2014

Developed a Remote Technique to Assess the Effectiveness of Thermal Insulation in Households in West Virginia

Prateek Vaish

Follow this and additional works at: <https://researchrepository.wvu.edu/etd>

Recommended Citation

Vaish, Prateek, "Developed a Remote Technique to Assess the Effectiveness of Thermal Insulation in Households in West Virginia" (2014). *Graduate Theses, Dissertations, and Problem Reports*. 6857.
<https://researchrepository.wvu.edu/etd/6857>

This Thesis is protected by copyright and/or related rights. It has been brought to you by the The Research Repository @ WVU with permission from the rights-holder(s). You are free to use this Thesis in any way that is permitted by the copyright and related rights legislation that applies to your use. For other uses you must obtain permission from the rights-holder(s) directly, unless additional rights are indicated by a Creative Commons license in the record and/ or on the work itself. This Thesis has been accepted for inclusion in WVU Graduate Theses, Dissertations, and Problem Reports collection by an authorized administrator of The Research Repository @ WVU. For more information, please contact researchrepository@mail.wvu.edu.

**Developed a Remote Technique to Assess the Effectiveness of Thermal Insulation in
Households in West Virginia**

By

Prateek Vaish

Thesis submitted to the College of Engineering and Mineral Resources

At West Virginia University

in partial fulfillment of the requirements

for the degree of

Master of Science

in

Mechanical and Aerospace Engineering

Kenneth H Means, Ph.D, P.E

Bhaskaran Gopalakrishnan, Ph.D., P.E, CEM, CPEnMS., LEED GA

Terence Musho, Ph.D

Mechanical and Aerospace Engineering

Morgantown, West Virginia

2014

Keywords: Insulation, Response, Predictors, Empirical Equation, MLR

Copyright 2014 (Prateek Vaish)

ABSTRACT

Developing a Remote Technique to Assess the Effectiveness of Thermal Insulation in Households in West Virginia

Prateek Vaish

Physical energy audits and interventional methods cannot sustain the increasing demand of assessing the effectiveness of existing thermal insulation in households. As for now, there does not exist a sufficiently accurate remote technology or method to assess the efficiency of a thermal envelope. Usually, the energy bills and the age of the furnace are good indicators of the performance of insulation in houses. To overcome the lack of availability of a proper framework to calculate the effectiveness of the thermal envelope, a standard methodology using multiple linear regression and temperature data acquired from a house has been developed. The major aim of the experiment was to develop a model equation which will assess the effectiveness of insulation in a house in West Virginia. If developed further, the model will be a very useful tool for energy auditors and consultants to help house owners understand the behavior of thermal insulation in their house.

The model requires four variables for input which are: 1) area of the house, 2) number of people in the house, 3) temperature difference (inside and ambient) and 4) air changes per hour inside the house. Extensive data acquisition was performed to develop a robust model. The model can now be used with minimum understanding of underlying concepts and can assess the effectiveness of thermal barrier which otherwise is very difficult to determine.

ACKNOWLEDGEMENT

I would like to thank my advisor Dr. Kenneth Means and Dr Bhaskaran Gopalakrishnan for their continued support, guidance and encouragement during the course of this research. I also wish to thank Dr. Terence Musho and Mr Subodh Chaudhari for their advice and support. I wish to extend my special thanks to Dr Chris Haddox for his invaluable help and support for the success of this project.

Above all, I wish to thank God and my family for their constant support and blessings, enabling my success and happiness in all my pursuits and endeavors in life.

Nomenclature

HVAC	-	Heating, Ventilation and Air Conditioning
ASHRAE	-	American Society of Heating Refrigeration and Air Conditioning Engineers
C_D	-	Drag Coefficient
MLR	-	Multiple Linear Regression
LCC	-	Life Cycle Cost
NC	-	Nonconformance
kWh	-	Kilo Watt Hour

Table of Contents

ABSTRACT.....	iii
ACKNOWLEDGEMENT	iv
Nomenclature.....	v
1.1 Energy Consumption	1
1.2 Energy Used in Buildings	2
1.3 Residential Energy Consumption	3
1.4 ASHRAE Standards.....	3
1.5 Need for Insulation check?	4
1.6 Energy Auditing.....	6
1.7 Energy Bills	8
1.8 Need for research	8
1.9 Parameters.....	9
1.9.1 Actual Energy Consumption	9
1.9.2 Ideal Heat Loss.....	9
1.9.3 Response.....	9
1.9.4 Infiltration Leakage Area	9
1.9.5 Temperature Difference	10
1.9.6 Occupancy	11
1.9.7 Leakage Area and Effect of Wind.....	13
1.10 Model Equation.....	15
1.11 Validation.....	16
1.12 Conclusion	17
2.1 Energy Usage	18
2.2 Thermal Insulation in Hot Climates.....	19
2.3 Insulation and Thermal Barrier.....	21
2.4 Effect on Energy Consumption.....	24
2.5 Empirical Modeling	27
3.1 Introduction.....	30
3.2 Data Collected.....	30
3.2.1 Temperature in the Houses:.....	30

3.2.2 Weather Data.....	32
3.2.3 Actual Energy Consumption	34
3.2.4 Blower Door Tests (Leakage Area)	35
3.3 Use of ASHRAE Equations	37
3.3.1 Heat Loss or Ideal Furnace Consumption	37
3.3.2 Response.....	38
3.3.3 Variables in the Model	39
3.3.3.1 Area	39
3.3.3.2 Occupancy	39
3.3.3.3 Air Changes Per Hour.....	40
3.4 Empirical Modeling	40
4.1 Insulation Effectiveness Study Data Analysis	43
4.2 Predictors for Multiple Linear Regression.....	44
4.3 Using Multiple Linear Regression to Determine First Order Coefficient	45
4.4 Model	45
4.4.1 Final Equation, Coefficients and ANOVA	49
5.1 Model Execution	52
5.2 Model Inputs:	52
5.2.1 House A:.....	52
5.2.2 House B:.....	54
5.3 Results and Discussion	56
6.1 Conclusion	59
6.2 Future Work	60

List of Figures

Figure 1.1 (a): Energy consumption in major G20 countries [2].....	1
Figure 1.1 (b): Consumption of Energy Source in US – 2009 [3].....	2
Figure 1.3: Total energy consumption in US homes: 1978 and 2005	3
Figure 1.4: Average Energy Consumption per Home and Number of Housing Units [6]	4
Figure 1.5 (a): Average Energy Consumption per Home and Number of Housing Units [1].....	4
Figure 1.5 (b): Heat Loss in a House-Weatherization (Accessed from web, 01/2014)	5
Figure 1.6: Energy Auditing Steps.....	7
Figure 1.7: Sample Energy Bill	8
Figure 1.9.4: Effective Air Leakage Areas (Low Rise Residential Applications).....	10
Figure 1.9.5 Effect of lowering thermostat setpoint on heat loss	11
Figure 1.9.6 (a): Sensible and Latent Heat Loss from People	12
Figure 1.9.6 (b): Continuous Whole Building Ventilation Rate.....	13
Figure 1.9.7 (a): Blower Door Test Setup and CFM50 Reading	14
Figure 1.9.7 (b): Basic Model Wind and Stack Coefficients.....	15
Figure 2.1: Distribution of Energy between Different Appliances[1]	18
Figure 2.2 (a): Annual Energy Savings vs Insulation Type [13]	19
Figure 2.2 (c): Heating demand vs wind speed with airtightness 1,3,6 with (a) mechanical exhaust only ventilation system (b) mechanical exhaust supply system	21
Figure 2.3 (a): Heat Flow through Various Thermal Insulation Systems.....	22
Figure 2.3 (b): Various Temperatures in the House without Radiant Barrier in Summer.....	23
Figure 2.3 (d): Contour of Temperature Distribution (a) XY plane (b) YZ plane.....	24
Figure 2.4 (a): The Effect of Occupants on Energy Usage for 1987-1988 Heating Season.....	25
Figure 2.4 (b): Temperature and Heat Gain Components of the exposed wall: (a) No insulation, (b) Interior Insulated, (c) Exterior Insulated	26
Figure 2.4 (c): Framework of Generating Typical Heating Load Profile	27
Figure 2.4 (d): Typical Heating Load Profile of a Dwelling	27
Figure 2.5 (a): Diagram of delivered heat power in the function of outside temperature (dark line) and a similar diagram only for hours with wind stronger than 6 m/s	29
Figure 2.5 (b): Regression Result of Each User Group	29

Figure 3.2.1 (a) Hourly Temperature Data in Building 775, Apt 1	31
Figure 3.2.1 (b) Hourly Temperature Data in Building 777, Apt 2	31
Figure 3.2.2 Hourly Meteorological Data by NCDC.....	33
Figure 3.2.3: kWh Reading	34
Figure 3.2.4: LBL n factor for ventilation	36
Figure 4.4.1: Residual Plots for Response	51

List of Tables

Table 3.2.3: kWh Usage in Residential Houses.....	35
Table 3.2.4: Air Leakage in Residential Houses.....	36
Table 3.3.3.2: Sensible and Latent Heat Loss from Human	39
Table 3.4: Data Set for Empirical Modeling.....	42
Table 4.4 (a): Predictand and Predictors for Multiple Linear Regression Analysis	46
Table 4.4 (b): Boundary Limits for Variables in the Model	46
Table 4.4 (b): Plots of Response (Predictand) with all the variables.....	48
Table 4.4.1 (a): Parameter Estimates of the Empirical Model.....	50
Table 4.4.1 (b): Summary of Fit	50
Table 4.4.1 (c): Analysis of Variance (ANOVA)	50
Table 5.3: Comparison of Results.....	56
Table 6.1 (a): Effectiveness Rating in Residential Households.....	58
Table 6.1 (b): Limitation of the Empirical Model	60

Chapter 1

Introduction

1.1 Energy Consumption

The energy consumption is increasing tremendously for the last four decades. The deposits of major sources of energy such as petroleum and coal are depleting at an alarming rate. It is estimated that the world energy consumption would increase by 49% from 2007 to 2035 [1]. In 2009 the world energy consumption decreased by 1.1% in comparison with 2008. This decrease in energy consumption was observed after 30 years and was the result of the economic crisis (average GDP drop across the world by 0.6%). Some Asian countries were not affected by recession and hence still observed increase in annual energy consumption. In North America, Europe and Commonwealth of Independent States, consumptions shrank by 4.5%, 5% and 8.5% respectively due to the slowdown in economic activity [1].

Due to recovery from recession and crisis, the energy consumption in Asia in 2010 increased by 5% compared to 2009 [2]. The Figure 1.1.1 below shows the energy consumption in major G20 countries from 2008 – 2010.

Figure 1.1 (a): Energy consumption in major G20 countries [2]

According to International Energy Agency (IEA), the world population increased by 5%, annual CO₂ emissions increased by 10% and the gross energy production increased 10% in four years (2004–2008) [2]. Despite advances in efficiency and sustainability, since the industrial revolution in the last two decades more than half of the world energy reserve has been consumed [2].

Till this date, dependence on oil is inevitable as an energy source even though there has been a tremendous advancement in alternate fuels. . The US consumes 25% of the world's energy with a share of global GDP at 22% [1, 2]. Figure 1.1.2 [3] shows the consumption of various energy sources in US in 2009 [Ramamoorthy, R, A Structured Approach for Facilitating the Implementation of ISO 50001 Standard in Manufacturing Industries, 2011].

Figure 1.1 (b): Consumption of Energy Source in US – 2009 [3]

1.2 Energy Used in Buildings

The energy consumed by the commercial sector is almost 20% of total energy consumption in United States. The top three uses of energy uses in commercial sector are space heating, cooling and lighting comprising of more than 50% of energy usage. It was found that there was a 69% increase in the commercial floor space and 58% increase in primary energy consumption, between the years 1980 and 2009. The EIA (Energy Information Administration), the primary energy consumption in commercial buildings will increase by 22% between the years 2009 and 2035. Commercial buildings consumed 17.9 quads of primary energy in 2009, representing 46.0% of building energy consumption and 18.9% of U.S. energy consumption. [4]

1.3 Residential Energy Consumption

Residential buildings include homes, apartments and mobile homes. In the recent years, an increase in energy consumption has been noticed in residential buildings. One of the reasons for increase energy consumption is that the standard of living has been increased too in recent years. This has led to increased usage of electric appliances and HVAC applications.

