AN ANALYSIS OF INTERNATIONAL ENERGY CONSERVATION CODE (IECC)-COMPLIANT SINGLE-FAMILY RESIDENTIAL ENERGY USE

A Dissertation

by

SEONGCHAN KIM

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2006

Major Subject: Architecture

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Approved by:

Chair of Committee,	Jeff S. Haberl
Committee Members,	Mark Clayton
	Charles Culp
	Dennis O'Neal
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ABSTRACT

An Analysis of International Energy Conservation Code (IECC)-Compliant Single-Family Residential Energy Use. (August 2006)

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Chair of Advisory Committee: Dr. Jeff S. Haberl

In 2001, the Texas State Senate passed Senate Bill 5 to reduce ozone levels by encouraging the reduction of emissions of NOx that were not regulated by the Texas Natural Resource Conservation Commission, including point sources (power plants), area sources (such as residential emissions), road mobile sources, and non-road mobile sources. For the building energy section, the Texas State Legislature adopted the 2000/2001 International Energy Conservation Code, as modified by the 2001 Supplement, as the state's building energy code. The 2000/2001 IECC is a comprehensive energy conservation code that establishes a standard for the insulation levels, glazing and cooling and heating system efficiencies through the use of prescriptive and performance-based provisions.

Therefore, the purpose of this research is to improve the accuracy of a 2000/2001 IECC-compliant performance simulation using the DOE-2.1e simulation program to investigate the energy performance of a typical single-family house. To achieve this purpose, several objectives had to be accomplished, including: 1) the development of an IECC-compliant simulation model, 2) the development and testing of specific improvements to the existing code-traceable model, 3) the calibration and installation of sensors in a case-study house, 4) the validation of the improved

simulation model with measured data from the case-study house, and 5) use the validated model to simulate the energy-conserving features of single-family residences that cannot be simulated with existing versions of the DOE-2.1e program.

In order to create the code-traceable IECC-compliant simulation model, a base-case house simulation was created and the results calibrated with measured energy and environmental data from the case-study house. This was done in order to obtain an improved simulation model that would more accurately represent the case-study building. The calibrated model was then used to verify the accuracy of the improved simulation methods against previous models and measured data.

After validation of the new simulation methodologies, the IECC simulation model was used to simulate different energy-conserving features for a single-family residence that could not be simulated with the previous version of the DOE-2 input file. Finally, areas for future work were identified in an effort to continue to improve the model.

DEDICATION

To

My Loving Parents and Wife Minsun

ACKNOWLEDGMENTS

It was a long journey to complete this study and there are numerous people who supported me during this journey. I would like to express my sincere appreciation to the chair of my committee, Dr. Jeff S. Haberl. Without his advice and guidance, this study could not have been achievable. I am also deeply grateful to Dr. Mark Clayton, Dr. Charles Culp and Dr. Dennis O'Neal, members of the advisory committee, for their unique contribution.

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Finally, I would like to share my pleasure in completing this study with my family, wife Minsun, and her family who have been waiting for this moment for a long time.

Thank you so much.

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CHAPTER I

INTRODUCTION

1.1 Background

In 1990, the U.S. Environmental Protection Agency (EPA) classified four areas including Beaumont-Port Arthur, El Paso, Dallas-Ft. Worth, and Houston-Galveston-Brazoria in Texas as non-attainment areas based on the EPA's 1-hour ozone standard where exceeding the national one-hour level standard of 0.12 parts-per-million (ppm). Specially, Houston-Galveston-Brazoria area was designated as a Severe II Non-Attainment Area and must reach attainment by November, 2007 (Texas Natural Resource Conservation Commission (TNRCC) 2000). The state of Texas' goal is to demonstrate attainment. In order to do that, significant reductions in NOx emissions are necessary in Texas's non-attainment areas to prevent sanctions including the withholding of federal highway funds of billions of dollars per year, or the withholding of EPA grants for state air pollution planning and control programs (Im 2003).

In 2001, the Texas State Senate passed Senate Bill 5 to reduce ozone levels by encouraging the reduction of emissions of NOx by sources that were not regulated by the TNRCC, including point sources (power plants), area sources (residential emissions, etc.), road mobile sources, and non-road mobile sources (TNRCC 2002).

For the building energy section, the Texas State Legislature adopted the 2000/2001 International Energy Conservation Code (IECC) as modified by the 2001 Supplement as the state's energy code (TNRCC 2002). The 2000/2001 IECC is a comprehensive energy conservation code that establishes a minimum for design and construction parameters such as the

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This thesis follows the style and format of the *ASHRAE Transactions*.

thermal properties of insulation on a wall, floor, roof, and the efficiency of the cooling and heating systems through the use of prescriptive and performance-based provisions.

However, although the 2000/2001 IECC provided fixed requirements such as the U-value for glazing, and R-values for exterior wall, ceiling, floor, basement wall, perimeter slab, and crawl spaces, different simulation results can occur when testing the same houses because the analyst needs to define other conditions not directly defined by the 2000/2001 IECC.

Furthermore, although there are serious heat losses or gains through duct system in the unconditioned space such as the attic and crawl space especially in the hot and humid climate zone, two of the most widely-used energy simulation programs cannot consider those losses (i.e., Depart of Energy (DOE)-2 or Building Load Analysis and System Thermodynamics (BLAST)) without specially written routines. Therefore, the energy simulation programs should also calculate the heat loss or gain through duct system using a specially-written routine.

Therefore, this research will concentrate on efforts to improve the IECC-compliant simulation and provide affordable solutions for analyzing the energy-efficiency single-family residential house. This research also investigated the individual and combined energy saving potential of various energy conservative strategies to minimize energy use of a residence in hot and humid climates.

1.2 Purpose and Objective

The purpose of this research is to improve the accuracy of a 2000/2001 IECC code simulation using the DOE-2.1e simulation program to evaluate the energy performance of a single-family residential house. To achieve this purpose, the following objectives have been defined:

1. Develop an accurate, code-traceable IECC model, which can then be used to simulate residential single-family houses in Texas according to the International Energy Conservation Code (IECC) (ICC 1999, 2001).

2. Develop and test specific improvements to the existing code-traceable model. These methods include:

- A comparison of various thermal mass walls according to the 2000/2001 IECC.
- Use of the Window-5 (LBNL 2001) simulation program
- Application of improved underground surface heat transfer calculations (Winkelmann 1998).
- Application of new residential HVAC system performance curves (Henderson et al. 2000).
- Application of new domestic hot water system curve (NREL 2001).
- Development of the duct model in an attic space using American Society of Heating, Refrigerating, and Air-conditioning Engineers (ASHRAE) Standard 152-2004 with a DOE-2.1e FUNCTION commands (ASHRAE 2004).

3. Calibrate and install proper sensors on a nearby case-study site in order to gather data to validate various aspects of the simulation models.

4. Validate the improved simulation model with measured data from the instrumented case-study house.

5. Use the validated model to simulate various types of energy-conserving features to a single-family residence that could not be simulated with the previous program.

1.3 Organization of the Dissertation

This chapter has discussed the background of the proposed research topic and purpose and objectives of the research.

Chapter II surveys and discusses the previous research in the area relating to this work to provide the basis for the development of this research. These areas surveyed previous studies about energy savings in residential houses, specific approaches to develop the simulation code for the residential house, reviews of existing building energy codes and standards, validation of computer simulation using calibrated simulation, and previous studies about the case-study house.

Chapter III discusses the importance of the study and contributions in this research area. The scope and limitation of the research are also discussed in this chapter.

Chapter IV discusses the methodology developed and applied in this research. It explains the case-study house, the data acquisition system and the calibration and installation of the sensors. It also describes the process of developing the International Energy Conservation Code (IECC) simulation code.

Chapter V presents the results of the data collection and simulation of the as-built, base-case house. It discusses the development and calibration process of the input file for the as-built case-study house. Several new simulation methodologies are also explained in this chapter.

Chapter VI discusses the International Energy Conservation Code (IECC) compliant house. It discusses the development process of the input file for the IECC-compliant house.

Chapter VII discusses the application of improved DOE-2 simulation methods to the IECC-compliant simulation with different wall types, attic types, window types, duct types, and system efficiency according to IECC requirement.

Finally, Chapter VIII summarizes this research work and proposes conclusions for the improvement of the research in this area.

CHAPTER II

LITERATURE REVIEW

2.1 Introduction

The study of energy use in residential houses in the United States has been of interest to many authors since the early 1970s, when the oil embargo made energy an important topic. The relevant literature for this thesis includes previous studies concerning: 1) energy savings in residential houses; 2) specific approaches to developing the simulation codes for residential houses; 3) reviews of existing building energy codes and standards; 4) validation of computer simulation model using calibrated simulation; and 5) previous works on the case-study buildings. This literature review includes ASHRAE publications, the Proceedings of the Symposium on Improving Systems in Hot and Humid Climates, selections from the journal of Energy and Buildings, Building and Environment and Energy, the Lawrence Berkeley National Laboratory (LBNL) reports, the Florida Solar Energy Center (FSEC) reports, the Energy System Laboratory publications, and related theses and dissertations from Texas A&M and other universities.

2.2 Previous Studies about Energy Savings on Residential Houses

There are numerous studies available for saving energy in residential houses. Significant research has also been published on the topic of reducing energy consumption. The studies reviewed include studies about improved glazing with low-e windows, shading devices, attic insulation, radiant barriers, duct leakage, and roof solar reflectance.

2.2.1 Glazing and Shading

Proper glazing type and shading devices on residential houses can make a significant contribution to reduce heating and cooling loads. Numerous studies have reported about glazing and shading device systems, including: Arasteh et al. (1985), Pletzer et al. (1987), Dubrous (1991), McCluney and Mills (1993), Soebarto and Degelman (1994), Sullivan et al. (1994), Carpenter et al. (1998), Anello et al. (2000), Farrar-Nagy et al. (2000), Tsangrassoulis et al. (2001), and Capeluto (2003); of these, the following are most important to this thesis.

Pletzer et al.(1987) studied load reduction and potential annual energy savings resulting from different glazing and shading devices on three residences in Austin, Texas. He investigated various types of windows and shading device such as blinds, draperies, window films, tinted windows, solar screens, overhangs and recessed windows. The analysis was performed by DOE-2 energy simulation program. In order to characterize the thermal properties of the windows and shading devices, their U-value and Shading Coefficient (SC) method were used for simulations. They concluded that when annual heating and cooling energy savings are normalized to glazing area they correlated well with the shading coefficient and overall U-value. Their study provides useful information to this study on energy savings from glazing and shading devices.

Farrar-Nagy et al. (2000) evaluated the interactions of solar heat gain reductions that impact the energy use of a specific house design in a hot and dry climate (Tucson, Arizona). This study described the hourly DOE-2 modeling which was compared with measured hourly data, as well as the testing procedures used to evaluate the prototype house, and summarized the relative impact of several solar load control strategies. They tested four combinations of glazing and shading, which are as follows: (1) standard glazing without shading, (2) spectrally-selective glazing (i.e., low-e) without shading, (3) standard glazing with shading, and (4) spectrally-selective glazing with shading. In order to define the window thermal properties, the shading coefficient (SC) and U-value were used for input of DOE-2 simulations. They found that a combination of high performance glazing (i.e., low-e) and shading achieves a 0.4 kW (14%) reduction in afternoon peak electricity demands and a 12.4 kWh (30%) reduction in daily total electricity used for air conditioning. For this study, window tests will be simulated according to similar kinds of glazing such as single-pane, double-pane and low-e glazing and simulation methods such as the Shading Coefficient method (LBNL 1981) and the spectrally-selective, multi-layer model used in the Window Library method (LBNL 1981).

Anello et al. (2000) compared single-pane windows in a side-by-side field test with double-pane, spectrally-selective, thermally-broken low-e windows. Two identical 2,122 square-foot houses were constructed in the same neighborhood in the Melbourne, Florida. One house had standard single-pane windows, and one house had the advanced spectrally-selective low-e windows. They performed a detailed simulation to compare the actual energy savings versus the predicted savings. The DOE-2 models of both houses were then created with both models identical except for the windows. This study also used the U-value and shading coefficient (SC) method to define the window thermal properties. They found that the simulation results indicated a 15% cooling energy savings, while measured results indicated a 14.7% cooling energy savings during the 17-day unoccupied period, which indicated good agreement between the model and the measured data. The simulation also showed that a standard house would consume 5,408 kWh for annual cooling while the improved house would consume only 4,471 kWh, a reduction in annual cooling use of 17%. The method and results from this study are important to this study because a similar simulation method using the DOE-2 program will be performed in order to compare and evaluate the impact of different glazing types on an IECC-compliant single-family house.

