAE Standard 136-1993, *A Method of Determining Air Change Rates in Detached Dwellings,* American Society of Heating, Refrigeration and Air Conditioning Engineers (2001).

53. CSGB Standard 149.10-M86, *Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method*, Canadian General Standards Board, Ottawa, (1986).

54. Walker, I. S., Wilson, D. J., and Sherman, M. H., "A Comparison of the Power Law to Quadratic Formulations for Air Infiltration Calculations," LBNL-41447, *Energy and Buildings,* Vol. 27, No. 3, pp. 293-299 (June 1997).

55. Nelson, Gary, Principal and President of The Energy Conservatory, Minneapolis, MN, 612-827-1117, www.EnergyConservatory.com, private communication, (2004).

56. *Using a Pressure Pan to Diagnose Duct Leakage*, Energy Conservatory, Minneapolis, MN, www.EnergyConservatory.com, pp. 2-5, (2000).

57. Sherman, M., and Palmiter, L.,"Uncertainties in Fan Pressurization Measurements", *Airflow Performance of Building Envelopes, Components, and Systems*, ASTM STP 1255, M. P. Modera and A.K. Persily, Eds., pp. 266-283, (1995).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

58. *Minneapolis Duct Blaster (Series B) Operation Manual*, The Energy Conservatory, Minneapolis, MN, www.EnergyConservatory.com, 12th Ed., p. 27. (September 2000).

59. *Automated Performance Testing Manual*, The Energy Conservatory, Minneapolis, MN, www.EnergyConservatory.com, pp. 29-40, (2000).

60. ANSI/ASHRAE Standard 152-2004, *Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems*, American Society of Heating, Refrigerating, and Air Conditioning Engineers, (2004).

61. http://www.mbmairduct.com/ images/design03.jpg (03-05-2006).

62. http://www2.latech.edu/~witriol/DNR/DNRhome.htm (03-04-2006).

63. Weber, Tim, and Weber, Lenz, "A Calculation Method for Air Infiltration Energy Loss Based on Climatic Data," *International Journal of Low-Energy and Sustainable Buildings*, Vol. 3, (2004). http://www.byv.kth.se/avd/byte/leas/pdf/LEASART_02_2004.pdf (01-28-2006).

64. ENERGY STAR Qualified Homes, National Builder Option Package. http://www.energystar.gov/ia/partners/bldrs_lenders_raters/downloads/NatBOPTRK_060206.pdf (08-23-06).

65. Walker, Iain S., Wilson, David J., and Sherman, Max H., "A Comparison of the Power Law to Quadratic Formulations for Air Infiltration Calculations", *Energy and Buildings*, Vol. 27, No. 3, pp. 293-299 (June 1997).

66. Duct Sealing, X-CEL Energy. http://www.xcelenergy.com/XLWEB/CDA/0,3080,1-1-3_749_8402_7985-6940-2_77_158-0,00.html (10-12-06).

67. Aerosol Ductwork Breakthrough: Ductwork Sealing Technology. http://www.aeroseal.com/hiw_05.html (10-12-06).

68. Modera, Mark P., "ASHRAE Standard 152 and Duct Leaks in Houses," American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., *ASHRAE Journal*, Vol. 47, No. 3, pp 28-33, (March 2005). http://www.doe2.com/download/DEER/Ducts/ASHRAEJ_2005-03_Modera.pdf (12-01-2006).

69. REM Home Energy Analysis Software. http://www.archenergy.com/products/rem/ (11-29-06).

70. http://www.fsec.ucf.edu/bldg/pubs/pf321/index.htm. (10-15-05).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.

71. Kinney, Larry, "Ductwork Systems in South-Western Homes: Problems and Opportunities," Midwest Research Institute, National Renewable Energy Laboratory Division, Southwest Energy Efficiency Report. http://www.swenergy.org/pubs/DuctTech.pdf#search=%22high%20duct%20leakage%20and%20energy%20consumption%22 (11-29-06).

72. Proctor, John, and Albright, Peggy, "Sizing Air Conditioners: If Bigger Is Not Better, What is?" *Home Energy Magazine Online*, Vol. 13, No. 5, (September/October 1996). http://homeenergy.org/archive/hem.dis.anl.gov/eehem/96/960907.html (11-15-2006).

73. TenWolde, Anton, and Rose, William B., (1999), "Issues Related to Venting of Attics and Cathedral Ceilings," ASHRAE Transactions, Vol.105, No.1, (February 1999). http://www.fpl.fs.fed.us/documnts/pdf1999/tenwo99a.pdf (11-02-06).

74. Winandy, Jerrold E., Barnes, Michael H., and Cherilyn, Hatfield A., Roof Temperature Histories in Matched Attics in Mississippi and Wisconsin, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, (December 2000). http://www.rmmn.org/documnts/fplrp/fplrp589.pdf. (11-05-2006).

75. U.S. Census Bureau. http://factfinder.census.gov/servlet/QTTable?_bm=y&-geo_id=04000US22&-qr_name=DEC_2000_SF3_U_DP4&-ds_name=DEC_2000_SF3_U&-_lang=en&-redoLog=false&-_sse=on (12-04-2006).

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.