Figure 1.3: Total energy consumption in US homes: 1978 and 2005

1.4 ASHRAE Standards

ASHRAE 90.2 is a residential standard published by American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) that provides guidance for meeting minimum energy efficiency requirements in low-rise buildings. ASHRAE 90.2 covers the seven climatic zones and has laid down 37 separate prescriptive paths. ASHRAE 90.2 energy efficient design of low rise buildings provides minimum requirement for such building designs [5]. The energy requirements are intended to be an advancement in energy efficiency, as well as being economical. Compliance is achieved through either the prescriptive or the systems analysis methods. The prescriptive criterion contains an independent energy requirement for each building component, such as exterior walls or duct insulation. This method is the easiest to use, but is the most stringent and offers the least design flexibility. The systems analysis approach bases compliance on achieving an acceptable annual energy cost for the building. This method

requires a detailed analysis, but allows for increased design flexibility, as well as accounting for energy efficient features such as passive solar or innovative designs. [6]

Figure 1—Exterior Wall Required U-Factors
Copyright 1993 by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. from ASHRAE Standard 90.2-1993. Used by permission.

Figure 1.4: Average Energy Consumption per Home and Number of Housing Units [6]

1.5 Need for Insulation check?

Energy used for heating accounts for almost 41% in United States. So there is a huge opportunity for energy savings by reducing heat loss. The purpose of insulation is to reduce this heat loss in winters acting as a thermal barrier.

Figure 1.5 (a): Average Energy Consumption per Home and Number of Housing Units [1]

The graph shows that the number of houses from 1980 has increased to 2009 and the energy usage per house has decreased from 1980 to 2009. Also it should be noted that the total amount of energy consumed is almost the same from 1980 to 2009. This shows that much has been done to reduce heat loss or in other words to improve insulation of a house.

Figure 1.5 (b): Heat Loss in a House-Weatherization (Accessed from web, 01/2014)

The figure shows the places which accounts for heat loss. These areas are to be addressed while checking for insulation. The major heat loss is due to infiltration or weatherization which accounts for almost 35% heating energy loss. Walls and floors account for 13% and 17% respectively.

Check for insulation is necessary to minimize the loss of energy from these areas. This loss can be reduced by retrofitting the insulation in various areas of the house.

In general it is more cost-effective to upgrade insulation than it is to upgrade the furnace. However, if the furnace is old, it is recommended to upgrade the furnace if you have to choose between the two options. The average lifetime for a furnace is between 15 and 20 years. The efficiency of furnaces has increased over the years, so the older the furnace, more likely it is that furnace will be inefficient. The average efficiency of new furnaces has increased from 63% (1972) to 83% (1995). Older furnaces, and furnaces which are used a lot are more cost-effective to replace than newer or infrequently used furnaces. Also, if the house is insulated at the time of furnace replacement, it may be possible to replace the existing system with a smaller capacity

furnace and save money on the price. The same holds true for A/C and other heating and cooling equipment. [7]

1.6 Energy Auditing

A home energy audit is a process to evaluate the energy consumption in the house. This process involves the energy auditor to analyze the past year energy bills and benchmark the energy profile. The next step involves a short interview with the building / home owner about the operation schedule of the main energy consuming appliances and the problems (if any) about them. The auditor then does a walk through in the house to note down readings and install data loggers or sub-meters to calculate the energy consumed by the equipment individually.

A home energy audit also involves a blower door test to assess the leakage in the house. The major part of this process is assessing the utilization of the HVAC unit because heating and cooling comprise of more than 60% of the energy used in a residential house. The final step is to develop a comprehensive report including all the energy conservation measures and an approximate implementation cost and payback period. The figure 1.5.1 shows a flow chart of the home energy audit process.

Figure 1.6: Energy Auditing Steps

1.7 Energy Bills

A residential electric bill is charged according to the number of kilowatt hours of power used during a period of one or two months. And the billing amount is generated by multiplying the rate per kilowatt hour with the total kilowatt hours used. Figure 1.6.1 shows a sample electric and a gas bill.

The image shows a sample energy bill from Consumers Energy. At the top, it displays the account number 199999987631 and the address 903 ANYSTREET, ANYTOWN MI 49999-9999. A warning box states: "IF YOU SMELL GAS, CALL US IMMEDIATELY DAY OR NIGHT AT 1-800-477-5050". The bill includes a table for meter readings with columns for Meter Number, Location, Begin Read, End Read, Type, Diff, Constant, Corr Fctr, Use, and Unit. The meter readings show a difference of 131 kWh. The total due is \$221.75, with a due date of 03/02/10. The bill also includes contact information for emergencies and non-emergencies.

Consumers Energy

Your Account Number
I 199999987631 000000221754 0000 2056 0 000000000000 H

"IF YOU SMELL GAS, CALL US IMMEDIATELY DAY OR NIGHT AT 1-800-477-5050"

LANSGING, MI 48937-0001

JOHN DOE
903 ANYSTREET
ANYTOWN MI 49999-9999

Corrections/Comments on Back

Due Date 03/02/10 Total Due \$221.75

Amount Enclosed \$

ECP / 100 06 2-11-2010

FOLD AT PERFORATION, DETACH AND MAIL TOP PORTION WITH YOUR PAYMENT 209999611762 2010/02

IN AN EMERGENCY, CALL US 24 HOURS A DAY AT 1-800-477-5050.

For non-emergencies or information about rates and services, call 1-800-477-5050, visit us on the Internet: www.consumersenergy.com, or use our 24-hour fax at 1-800-363-4806.

NAME	JOHN DOE	ACCOUNT NO.	1999 9998 7631
SERVICE ADDRESS	903 ANYSTREET ANYTOWN MI 49999-9999	BILLING PERIOD	01/09/10-02/05/10
		DAYS BILLED	28
		DUE DATE	03/02/10

RATE: 1000W Elec Res Rate RS
250 Gas Res Serv Rate A - With Sp Htg

POD: 0000002782094
POD: 0000002782095

METER NUMBER	LOCATION	BEGIN READ	END READ	READ TYPE	DIFF	CONSTANT	CORR FCTR	METER ENERGY USE	UNIT
59779953	903 ANYSTREET	23201	23826	ACT	131	0.1	1.00000	625	KWH
23029488	903 ANYSTREET	3219	3350	ACT				13.1	MCF

Figure 1.7: Sample Energy Bill

In this study, the readings from the electric bills and readings from actual meters are used to estimate the energy used by the HVAC units. It was estimated that the out of total electricity charge, 41% was used for space heating and out of total gas bill (if any), 60% was used for space heating.

1.8 Need for research

Till this date, there is no non-invasive method or straight forward formula to assess the effectiveness of the insulation of a house. The only possible way is to get an energy audit done which cost, anywhere from \$300-\$1,000, depending on the size of the house. So, the whole idea of this research is to do a remote audit which will include only the use of energy bills and the drawing of the house. The equation developed from this research will give a rating of the

effectiveness of the thermal blanket of the residential house or in other words, will show how good the insulation is. This method will be very cost effective and will give an idea to the homeowner about what to do next.

1.9 Parameters

During this research some parameters were selected which effect the insulation or heating loads in a house. There are many factors on which the heating loads depend but due to some restrictions (explained in upcoming sections), only the following variables were taken into account:

1.9.1 Actual Energy Consumption

The energy used in heating is used as a reference in this study. Most of the furnaces in the experiment were electric. The kWh readings were taken from the utility meters. At the end of experiment the difference of readings from the first day and the last day was used as the actual energy consumption.

1.9.2 Ideal Heat Loss

The ideal heat loss is the energy loss from a residential house. This loss is calculated by International Energy Conservation Code (IECC) standards for Monongalia County, WV. This heat loss takes into account the design and size of the house and the R values and U values described the code.

The standard also takes into account the orientation of the windows and doors for solar heat gain. In this study, these variations are assumed to be same for all houses.

1.9.3 Response

Response is the ratio of ideal heat loss and the actual energy consumption. The response signifies the effectiveness of the thermal envelope in the house. It gives an idea of how well the house is insulated and if there is a need to make some changes regarding the same.

1.9.4 Infiltration Leakage Area

The area of the house is usually directly proportional to the leakage area of the house but this cannot be generalized as the leakage area is also dependent on the make of the house, climatic

conditions and the yearly maintenance done in the house. ASHRAE Fundamentals Handbook 1997 has specified some values for effective leakage area according to the size and type of walls, roof, floor, windows, electric sockets, doors and vents. These values hold good for low-rise buildings. The effective air leakage area is based on a pressure difference of 0.016 in of water and a C_D (drag coefficient) of 1. So, if estimation has to be made according to the ASHRAE handbook, the leakage will be more if the size of the house is more.

	Units	Best Estimate	Minimum	Maximum
Ceiling	in ² /ft ²	0.026	0.011	0.04
Door Frame, Wood	in ² /ft ²	0.004	0.001	0.004
Door, General	in ² /ft ²	0.015	0.011	0.021
Electrical outlets	in ² /ea	0.023	0.012	0.54
Ceiling-wall joint	in ² /lft	0.07	0.0075	0.12
Vents	in ² /ea	1.6	0.39	3.1
Walls, clay brick cavity wall	in ² /ft ²	0.0098	0.0007	0.033
Windows, not weatherstripped	in ² /ft ²	0.023	0.011	0.035

Figure 1.9.4: Effective Air Leakage Areas (Low Rise Residential Applications)

1.9.5 Temperature Difference

Temperature difference plays a very significant role in determining the effectiveness of the insulation. Temperature difference is calculated by recording the temperatures inside and outside the house. The temperature inside the house is governed by the set point temperature and the temperature inside the house depends on all the factors mentioned above. Figure 1.9.5 shows a graph between heat loss and the set point temperature.

Figure 1.9.5 Effect of lowering thermostat setpoint on heat loss

The graph shows that there is a significant decrease in heat loss as the set temperature is decreased [8]. Decreasing the set point temperature will decrease the temperature inside the house which will bring down the temperature difference. As the temperature difference is decreased, assuming all conditions remain same, the heat loss will be decreased.

1.9.6 Occupancy

Metabolic functions dissipate heat from the human body into the rooms in the form of latent heat and sensible heat. The heat from convection and radiation is sensible heat and the heat from evaporation is known as latent heat. Under normal conditions the rate of heat transfer from a human body varies from 100 W at sedentary conditions to 1,000 watt at high physical work conditions.

Degree of Activity	Typical Application	Average Metabolic rate - male adult (W)	Room Dry Bulb Temperature (°C)											
			28		27		26		24		22		20	
			Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.
Seated at rest	Cinema, theatre, school	100	50	50	55	45	60	40	67	33	72	28	79	21
Seated, very light work	Computer working	120	50	70	55	65	60	60	70	50	78	42	84	36
Office work	Hotel reception, cashier	130	50	80	56	74	60	70	70	60	78	52	86	44
Standing, walking slowly	Laboratory work	130	50	80	56	74	60	70	70	60	78	52	86	44
Walking, seated		150	53	97	58	92	64	86	76	74	84	66	90	60
Moderate work	Servant, hair dresser	160	55	105	60	100	68	92	80	80	90	70	98	62
Light bench work	Mechanical production	220	55	165	52	158	70	150	85	135	100	120	115	105
Moderate Dancing	Party	250	62	188	70	180	78	172	94	156	110	140	125	125
Fast walking	Mountain walking	300	80	220	88	212	96	204	110	190	130	170	145	155
Heavy work	Athletics	430	132	298	138	292	144	286	154	276	170	260	188	24

Figure 1.9.6 (a): Sensible and Latent Heat Loss from People

Though the heating load should decrease with increase in number of people, as it will account for more and more heat but it also increases the amount of carbon dioxide and thus it increases the air changes per hour. Thus the heating unit has to work more to meet the ventilation demands.

ASHRAE Standard 62.2 Table 4.1a					
Continuous Whole-Building Ventilation Rate in cfm					
Floor Area (sq ft)	Number of Bedrooms				
	0 - 1	3-Feb	5-Apr	7-Jun	> 7
< 1500	30	45	60	75	90
1501 – 3000	45	60	75	90	105
3001 – 4500	60	75	90	105	120
4501 – 6000	75	90	105	120	135
6001 – 7500	90	105	120	135	150
> 7500	105	120	135	150	165

Figure 1.9.6 (b): Continuous Whole Building Ventilation Rate

1.9.7 Leakage Area and Effect of Wind

Leakage area of the house was measured by performing blower door tests. A blower door is a diagnostic tool to assess the air tightness of a house. The test consists of a blower fan which is calibrated and is fitted on the outside door of the house. The door is sealed by a thick cloth as shown in the figure. Before, turning the fan ON, the HVAC unit is turned off, all the vents, windows and openings of the house are sealed with a duct tape. Then the fan is turned on and it creates a pressure difference by blowing the air out of the house. This pressure difference forces air through all holes and penetrations in the building. The reading noted when the pressure becomes -50 Pa is known as CFM₅₀. The CFM₅₀ can be used to calculate the ACH at natural conditions which is further explained in chapter 3.