2.2.2 Attic Insulation and Radiant Barriers

Attic insulation and radiant barriers have been found to be an important component in reducing heating and cooling loads in residential buildings. Numerous studies have been performed including: Levins and Hall (1990), Medina (1992), Wilkes and Childs (1993), Al-

Asmar et al. (1996), Moujaes (1996), Noboa et al. (1996), Parker (1998), Walker (1998), and Petrie et al. (1998); of these, the following are the most important to this study.

Medina (1992) tested the performance of radiant barriers under full weather conditions in central Texas using a side-by-side comparison of two test houses with identical floor plans and thermal characteristics. The ceiling heat flux was reduced as a result of retrofitting with radiant barriers by approximately 34 percent when the attics were vented, and 28 percent when the attics were not vented. The ceiling cooling load reductions translated to an approximately 2-4 percent space cooling reduction. Parker (1998) performed a similar study on an attic space. He developed an attic model using the DOE-2 simulation program in order to determine the possible savings in cooling electricity use according to the amount of insulation and ventilation of attics in Florida. The author found an average savings of 19%. These findings are important to the thesis because an estimation of the savings attributable to the attic modification will be simulated using a specially modified version of a DOE-2 simulation on the case-study house.

Al-Asmar et al. (1996) performed an experimental study to evaluate the impact of radiant barrier systems on summer cooling loads in residential buildings under ASHRAE Research Project 577-RP, "Attic radiant barrier systems". In this study, a simulated attic was built inside the entire area of a 24-ft by 12-ft environmental chamber with roof temperatures that varied from 120°F to 160°F. For the experiment, attic ventilation rates varied from 0 to 2.0 cfm/ft^2, nominal R-11 and R-19 insulations were used, and a radiant barrier mounted under the roof was used. The results showed reductions in attic heat gains ranging from 17% to 26% with no ventilation and from 24% to 42% when the attic was ventilated. The radiant barrier reduced attic temperatures 10°F to 15°F under typical conditions. This study is important to this study because the attic temperature change with and without radiant barrier could be simulated to investigate the effect of radiant barrier in the case-study house.

Finally, according to Walker (1998), a radiant barrier is one method of reducing summer-time temperatures in attics. Furthermore, during the cooling season, the attic must be well ventilated to have a significant impact. However, during heating season, radiant barriers were shown to have a small effect. This study is also important to this thesis because the effect of radiant barriers can be simulated in order to evaluate the energy savings for hot and humid climates where cooling energy is dominant.

2.2.3 Duct Leakage

Duct systems in residential houses, especially in an unconditioned space such as the attic or crawl space can have significant heat loss or gain to the surrounding unconditioned space through the duct systems. Numerous studies have reported on the residential duct system, including: Andrews et al. (1996, 1998), Lambert and Robison (1989), Modera (1989), Cummings (1991), Proctor (1992a, 1992b), Parker et al. (1993), O'Neal et al. (1996), Gu et al. (1998), Cummings et al. (2000), and Levinson et al. (2000); of these, the following are the most important to this thesis.

Cummings (1991) tested duct leakage using tracer gas tests in 91 homes in Florida. He found, on average, about 12% of the house infiltration occurs in the duct system. Duct repairs were made on 25 homes and cooling energy use was monitored before and after the duct repair. The study showed that the air-conditioning energy use decreased 18% due to the duct repairs.

O'Neal et al. (1996) performed a study to quantify the effect of return air leakage and humidity from hot and humid attic spaces on the performance of residential air conditioners. They found that the effective capacity decreased with an increased return air leakage and high humidity in the same temperature condition, and that leakage rates that have high attic humidity caused more reduction of capacity. If the maximum capacity occurred at 0% duct leakage in 150ºF of attic temperature, the system capacity dropped 25.8% at 9.1% duct leakage for 10%

relative humidity in the attic space. When the relative humidity in the attic space reached to 14.2%, the system capacity dropped to 39.5%. They concluded that attic conditions, especially attic humidity, were important factors in decreasing the capacity with increased duct air leakage. Both of these studies are important because the case-study house for this study has the duct system in a humid attic space, and the evaluation of the heat loss and gain of the measured conditions will be examined.

2.2.4 Roof Solar Reflectance

According to the EPA (2004), over 90% of the roofs in the United States are dark-colored. These low-reflectance surfaces reach temperatures of 150 to 190°F in the summer, which contributes to an increase in the cooling energy use, higher utility bills, and requires higher peak electricity use. Therefore, the roof color and thermal properties also play an important part in improving the energy efficiency of a residential building. Several studies related to this issue have been published by Parker and Barkaszi (1997), Konopacki and Akbari (1998), Akbari et al. (1997, 1999), Akridge (1998), Hens (1998), Hildebrant (1998), Parker and Sherwin (1998), and Petrie et al. (1998); of these, the following are the most important to this thesis.

Parker and Barkaszi (1997) experimented on the impact of reflective roof coatings on air-conditioning energy use in nine residential houses in the Florida region. They found that measured cooling energy savings were from 2% to 43%, with the average at 19%. This research is important to this study because the effect of the color of a roof on the house's cooling energy use could be investigated for similar climate such as Texas (a hot and humid climate).

Akbari et al. (1999) performed quantitative estimates of the savings on cooling and heating energy use for residential and commercial buildings by changing roof reflectivity from 0.25 to 0.70 in several climates. Prototypical buildings were simulated with reflective (light color) and absorptive (dark color) roofs. Savings were estimated for 11 US metropolitan statistical areas (MSAs) in a variety of climates including: Atlanta, Chicago, Los Angeles, Dallas/Fort Worth, Houston, Miami/Fort Lauderdale, New Orleans, New York, Philadelphia, Phoenix and the DC/Baltimore. Simulation for single-family residential and commercial buildings including offices, retail stores, primary and secondary schools, hospitals, nursing homes, and grocery stores were developed using the DOE-2 building energy simulation model. Building energy simulation showed peak cooling demand savings of 20%-40% in residences and 5%-10% in offices. The total savings for all 11 MSAs were: annual electricity savings-2.6 terawatt hours (TWh), with peak electricity savings of 1.7 gigawatts (GW). This study also mentioned that the more complex DOE-2 models including a roof composite model, and a duct loss model in the attic space, were needed in order to evaluate the electricity usage more precisely. This study is important to this study because the DOE-2.1e program with an added duct model will be used to evaluate a building's energy performance and to investigate the effects of the color of different roof systems.

2.3 Development of a Code-compliant Simulation for Single-family Residences.

As a building energy simulation program, DOE-2 is widely used and well-known to most building energy analysts. DOE-2.1e version 119 is a recently released version of the DOE-2 building energy simulation program. It has the capability to calculate both the annual and the peak energy performance of buildings. In addition, more accurate simulation methods such as National Fenestration Rating Council's (NFRC) procedure for window calculation with the Window 5 computer program (LBNL, 2001), the modeling of exterior envelopes with the DOE-2.1's custom-weighting-factors (CWFs), use of LBNL's new procedure for slab heat flows, improved models for the attic, duct, A/C, furnaces and heat pumps have all been developed to be combined with the DOE-2.1e program to improve its performance.

2.3.1 National Fenestration Rating Council (NFRC) Calculation and Window Simulation

The National Fenestration Rating Council (NFRC) has developed a fair, accurate, and credible rating system for the optical and thermal performance of windows and other fenestration products (NFRC 2002a, 2002b). NFRC's rating systems are aimed at facilitating the selection and development of efficient window products. Several studies were performed to test window simulations and apply NFRC window calculation procedures to the DOE-2.1e program by Baker et al. (1990), Dubrous and Wilson (1992), Smith et al. (1993), Harrison and Wonderen (1994), Reilly et al. (1995), LBNL (1981), and NFRC (2002a, 2002b); of these, the following are most relevant to this study.

Reilly et al. (1995) performed widow simulations using the DOE 2.1e program to evaluate the difference between the detailed approach (National Fenestration Rating Council U-value procedure 100-91) and a constant shading-coefficient approach (i.e., ASHRAE method). The detailed modeling approach utilize the WINDOW-4 computer program (LBNL 1992), which uses the NFRC procedures. They found that ASHRAE method has limitations, which can seriously affect the accuracy of calculating peak cooling loads since ASHRAE method determine the solar gain using a reference glazing consisting of 1/8-in clear glass under ASHRAE standard summer conditions (95ºF outside temperature and 75ºF inside temperature and 7.5 mph wind speed). The solar gain for different glazing is then determined each hour by multiplying the solar gain of the reference glazing by the shading coefficient of the selected glazing. For example, in the case of hourly solar gain, the results showed that the commonly used shading-coefficient method underpredicts by up to 35% for single/reflective glass and overpredicts by up to 12% for double/clear glass compared to the detailed method when using vertical, south-facing glazing on a clear June day in Chicago. Therefore, they recommended the use of a detailed method of NFRC based window calculations for any simulation. This study is important to this research because a similar testing for the modeling of the window will be used to develop an accurate IECC simulation model.

According to LBNL (1993), there are three methods for specifying window properties on DOE-2 program: 1) the Shading Coefficient method, 2) Glass-Type-Code ≤ 11 and 3) Glass-Type-Code ≥ 1000 (Window Library method). The first input method requires users to input shading coefficient and glazing conductance, the second input method restricts user to the predefined U-values and SHGF of the window library and the third input method allows users to add new windows to the DOE-2 library. The Shading Coefficient method can be convenient for conceptual design because of simple input requirements. However, the results can be inaccurate for multipane, low-e glazing. The Window Library method has a more detailed angular calculation and conduction consideration. However, it can result on a 50-100% increase in the LOAD calculation time depending on the number of unique windows. Nevertheless, as the calculation capability of modern computers improved, the consideration of LOAD calculation time is not a primary for most simulations. For the current study, this report provides the information about how to use the two methods of window simulation with the DOE-2 program and uses the two methods to simulate various window types to compare how the two methods are different.

The NFRC (2002a, 2002b) developed a uniform and accurate means for evaluating window U-factors (NFRC 2002a), and Solar Heat Gain Coefficient (SHGC) (NFRC 2002b) of fenestration systems using state-of-the-art simulation procedures validated with physical testing. The U-factors and SHGC established by this procedure were determined at a fixed set of environmental conditions. The Window-5 simulation program, which was mentioned previously, was developed by the Windows and Daylighting Group at Lawrence Berkeley Laboratory for calculating total window thermal performance indices such as U-value, solar heat gain coefficients, shading coefficient, and visible transmittance (LBNL 2001). The Window-5 program provides a versatile heat transfer analysis tool, which is consistent with the rating procedure developed by the NFRC. Therefore, this program can be used to design a specific window, and to rate and compare performance characteristics of different windows in the Window-5 library. Furthermore, the window data, which is created in this program, can be linked with the DOE-2.1E simulation program to provide more accurate simulation. Therefore, Window-5 (i.e., the new version of Window-4) will be used to create the window types that have the same thermal properties as the 2000/2001 IECC code-compliant simulations to evaluate the window performance of residential building.

2.3.2 Exterior Envelope

DOE-2 has different simulation methods for simulating exterior walls that show different results for the same architectural dimension and same total R-value. This is because DOE-2 allows for a wall to be modified using a single R-value, or modeled using layers and real materials. Since the 2000/2001 IECC gives only R-values of the exterior wall, the proper simulation method of an exterior wall should be considered for reasonable results. Several authors have previously studied exterior wall performance including Christian (1991), Lam (1995), Kosny et al. (1998), Meldem and Winkelmann (1998), Bakos (2000), Kossecka and Kosny (2002), and Ghatti et al. (2003); of these, the following are the most important to this study.

According to Christian (1991), the Council of American Building Officials' Model Energy Code Committee (CABO MEC) accepted the use of exterior thermal mass credits (i.e., for heat capacity greater than or equal to 6 Btu/ft^2-ºF), which allowed for the creation of Thermal Mass Credit Tables for builders according to thermal mass located on the inside or the outside of the insulation and an integral case. However, Christian (1991) stated that these tables couldn't satisfy the various types of thermal mass walls because of over-simplification. Therefore, work on the alternative method for predicting the effect of exterior envelope thermal mass was performed. They performed thermal performance measurements on 14 test houses in two locations (the National Institute of Standards and Technology in Maryland and Santa Fe, New Mexico) with various amounts of external wall mass, including wood-frame, masonry, adobe and log, and modeled test houses. More than 100 comparisons of model predictions with measured data were made using the DOE-2.1c, BLAST and DEROB. The experimental data and the DOE-2.1c predictions came reasonably close within a tolerance of 20% to the measured data. Next, the heating and cooling loads and the characteristic influence of thermal mass wall on the hourly behavior from computer simulations were reinvestigated to validate the MEC table. He concluded that although the MEC table may not be the right values to be used for all typical conditions, in general, the experiments, simulation data, and MEC mass credit tables show that insulation placed on the outside of the thermal mass is best for most climate. This study is important to this research because the 2000/2001 IECC also has a high-mass wall of 6 Btu/ft^2-°F or higher. Therefore, this study will also evaluate the thermal mass effect according to different kinds of wall types.

Meldem and Winkelmann (1998) performed thermal measurements on test houses and compared these measurements with the predictions of DOE-2.1e to validate the thermal analysis capability of DOE-2. Three buildings were measured: 1) A house with conventional stud wall construction (low-mass house), 2) A house of the same geometry, but with 4-inch thick concrete walls with exterior insulation (high-mass house), 3) A medium-mass house with clerestory windows. In the research, the low-mass and high-mass houses, which are identical except for the construction of the exterior and interior walls were investigated. They developed DOE-2 models and calibrated the input models to reduce discrepancies between the DOE-2 predictions and the measurements of inside air temperature by modifying infiltration rates, ground surface absorptance, ground surface temperature, and foundation heat transfer. Finally, they concluded that DOE-2 is in excellent agreement with the measurements for all of the configurations for both the low-mass and high-mass houses. The method and results from this results provide useful information because this study will also investigate the thermal performance of the light-mass wall in the Habitat for Humanity case-study house, and several theoretical high-mass walls which are typical of those in use. Various parameters which are mentioned in this research will be considered during calibration process of DOE-2 input model.

2.3.3 Heat Flow in Underground Surfaces

Heat flow through a building foundation represents one of more complicated aspects in building thermal simulation due to large thermal mass and slow time response. Studies about heat flow through underground surface were performed by Kusuda and Achenbach (1965), Huang et al. (1988), Mathew and Richards (1989), Swaid and Hoffman (1989), Mihalakakou et al. (1992), Winkelmann (1998), Meldem and Winkelmann (1998), and Huang et al. (2000); of these, the following are most important to this study because they provide detailed information about modeling of heat transfer to an underground surface in DOE-2.1e.

The heat transfer from the building to the ground through the slab-on-grade is calculated by DOE-2 as $U \cdot A \cdot \Delta T$, where U is the conductance of the slab, A is its area, and ΔT is the temperature difference between the inside air and the ground temperature (LBNL 1981). However, this formulation is over-simplified in that it ignores 2-dimensional conduction effects (Meldam and Winkelmann 1998). Therefore, Huang et al. (1988) developed the foundation heat flow method to combine the DOE 2.1c program with a two-dimensional finite difference foundation model in order to better simulate foundations in a prototypical house, because energy simulation programs generally model a building's foundation as a one-dimensional layer using a very approximate method. Huang et al. developed tables based on a two-dimensional finite-difference method for the DOE input that include the perimeter conductance per perimeter foot for slab, basement, and crawl space conditions.

Winkelmann (1998) performed a similar study. He developed an improved method for modeling underground surfaces based on the previous work by Huang et al. (1988). He suggested that DOE-2 users should specify an effective U-value instead of using raw U-value with a U-EFFECTIVE DOE-2 keyword when modeling the underground surface. He determined that if the raw U-value of a surface was used, the heat transfer would be grossly overcalculated because the heat transfer occured mainly through the surface's exposed perimeter region, rather than uniformly over the whole area of the surface. He also showed details such as: 1) how to model the effective resistance of an underground surface that can consider that underground surface and the inside air film, soil, and a fictitious insulation layer; 2) how to calculate U-EFFECTIVE; and 3) how to write DOE-2 input code for slab-on-grade, basement wall, and crawl space wall conditions. Furthermore, Meldem and Winkelmann (1998) tested the difference between simple models, which DOE-2 used for the heat transfer calculation for an underground surface, and a detailed model developed by Huang et al. (1988). Their results showed that the finite difference model by Huang et al. (1998) was substantially in better agreement with the measurement.

Huang et al. (2000) continued to develop an improved ground surface model using a two-dimensional finite difference method based on previous works by Huang et al. (1988) and Winkelmann (1998). In order to give more detailed simulation modeling method, they divided a foundation into two regions. One is the perimeter area that is coupled to outside air and the other is the core region that is couple to the ground temperature. They provided a set of the five-foundation conductance in a tabular format for DOE-2.1e modeling. These foundation conductances were derived from multi-linear regressions of heat flow of 52 slab foundations, 21 crawl spaces, and 23 basements. In order to incorporate an improved method in DOE-2.1e, several new DOE-2 keywords of the input were required. Those are PERIM-EXPOSED, PERIM-COND-WEEK, PERIM-COND-MONTH, PERIM-COND-YEAR, CORE-COND-MONTH and CORE-COND-YEAR, which were added to the commands UNDERGROUND-WALL and UNDERGROUND-FLOOR (to be available in a future version of DOE-2.1e). The authors also provided an example of DOE-2.1e input file including new keywords for the modeling of underground surfaces and described how the various input values were determined.

These studies are important to this study because this detailed modeling method for underground surface is applicable to this study when the new version of DOE-2.1e is published, and should provide an improved modeling method for underground surfaces of slab-on-grade in order to improve the IECC simulation code beyond the work performed in this study.

2.3.4 Attic Model

In the case of duct systems in an unconditioned space such as an attic or a crawl space, the heat loss or gain of the duct systems to the unconditioned space is often greater than expected. In the case of an attic space, summer afternoon temperature often reaches 122°F or higher (Parker et al. 1993). Since the attic space is directly affecting the duct systems in many cases, an improved modeling of the attic space is important to investigate duct heat loss more accurately. Several studies about attic thermal behavior and attic modeling were performed by Parker et al. (1991), Medina (1992), Winiarski and O'Neal (1996), Parker and Sherwin (1998), Romero and Brenner (1998), Holton and Beggs (1999) and Parker et al. (1999). Of these, the following are most important to this research.

Medina (1992) developed a transient heat and mass transfer model to predict ceiling and roof heat gain/loss through the attic space in residences, and to accurately estimate savings in cooling and heating loads produced by the use of radiant barriers. This model considered all modes of heat transfer such as transient conduction, natural and forced convection, radiation within the attic, and the solar load on the external surfaces of the attic using the Heat Balance Method in the attic space. This simulation model was also used to run simulations and parametric studies under diverse climates, insulation levels and attic airflow patterns. This study is important for this study in order to understand the effect of thermal behaviors on the attic space, and provides useful information to develop an improved attic model for simulating the IECC-compliant residential house.

Parker et al. (1999) modeled the residential attic with the DOE-2 simulation program as a buffer space for the conditioned residential zone. Convective and radiative exchange between the roof decking and the attic insulation was accomplished by setting the interior film coefficient according to the values suggested in the ASHRAE Handbook of Fundamentals (1997) depending on the slope and surface emittance. Ventilation to the attic is specified in the model as a free ventilation inlet area into the attic. Common attic spaces were assumed to have soffit and ridge ventilation such that they meet the current code recommendation for a 1:300 ventilation area to attic floor area ratio. This paper provides specific information to this study to develop an attic model and also mentions the need to run more detailed attic models for accurate results.

2.3.5 Duct Model

There are a number of computer simulation programs that predict energy use in buildings. However, the inclusion of heat loss or gain through duct systems has received little attention in most simulation programs. Even the nationally-supported DOE-2 program (i.e., DOE-2.1e, version 119) has an over-simplified duct heat loss calculation that is driven by a constant duct air loss and a constant delta-T heat gain. Therefore, several studies of duct models were reviewed, including: Francisco and Palmiter (1998, 2000), Walker (1998), Parker et al. (1998, 1999), Gu et al. (1996), Xu et al. (2002), Siegel et al. (2003), Proctor (1998a, 1998b), Strunk (2000), Andrews et al. (1998), and ASHRAE (2004). The following are the most relevant to this study.

Walker (1998) developed the default values of many of the input parameters required to perform the ASHRAE Standard 152-2004 - Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems (ASHRAE 2004). Standard 152-2004 is a proposed method of testing the efficiency of HVAC energy distribution within residential buildings. These default values were taken from measured field data in houses, laboratory testing, simple heat transfer analyses, etc. They included the information related to the modeling of the duct system, and a duct surface area estimation method for supply ducts and return ducts, default duct leakage as a fraction of the fan flow, equipment efficiency as a function of fan flow, delivery effectiveness (DE) and the distribution system's efficiency. This study is important for this study because the default values in Standard 152-2004 can be used to develop residential simulation models and compare with published delivery effectiveness values, by applying specific values to each simulation case.

The Florida Solar Energy Center (FSEC) developed EnergyGauge, which allows for the calculation and rating of energy use of residential buildings around the United States (FSEC 1992). This software uses the DOE 2.1e hourly simulation program. Therefore, the calculations of hour-by-hour performance allow users to examine many different forms of energy conservation. This software also has the capability to analyze the interaction between the building's thermal distribution system and the building's envelope, because the researchers found that conductive gains or losses and leakage from the distribution system can represent as much as 30% of the building's peak heating and cooling loads (Parker et al. 1998). FSEC's duct heat transfer model was implemented as a function command within the SYSTEM simulation module in the DOE 2.1e for the residential system type. This duct heat transfer model considers both the heat gain and loss of the duct system from environments such as the attic, crawl space, basement, or garage, the system's coefficient of performance (COP), and the air conditioner electricity demand. Although the researchers suggested a concept and provided selected formulas for the duct heat transfer model in their study, their program source code for DOE 2.1e are not available to the public. Nevertheless, this work is important to this study because a similar modeling concept for the duct heat transfer model will be used to develop the proposed IECC code-traceable simulation model, which can then be tested against the FSEC model.

2.3.6 Air Conditioner, Furnace, Heat Pump and Boiler Performance Curves

HVAC system simulation models have a critical role in analyzing the energy performance of a building. The performance of HVAC systems in residential buildings have improved significantly over the past ten years. Therefore, new HVAC system models are sometimes required to simulate the newer systems. Modera (1993), Meier and Hill (1997), Al-Homoud (1997), Henderson et al. (2000), Jaber (2002), and Gu et al. (2003) studied the efficiency and performance curves of residential HVAC systems. The following is the most important to this study.

Henderson et al. (2000) developed an improved approach to properly account for the part load performance of the RESYS (residential air conditioning system) in DOE-2. This was badly needed because DOE-2 provides default empirical curves for residential systems that were developed almost 20 years ago. The residential air conditioning system (RESYS) in DOE-2 uses a time constant (τ or tau) of 76 seconds for the air conditioner capacity at startup, and a maximum thermostat cycling rate (Nmax) of 3.125 cycles per hour. However, according to

Henderson et al. (2000), modern air conditioners typically have a time constant of 40 to 60 seconds, and 2.5 cycles per hour for the thermostat cycling rate. Therefore, their study suggested a new Energy Input Ratio (EIR) coefficient that is more appropriate for defining modern air conditioning systems. The results showed that the new curves improved the performance to within 4 and 11% of measurements from newer A/C systems whereas the default curves could only predict 24% of the part load efficiency loss when compared to field studies that showed a 5-10% energy loss. This means that the improved model's predictions are much closer to the field study. They also suggested improved furnace, heat pump, and boiler performance curves using similar field studies. This study is important to this study because the RESYS system in DOE-2 is used for the primary system in the IECC-compliant house, which can be improved using the suggested efficiency curves.