Figure 1.9.7 (a): Blower Door Test Setup and CFM50 Reading

Air infiltration rate can vary from 0.1 ACH to 1.5 ACH depending on the weather conditions. Air infiltration depends on air leakage, pressure difference caused by temperature difference and forces of the wind.

$$Q = \frac{ACH \cdot A \cdot H}{60}$$

Where,

ACH = Air changes per hour

A = Area, ft²

H = Height, ft

Q = cubic feet per minute of air

The speed of wind has a considerable effect on the infiltration rate in the houses. At low wind speeds infiltration occurs mostly via stack effect and at high wind speeds, the enhanced air infiltration is driven by wind and temperature effect [9].

$$Q = A_L \cdot \sqrt{C_s \cdot \Delta T + C_w \cdot U^2}$$

Table 4 Basic Model Stack Coefficient C_s			
	House Height (Stories)		
	One	Two	Three
Stack coefficient	0.0150	0.0299	0.0449

Table 5 Local Shelter Classes	
Shelter Class	Description
1	No obstructions or local shielding
2	Typical shelter for an isolated rural house
3	Typical shelter caused by other buildings across street from building under study
4	Typical shelter for urban buildings on larger lots where sheltering obstacles are more than one building height away
5	Typical shelter produced by buildings or other structures immediately adjacent (closer than one house height): e.g., neighboring houses on same side of street, trees, bushes, etc.

Table 6 Basic Model Wind Coefficient C_w			
Shelter Class	House Height (Stories)		
	One	Two	Three
1	0.0119	0.0157	0.0184
2	0.0092	0.0121	0.0143
3	0.0065	0.0086	0.0101
4	0.0039	0.0051	0.0060
5	0.0012	0.0016	0.0018

Figure 1.9.7 (b): Basic Model Wind and Stack Coefficients

Where,

A_L = Leakage area, in²

C_s = Stack Coefficient

ΔT = Temperature Difference

C_w = Wind Coefficient

U = Wind Velocity, mph

As seen in the equations, the frequency of opening and closing of the doors in the house will have an effect on heat loss depending on the average velocity of wind. It will also depend on the pressure difference (inside and outside the house) which is the stack effect

1.10 Model Equation

After the data collection and calculations, the final variables are as follows:

- Response (Ideal energy consumption/Actual Energy consumption)
- Area of the House
- Temperature Difference
- Number of Occupants
- Air Changes Per Hour

A statistical technique known as multiple linear regression is utilized in this experiment to establish a relationship between these variables and the response. Multiple linear regression models the relationship of all the variables and response by fitting a linear equation between the observed data. The dependent variable is called a predictand (response) and the independent variable is known as the predictor. Multiple Regression is based on the method of least squares, in which the best fitted of the data is obtained by minimizing the sum of least squares of the vertical deviations from each data point. [10]

It is recommended to use 4-5 data points for every variable in the equation for statistical modeling. In this model, the equation was developed using 15 data points and it was found the adjusted coefficient of determination was a significant value and validation examples yielded satisfactory results.

Multiple Regression is not a time series method and the variables are sometimes not independent of each other. [11] The following equation illustrates the multiple regression model with two variables which describes a space in three dimensional space of Y, X₁ and X₂:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \varepsilon$$

Where,

β_0 = Intercept of the plane

β_1 = Partial Regression Coefficient

β_2 = Partial Regression Coefficient

β_3 = Partial Regression Coefficient

β_4 = Partial Regression Coefficient

In the experiment, the final regression equation will be:

$$R = \beta_0 + \beta_1 \text{Area} + \beta_2 \text{Temp Diff} + \beta_3 \text{Occupants} + \beta_4 \text{ACH}$$

It should be noted that the wind speed data is used from the National Climate Data Center website and all data points have same value of wind speed. Due to this reason the wind speed is rendered insignificant in the regression analysis but practically it is significant [10].

1.11 Validation

The model will be validated by populating the equation by data collected again from the houses of the same buildings or different buildings. The purpose of this test will be to compare the actual energy consumption (kWh) with the values predicted by the model equation.

The energy consumption value predicted by the model will be for nine days because the test has been done for nine days. If the both the values are in closed proximity and in an error range of 0.2, the model will be considered valid for climatic zone 5 in heating season.

1.12 Conclusion

The equation obtained after the multiple regression analysis concludes that, by knowing the temperature difference for a period of 5-6 days and some minimal data for a residential house in climate zone 5 in North America, the effectiveness of the insulation or the thermal envelope can be calculated.

This study is limited to zone 5 because all the data is collected from Morgantown, WV region and it is still not established how the equation will behave if it is used in any other part of the world except zone 5. One more limitation to this study is that it can only be used in residential houses which have their dedicated heating units unlike in commercial buildings which have centralized heating/cooling units.

Chapter 2

Literature Review

This chapter discusses the existing research work in understanding the creep phenomena. Different testing methodologies and various kinds of equipment's which evolved over the years in unconfined and confined conditions are also summarized.

2.1 Energy Usage

Most of the energy use in a household in America is being used in heating or cooling. One of the reasons for this high energy percentage of heating and cooling can be inadequate or ineffective insulation.

Figure 2.1: Distribution of Energy between Different Appliances[1]

The effectiveness of insulation is dependent on various factors. The main factors are type of insulation, climate, air infiltration in the house, type of heating system, age of heating system, physical activity in the house and number of people living in the house.

Insulation works by limiting the air movement between two boundaries. Batts, blankets, loose fill and low density foams, all serve this purpose. Air sealing also acts as an effective insulator by restricting air movement and prevents convection and also prevents water vapor to enter the wall[2].

2.2 Thermal Insulation in Hot Climates

The insulation is not necessarily better if it is thicker. It has to be of the right material and right thickness. In an experiment to find the effectiveness of thermal insulation in different buildings with no insulation was simulated using the Enerwin Hourly Building Energy Simulation Program[12] and different types of insulations were added in the simulation. The experiment was carried out in two different climatic zones, one being a hot-arid and other being a hot humid in middle east Asia. The Life Cycle Cost (LCC) analysis was also done with following functions:

- Building type
- Type and cost of insulation
- Cost of Energy (the value of energy saved) [13]

Figure 2.2 (a): Annual Energy Savings vs Insulation Type [13]

The table shows the percentage of reduction in cooling load with different insulations. The results from this experiment clearly show a distinct amount of reduction in energy usage by using insulation for walls and roofs in the residential and office buildings. Also, this research concluded that by using building envelope insulations there will be cost savings as a smaller HVAC system will be required due to reduced cooling loads.

Kashiwagi and Moor (1993) investigated the relationship between energy cost, insulation and its design [14] using Porter's Value Chain Analysis [15]. Two models were developed during this study, the first one is an analysis of effects of building configuration and environmental factors and the second one deals with energy savings and the equivalent uniform annual cost (EUAC) of roofing systems. The factors which were investigated were:

- R value of insulation and overall R-value of building insulation
- Cost of heating and cooling facilities
- Outside and inside temperatures
- Window areas and building component infiltration points

Location—Phoenix, AZ			Location—Eau Clair, WI		
Effect of Energy Cost					
Energy Cost (Times)	EUAC*	Payback	Energy Cost (Times)	EUAC	Payback
1.0	0.34	19	1.0	0.29	13
1.5	0.33	18	1.5	0.29	13
2.0	0.33	18	2.0	0.29	13
2.5	0.33	17	2.5	0.29	13
3.0	0.32	16	3.0	0.29	12
3.5	0.32	16	3.5	0.29	12
Effect of PUF Thickness					
PUF (in)	EUAC	Payback	PUF (in)	EUAC	Payback
1.0	0.29	12	1.0	0.26	10
1.5	0.34	19	1.5	0.29	13
2.0	0.39	N/A	2.0	0.33	18
Effect of Service Life					
Service Life (yrs) EUAC	1-inch	1.5-inch	Service Life (yrs) EUAC	1-inch	1.5-inch
10	0.36	0.43	10	0.34	0.38
15	0.31	0.36	15	0.28	0.32
20	0.29	0.34	20	0.26	0.29
25	0.28	0.33	25	0.25	0.28
30	0.28	0.32	30	0.25	0.28
Effect of Design R-Value					
R-Value (Times)	EUAC	Payback	R-Value (Times)	EUAC	Payback
0.8	0.34	21	0.8	0.31	14
0.9	0.34	20	0.9	0.30	13
1.0	0.34	19	1.0	0.29	13
1.1	0.34	19	1.1	0.29	12
1.2	0.33	19	1.2	0.28	12
Effect of PUF Installation Cost					
Cost (Times)	EUAC	Payback	Cost (Times)	EUAC	Payback
0.90	0.30	13	0.90	0.26	10
1.00	0.34	19	1.00	0.29	13
1.50	0.52	N/A	1.50	0.47	N/A

Figure 2.2 (b): Sensitivity Analysis for PUF on Concrete Deck [14]

The results of this study indicate that a thickness of 1.5 inches of Poly Urethane Foam (PUF) is best suitable and economic for Phoenix, AZ. Whereas in Eau Clair, WI the most economic thickness of PUF as insulation is one inch. Now for the cost analysis, it was calculated that, by increasing the thickness of PUF to 1.5 inch, it will ensure better period of service. But, the net loss will still be \$0.02/ft²/yr and \$0.04/ft²/yr for Eau Clair and Phoenix respectively. By the EAUC analysis it was observed that there was \$0.02/ft²/yr for an increase of 350% in energy costs of the waterproofing/insulation system for Phoenix, AZ. However, no savings were observed for Eau Clair, WI as energy cost was not a significant factor while considering waterproofing/insulation alternatives. It was also noted during the study that the service factor has a big impact on savings.

Mattson studied the influence of wind speed and other factors on the air change rate of single family house. The paper concludes that stack effect is very minimal in tight houses with exhaust-only ventilation system and is influential in exhaust-supply system. The reason for houses with exhaust-supply system, more sensitive to wind speed is due to the inlet vents [16].

Figure 2.2 (c): Heating demand vs wind speed with airtightness 1,3,6 with (a) mechanical exhaust only ventilation system (b) mechanical exhaust supply system

2.3 Insulation and Thermal Barrier

Carlos J Hilado (1979) developed a method to determine the thermal insulation effectiveness at cryogenic temperatures. The study comprised of fabrication of test specimen which were three feet long aluminum pipes coated with one inch of PUF with 25 millimeters of polyvinyl chloride

jacket and 6 inches of cellular glass in three layers [17]. Extreme low temperatures were obtained during this study by using liquid nitrogen and solid carbon dioxide (Dry Ice). For the calculations, it was assumed that heat transferred from the surroundings was equal to the heat of vaporization of the coolant which in this case were liquid nitrogen and solid carbon dioxide. The time taken to reach the steady state was 30 to 90 minutes. The results of this study are shown below.

PIPE TEMPERATURE °C. °F.		THERMAL INSULATION SYSTEM	HEAT TRANSFER RATE				
			BTU PER HOUR				BTU PER HOUR PER FOOT OF PIPE
			1	2	3	AVERAGE	
-196	-320	1 inch cellular urethane A, PVC	144.5	137.0	—	140.8	46.9
		1 inch cellular urethane B, PVC	153.0	153.0	154.0	153.3	51.1
		4 inches cellular glass, mastic	258.5	—	—	258.5	86.2
		6 inches cellular glass, mastic	208.5	198.5	—	203.5	67.8
-78	-109	1 inch cellular urethane A, PVC	68.0	69.0	—	68.5	22.8
		1 inch cellular urethane B, PVC	71.1	69.0	—	70.0	23.4
		4 inches cellular glass, mastic	107.0	—	—	107.0	35.6
		6 inches cellular glass, mastic	105.0	—	—	105.0	35.0

Figure 2.3 (a): Heat Flow through Various Thermal Insulation Systems

The results clearly show that the heat flow behavior for pipe insulation is very much different from heat flow behavior for insulation on flat surfaces. The results of the experiment indicated that 75% of heat flow was permitted at -320°F and 65% heat flow was permitted at -109°F. In both cases the thermal insulation material was polyurethane foam (PUF) with 6 inches of cellular glass. The results of this experiment also indicate that low conductivity materials are better for small diameter pipes. The 2:1 to 3:1 advantage of polyurethane foam over cellulose glass on flat surfaces becomes 4:1 to 6:1 advantage on 3 inches nominal diameter pipe [17]. The estimated error for this study was estimated to be 5%.

Further, a thesis done by Somayeh Asadi at Louisiana State University on “Thermal Performance and Cost Effectiveness of Radiant Barrier Thermal Insulation Materials in Residential Construction” involved the installation of thermocouples, data loggers and wireless Vantage Pro was installed in both houses for eight months [18].

Figure 2.3 (b): Various Temperatures in the House without Radiant Barrier in Summer

The results of this study show that there was a difference of 6°C in the attic air temperature with radiant barrier. Also, it was noticed that due to low emissivity and absorptivity, there was a decrease in infrared radiation on the attic floor. The results of this study also indicate that heating loads can be decreased by 11% by using radiant energy barrier depending on the climatic zone.

Figure 2.3 (c): Various Temperatures in the House with Radiant Barrier in Summer

A 3-D transient model was developed to calculate the temperature distribution in different parts of the house. This modeling was done using the ABAQUS 6.9 software. The results of the finite element analysis are shown in Figure 2.3 (d)

Figure 2.3 (d): Contour of Temperature Distribution (a) XY plane (b) YZ plane

The results of the FE study clearly indicated that there was a 21% reduction in heat flux by using radiant barrier systems. This reduction in heat flux reduced the cooling load in the houses by 18 percent.

2.4 Effect on Energy Consumption

Amery and Kippenhan monitored the energy consumption of single family houses for 15 years. Two of the houses were constructed according to the existing standards at the time of construction and two houses were constructed with improved thermal resistance. There was a significant difference in the lifestyle of all the four families. But the author concluded that the space energy heating behavior remained remarkably constant. It was observed that even though there was wear and tear in the houses over the years but the energy consumption of the houses almost remained the same. [19]

Figure 2.4 (a): The Effect of Occupants on Energy Usage for 1987-1988 Heating Season

The MSC house had a heat recovery system. The energy required to heat the outside air in the occupied 1980 house was almost double than heating the unoccupied house (29% as compared to 14%). On the other hand, for the Model Conservation Standard (MCS) house with forced infiltration the energy required to heat the unoccupied house was more than occupied house (40% as compared to 29%).

An experimental study was done in Thailand to assess the behavior of different thicknesses of insulation on air conditioning loads, when placed on inside and outside portions of the wall. The data was collected from data loggers and thermocouples and a small weather station in the nearby area. The experimental and simulated values of heat flux, solar radiation and cooling coil loads were compared and the simulation software used was BESim. The experiment room was assumed to serve consecutively three residential functions of bedroom (BR), living room (LR) and studio room (STR). This paper concluded that when there is no window on the wall, an insulation placed on the interior will improve wall performance and will be cost effective (Life Cycle Cost analysis). On the other hand, insulation placed on the exposed of the wall increases the heat transfer and thus increasing the temperature [20].

Figure 2.4 (b): Temperature and Heat Gain Components of the exposed wall: (a) No insulation, (b) Interior Insulated, (c) Exterior Insulated

Yao and Steemers presented a Simple Method of Formulating Load Profile (SMLP) in 2004 for UK buildings. A thermal resistant network method was used to create load profile for domestic space heating for different houses. This method can predict the daily usage profile for heating, hot water demand and appliances. The paper makes use of the data provided by www.statistics.gov.uk about the energy consumption for space heating, water heating, appliances and composition of household in recent years. The heating load profile depends on air

temperature, orientation of the building, local climate, etc. The paper validates the SMLP by profiling 100 households and load trends of national data. The R^2 value obtained in this comparison was 0.8425 which indicates that the co-relation is significant and the method is applicable [21].

Figure 2.4 (c): Framework of Generating Typical Heating Load Profile

Figure 2.4 (d): Typical Heating Load Profile of a Dwelling

2.5 Empirical Modeling

Carlo and Lamberts developed a regression equation using 5000 alternatives to predict an electricity consumption indicator which had the variables like wall to window ratio, solar heat gain coefficient, solar protection angles, building volume indicators, and the roof U value.

$$\begin{aligned}
EC = & -175.30 \left(\frac{A_p}{A_{tot}} \right) - 212.79 \left(\frac{A_{env}}{V_{tot}} \right) + 21.86 WWR \\
& + 5.59 SHGC - 0.19 VSA + 0.15 HSA + 2.34 U_{roof} \\
& + 0.19 ILD \cdot Sch \left(\frac{A_{proof}}{A_{tot}} \right) \left(\frac{A_{env}}{V_{tot}} \right) \\
& + 213.35 \left(\frac{A_{proof}}{A_{tot}} \right) \left(\frac{A_{env}}{V_{tot}} \right) - 0.04 WWR \cdot SHGC \cdot VSA \\
& - 0.45 WWR \cdot HSA \quad (A_{proof} < 500 \text{ m}^2)
\end{aligned} \tag{1}$$

$$\begin{aligned}
EC = & -14.14 \left(\frac{A_p}{A_{tot}} \right) - 113.94 \left(\frac{A_{env}}{V_{tot}} \right) + 50.82 WWR \\
& + 4.86 SHGC - 0.32 VSA + 0.26 HSA + 1.76 U_{roof} \\
& - 0.13 ILD \cdot Sch \left(\frac{V_{tot}}{A_{env}} \right) - 0.54 WWR \cdot HSA + 0.92 ILD \\
& + 1.74 Sch + 0.81 ILD \cdot Sch \quad (A_{proof} > 500 \text{ m}^2)
\end{aligned} \tag{2}$$

where A_{proof} is the area of the horizontal projection of the building (m^2); A_{tot} is the total floor area (m^2); A_{env} is the envelope area (m^2); V_{tot} is the building volume (m^3); WWR is the window to wall ratio; VSA is the vertical shading angle ($^\circ$); HSA is the horizontal shading angle ($^\circ$); Sch is the lighting, equipment and occupation schedule (h); ILD is the internal load density (W/m^2).

The limitations of this model include the exclusion of U_{value} of walls, defined shape factor range and inapplicability on large buildings and small or tall buildings. [22]

Wojdyga (2008) assessed the effect of various weather conditions on heat demand in district heating systems. The article concluded that the influence of wind on heat power demand is lower than the influence of solar radiation. It was also concluded that even a small amount of heat loss through walls in energy efficient buildings with low heat transfer coefficient walls, it is surpluses of solar radiation through these walls that can affect the work conditions of central heating systems. [23]

Figure 2.5 (a): Diagram of delivered heat power in the function of outside temperature (dark line) and a similar diagram only for hours with wind stronger than 6 m/s

Chung and Hui benchmarked the energy efficiency of private buildings in Hong Kong in 2002 by dividing them into three grades, A, B and C based on the quality of the facility. After performing multiple linear regressions between EUI (Energy Use Intensities) and factors like operating hours, it was concluded that grade A buildings should focus on lighting control, office equipment and water side distribution. Grade A/B buildings should focus on water side distribution control and chiller equipment and grade C buildings should focus on lighting equipment, chillers and office equipment. [25]

		Grade A/B		Grade C		Grade A
R-square		0.3710	0.3628	0.5082	0.4669	0.7387
Factor Type	Significant factors	A1 (CS/AC)	A2 (Tenant/AC)	A3 (CS/no AC)	A4 (Tenant/no AC)	A5 (Whole)
People	Occupants behaviour and Maintenance factor	NS	-54.3 (26.7)	NS	-47.6 [*] (41.2)	NS
	Indoor temperature set point	NS	NS	-43.9 [*] (13.4)	NS	NS
Energy end-use	Chiller equipment type	-122.8 (63.1)	NA	52.6 [*] , ^B (17.5)	NS	NS
	Air side distribution type	NS	NS	NS	NS	NS
	Air side control ^B	NS	NS	NS	NS	-385.0 [*] (140.5)
	Water side distribution type	NS	NA	NA	NA	NS
	Water side distribution control ^B	-205.0 [*] (67.703)	NA	NA	NA	NS
	Lighting equipment	NS	NS	-18.1 (8.9)	-100.4 [*] (35.8)	NS
	Lighting control ^B	NA	NS	NS	NS	-292.0 [*] (103.9)
	Office equipment	NA	67.7 [*] (26.7)	NS	137.6 [*] (39.6)	532.9 [*] (204.9)

NS = not significant in the stepwise multiple regression model; NA = not applicable; B = binary measure; the value in parenthesis() = standard error.
^{*} Significant at the 5% level.

Figure 2.5 (b): Regression Result of Each User Group

Chapter 3

METHODOLOGY

This chapter discusses the comprehensive testing methodology developed to determine the effect of different factors on heat loss in various houses which are selected as specimen in the experiment.

3.1 Introduction

The experiment comprised of collecting data from 20 different small independent houses. The heating system in the houses try to maintain the set point temperature on the thermostat. The amount of heat put in the system or the work done by the heating furnace/heat pump is determined by the variable factors inside and outside the house which are explained in chapter 1. The experiment is designed in such a manner that it covers the effect of all the significant variables which can be fitted in the empirical model. The calculations are done based on ASHRAE 90.2 codes and the data is collected through HOBO data loggers.

3.2 Data Collected

The data collected for the experimented is as follows:

3.2.1 Temperature in the Houses:

The equipment used in this experiment to get the temperature inside the house was a HOBO data logger for recording temperature and relative humidity measurements at constant intervals for a specified period.

The HOBO U12 Temperature/Relative Humidity/Light/External Data Logger is a four-channel logger with 12-bit resolution and can record up to 43,000 measurements or events. The external channel accepts a variety of sensors, including temperature, and split-core AC current sensors as well as 4-20 mA and voltage input cables. The logger uses a direct USB interface for launching and data readout by a computer.

Figure 3.2.1 (a) Hourly Temperature Data in Building 775, Apt 1

Figure 3.2.1 (b) Hourly Temperature Data in Building 777, Apt 2

An interval of 30 seconds is initialized in the loggers, which means that a temperature value will be recorded inside the house every 30 seconds. These data loggers are kept somewhere near thermostat in the house.

3.2.2 Weather Data

The weather data for empirical modeling which includes the hourly point temperature, wind speed, precipitation and weather conditions, was requested and successfully received from National Climatic Data Center. NOAA's (National Oceanic and Atmospheric Administration)

National Climatic Data Center is responsible for preserving, monitoring, assessing and providing public access to the Nation's treasure of climate and historical weather data

Date	Time (LST)	Station Type	Sky Conditions	Visibility (SM)	Weather Type	Dry Bulb Temp		Wet Bulb Temp		Dew Point Temp		Rel Humd %	Wind Speed (MPH)	Wind Dir	Wind Gusts (MPH)	Station Pressure (in. hg)	Press Tend	Net 3-hr Chg (mb)	Sea Level Pressure (in. hg)	Report Type	Precip. Total (in)	Alti-meter (in. hg)
						(F)	(C)	(F)	(C)	(F)	(C)											
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
01	0053	12	OVC021	10.00		35	1.7	31	-0.4	25	-3.9	67	7	220		28.69			30.06	AA		30.03
01	0153	12	BKN025 OVC029	9.00		35	1.7	32	-0.2	26	-3.3	70	7	220		28.69			30.05	AA		30.02
01	0212	12	OVC025	2.50	-SN	34	1.0	32	-0.1	28	-2.0	79	8	220		28.69			M	SP		30.03
01	0221	12	OVC023	3.00	-SN	34	1.0	32	-0.1	28	-2.0	79	7	210		28.69			M	SP		30.03
01	0251	12	SCT019 OVC025	2.50	-SN BR	34	1.0	32	-0.1	28	-2.0	79	5	210		28.70			M	SP		30.04
01	0253	12	FEW012 SCT017 OVC025	2.00	-SN BR	33	0.6	31	-0.3	29	-1.7	85	3	210		28.70			30.07	AA	T	30.04
01	0256	12	FEW009 SCT017 OVC025	1.75	-SN BR	32	0.0	30	-0.8	28	-2.0	85	5	200		28.69			M	SP		30.03
01	0320	12	BKN009 BKN017 OVC027	2.50	-SN BR	32	0.0	31	-0.4	30	-1.0	92	5	210		28.69			M	SP		30.03
01	0323	12	SCT007 BKN011 OVC027	3.00	-SN BR	32	0.0	31	-0.4	30	-1.0	92	5	210		28.69			M	SP		30.03
01	0336	12	BKN009 OVC015	4.00	-SN BR	32	0.0	31	-0.4	30	-1.0	92	8	210		28.69			M	SP		30.03
01	0353	12	OVC009	5.00	BR	32	0.0	31	-0.4	30	-1.1	92	5	210		28.69			30.06	AA	T	30.02
01	0410	12	OVC009	2.00	-SN BR	32	0.0	31	-0.4	30	-1.0	92	3	210		28.69			M	SP		30.02
01	0417	12	BKN007 OVC011	1.75	-SN BR	32	0.0	31	-0.4	30	-1.0	92	3	210		28.69			M	SP		30.02
01	0453	12	OVC007	1.75	-SN BR	32	0.0	31	-0.4	30	-1.1	92	6	210		28.68			30.04	AA	T	30.01
01	0505	12	BKN007 OVC011	2.00	-SN BR	32	0.0	31	-0.4	30	-1.0	92	5	210		28.68			M	SP		30.01
01	0527	12	BKN007 OVC011	3.00	BR	32	0.0	31	-0.4	30	-1.0	92	6	200		28.68			M	SP		30.00
01	0553	12	BKN007 OVC011	3.00	BR	32	0.0	32	-0.2	31	-0.6	96	5	200		28.68			30.03	AA	T	30.00
01	0604	12	OVC007	2.50	BR	32	0.0	31	-0.4	30	-1.0	92	3	210		28.68			M	SP		30.00
01	0613	12	BKN007 OVC011	3.00	BR	32	0.0	31	-0.4	30	-1.0	92	3	210		28.68			M	SP		30.00
01	0642	12	BKN007 OVC023	2.50	BR	32	0.0	31	-0.4	30	-1.0	92	3	200		28.68			M	SP		30.00
01	0648	12	SCT007 OVC021	1.75	-SN BR	32	0.0	31	-0.4	30	-1.0	92	5	210		28.68			M	SP		30.00
01	0653	12	FEW004 SCT007 OVC019	1.50	-SN BR	32	0.0	32	-0.2	31	-0.6	96	5	210		28.68			30.03	AA	T	30.00
01	0705	12	BKN004 BKN007 OVC017	1.50	-SN BR	32	0.0	31	-0.4	30	-1.0	92	3	210		28.68			M	SP		30.00
01	0721	12	BKN004 OVC017	2.00	BR	32	0.0	31	-0.4	30	-1.0	92	5	210		28.68			M	SP		30.01
01	0753	12	BKN004 OVC007	2.00	BR	32	0.0	32	-0.2	31	-0.6	96	5	210		28.68			30.03	AA	0.01	30.00
01	0804	12	OVC004	1.50	BR	32	0.0	31	-0.4	30	-1.0	92	3	210		28.68			M	SP		30.01
01	0828	12	BKN006 OVC026	2.00	BR	32	0.0	31	-0.4	30	-1.0	92	5	200		28.68			M	SP		30.01
01	0841	12	BKN004 OVC009	2.00	BR	32	0.0	31	-0.4	30	-1.0	92	6	200		28.69			M	SP		30.02
01	0849	12	BKN004 BKN018 OVC042	3.00	BR	32	0.0	31	-0.4	30	-1.0	92	6	210		28.69			M	SP		30.03
01	0853	12	FEW002 BKN006 OVC048	3.00	BR	32	0.0	32	-0.2	31	-0.6	96	6	200		28.69			30.06	AA	0.01	30.03