2.4 Reviews of Existing Building Energy Codes and Standards

A number of energy codes and standards have been developed to improve the energy performance of residential houses. These include the Model Energy Code (MEC) (International Code Council, 1995), the International Energy Conservation Code (IECC) 2000 and the 2001 IECC Supplement (International Code Council 1999, 2001), California Title 24 (California Energy Commission 2004), and ASHRAE Standard 90.2-2001 - Energy Efficient Design of New Low-Rise Residential Buildings (ASHRAE 2001a). These codes are all based on thermal load calculations of the building's envelop and efficient HVAC systems according to climate zones. Their purpose is to improve the energy efficiency of the nation's buildings through new technologies and better building practices. In order to develop a reasonable base-case residential model for this study, a review of the existing building energy codes, programs and standards is necessary.

2.4.1 Model Energy Code (MEC)

The Model Energy Code (MEC) contains energy-related building requirements that apply to many new U.S. residences. The MEC was previously maintained by the Council of American Building Officials (CABO), which was comprised of three U.S. model code groups: the Building Officials and Code Administrators, International (BOCA), the International Conference of Building Officials (ICBO), and the Southern Building Code Congress International (SBCCI). These groups subsequently combined into the International Code Council (ICC) and the ICC issued the 1998 MEC under a new name, the 1998 International Energy Conservation Code (ICC 1998). Both the MEC and the IECC codes specify thermal envelope requirements for one and two-family residential buildings as well as multifamily residential buildings. Thermal envelope requirements include the maximum allowable U-value for walls, ceilings, floors, crawl space walls, and basement walls, and the minimum R-value for slab floors. To comply with the code, a building must be constructed with components either meeting or exceeding these requirements.

The MEC provides three methods for checking compliance with the code: 1) the Prescriptive Approach, 2) the Trade-Off Approach, and 3) the Software Approach. For the Prescriptive Approach, the builder must select a package of insulation and window requirements from a list of packages developed for a specific climate zone. Once selected, the building simply meets or exceeds all requirements in order to achieve compliance. For the Trade-Off Approach, the builder can trade-off insulation for ceiling, wall, floor, basement wall, slab-edge, crawl space, and window efficiency levels in different parts of the building. This approach calculates whether or not the house as a whole meets the overall code insulation and window requirements.

The Software Approach allows builders to compare different insulation levels to select a package that works best for the proposed work with a minimum level of input, as well as to trade off basement wall, slab-edge, and crawl space wall insulation and insulation R-values when necessary. For this approach, researchers developed the REScheck software for the PC version 3.5 (Energy Efficiency and Renewable Energy 2003) and REScheck for the web. REScheck performs a simple UA calculation (U is U-factor and A is Area) to determine the overall UA of the suggested building. This UA is then compared against the building conforming to the code requirement. If the total heat loss (UA) through the envelope of the suggested building does not exceed the total heat loss from the same building conforming to the code, then the software declares that the suggested building is passed. Although this software allows a user to check total heat loss conveniently, the result cannot consider complex affects such as thermal mass, underground surface, etc. because of the simple calculation method. The MEC is important to this study because it explains how the current IECC has been developed and improved up to the current version.

2.4.2 2000/2001 International Energy Conservation Code (IECC)

As previously mentioned, the 2000 International Energy Conservation Code (IECC) including the 2001 Supplement addresses the design of energy-efficient building envelopes and the installation of energy-efficient mechanical, lighting and power systems through requirements emphasizing performance. This comprehensive code establishes minimum regulations for energy-efficient buildings by using prescriptive and performance-related provisions. The code for this area (i.e., HDD 1500- 1999, Texas) sets a minimum requirement for the building envelope, and HVAC system specifications for residential houses. In the case of a residence with a window area that is 15 percent of the gross exterior area, these provisions include an envelope requirement of R-13 insulation for exterior walls, R-26 for the ceiling, and R-0 for the slab perimeter. For the HVAC system, R-8 is required for the supply ducts, R-4 is required for the return duct, the air conditioner should have a minimum Seasonal Energy Efficient Rating

(SEER) of 10 or higher, the furnace should have an Annual Fuel Utilization Efficiency (AFUE) of 78% or higher, and heat pumps should have a Heating Seasonal Performance Factor (HSPF) of 6.8 or higher. The 2000/2001 IECC is important for this study to develop the residential house model because Texas adopted the 2000 IECC as modified by the 2001 Supplement as its official building energy efficiency code.

2.4.3 California Title 24

California Title 24 was established in 1978 in response to a state mandate to reduce California's energy consumption and contain energy efficiency standards for both residential and non-residential buildings. With the 2000/2001 California energy crises, the importance of conservation and efficiency has been brought to the forefront again. California's Title 24 has resulted in a savings of over $36 billion in electricity and natural gas costs since 1978, and is estimated to save an additional $43 billion by 2013 (California Energy Commission, 2004). The approach of Title 24 is similar to that of the 2000/2001 IECC because it defines a minimum insulation R-value for ceiling, wall and floor insulation, glazing/fenestration, a minimum HVAC efficiency and water heating equipment efficiencies, as well as other requirements. Title 24 provides Residential Compliance Forms as templates to compare against the code requirement. As the requirements of templates are filled-out, each category such as exterior, fenestration, HVAC system and other appliances is evaluated a "Pass" or "Fail". Title 24 also provides an energy analysis computer program for residential and non-residential buildings to predict the energy usage of proposed houses, as well as to evaluate whether or not the performance of the house is in accordance with the California's Title 24. The approved programs for Residential Buildings include CALRES2 (California Energy Commission 2001), Energy Pro (Energy Soft 2002), and Micropas 6 (Enercomp Inc. 2002). This standard is also important to this research because the procedure of California's Title 24 is similar to the proposed IECC procedure and also provides helpful information to understand the IECC procedure.

2.4.4 ASHRAE Standard 90.2-2001

ASHRAE Standard 90.2-2001 (Energy Efficient Design of New Low-Rise Residential Buildings) (ASHRAE 2001) sets forth design requirements for new residential dwelling units for human occupancy. For the purposes of this standard, residential dwelling units include single-family houses, multi-family houses (of three stories or fewer, above grade), and manufactured houses (mobile and modular homes).

This standard covers the building's envelope, heating equipment and systems, air-conditioning equipment and systems, domestic hot water heating equipment and systems, as well as provisions for overall building design alternatives and trade-offs. This standard allows two optional methods. One is an envelope performance path trade-off method that allows the user the option of demonstrating compliance by trading the performance of individual envelope components. The other is the annual energy cost method, which is a compliance path that recognizes innovative designs, materials and equipment when they cannot adequately be evaluated under prescriptive procedures. Although this standard is not considered to this study since this study is limited to the 2000/2001 IECC, this standard provides comparative requirements of residential houses for energy efficient design.

2.5 Validation of Computer Simulation Using Calibrated Simulation

Design engineers, architects, and energy management specialists typically use building simulation programs to assist in preliminary calculations for equipment selection, new building code compliance and energy conservation studies (Bronson 1992). Therefore, well-calibrated simulation models play a major role in the measurement of the retrofit savings since they can be used to calculate the energy savings for specific combinations of retrofits (Haberl et al. 1995). Several authors have studied calibrated simulations, including Hsieh (1988), Kaplan et al. (1990), Subbarao et al. (1990), Bronson (1992), Bronson et al. (1992), Koran et al. (1992), Bou-Saada (1994), Soebarto and Degelman (1994), Haberl et al. (1995), Elberling and Bourne (1996), and Bou-Saada (1998). Some significant studies in this area include Koran et al. (1992), Elberling and Bourne (1996), Haberl and Bou-Saada (1998), and Neymark et al. (2002).

Koran et al. (1992) applied two methodologies for calibrating a building energy simulation using a small building. These included the monthly end-use energy consumption tuning (MCT) methodology and the short term energy monitoring (STEM) tuning methodology. Both calibrations incorporated hourly monitored site weather data and information from building audits. The Monthly Consumption Tuning (MCT) adjusted the simulation to match monitored data for each end-use on a monthly and a seasonal basis, and Short-Term Energy Monitoring (STEM) methodology focused on evaluating the building's shell such as the building's overall conductance, glazing shading coefficient, thermal capacities, and heating system efficiency using a three-day period measurements. The two calibrated models estimated annual HVAC energy use within 11% of monitored consumption. Although the case-study building of Koran et al.'s research was a small office building, the overall calibration procedure gives helpful advice to the current study.

Elberling and Bourne (1996) conducted a comparison of energy savings between an existing home and 2 newly constructed homes in California, which was applied to California's Title 24 Building Efficiency Standards using the DOE-2.1e model. In order to ensure the DOE-2.1e model accurately represented the new homes, the model was calibrated using one-year of monitored site weather, indoor and outdoor temperatures, relative humidity, and electric and gas consumption data (i.e., whole-building and end-use data). The results showed that 64% and 61% of the energy savings were estimated from the 2 new homes. This study provides useful guidance to the current work, which seek to calibrate the IECC simulation model to one-year of measured data from the case-study house, and to evaluate several types of IECC residential houses.

Haberl and Bou-Saada (1998) reviewed calibration methods such as graphical methods and architectural rendering, and presented new hourly calibration methods with graphical procedures and statistical goodness-of-fit parameters in order to quantitatively compare simulated data to measured data. These statistical methods include a monthly mean difference, and hourly mean bias error (MBE) for each month, and an hourly coefficient of variation of the root mean squared error (CV (RMSE)) (Kreider and Haberl 1994a, 1994b; Haberl and Thamilseran 1996). They achieved an MBE of -0.7% and an hourly CV (RMSE) of 23.1%, which was considered acceptable as a final calibration, because according to Kreider and Haberl (1994a, 1994b), the best empirical models were capable of producing an hourly CV (RMSE) in the 10 to 20% range. This specific calibration procedure using the statistical CV (RMSE) and MBE will be used to calibrate the case-study house in the residential DOE-2 model.

Neymark et al. (2002) developed the procedures to test the ability of whole-building simulation programs to model the performance of unitary space-cooling equipment that is typically modeled using manufacturer design data presented as empirically derived performance maps. DOE-2 program was verified partially using the developed procedures after correcting errors using HVAC BESTEST diagnostics. Neymarks' results showed that the mean of all simulated results of total energy consumption for the program were on average within <1% of the analytical solution results, with variations of up to 2%. Their research provided a procedure to correct the simulation input file in the case that system information could be obtained from the manufacturers. Since their procedures need to have the detailed experimental conditions and manufacturer's data for each HVAC system to compare the simulation results with the measured data, the BESTEST method was not used for this research.

2.6 Previous Works on the Case-Study Buildings

The case-study building, a Habitat for Humanity house in Bryan, Texas, is a low cost, high quality, energy efficient house constructed with volunteer labor and materials that utilize no or low-interest loans to keep monthly payments low (Kootin-Sanwu et al. 2000). Houses constructed as part of the Habitat for Humanity program are equipped with energy saving features incorporated to lower the owners' costs. Several of the previous residential studies were performed using a case-study house with measured data including: Dumont and Snodgrass (1990), Sieber et al. (1993), Parker et al. (1995), Lister et al. (1996), Haberl et al. (1998), Henry and Patenaude (1998), Kootin-Sanwu et al. (2000), NREL (2001), and Kootin-Sanwu (2004). Of these, the following are the most relevant to this study because they studied very similar case-study house which will be used for this research.

Haberl et al. (1998) used a calibrated simulation and measured data to study an evaluation of residential energy conservation options using two identical Haibtat for Humanity houses in Houston. They developed calibrated DOE-2 models, which matched measured data to within an acceptable range (5-10%). The calibrated DOE-2 model was then used to perform the analysis to determine the energy savings of several energy conservation options such as improved air conditioner efficiency, adding solar screens to the house, and shell tightening. This study is important to this study because the detailed procedures to measure the performance of the Houston Habitat for Humanity houses are very similar to the procedures proposed to evaluate the case-study house in Bryan, Texas.

In the work by Kootin-Sanwu et al. (2000), the case-study building is a single-story 1,120 ft^2, three-bedroom house with an attic space, located in Bryan, Texas. They studied the energy consumption and environmental consumption by installing a 48-channel data logger to record 15-minute data. Measured data included air conditioner, blower, clothes washer / dryer, refrigerator, and other appliances, natural gas monitoring for monitoring energy consumption, and environmental monitoring such as temperature and relative humidity for return, supply, attic space, and outside air, horizontal solar radiation, carbon dioxide and wind speed. Kootin-Sanwu (2004) also developed guidelines for cost-effective and low-income housing using that Habitat for Humanity house. To confirm his results, he developed baseline energy models of the 28 Habitat for Humanity using the PRIncton Scorekeeping Method (PRISM) (Fels 1986). The case-study house was then compared to the 28 selected Habitats for Humanity homes to ascertain normal energy use levels. Detailed and calibrated building energy simulation model of the case-study house using DOE-2.1e was then developed with data obtained from an on-site weather station. This calibrated model was then used to evaluate the energy conservation design options to determine the projected energy use. These studies are important to the current work because the previously studied Habitat Humanity house will be used for the current case-study house. The previous studies also provided detailed information about the architectural dimensions of house, sensor types and locations.