Figure 3.2.2 Hourly Meteorological Data by NCDC

3.2.3 Actual Energy Consumption

The readings from the electric meters were noted down before and after the experiment. The difference of these values was the total electricity or the gas consumption in a particular house. As defined by ASHRAE that 41.5% of the total energy used in a residential house is used for heating loads in North America, so 41.5% of the actual consumption in a house (difference of before and after readings) was the energy used for heating during the period of experiment (assumption in the model). Figure 3.2.3 shows the kWh reading obtained from the electricity meter from one of the houses.

Figure 3.2.3: kWh Reading

S. No	Building Name	Apt No	Energy Usage (kWh)
1	MTW	102	1,579
2		201	2,000
3		202	1,500
4		301	1,800
5		302	1,720

S. No	Building Name	Apt No	Energy Usage (kWh)
6	775	1	588
7		3	1038
8		102	761
9		203	480
10		205	837
11		4	434
12	777	1	938
13		2	445
14		103	845
15		106	590

Table 3.2.3: kWh Usage in Residential Houses

3.2.4 Blower Door Tests (Leakage Area)

Blower door tests were done on every floor of all the three buildings. The purpose of all these tests was to find leakage area of the house. The house was depressurized to -50 Pa by a fan which has a variable speed drive installed on it. The readings noted down from the experiment was CFM at 50 Pa. The gauge in the blower door test gave the cfm reading and following equations were used to calculate the leakage at natural conditions.

$$\text{Natural CFM} = \frac{\text{CFM}_{50}}{n}$$

$$\text{Natural CFM} = \frac{935}{18.2}$$

Now, to convert cfm to air changes per hour:

$$\text{ACH} = \frac{\text{Natural CFM} \times 60}{\text{Area} \times \text{Height}}$$

Where,

n = Lawrence Berkeley Laboratory (LBL) n factor for ventilation, 18.2

LBL "N" FACTORS			
Zone	N Factor	# of Stories	Height Correction Factor
1	14-17	1	1
2	17-20	1.5	0.89
3	20-23	2	0.81
4	23-26	2.5	0.76
		3	0.72

Figure 3.2.4: LBL n factor for ventilation

S. No	Building Name	Apt No	Air Leakage (at 50 Pa)
1	MTW	102	601
2		201	532
3		202	536
4		301	596
5		302	594
6	775	1	931
7		3	940
8		102	810
9		203	1,471
10		205	1,420
11		4	950
12	777	1	931
13		2	951
14		103	810
15		106	820

Table 3.2.4: Air Leakage in Residential Houses

3.3 Use of ASHRAE Equations

For calculating the values of heat loss by different factors such as wind, infiltrations etc some equations are used from ASHRAE Handbook 2009 and standard values are used in some equations.

3.3.1 Heat Loss or Ideal Furnace Consumption

The ideal furnace consumption can be evaluated by calculating the heat loss taking in account the area of the particular house and R and U values specified by IECC 2009 for Monongalia County. Figure 3.5.1 shows the R values and U values for West Virginia.

Climate Zone 5 and 4 Marine	
Ceiling R-value	38
Wood Frame Wall R-value	20 or 13+5^h
Mass Wall R-value i	13/17
Floor R-value	30^s
Basement Wall R-value c	10/13
Slab R-value d, Depth	10, 2 ft
Crawlspace Wall R-value c	10/13
Fenestration U-Factor b	0.35
Skylight U-Factor b	0.6
Glazed fenestration SHGC b, e	NR

a. R-values are minimums. U-factors and SHGC are maximums. R-19 batts compressed into a nominal 2x6 framing cavity such that the R-value is reduced by R-1 or more shall be marked with the compressed batt R-value in addition to the full thickness R-value.

b. The fenestration U-factor column excludes skylights. The SHGC column applies to all glazed fenestration.

c. "15/19" means R-15 continuous insulated sheathing on the interior or exterior of the home or R-19 cavity insulation at the interior of the basement wall. "10/13" means R-10 continuous insulated sheathing on the interior or exterior of the home or R-13 cavity insulation at the interior of the basement wall.

d. R-5 shall be added to the required slab edge R-values for heated slabs. Insulation depth shall be the depth of the footing or 2 feet, whichever is less in zones 1 through 3 for heated slabs.

e. There are no SHGC requirements in the Marine zone.

- f. Basement Wall Insulation is not required in warm-humid locations.
- g. Or insulation sufficient to fill the framing cavity. R-19 is minimum.
- h. "13+5" means R-13 cavity insulation plus R-5 insulated sheathing. If structural sheathing covers 25 percent or less of the exterior, insulating sheathing is not required where structural sheathing is used. If structural sheathing covers more than 25 percent of exterior, structural sheathing shall be supplemented with insulated sheathing of at least R-2.
- i. The second R-value applies when more than half the insulation is on the interior of the wall.
- j. For impact rated fenestration complying with Section R301.2.1.2 of the International Residential Code or Section 1608.1.2 of the International Building code, the maximum U-factor shall be 0.75 in Zone 2 and 0.65 in Zone 3.

The equation used is:

$$Q = U A \Delta T$$

$$\text{Ideal Consumption (9 days)} = ((\text{Area}_{\text{Floor}} / R_{\text{Floor}}) + (\text{Area}_{\text{Walls}} / R_{\text{Floor}}) + (\text{Area}_{\text{Roof}} / R_{\text{Roof}}) + (U_{\text{Windows}} \times \text{Area}_{\text{windows}})) \times \Delta T \times 24 \times 9 \times 293 / 1,000,000$$

Where,

U = Overall Heat transfer coefficient, BTU/(h °F ft²)

A = Area, ft²

ΔT = Temperature difference (between inside and outside the house), °F

(Note: 1 MMBtu = 293 kWh)

3.3.2 Response

The response of the model is calculated by dividing the ideal consumption (calculated) by the formula described above and the actual consumption which is the noted kWh consumption.

$$\text{Res} = \frac{\text{Ideal Consumption}}{\text{Actual Consumption}}$$

Where,

Res = Response, no units

Actual Consumption = Actual energy consumption noted from the utility meter, kWh

3.3.3 Variables in the Model

The variables which are used in this research are described below. These variables have an effect on the response and are proved significant in the analysis explained in the next chapter.

3.3.3.1 Area

The area of the house has an effect on the heat loss and power consumption. Generally, bigger house have more leakage but the leakage also depends on the year the house was built in. The climatic conditions also play a significant role on the response factor of the house. Figure 1.9.4 documents the air leakage values from different parts in low-rise residential houses.

3.3.3.2 Occupancy

Human body emits some heat in the environment which depends upon the weight of the person and the activity done. The total amount of heat produced is equal to calories consumed minus the work done by the person. Table 3.3.3.2 gives the values of heat emitted at different levels of activities.

Degree of Activity	Typical Application	Average Metabolic rate - male adult (W)	Room Dry Bulb Temperature (°C)											
			28		27		26		24		22		20	
			Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.	Sens.	Lat.
Seated at rest	Cinema, theatre, school	100	50	50	55	45	60	40	67	33	72	28	79	21
Seated, very light work	Computer working	120	50	70	55	65	60	60	70	50	78	42	84	36
Office work	Hotel reception, cashier	130	50	80	56	74	60	70	70	60	78	52	86	44
Standing, walking slowly	Laboratory work	130	50	80	56	74	60	70	70	60	78	52	86	44
Walking, seated		150	53	97	58	92	64	86	76	74	84	66	90	60
Moderate work	Servant, hair dresser	160	55	105	60	100	68	92	80	80	90	70	98	62
Light bench work	Mechanical production	220	55	165	52	158	70	150	85	135	100	120	115	105
Moderate Dancing	Party	250	62	188	70	180	78	172	94	156	110	140	125	125
Fast walking	Mountain walking	300	80	220	88	212	96	204	110	190	130	170	145	155
Heavy work	Athletics	430	132	298	138	292	144	286	154	276	170	260	188	24

Table 3.3.3.2: Sensible and Latent Heat Loss from Human

For the empirical modeling of this experiment, we have used the value to be 256 Btu/hr per person.

3.3.3.3 Air Changes Per Hour

Air infiltration rate can vary from 0.1 ACH to 1.5 ACH depending on the weather conditions. Air infiltration depends on air leakage, pressure difference cause by temperature difference and forces of the wind.

$$ACH = \frac{Q \cdot 60}{A \cdot H}$$

Where,

ACH = Air changes per hour

A = Area, ft²

H = Height, ft

The speed of wind has a considerable effect on the infiltration rate in the houses. At low wind speeds infiltration occurs mostly via stack effect and at high wind speeds, the enhanced air infiltration is driven by wind and temperature effect. [9]

$$Q = A_L \cdot \sqrt{C_s \cdot \Delta T + C_w \cdot U^2}$$

Where,

A_L = Leakage area, in²

C_s = Stack Coefficient

ΔT = Temperature Difference

C_w = Wind Coefficient

U = Wind Velocity, mph

3.4 Empirical Modeling

The method used in this research to develop an equation for analyzing the effectiveness of the insulation of a residential house is regression analysis. A multiple linear regression was done between the response and variables: area, occupancy, temperature difference and air changes per

hour. ACH include the effect of wind because the CFM₅₀ readings from the blower door tests does not neglect the heat loss due to winds.

All the calculations were performed in MS Excel and the calculated values were imported to Minitab 15 software to develop the empirical model using Multiple Linear Regression (MLR).

S. No	Building Name	Apt No	Actual Consumption (kWh)	Ideal Consumption (kWh)	Response	Area (sq ft)	Temp Difference (°F)	No of Residents	Air Changes per Hour
1	MTW	102	655	386	0.59	770	30.93	4	0.32
2		201	830	428	0.52	770	34.24	4	0.28
3		202	623	378	0.61	770	30.27	4	0.29
4		301	747	405	0.54	770	32.42	5	0.32
5		302	714	391	0.55	770	31.27	5	0.32
6	775	1	244	405	1.66	667	37.39	3	0.58
7		3	431	418	0.97	667	38.55	2	0.58
8		102	316	407	1.29	667	37.61	2	0.50
9		203	199	377	1.89	667	34.80	2	0.91
10		205	347	394	1.13	667	36.38	6	0.88
11		4	180	372	2.07	667	34.35	3	0.59
12	777	1	389	405	1.04	667	37.39	3	0.58
13		2	185	373	2.02	667	34.45	1	0.59
14		103	351	417	1.19	667	38.53	2	0.50
15		106	245	367	1.50	667	33.90	2	0.51

Table 3.4: Data Set for Empirical Modeling

CHAPTER 4

DESIGN AND DEVELOPMENT OF MODEL

Multiple linear regression (MLR) is a method used to model the linear relationship between a dependent variable (predictand) and one or more independent variables (predictors). The predictors used in the study are variables (inside and outside the house) that effect the response of thermal barriers or insulation. All the values of predictands have been recorded and documented for this study. None of the predictands are calculated or assumed. The predictors and predictands were analyzed by means of multiple linear regression (MLR) using the Minitab 15 program. The various stages in the design and development of the model are explained below

4.1 Insulation Effectiveness Study Data Analysis

The data in this study were obtained by installing data loggers, performing blower door tests, walk-around data collection from houses and from trusted weather data websites. These data values can be found in chapter 3. The data were formatted into a spreadsheet and analyzed. All data houses which were rejected had one or more reasons in common from the following table.