Im (2003) used ASHRAE's Inverse Model Toolkit (IMT) to compare the normalized energy use before and after IECC (International Energy Conservation Code) application of the case-study house. ASHRAE's Inverse Model Toolkit (IMT) is a FORTRAN 90 application for regression modeling of building energy use (Kissock et al. 2001). This toolkit can identify best-fit regression models for measuring retrofit savings in buildings. The IMT includes PRISM's variable-based degree-day algorithms, and it includes traditional linear, least square regression models, change-point linear models, multi-linear regression models, and combined models. For this study, IMT toolkit will be used to normalize energy use for case-study house.

2.7 Previous Work on the 2000/2001 IECC-Compliant Simulation

In order to quantify the reduction of NOx emissions by the implementation of the 2000/2001 IECC in new construction, simulation models have been being developed for both single-family and multi-family configuration by the Energy Systems Laboratory (ESL) and the developed simulation input models were previously utilized for several studies including Haberl et al. (2003a, 2003b, 2004a, 2004b, 2004c, 2004d), Ahmad et al. (2005), Malhotra (2005), and Mukhopadhyay (2005); of these, the following are most important to this study.

Ahmad et al. (2005) modified the single-family and multi family residential simulation input model developed by the Energy Systems Laboratory (ESL) to accommodate the different scenarios of envelope construction and HVAC equipment according to the 2000/2001 IECC. Then, simulation models, created with the DOE-2.1e simulation program were then linked to a web-based graphic user interface and the US EPA's eGRID which is the EPA's Emissions and Generation Resource Integrated database to convert the energy savings to NOx emissions reduction. A complete set of comparisons includes three simulation runs were performed; 1) a Pre-code run based on the construction characteristics published by the National Association of Home Builders (2004) for 1999, 2) a Code-compliant run based on the minimum construction requirement of the 2000/2001 IECC, and 3) a run using the user input. This paper is important to this study, because the single-family simulation input file for this study was modified based on Ahmad et al.'s study.

Malhotra (2005) analyzed the energy-efficient design strategies about the building configuration, materials, mechanical and electrical systems, equipment and applies using a simulation model of a prototype house with the DOE-2 energy simulation program. The simulation model was also adopted from the input file (SNGFAM2ST.INP) developed by the ESL. This study developed generalized design guidelines for achieving maximum energy-efficiency in single-family detached house. This study also used the simulation model which was developed by Energy Systems Laboratory (ESL). For a great number of simulations, the following supplementary programs (BDI (Batch DOE-2 Input)) and files (BDI spreadsheet) developed by the ESL were used to perform the DOE-2 simulation in the batch mode. This study provided useful information to perform a lot of simulations using batch mode because the current work used the same supplementary programs of BDI and BDI spreadsheet for numerous simulations.

2.8 Summary of Literature Review

The literature review has presented the background of energy savings on residential houses, specific approach to develop the simulation code for the residential house, review of existing building energy codes and standards, validation of computer simulation using calibrated simulation and previous works on the case-study buildings.

Portions of this research will make use of information from the described methods in each section. Works by National Fenestration Rating Council (NFRC 2002a, 2002b), Reilly et al. (1995), Christian (1991), Meldem and Winkelmann (1998), Huang et al. (1998), Medina (1992), Parker et al. (1999), and Henderson et al. (2000) are useful in the development of improved simulation input file of the base-case house and International Energy Conservation Code (IECC) compliant house. The work of ASHRAE (2004) is important to develop the duct model on DOE-2.1e simulation program. Researches by Koran et al. (1992), Elberling and Bourne (1996), Haberl and Bou-Saada (1998) are also important in the examination of the energy use of the developed simulation model. Works by Ahmad et al. (2005) and Malhotra (2005) provide useful information about DOE-2 simulation input files for the current study.

CHAPTER III

SIGNIFICANCE AND LIMITATION OF THE WORK

3.1 Expected Contributions from the Research

This research is expected to provide the following benefits toward the development of energy efficient residential building modeling.

1) The installation of new sensors in the case-study house and recalibration of existing sensors to provide measured data for calibration purpose.

2) The provision of an improved residential simulation models, including: thermal mass, detailed window simulation method, improved underground heat transfer and improved HVAC model.

3) The development of residential HVAC duct model to be used for evaluating duct heat loss / gain in unconditioned spaces.

4) Use of the improved model to make recommendations for changes in residential construction and HVAC installation that could save energy, reduce peak demands and result in more comfortable residential housing according to climate variations.

3.2 Limitations of the Research

The limitations of this study include:

1) This research focuses on the analysis of residential house based on the 2000/2001 International Energy Conservation Code (IECC). Therefore, the code-compliant model was adjusted to match the requirements of the 2000/2001 IECC.

2) The analysis of energy use of the as-built house and code compliant house are limited to those that DOE-2.1e version 119 can simulate.

3) The analyses were performed using a single-family house in the hot and humid climate of Texas.

4) Duct loss calculations in this research follow the method of ASHRAE 152-2004 (Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems).

CHAPTER IV

METHODOLOGY

This chapter discusses the methodology used in this research. It includes a description of the case-study building, measurements and data collection, the calibrated DOE-2 simulation method, analysis of the International Energy Conservation Code (IECC) and development of the computer simulation model of an IECC-compliant residence.

4.1 Introduction

The methodologies used in this dissertation consist of a number of tasks: 1) Measurement and analysis of the case-study house, 2) Building thermal simulation of the case-study house, 3) Analysis of the 2000 International Energy Conservation Code (IECC) and 2001 Supplement, 4) Development of the IECC-compliant computer simulation model, and 5) Analysis of energy-efficient construction using the improved model.

Figure 4.1 shows the steps that were followed in this study. First, the calibration and installation of sensors that measure the 15-minute energy use, weather conditions and the indoor environmental conditions of the case-study house were performed. In the second step, the DOE-2.1e (version 119) building simulation program was used to analyze the energy use and to apply new simulation methodologies such as attic space, duct model, new system / domestic hot water curves and new underground surface simulation method. A weather file developed by the case-study house from on-site measured weather data using the DOE-2 weather processor and other data processing routines developed by Bronson (1992) saved considerable effort in the pre-processing of measured data. The calibration process was initiated by creating an as-built case-study house input file.

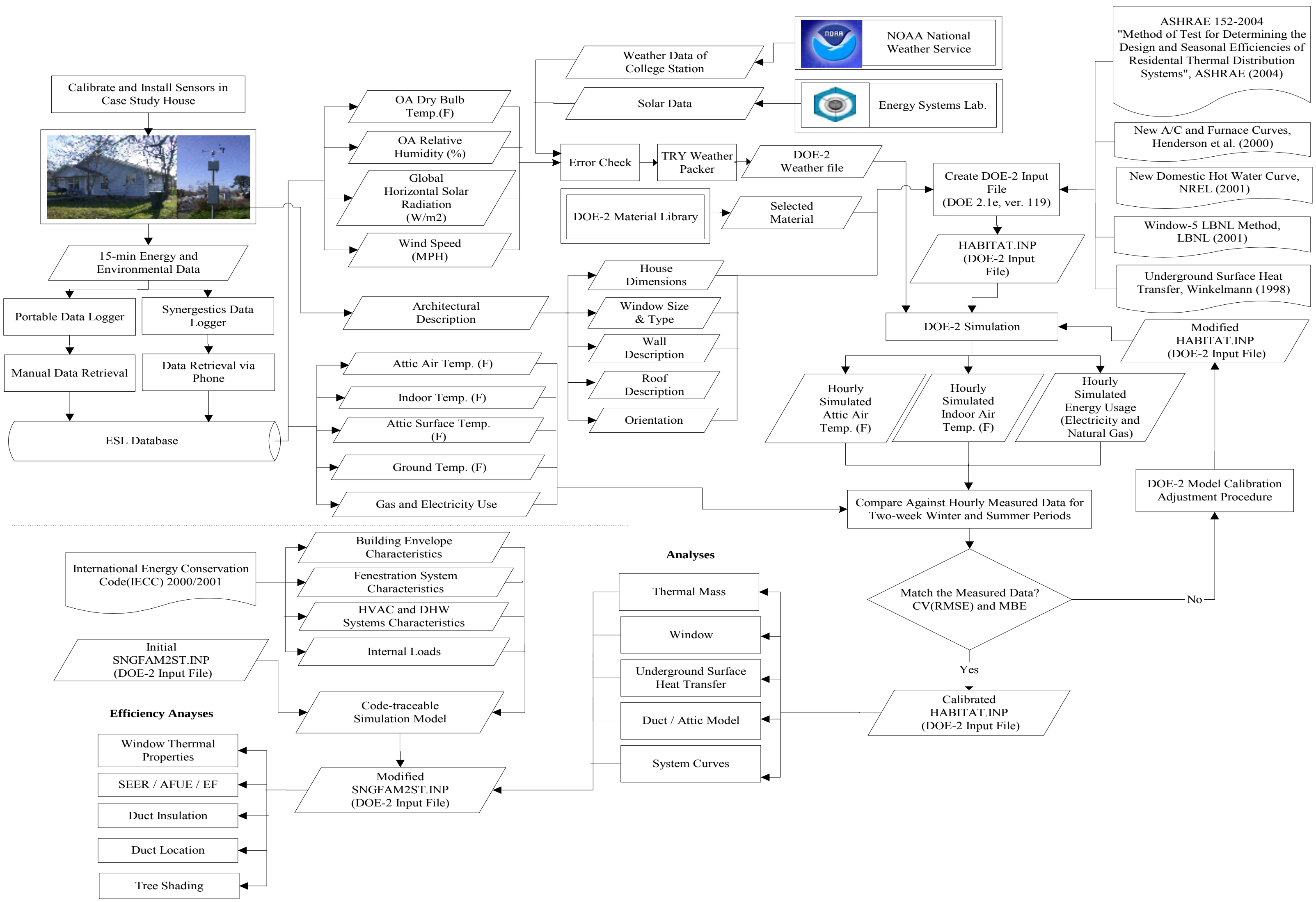


Figure 4.1 Research method diagram

This required repeated runs of the as-built base-case input file using the measured data while varying different parameters in the computer model. The best model was selected statistically by comparing the measured data and the DOE-2.1e simulation results using the CV(RMSE) and the MBE. Definitions of these terms are explained later in this chapter.

The third step involved the development of the initial simulation model of the code-compliant base-case model using the 2000/2001 IECC specification. This includes the decision and incorporation of the size of the house, layout, occupancy, envelope, HVAC / DHW systems, lighting, and equipment to DOE-2 simulation input file. The fourth step involved the application of the improved simulation methods which were verified from the as-built case-study house simulation. The fifth step involved the energy efficiency analysis using the modified IECC-compliant simulation model. This analysis included the variation of different thermal mass wall, fenestration system, duct location, system efficiency, etc.

4.2 Analysis of the Case-Study House

This section of the dissertation presents drawings of the case-study house, the details of the materials use in the construction and the installed equipment. It also describes the sensors used in the monitoring of the case-study house, data analysis, and analysis of the case-study house which uses the DOE-2.1e building energy simulation program.

4.2.1 Information of the Case-Study House in Bryan, Texas

The case-study house located at Bryan, Texas is a single-story Habitat for Humanity house built in 1997. This house has one living room, a dining room, a kitchen, a utility area, 3 bedrooms, 1 ½ bathrooms, a front and a back porch. The total area is 1,333 ft^2 (Kootin-Sanwu 2004). Table 4.1 shows the material specification of the case-study house.