S.No.	Reason for Rejection
1.	Houses in apartment buildings with centralized heating
2.	Houses with any type of gas usage
3.	Houses with area more than 800 sq ft
4.	Houses with a heating setback control

The exception made for the data houses was in house no 203 and 205 in building 775. The recorded CFM₅₀ value was significantly than the expected value. But due to considerable explanations for this anomaly, these high values were deemed correct for the model. The houses with gas usage could not be populated in the model because it was not safe to perform the blower door tests in those houses as it would have risked the forced convection of carbon monoxide inside the house. Houses with more than 800 ft² were not used in the model to avoid any outliers.

4.2 Predictors for Multiple Linear Regression

The predictors chosen in MLR are area, temperature difference, number of occupants and ACH (air changes per hour). The area of the house increases the energy usage and also the energy lost by walls and it is observed that the leakage in older and big houses is comparatively more. The temperature difference has a positive relationship with the response, it increases the energy usage. The number of occupants decrease the energy used in the house by adding heat to the system. The ACH is dependent on the leakage area of the house. It is directly proportional to the kWh used. The scatter plots of response with all the predictors are shown in Figures below.

Figure 4.2: Plots of Response (Predictands) with all the variables.

The reason for comparatively low coefficients of determination than the final regression equation (explained later in the chapter) for linear fitted values shown in the graphs above is that all the data points were randomly collected and there may not be a linear relationship with the response. Also the response is affected by many other factors like climatic zone, setback control, type of

insulation, grade and type of heating equipment. The scope of this experiment did not allow the use of these variables.

4.3 Using Multiple Linear Regression to Determine First Order Coefficient

Multiple linear regression is a method used to model the linear relationship between a dependent variable (predictand) and one or more independent variables (predictor).

The coefficient of determination (R^2) is the proportion of variance accounted for, explained, or described by regression.

4.4 Model

Multiple linear regression (MLR) was performed using the three predictand response R (Ideal Energy consumption/actual energy consumption), and the predictors: area, temperature difference, number of occupants, air changes per hour, natural CFM, $\ln(\text{ACH})$ and $\ln(\text{natural CFM})$. The response trials were used to narrow down the results obtained by the regression analysis. Table 4.4 shows the response and predictors used to develop the model.

S. No	Building Name	Apt No	Actual Consumption (kWh)	Ideal Consumption (kWh)	Response	Area (sq ft)	Temp Difference	No of Occupants	Air Changes per Hour
1	MTW	102	655	386	0.59	770	30.93	4	0.32
2		201	830	428	0.52	770	34.24	4	0.28
3		202	623	378	0.61	770	30.27	4	0.29
4		301	747	405	0.54	770	32.42	5	0.32
5		302	714	391	0.55	770	31.27	5	0.32
6	775	1	244	405	1.66	700	37.39	3	0.58
7		3	431	418	0.97	700	38.55	2	0.58
8		102	316	407	1.29	700	37.61	2	0.50
9		203	199	377	1.89	700	34.80	2	0.91
10		205	347	394	1.13	700	36.38	6	0.88
11		4	180	372	2.07	700	34.35	3	0.59
12	777	1	389	405	1.04	700	37.39	3	0.58
13		2	185	373	2.02	700	34.45	1	0.59
14		103	351	417	1.19	700	38.53	2	0.50
15		106	245	367	1.50	700	33.90	2	0.51

Table 4.4 (a): Predictand and Predictors for Multiple Linear Regression Analysis

Variable	Lower Limit	Upper Limit
Area (ft ²)	700	770
Temperature Difference (F)	30.27	38.55
Number of Occupants	1	6
Air Changes per Hour	0.28	0.91

Table 4.4 (b): Boundary Limits for Variables in the Model

In the first case, regression for thermal barrier response was done using all the variables: area, temperature difference, number of occupants and natural ACH. It should be noted that predictors: natural ACH, natural CFM, $\ln(\text{ACH})$ and $\ln(\text{nCFM})$ are all variables derived from the same quantity. Hence, only one of these variables can be used as a predictor in the model. Similarly, in the next case only three variables were used and so on one variable was neglected in every case. After these four cases, the variables ACH, natural CFM, $\ln(\text{ACH})$ and $\ln(\text{nCFM})$ were regressed one by one in the model. Table 4.4 (b) shows the different multiple linear regressions, the predictor, the coefficients and the corresponding coefficient of determination. (Complete results of all the regression trials are documented in the Appendix).

As shown in table 4.4 (b), the coefficient of determination (R^2) and the adjusted coefficient of determination ($\text{adj } R^2$) for all multiple linear regression iterations were in the range of 72.3% to 84.7%. This signifies that there was not very much difference in R^2 values but there was not enough explanation for the use of transformation values ($\ln(\text{ACH})$ and $\ln(\text{nCFM})$) though the model demonstrated a better P-value by using the $\ln(\text{ACH})$ and $\ln(\text{nCFM})$ predictors.

After performing Multiple Linear Regression (MLR) analysis on different combination of predictand and predictors, it was concluded that the MLR with response vs area, temperature difference, number of occupants and Air Changes per Hour produced the best results and best fit. The P-value associated with ACH was 0.50, which concludes that the variable is not very significant in the equation but mathematically it is proved that there is a direct positive relationship between the energy consumed for heating and the air leakage (which affects ACH).

Trial Number	Predictand	Coefficient	Area	Del T	Occupants	ACH	nCFM	ln(nCFM)	ln(ACH)	R-sq
1	R	13.96	-0.01	-0.12	-0.10	0.50	-	-	-	84.9
2	R	2.6309	-	-0.0488	-0.2417	2.0465	-	-	-	78.9
3	R	3.2599	-0.0031	-	-0.1601	1.1891	-	-	-	73.2
4	R	17.4523	-0.0160	-0.0565	-	-0.1440	-	-	-	82.1
5	R	16.2495	-0.0142	-0.1387	-0.0775	-	-	-	-	84.3
6	R	14.1239	-0.0119	-0.1284	-0.1067	-	0.0057	-	-	85.0
7	R	12.3374	-0.0111	-0.1268	-0.1103	-	-	0.3788	-	85.0
8	R	13.6851	-0.0106	-0.1268	-0.1103	-	-	-	0.3788	85.1

Table 4.4 (c): Plots of Response (Predictand) with all the variables.

4.4.1 Final Equation, Coefficients and ANOVA

The final empirical equation is:

$$\text{Response} = 13.96 - 0.0117 \text{ Area} - 0.1284 \text{ Del T} - 0.1067 \text{ Occupants} + 0.5089 \text{ ACH}$$

Where,

Response	Ratio of Ideal Energy Consumption and Actual Energy Consumption
β_0	First Coefficient
Area	Area of House
Del T	Difference between house temperature and ambient temperature
Occupants	Number of occupants in the house
ACH	Air Changes per hour

Table 4.4.1 (a) shows the parameter estimates for the model. The table shows the predictors, coefficients, standard error of coefficients, T-test and P-test values. It should be noted that the standard error coefficient and P-test value of ACH predictor is quite high and is not considered very significant in the empirical equation. But mathematically, it has been proved that there is a significant effect of ACH and it cannot be neglected. This relation is proved in the following equations.

$$Q = A_L \cdot \sqrt{C_s \cdot \Delta T + C_w \cdot U^2}$$
$$ACH = \frac{60 \cdot Q}{V}$$

Where,

- A_L = Leakage area, in²
- C_s = Stack Coefficient
- ΔT = Temperature Difference
- C_w = Wind Coefficient
- U = Wind Velocity, mph
- Q = Heat Loss
- ACH = Air Changes Per Hour

Predictor	Coeff	SE Coeff	T	P
Constant	9.913	3.14	3.16	0.01
Area	-0.006639	0.002691	-2.47	0.033
Del T	-0.12356	0.04397	-2.81	0.018
Occupants	-0.10248	0.07417	-1.38	0.197
ACH	0.467	0.6817	0.69	0.509

Table 4.4.1 (a): Parameter Estimates of the Empirical Model

Regression Statistics	
Multiple R	0.92
R Square	0.85
Adjusted R Square	0.78
Standard Error	0.26
Observations	15

Table 4.4.1 (b): Summary of Fit

	Df	Sum of Squares	Mean Square	F	Significance F
Regression	4	3.6645	0.9161	13.6743	0.0005
Residual	10	0.6700	0.0670	-	-
Total	14	4.3344	-	-	-

Table 4.4.1 (c): Analysis of Variance (ANOVA)

Figure 4.4.1: Residual Plots for Response

CHAPTER 5

MODEL VALIDATION AND RESULTS

5.1 Model Execution

This chapter deals with the execution of empirical model by using real-time data from one of the buildings from which data was collected during the conduct of this research. The goal here is to present the data collected from the site visits and demonstrate its use in the model inputs section.

5.2 Model Inputs:

The data collection has been done through installing the data loggers again and doing the blower door test again to get the CFM₅₀ reading. Extensive details on area, temperature difference, and house parameters were collected during the house visits. The following sections utilize data collected to illustrate the workings of the empirical model. However, the models can be applied to variety of parameters as considered and reported earlier. It should be noted that not all response variables will be applicable to specific indoor and outdoor conditions.

Since all the parameter and their affects were discussed in detail in the previous section, this section will exclusively focus on the calculations and the values for outputs in table format. The details of the two houses will be discussed as House A and House B.

5.2.1 House A:

The product parameters:

Area: 667 ft²

Height: 8 ft

Temperature Difference: 31.11 °F

Occupants: 2

CFM₅₀: 935 cfm

Now the next step would be to convert the CFM₅₀ to natural ACH:

$$\text{Natural CFM} = \frac{\text{CFM}_{50}}{n}$$

$$\text{Natural CFM} = \frac{935}{18.2}$$

$$= 51.5 \text{ cfm}$$

Now, to convert cfm to air changes per hour:

$$\text{ACH} = \frac{\text{Natural CFM} \times 60}{\text{Area} \times \text{Height}}$$

$$= \frac{51.5 \times 60}{667 \times 8}$$

$$= 0.58 \text{ ACH}$$

The model was populated with data collected from the house A. The response results were obtained from the model and screenshots are provided in the section below.

The equation is as follows:

$$\text{Response} = 13.96 - 0.0117 \text{ Area} - 0.1284 \text{ Del T} - 0.1067 \text{ Occupants} + 0.5089 \text{ ACH}$$

$$= 13.96 - (0.0117 \times 667) - (0.1284 \times 31.11) - (0.1067 \times 3) + (0.5089 \times 0.58)$$

$$= 2.25$$

$$= ((667/38)+(832/13)+(667/10)+(0.5*60) \times 31.11)*24*9*293/1000000$$

$$= 351 \text{ kWh}$$

$$(1\text{MMBtu} = 293\text{kWh})$$

$$\text{kWh consumption} = \text{Ideal Consumption} / \text{Response}$$

$$= 351/2.25$$

$$= 156 \text{ kWh}$$

5.2.2 House B:

The product parameters:

Area: 667 ft²

Height: 8 ft

Temperature Difference: 33.55 °F

Occupants: 3

CFM₅₀: 940 cfm

Now the next step would be to convert the CFM₅₀ to natural ACH:

$$\begin{aligned}\text{Natural CFM} &= \frac{\text{CFM}_{50}}{n} \\ \text{Natural CFM} &= \frac{940}{18.2} \\ &= 51.6 \text{ cfm}\end{aligned}$$

Now, to convert cfm to air changes per hour:

$$\begin{aligned}\text{ACH} &= \frac{\text{Natural CFM} \times 60}{\text{Area} \times \text{Height}} \\ &= \frac{51.6 \times 60}{667 \times 8} \\ &= 0.58 \text{ ACH}\end{aligned}$$

The model was populated with data collected from the house A. The response results were obtained from the model and screenshots are provided in the section below.

The equation is as follows:

$$\text{Response} = 13.96 - 0.0117 \text{ Area} - 0.1284 \text{ Del T} - 0.1067 \text{ Occupants} + 0.5089 \text{ ACH}$$

$$= 13.96 - (0.0117 \times 667) - (0.1284 \times 33.55) - (0.1067 \times 3) + (0.5089 \times 0.58)$$

$$= 1.83$$

$$\text{Ideal Consumption (9 days)} = ((\text{Area}_{\text{Floor}} / R_{\text{Floor}}) + (\text{Area}_{\text{Walls}} / R_{\text{Floor}}) + (\text{Area}_{\text{Roof}} / R_{\text{Roof}}) + (U_{\text{Windows}} \times \text{Area}_{\text{windows}})) \times \Delta T \times 24 \times 9 \times 293 / 1,000,000$$

$$= ((667/38) + (832/13) + (667/10) + (0.5 \times 60) \times 33.55) \times 24 \times 9 \times 293 / 1000000$$

$$= 378 \text{ kWh} \quad (1 \text{ MMBtu} = 293 \text{ kWh})$$

$$\text{kWh consumption} = \text{Ideal Consumption} / \text{Response}$$

$$= 378 / 1.83$$

$$= 207 \text{ kWh}$$

This value matches with the energy consumption values recorded for this period and will be verified through energy bills too.