Table 4.1 Material used in construction

	Material
Floor	- 4” concrete slab and 30” deep ground beams which are 12” wide - Linoleum tile
Exterior walls	- Vinyl siding and ½” plywood wrapped with “Tyvek” moisture barrier - ½“ gypsum, R-13 insulation - Composite 2x4” stud wall
Interior walls	- 2x4” stud wall - ½ ”gypsum - Blown-in treated cellulose insulation.
Ceiling	- 5/8” fire coded gypsum board - 12” of blown-in fiberglass insulation.
Roof	- Composite shingles - 5/8” plywood deck - 2x4” trusses set at 24” centers
Window	- Double pane clear with aluminum frame, without thermal break

The heating, ventilation and air-conditioning system consists of a 10.5 SEER (Seasonal Energy Efficiency Ratio) air-conditioning unit (2.5 tons), a furnace with 80% AFUE (Annual Fuel Utilization Efficiency), and a 0.56 EF (Energy Factor) domestic hot water system with 40-gallon tank size. Figures 4.2 to 4.5 show the pictures of the case-study house.

Figure 4.2 Front side of case-study house (facing northeast)

Figure 4.3 Back side of case-study house (facing southwest)

Figure 4.4   Left side of case-study house (facing southeast)

Figure 4.5   Right side of case-study house (facing northwest)

4.2.2 Measurement and Data Collection

This section discusses the equipment and the sensors used for monitoring the case-study house. This includes: the description of data acquisition system, the instrument calibration, installation of sensors, collection of data and cross checking of data against utility bills.

4.2.2.1 Instrument Calibration

Several sensors were used to measure the indoor and outdoor environmental condition and energy consumption. To measure environmental condition, temperature, humidity, solar radiation and wind speed were used. Electricity, gas, and domestic hot water use were used for measurement of the energy consumption. With the exception of the newly installed sensors in the attic space, the sensors at the case-study house were installed as a part of the previous study by Kootin-Sanwu (2004). Therefore, all sensors were inspected and recalibrated. National Institute of Standards and Technology (NIST) and American Society for Testing and Materials (ASTM 2001a, 2001b) calibration methods were used for the calibration procedures. The results using the pre-installation calibration are presented in this section. The post-morten calibration procedures, results and discussions are presented in Appendix A.

For the measurement of electricity use from the case-study house, the current from the transducers at the electric panel using a hand-held amp meter was measured and compared with the measurement from the readings on the data logger. In the case of the measurement of gas meter, manual readings of the utility for one-week were compared with data logger for the same period.

4.2.2.2 Installation of Sensors

Figure 4.6 shows the location of each sensor. A gas meter was installed at the rear of the house and was connected with the house's gas system and the data logger. In order to collect data from the case-study house, a C180E Synergistics Data Logger (Figures 4.7 and 4.8) was used and located in the backyard of the case-study house. This data logger has 16 power inputs, 16 digital inputs and 16 analog inputs, and can simultaneously monitored the analog, power and digital signals from the sensors located in the house (Kootin-Sanwoo 2004). This synergistics data logger can be remotely operated and data from logger can be downloaded using a computer program via modem using the Parset program that is supplied by the manufacturer (Synergistics 1994). After recalibrating the sensors, they were connected to the data logger to measure indoor and outdoor environmental conditions, and the energy use of the house every 15 minutes. The temperature and humidity sensors were installed in the supply air duct, the end of the duct, attic space, and in the return grill. A flow meter was installed on the domestic hot water heater in the utility room and was connected to the Btu meter at the rear of the house. Three new portable sensors were also located in the attic to measure inside roof surface temperatures.

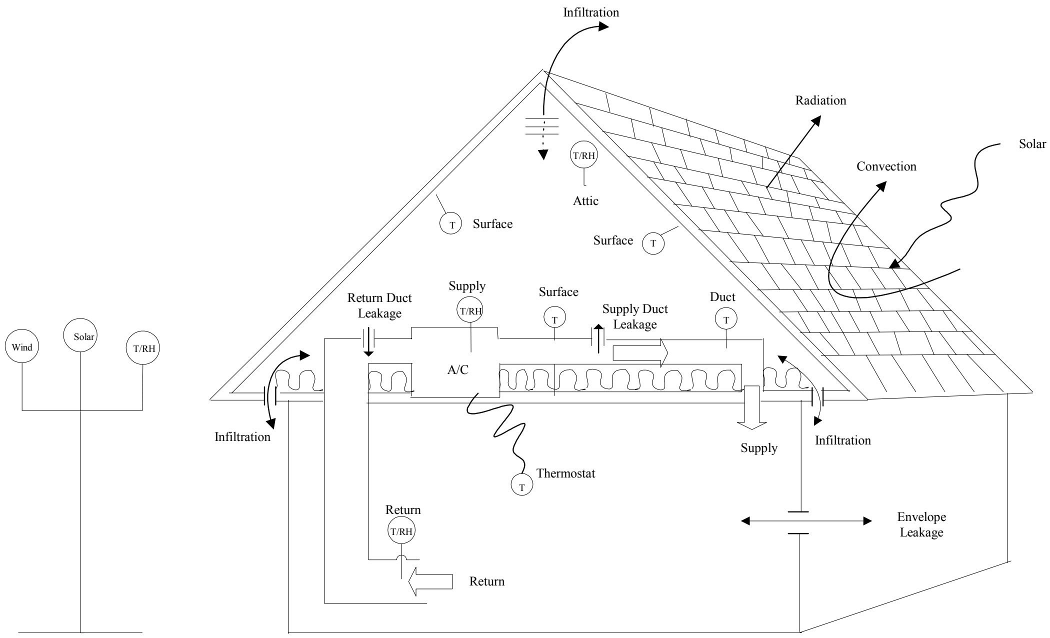


Figure 4.6 Diagram of sensor location

Figure 4.7 Data logger (Synergistics C180E) with weather station on case-study house

Figure 4.8 Data logger (Synergistics Data Logger C180E)

Table 4.2 describes specific information about various monitoring channels and Figures 4.9 to 4.17 are photos of the sensors installed on the case-study house.

Table 4.2 Monitoring channel description

Power channels		ESL Channel
Phase I	The electricity use for the first phase of the house (kW)	CH3789
Phase II	The electricity use for the second phase of the house (kW)	CH3790
Dryer	The electricity use for the dryer (kW)	CH4151
Air conditioner	The electricity use for the air conditioner (kW)	CH4152
Air conditioner Blower	The electricity use air conditioner blower (kW)	CH4153
Refrigerator	The electricity use refrigerator (kW)	CH3794
Freezer	This electricity use for the freezer (kW)	CH4154
Washer	This electricity use for the dishwasher (kW)	CH3796
Dishwasher	This electricity use for the washer (kW)	CH3797
Analog channels		ESL Channel
Ground Temperature -N	The ground temperature for the north sensor (°F)	CH3798
Ground Temperature -C	The ground temperature for the center sensor (°F)	CH3799
Ground Temperature -S	The ground temperature for the south sensor (°F)	CH3800
Supply Relative Humidity	The relative humidity of the supply air from the air-conditioning coils (%)	CH3801
Supply Temperature	The temperature of the supply air from the air-conditioning system (°F)	CH3802
Return Relative Humidity	The relative humidity of indoor air of the house (%)	CH3803
Return Temperature	The temperature of the indoor air of the house (°F)	CH3804
CO_2 sensor	The carbon dioxide concentration inside the house (ppm)	CH3805
Duct Temperature	The temperature of the duct air from the air-conditioning system (°F)	CH3806
Solar Radiation	The solar radiation at the on-site weather station at the house (W/m^2)	CH3807
Wind Speed	The wind speed outside the house (mph)	CH3808
OA Relative Humidity	The relative humidity of the outdoor air at the on-site weather station (%)	CH3809
OA Temperature	The temperature of the outdoor air the on-site weather station (°F)	CH3810
Attic Relative Humidity	The relative humidity of the attic air of the house (%)	CH3811
Attic Temperature	The temperature of the attic air of the house (°F)	CH3812
Digital channels		ESL Channel
Flow Meter	The flow meter of the of the house (gallons)	CH3813
Btu Meter	The Btu meter of domestic water heater (Btu)	CH3814
Gas Meter	The gas meter the house (Cubic Feet)	CH3815
Portable sensors		ESL Channel
Surface temperature 1	Inside roof surface temperature (Southeast facing)	N/A
Surface temperature 2	Inside roof surface temperature (Northwest facing)	N/A
Surface temperature 3	Inside roof surface temperature (Attic floor)	N/A

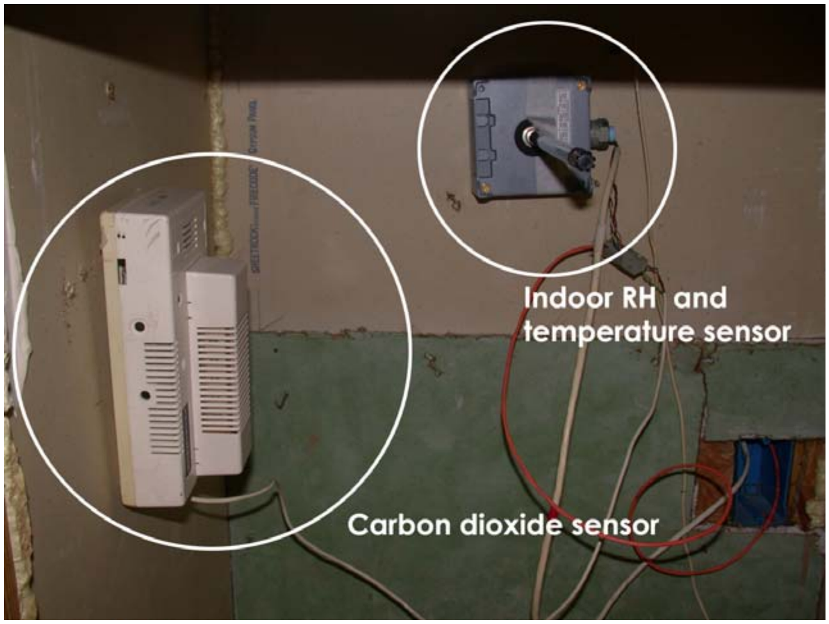


Figure 4.9 Indoor temperature / relative humidity sensor and carbon dioxide sensor

Figure 4.10 Attic temperature / relative humidity sensor with radiation shield and insulation