5.3 Results and Discussion

The model has been populated with the data collected in the host houses and results were obtained. The calculations on different losses and heat inputs were discussed in section 5.2. Table 5.2 compared the actual energy consumption with predicted energy consumption. The actual consumption was observed for one day and then was extrapolated for nine days. An average error of 15% is noted between the predicted values and the actual values of energy consumption. Table 5.3 shows the model values of energy consumption, actual values of energy consumption and the error found in the model.

	Energy Consumption from the Model (kWh)	Actual Energy Consumption (kWh)	Error
House A	156	184	15.21%
House B	207	231	13.04%

Table 5.3: Comparison of Results

This section verifies that the model is valid and holds good within the 20% error limits and subsets of the range of the values used to populate the empirical model.

This model can be used to predict the energy consumption and the effectiveness of the thermal envelope within the limitations. The limitations of this model are:

1. The area of the house should not exceed 770 sq ft.
2. The thermostat inside the house should not be calibrated and it should not be programmed for setback control
3. The model cannot be used for summer months
4. The model can give readings with 30% error
5. The empirical model produce meaningful results only when the variables are in the ranges of values used to develop the empirical equation
6. ACH will have to be estimated as it is not possible to perform a blower door test every time the equation/model is used.

Suggestions to Home Owners:

1. The variables should be within the limits as mentioned in Table 4.4 (b) to avoid absurd and negative response values.
2. For calculating ACH, following steps should be followed:
 - a. Calculate effective leakage area using the following table

	Units	Best Estimate	Minimum	Maximum
Ceiling	in2/ft2	0.026	0.011	0.04
Door Frame, Wood	in2/ft2	0.004	0.001	0.004
Door, General	in2/ft2	0.015	0.011	0.021
Electrical outlets	in2/ea	0.023	0.012	0.54
Ceiling-wall joint	in2/lfte	0.07	0.0075	0.12
Vents	in2/ea	1.6	0.39	3.1
Walls, clay brick cavity wall	in2/ft2	0.0098	0.0007	0.033
Windows, not weatherstripped	in2/ft2	0.023	0.011	0.035

- b. Calculate CFM₅₀:

$$\text{CFM}_{50} = \text{ELA} \times 10$$

- c. Calculate natural CFM:

$$\text{Natural CFM} = \frac{\text{CFM}_{50}}{n}$$

- d. Convert natural cfm to air changes per hour:

$$ACH = \frac{\text{Natural CFM} \times 60}{\text{Area} \times \text{Height}}$$

Where,

n = Lawrence Berkeley Laboratory (LBL) n factor for ventilation, 18.2

3. Once the response and all the variables are known, the effectiveness of thermal insulation can be assessed using the following table.

Response	Rating	Description
Less than 1	Bad	Action needed immediately
Equal to 1	OK	No action required but may require in near future
Greater than 1	Good	No action required

Table 5.3: Effectiveness Rating in Residential Households

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

Based on the data analysis done by Multiple Linear Regression technique, an empirical equation was formulated to calculate the response if the variables, area, temperature difference and air changes per hour is known.

The response rating was developed after assessing the houses and analyzing the utility bills of the houses which were used to formulate the empirical equations. These equations are empirically correct because they meet the MLR assumptions; the R^2 values are quite high for an experimental study, which signifies that they explain considerable part of the observed variation in the data. Also, the results obtained from the empirical equation for the calculation of response are in close proximity with the experimental values. Consequently, these equations are reliable predictors of response and effectiveness of thermal barrier of a household insulation.

Empirical equations were also formulated by using a combination of other variables but the fit was obtained using the final four variables mentioned above. Most of the MLR equations produced satisfactory results and yielded high R^2 values. Some of the equations violated the MLR assumptions and hence were considered unreliable to be used. The empirical model was validating by testing the value of response from the empirical equation and then comparing it with the energy consumption in kWh in real time.

To check the robustness of the empirical equations, various random values were used to generate response functions and the results concluded the following limitations in the empirical model explained in the Table below.

S.NO	Limitation	Reason
1.	Size of the house	No outlier population
2.	Season	Only heavy winter season could be used

Table 6.1 (a): Limitation of the Empirical Model

Therefore the final conclusions of the study are as follows.

1. A good estimate of a house's insulation effectiveness and the energy consumption in the form of electricity can be found out using the model equation developed.
2. The model will have outliers in specific cases.
3. The model equation is developed only for small apartments and for zone 5 winter season.
4. The model can be used to rate the effectiveness of house insulation.

6.2 Future Work

The ongoing research and more data points are required to make the model more reliable. Any system has to be refined by including minute details that can affect the system output. The development of empirical model in this study has given a feasible methodology to help the house owners to analyze their furnace heating utilization and insulation effectiveness for determining whether the house need any commissioning or retro-commissioning. However, the following work would further improve the appearance, comfort, robustness, and credibility of the empirical model.

1. Populating the model with more data points to get good significance on ACH variable.
2. The heating energy consumption used in the model should be obtained by installing a current transducer.
3. The temperature difference readings and energy consumption reading should be taken at small intervals for long periods to retrieve more accurate data.
4. The model should also include data from houses which have more than one floor and whose area is more than 770 sq ft.

5. The model should also include data from houses which are located outside West Virginia which have more than one floor and whose area is more than 770 sq ft to make it more robust and valid in other parts of the world.
6. Evaluate more accurate ideal heating energy consumption by simulating the houses in eQUEST.
7. The model should be validated on an experimental model house where the variables can be varied and the response/results are already known.

APPENDIX C

Multiple Linear Regression Reports from Minitab 15

To provide a better understanding of the various data and plots, an explanation of the different components is presented below.

Summary of Fit Table

- “R Square” (R^2) is the coefficient of determination, which is the proportion of variance accounted for, explained, or described by the regression model. If the regression is perfect, the R^2 value is one. If the regression is a failure and the sum of squares of errors equals the total sum of squares, no variance is accounted for by regression and R^2 is zero.
- “R Square Adj” is the adjusted R^2 value, which measures the proportion of the variation in the predictand accounted for by the predictors. Adjusted R^2 allows for the degrees of freedom associated with the sums of squares.
- “Root Mean Square Error” is the square of the differences between values predicted by a model and the observed values being modeled.
- “Mean of Response” is the values of the predictand calculated from the regression parameters and a given value of the predictor. This is an estimate of the mean of the predictand associated with an explanatory value of the predictor. The mean of response is used in the plots as a horizontal reference point.
- “Observations” are the number of data points used in the regression model.

Analysis of Variance Table

- “Source” has three rows, one for total variability and one for each of the two pieces comprising the total, Model or Regression, and Error or Residual. The “C” in “C Total” stands for corrected.
- “DF” is the degrees of freedom. For the Model, the number of degrees of freedom is the number of predictors used for the regression. For the Error, the degrees of freedom is the

number of observations minus the number of predictors minus 1. The degrees of freedom for C Total is the sum of the degrees of freedom for the Model and the Error.

- “Sum of Squares” is a way to find the function which best fits (least varies) from the data. It is the total variability in the response which is calculated from $\sum (y - \bar{y})^2$, where $\bar{y}$ is the sample mean. The “Corrected” in “C Total” refers to subtracting the sample mean before squaring. The amount of variation in the data that cannot be accounted for by this simple method of prediction is given by the total sum of squares. When the regression model is used for prediction, the uncertainty that remains is the variability about the regression line, $\sum (y - \hat{y})^2$, where $\hat{y}$ is the predicted value of the predictand. This is the Error sum of squares. The difference between the Total sum of squares and the Error sum of squares is the Model sum of squares, which is equal to $\sum (\hat{y} - \bar{y})^2$.
- “Mean Squares” are the sum of squares divided by the corresponding degrees of freedom.
- “F Ratio” is the test statistic used to decide whether a model as a whole has a statistically significant predictive capability, that is, whether the regression sum of squares is big enough, considering the number of variables needed to achieve it. F is the ratio of the Model mean square to the Error mean square.

Parameter Estimates Table

- “Term” is the predictor.
- “Estimate” is the regression coefficients in the regression equation.
- “Standard Error” is an estimate of the standard deviation of the regression coefficients.
- “t ratio” tests the hypothesis that a population regression coefficient is 0 when the other predictors are in the model. It is the ratio of the sample regression coefficient to its standard error.

The different models which were tested during the development of final equation are as follows:

1. Regression Analysis: Response versus Del T, Occupants, ACH

Predictor	Coeff	SE Coeff	T	P
Constant	2.631	1.44	1.83	0.095
Del T	-0.04881	0.04148	-1.18	0.264
Occupants	-0.24173	0.06969	-3.47	0.005
ACH	2.0466	0.5417	3.78	0.003

Parameter Estimates of the Empirical Model

Regression Statistics	
Multiple R	0.866468
R Square	0.750767
Adjusted R Square	0.682794
Standard Error	0.331462
Observations	15

Summary of Fit

	Df	Sum of Squares	Mean Square	F	Significance F
Regression	4	3.6645	0.9161	13.6743	0.0005
Residual	10	0.6700	0.0670	-	-
Total	14	4.3344	-	-	-

Analysis of Variance (ANOVA)

2. Regression Analysis: Response versus Area, Occupants, ACH

Predictor	Coeff	SE Coeff	T	P
Constant	3.26	3.19	1.02	0.33
Area	0.00	0.00	-0.72	0.49
Occupants	-0.16	0.10	-1.68	0.12
ACH	1.19	0.90	1.33	0.21

Parameter Estimates of the Empirical Model

Regression Statistics	
Multiple R	0.86
R Square	0.73
Adjusted R Square	0.66
Standard Error	0.34
Observations	15

Summary of Fit

	Df	Sum of Squares	Mean Square	F	Significance F
Regression	3.0	3.5	1.2	10.0	0.0018
Residual	11.0	1.3	0.1		
Total	14.0	4.8			

Analysis of Variance (ANOVA)

3. Regression Analysis: Response versus Area, Temperature Difference, ACH

Predictor	Coeff	SE Coeff	T	P
Constant	17.45	3.96	4.41	0.00
Area	-0.02	0.00	-4.59	0.00
ACH	-0.06	0.65	-0.09	0.93
Del T	-0.14	0.05	-3.11	0.01

Parameter Estimates of the Empirical Model

Regression Statistics	
Multiple R	0.91
R Square	0.82
Adjusted R Square	0.77
Standard Error	0.28
Observations	15

Summary of Fit

	Df	Sum of Squares	Mean Square	F	Significance F
Regression	3	3.98	1.33	16.84	0.000201
Residual	11	0.87	0.08		
Total	14	4.85			

Analysis of Variance (ANOVA)

4. Regression Analysis: Response versus Area, Temperature Difference, Occupants

Predictor	Coeff	SE Coeff	T	P
Constant	16.25	3.04	5.34	0.00
Area	-0.01	0.00	-5.39	0.00
Del T	-0.14	0.04	-3.28	0.01
Occupants	-0.08	0.06	-1.23	0.24

Parameter Estimates of the Empirical Model

Regression Statistics	
Multiple R	0.92
R Square	0.84
Adjusted R Square	0.80
Standard Error	0.26
Observations	15

Summary of Fit

	Df	Sum of Squares	Mean Square	F	Significance F
Regression	3	4.09	1.36	19.64	0.0001
Residual	11	0.76	0.07		
Total	14	4.85			

Analysis of Variance (ANOVA)

5. Regression Analysis: Response versus Area, Temperature Difference, Occupants, natural CFM

Predictor	Coeff	SE Coeff	T	P
Constant	14.12	4.41	3.20	0.01
Area	-0.01	0.00	-2.78	0.02
Del T	-0.13	0.05	-2.80	0.02
Occupants	-0.11	0.08	-1.38	0.20
Natural CFM	0.01	0.01	0.68	0.51

Parameter Estimates of the Empirical Model

Regression Statistics	
Multiple R	0.92
R Square	0.85
Adjusted R Square	0.79
Standard Error	0.27
Observations	15

Summary of Fit

	Df	Sum of Squares	Mean Square	F	Significance F
Regression	4	4.12	1.03	14.13	0.0004
Residual	10	0.73	0.07		
Total	14	4.85			

Analysis of Variance (ANOVA)