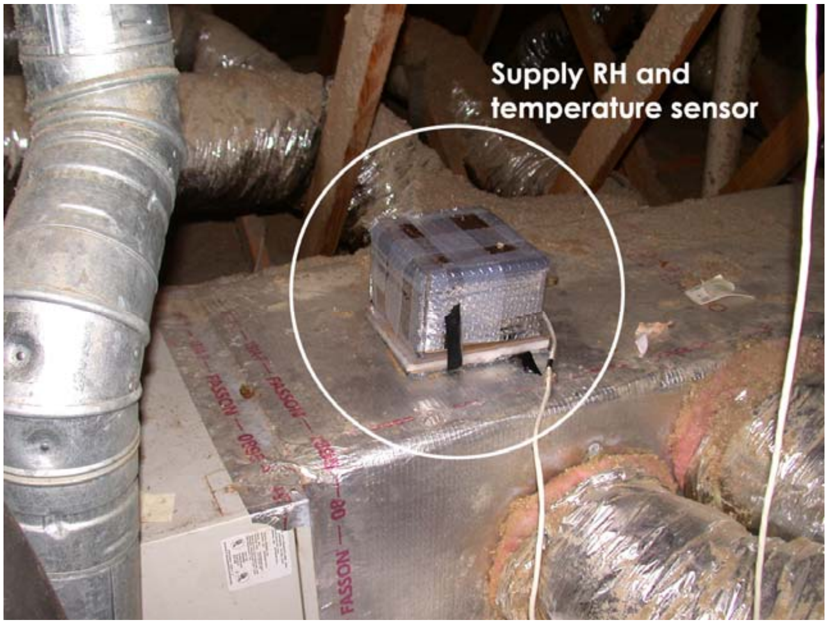


Figure 4.11 Supply temperature / relative humidity sensor with insulation

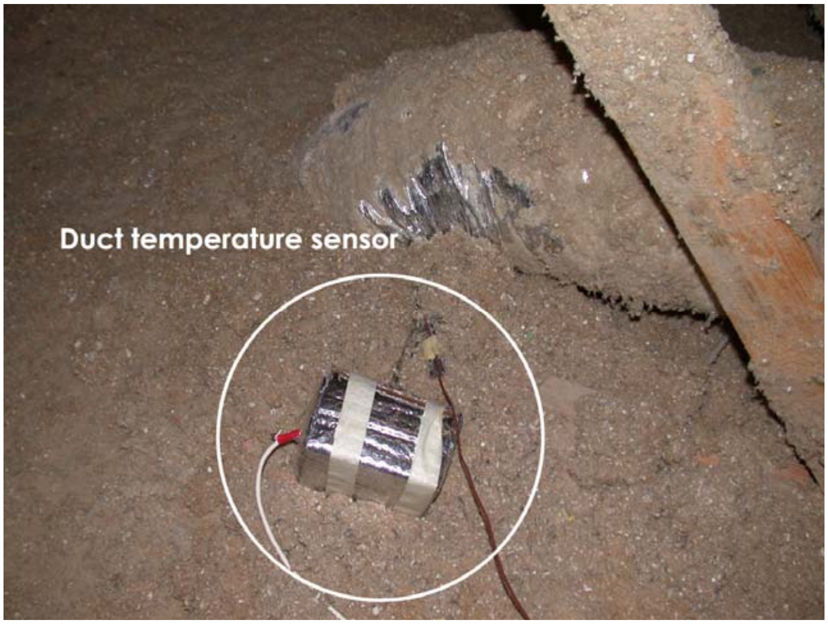


Figure 4.12 Duct temperature sensor with insulation

Figure 4.13 J-type thermocouple for measuring surface temperature of roof

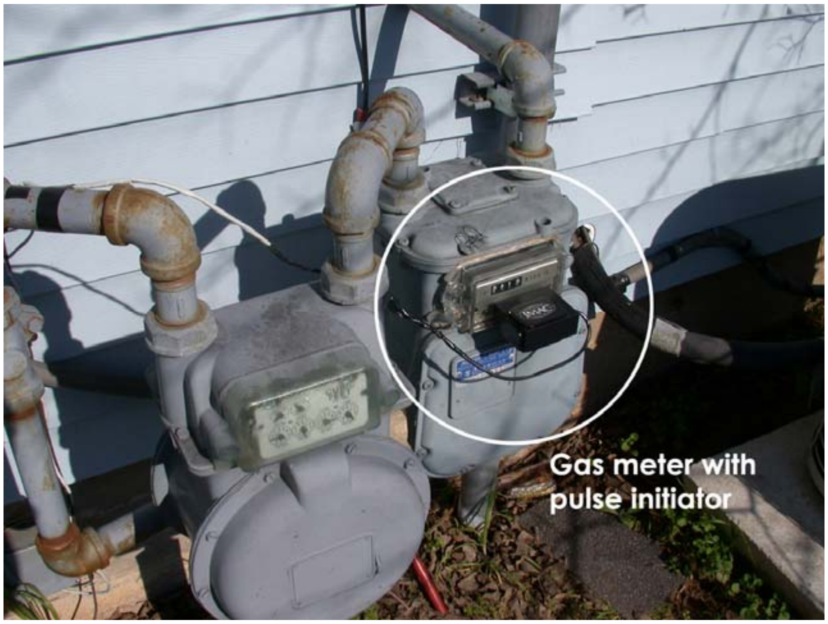


Figure 4.14 Gas meter with pulse initiator

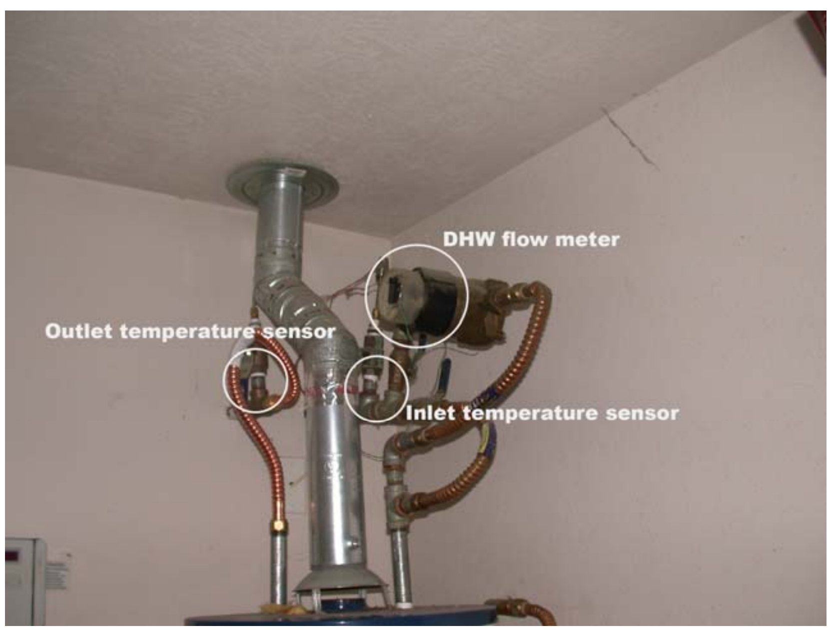


Figure 4.15   Flow meter attached to the domestic hot water heater

Figure 4.16   DHW Btu meter

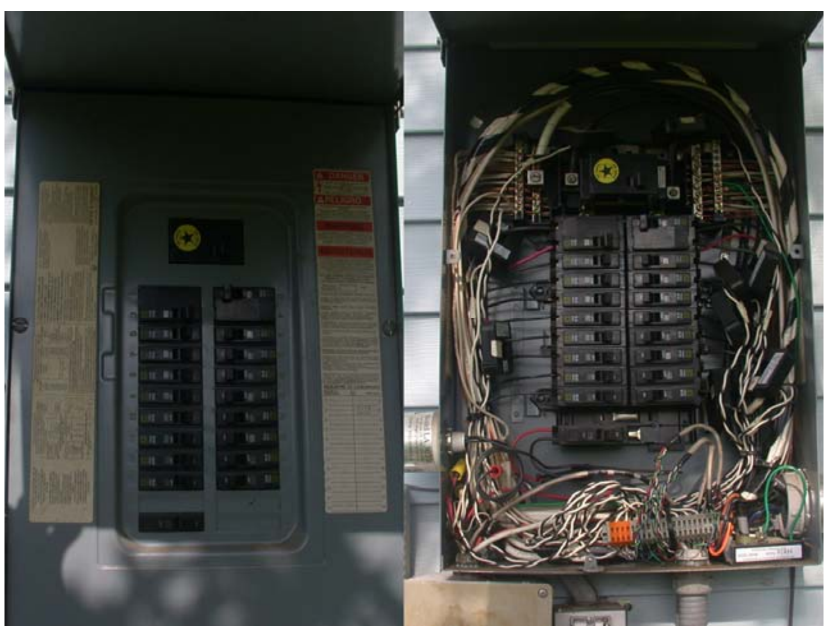


Figure 4.17   Electrical panel with the current transducers, face on (left) and face off (right)

4.2.2.3 Collection of Data

The data collection process includes: 1) polling, 2) error-checking and 3) uploading of the data to the ESL's UNIX database (Figure 4.18). Polling data from the data logger at the case-study house was performed remotely with a computer in the Energy Systems Laboratory (ESL) using a modem and the telephone line connected to the data logger. The previous week's data, which is stored in the memory of the logger, were downloaded into the Energy Systems Laboratory's database every week using the PARSET program (Synergistics 1994), and were then loaded to the ESL database. The error-checking task includes the inspection of downloaded data from case-study house. This includes 1) the examination of the maximum and the minimum value of the data, 2) graphical inspection to validate the pattern of the data and 3) checking for any occurrence of data points that were shown by -99 at the series records, which means no data or out of range.

Figures 4.19 to 4.41 are two-week sample data plots of a summer period (Aug 1, 2004 – Aug 14, 2004) that show energy use and environmental data from the case-study house.

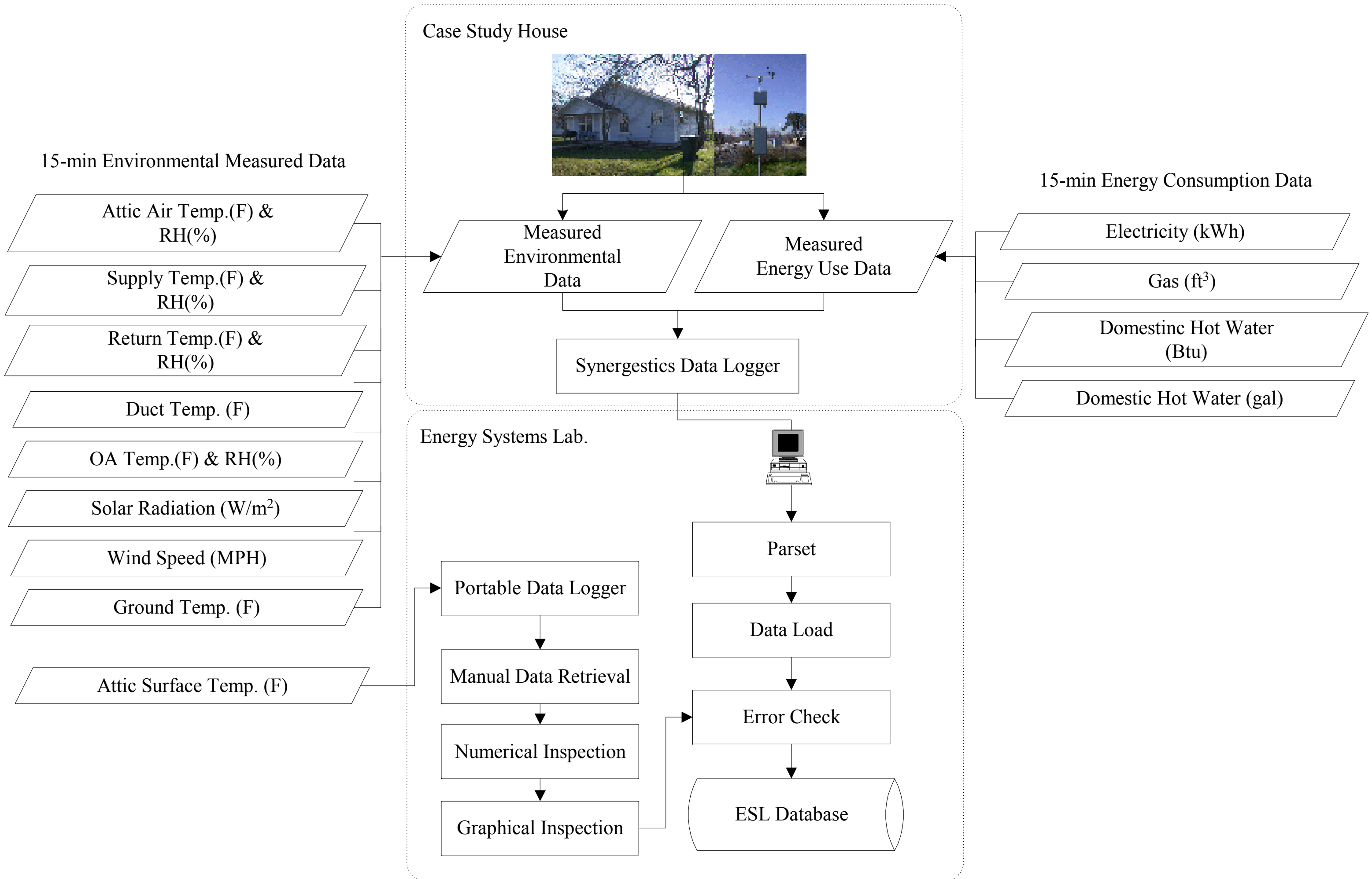


Figure 4.18 Procedure for collecting data

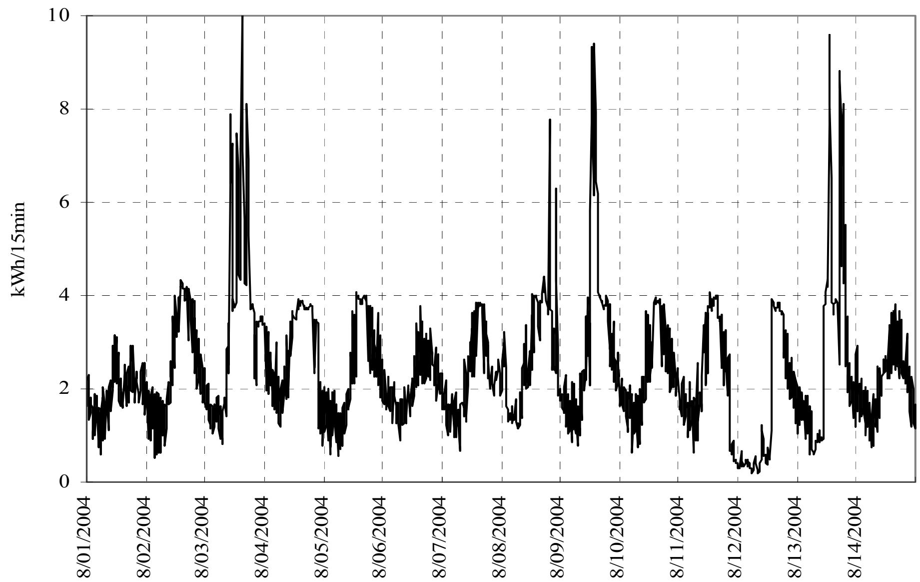


Figure 4.19 Whole-building electricity use of house (CH3789+CH3790)