6. Regression Analysis: Response versus Area, Temperature Difference, Occupants, log (natural CFM)

Predictor	Coeff	SE Coeff	T	P
Constant	12.34	6.16	2.00	0.07
Area	-0.01	0.00	-2.23	0.05
Del T	-0.13	0.05	-2.75	0.02
Occupants	-0.11	0.08	-1.41	0.19
Ln(natural CFM)	0.38	0.52	0.74	0.48

Parameter Estimates of the Empirical Model

Regression Statistics	
Multiple R	0.92
R Square	0.85
Adjusted R Square	0.79
Standard Error	0.27
Observations	15

Summary of Fit

	Df	Sum of Squares	Mean Square	F	Significance F
Regression	4	4.12	1.03	14.13	0.0004
Residual	10	0.73	0.07		
Total	14	4.85			

Analysis of Variance (ANOVA)

7. Regression Analysis: Response versus Area, Temperature Difference, Occupants, log (ACH)

Predictor	Coeff	SE Coeff	T	P
Constant	13.69	4.67	2.93	0.02
Area	-0.01	0.01	-1.89	0.09
Del T	-0.13	0.05	-2.75	0.02
Occupants	-0.11	0.08	-1.41	0.19
Ln(ACH)	0.38	0.52	0.74	0.48

Parameter Estimates of the Empirical Model

Regression Statistics	
Multiple R	0.92
R Square	0.85
Adjusted R Square	0.79
Standard Error	0.27
Observations	15

Summary of Fit

	Df	Sum of Squares	Mean Square	F	Significance F
Regression	4	4.13	1.03	14.25	0.0004
Residual	10	0.72	0.07		
Total	14	4.85			

Analysis of Variance (ANOVA)

Temperature Data Collected (Sample- Building 777, Apt#205)

Date Time	Temp_Inside
11/8/2013	
22:53	74.424
11/8/2013	
23:53	74.206
11/9/2013 0:53	74.077
11/9/2013 1:53	74.554
11/9/2013 2:53	74.381
11/9/2013 3:53	74.12
11/9/2013 4:53	74.511
11/9/2013 5:53	74.163
11/9/2013 6:53	74.295
11/9/2013 7:53	74.295
11/9/2013 8:53	74.163
11/9/2013 9:53	74.163
11/9/2013	
10:53	74.163
11/9/2013	
11:53	74.163
11/9/2013	
12:53	74.163
11/9/2013	
13:53	74.163
11/9/2013	
14:53	74.511
11/9/2013	
15:53	74.424
11/9/2013	
16:53	74.25
11/9/2013	
17:53	74.338
11/9/2013	
18:53	74.338
11/9/2013	
19:53	74.12
11/9/2013	
20:53	74.295
11/9/2013	
21:53	74.163
11/9/2013	
22:53	74.424

11/9/2013	
23:53	74.163
11/10/2013	
0:53	74.338
11/10/2013	
1:53	74.424
11/10/2013	
2:53	74.163
11/10/2013	
3:53	74.467
11/10/2013	
4:53	74.077
11/10/2013	
5:53	74.12
11/10/2013	
6:53	74.163
11/10/2013	
7:53	74.25
11/10/2013	
8:53	74.511
11/10/2013	
9:53	74.077
11/10/2013	
10:53	74.467
11/10/2013	
11:53	74.163
11/10/2013	
12:53	74.163
11/10/2013	
13:53	74.338
11/10/2013	
14:53	74.163
11/10/2013	
15:53	74.467
11/10/2013	
16:53	74.12
11/10/2013	
17:53	74.381
11/10/2013	
18:53	74.424
11/10/2013	
19:53	74.338
11/10/2013	
20:53	74.554
11/10/2013	
21:53	74.554
11/10/2013	74.381

22:53	
11/10/2013	
23:53	74.12
11/11/2013	
0:53	74.163
11/11/2013	
1:53	74.163
11/11/2013	
2:53	74.12
11/11/2013	
3:53	74.077
11/11/2013	
4:53	74.077
11/11/2013	
5:53	74.424
11/11/2013	
6:53	74.12
11/11/2013	
7:53	74.077
11/11/2013	
8:53	74.511
11/11/2013	
9:53	74.467
11/11/2013	
10:53	74.597
11/11/2013	
11:53	74.64
11/11/2013	
12:53	74.077
11/11/2013	
13:53	74.338
11/11/2013	
14:53	74.338
11/11/2013	
15:53	74.25
11/11/2013	
16:53	73.861
11/11/2013	
17:53	73.126
11/11/2013	
18:53	72.48
11/11/2013	
19:53	72.007
11/11/2013	
20:53	71.62
11/11/2013	
21:53	74.856

11/11/2013	
22:53	75.204
11/11/2013	
23:53	75.29
11/12/2013	
0:53	75.463
11/12/2013	
1:53	75.551
11/12/2013	
2:53	75.117
11/12/2013	
3:53	75.463
11/12/2013	
4:53	75.117
11/12/2013	
5:53	75.029
11/12/2013	
6:53	75.333
11/12/2013	
7:53	75.204
11/12/2013	
8:53	75.029
11/12/2013	
9:53	75.16
11/12/2013	
10:53	75.376
11/12/2013	
11:53	75.074
11/12/2013	
12:53	74.163
11/12/2013	
13:53	74.163
11/12/2013	
14:53	72.955
11/12/2013	
15:53	71.877
11/12/2013	
16:53	70.974
11/12/2013	
17:53	70.286
11/12/2013	
18:53	69.685
11/12/2013	
19:53	69.643
11/12/2013	
20:53	73.731
11/12/2013	76.246

21:53	
11/12/2013	
22:53	76.681
11/12/2013	
23:53	76.375
11/13/2013	
0:53	76.375
11/13/2013	
1:53	76.464
11/13/2013	
2:53	76.071
11/13/2013	
3:53	76.114
11/13/2013	
4:53	76.203
11/13/2013	
5:53	76.028
11/13/2013	
6:53	76.246
11/13/2013	
7:53	76.071
11/13/2013	
8:53	74.943
11/13/2013	
9:53	74.163
11/13/2013	
10:53	73.645
11/13/2013	
11:53	72.997
11/13/2013	
12:53	72.523
11/13/2013	
13:53	72.007
11/13/2013	
14:53	71.62
11/13/2013	
15:53	71.964
11/13/2013	
16:53	72.007
11/13/2013	
17:53	71.404
11/13/2013	
18:53	70.887
11/13/2013	
19:53	70.459
11/13/2013	
20:53	70.072

11/13/2013	
21:53	70.201
11/13/2013	
22:53	70.587
11/13/2013	
23:53	70.372
11/14/2013	
0:53	74.554
11/14/2013	
1:53	75.16
11/14/2013	
2:53	73.818
11/14/2013	
3:53	73.299
11/14/2013	
4:53	72.955
11/14/2013	
5:53	73.126
11/14/2013	
6:53	73.429
11/14/2013	
7:53	73.04
11/14/2013	
8:53	73.083
11/14/2013	
9:53	73.342
11/14/2013	
10:53	73.299
11/14/2013	
11:53	72.912
11/14/2013	
12:53	73.213
11/14/2013	
13:53	73.04
11/14/2013	
14:53	73.04
11/14/2013	
15:53	73.213
11/14/2013	
16:53	73.04
11/14/2013	
17:53	72.48
11/14/2013	
18:53	71.877
11/14/2013	
19:53	71.964
11/14/2013	75.204

20:53	
11/14/2013	
21:53	75.204
11/14/2013	
22:53	74.338
11/14/2013	
23:53	74.077
11/15/2013	
0:53	74.12
11/15/2013	
1:53	73.947
11/15/2013	
2:53	74.295
11/15/2013	
3:53	73.904
11/15/2013	
4:53	74.034
11/15/2013	
5:53	74.295
11/15/2013	
6:53	74.077
11/15/2013	
7:53	73.99
11/15/2013	
8:53	74.338
11/15/2013	
9:53	74.163
11/15/2013	
10:53	73.947
11/15/2013	
11:53	74.12
11/15/2013	
12:53	74.295
11/15/2013	
13:53	74.163
11/15/2013	
14:53	74.163
11/15/2013	
15:53	74.077
11/15/2013	
16:53	74.424
11/15/2013	
17:53	74.12
11/15/2013	
18:53	74.163
11/15/2013	
19:53	74.424

11/15/2013	
20:53	74.25
11/15/2013	
21:53	74.163
11/15/2013	
22:53	74.163
11/15/2013	
23:53	74.077
11/16/2013	
0:53	74.381
11/16/2013	
1:53	74.163
11/16/2013	
2:53	74.424
11/16/2013	
3:53	74.12
11/16/2013	
4:53	74.511
11/16/2013	
5:53	74.163
11/16/2013	
6:53	74.163
11/16/2013	
7:53	74.163
11/16/2013	
8:53	74.338
11/16/2013	
9:53	74.077
11/16/2013	
10:53	74.597
11/16/2013	
11:53	74.424
11/16/2013	
12:53	74.25
11/16/2013	
13:53	74.683
11/16/2013	
14:53	74.727
11/16/2013	
15:53	74.683
11/16/2013	
16:53	80.316

References

1. http://www1.eere.energy.gov/consumer/tips/m/home_energy.html
2. US DOE fact sheet
3. Industrial Sector Energy Consumption.
<http://www.eia.doe.gov/totalenergy/data/annual/#consumption> (accessed January 17, 2011).
4. Building Energy Data book
<http://buildingsdatabook.eren.doe.gov/default.aspx> (accessed January, 2014)
5. ASHRAE 90.2
<http://www.energyefficiencymatters.org/what-is-ashrae-standard-90-2> (accessed January, 2014)
6. http://yanpage.narod.ru/NCMA_TEKs/TEKs/Wce2743723fb62.htm# (accessed January, 2014)
7. Insulations
<http://homeenergysaver.lbl.gov/consumer/faqs#g3> (accessed January, 2014)
8. Set Back Temperature Control – Utilities Savings Factsheet
(http://portal.ncdenr.org/c/document_library/get_file?uuid=6f993424-2f12-459c-8526-099318b59c3d&groupId=38322)
9. King, J.C., Trechsel, R.Heinz, Building Air Change Rate and Infiltration Measurements: A Symposium, Issue 719
10. Regression Analysis
<http://www.stat.yale.edu/Courses/1997-98/101/linmult.htm> (accessed January, 2014)
11. http://reliawiki.org/index.php/Multiple_Linear_Regression_Analysis (accessed January, 2014)
12. EnerWin Software Manual (1996). Energy Calculation for Windows, Texas A and M University, College Station, TX, USA
13. Al-Homoud, S.Mohammad, 2003, “The Effectiveness of Thermal Insulation in Different Types of Buildings in Hot Climates”, Journal of Thermal Envelope and Building Science , pp. 235-247

14. Kashiwagi, Dean.T, Moor, C.William, 1993, "The Relationship between Energy Cost and Conservation Measures, Building Design and Insulation Levels", Journal of Building Physics, Vol 16 no. 4, pp. 375-394
15. Porte, M, 1985, "Competitive Advantage, Creating and Sustaining Superior Performance", NY: The Free Press
16. Mattsson, Bjorn, 2006, "The influence of wind speed, terrain and ventilation system on the air change rate of a single-family house", Energy, 31(5), pp 719-731
17. Hilado, J C, 1979, "Laboratory Method for Determining Effectiveness Of Thermal Insulation", Journal of Building Physics, pp- 3-32
18. Asadi, Somayeh, 2011, "Thesis: Evaluation of the thermal performance and cost effectiveness of radiant barrier thermal insulation materials in residential construction", Louisiana State University
19. Amery, A.F., Kippenhan, C.J., "A long term study of residential home heating consumption and the effect of occupant behavior on homes in the Pacific Northwest constructed according to improved thermal standards", Energy, 31, pp: 677-693
20. Tumma, Preecha, Chirarattananon, Surapong, Hien, Vu Duc , Chaiwiwatworakul, Pipat, Rakkwamsuk, Pattana, 2013, "Thermal Performance of insulated walls enclosing residential spaces in Thailand", Energy and Buildings, 61, pp: 323-332
21. Yao, Runming, Steemers, Koen, 2004, "A method of formulating energy load profile for domestic buildings in the UK", Energy and Buildings, 37, pp-663-671
22. Carlos,J, Lamberts, R, 2008, "Development of envelope efficiency labels for commercial buildings: Effect of different variables on electricity consumption", Energy and Buildings, 40(11)
23. Wojdyga, K, 2008, "An influence of weather conditions on heat demand in district heating systems", Energy and Buildings, 40
24. Mattsson, B, 2004 "The influence of wind speed, terrain and ventilation system on the air change rate of a single-family house", Proceedings of ASME-ZSIS international thermal science seminar II, Bled, Slovenia
25. Chung, W, Hui, Y.V., 2009 "A study of energy efficiency of private buildings n Hong Kong", Energy and Buildings, 41(6), pp:696-701