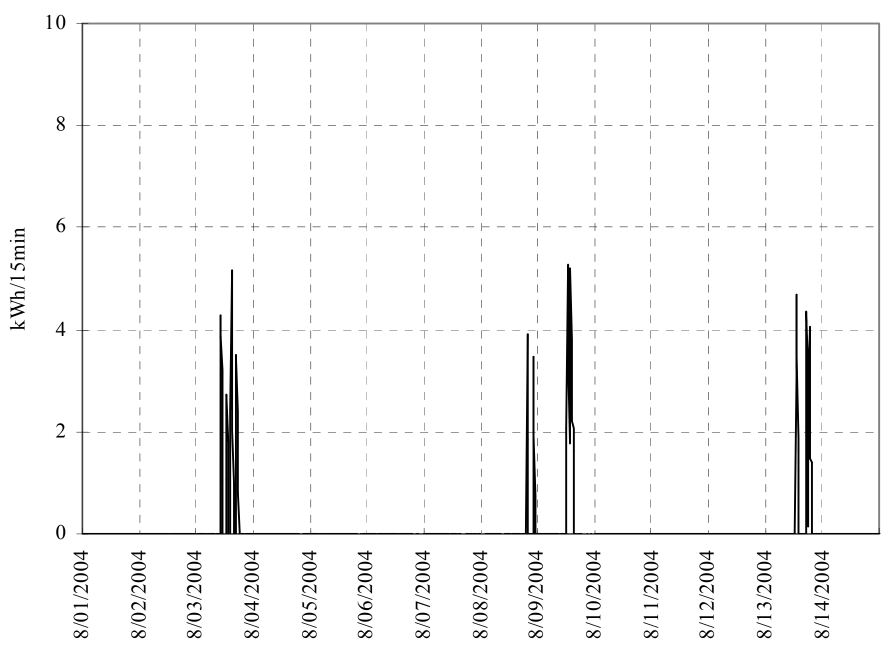


Figure 4.20 Electricity use for the dryer (CH4151)

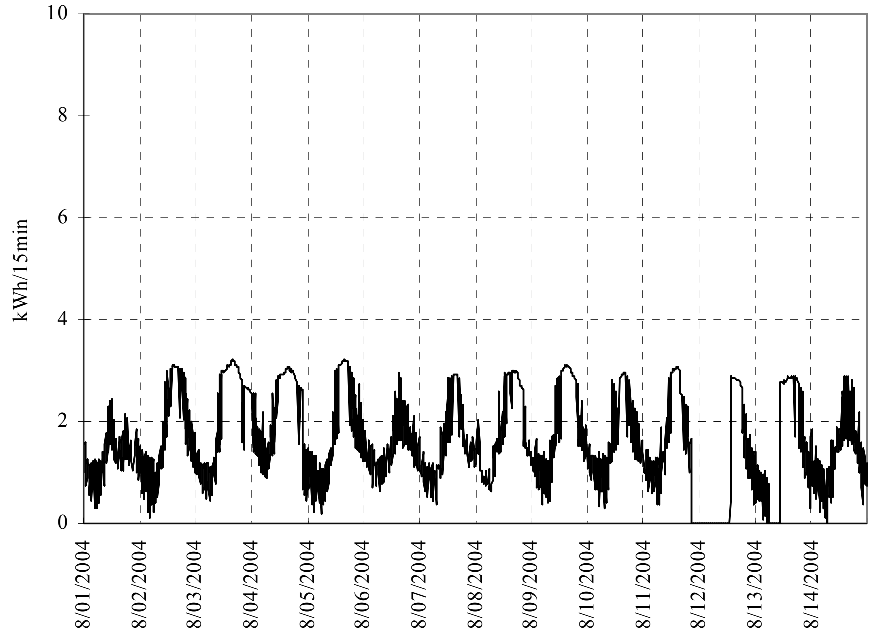


Figure 4.21 Electricity use for the air conditioner (CH4152)

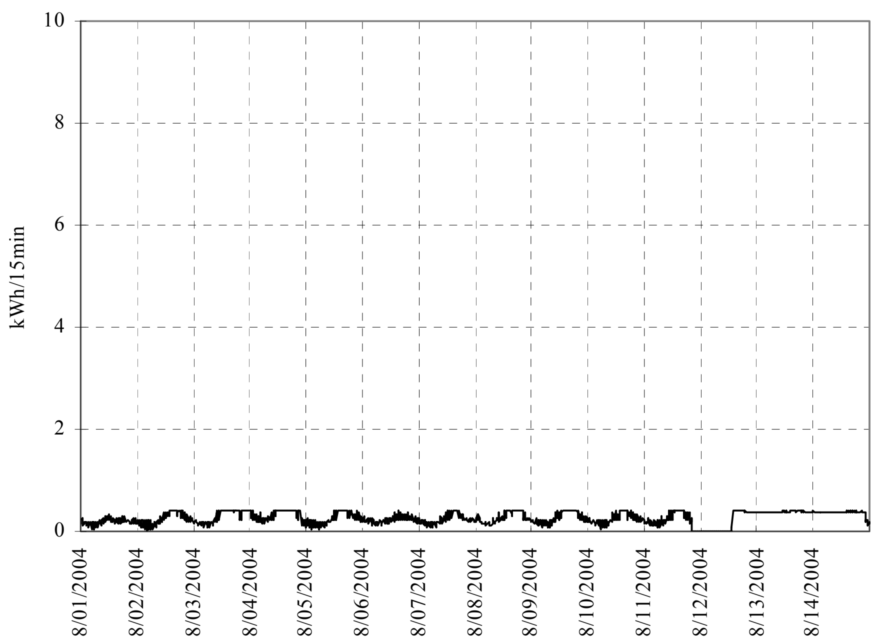


Figure 4.22 Electricity use for the air conditioner blower (CH4153)

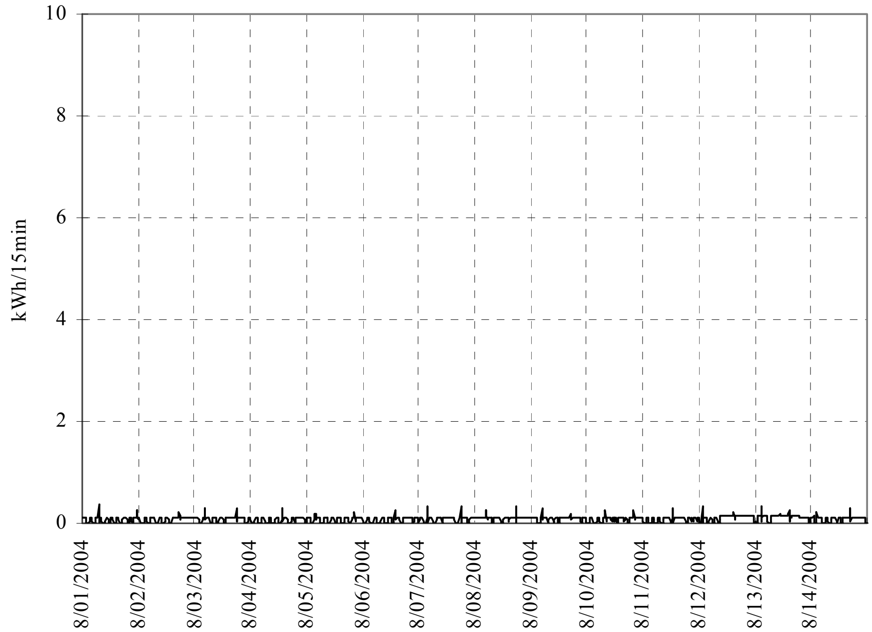


Figure 4.23 Electricity use for the refrigerator (CH3794)

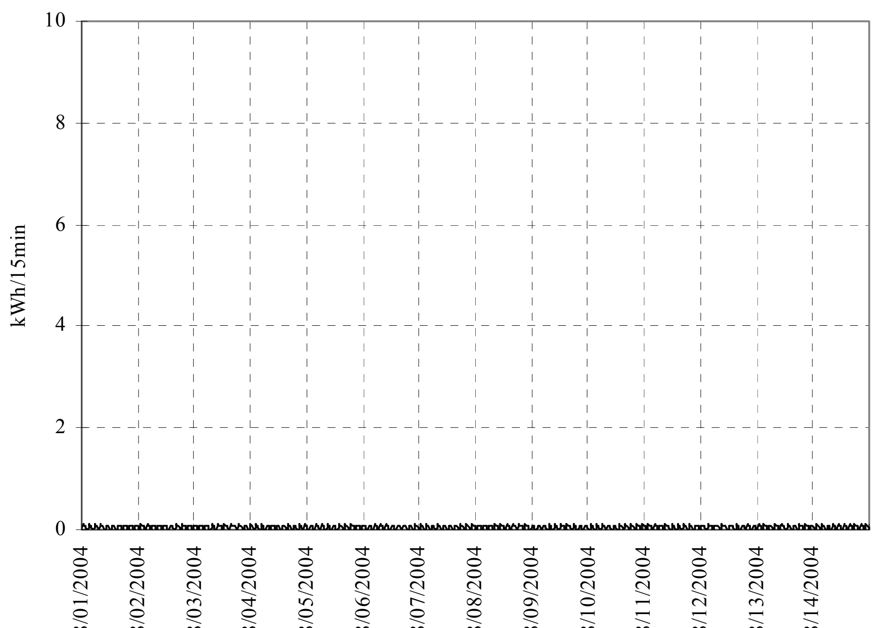


Figure 4.24 Electricity use for the freezer (CH4154)

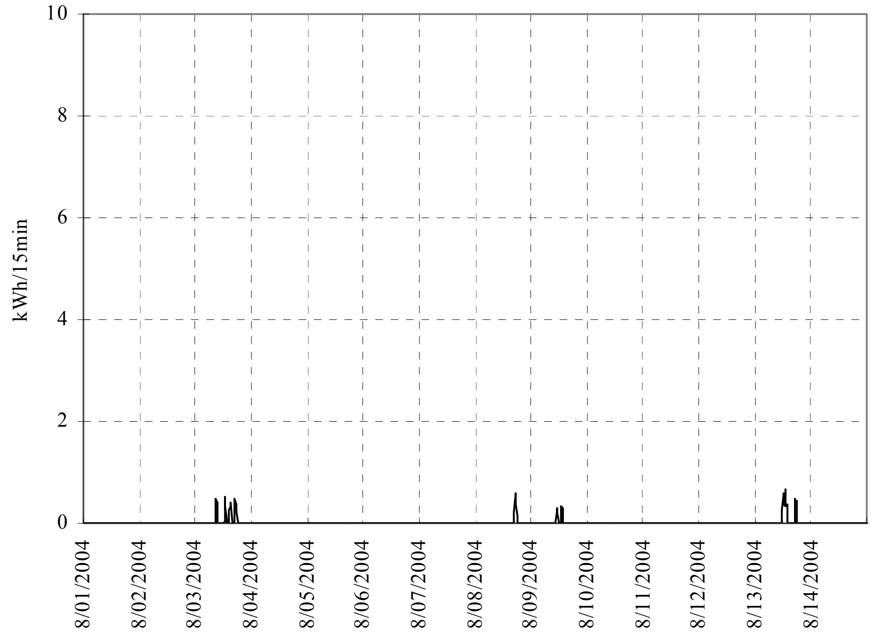


Figure 4.25 Electricity use for the washer (CH3796)

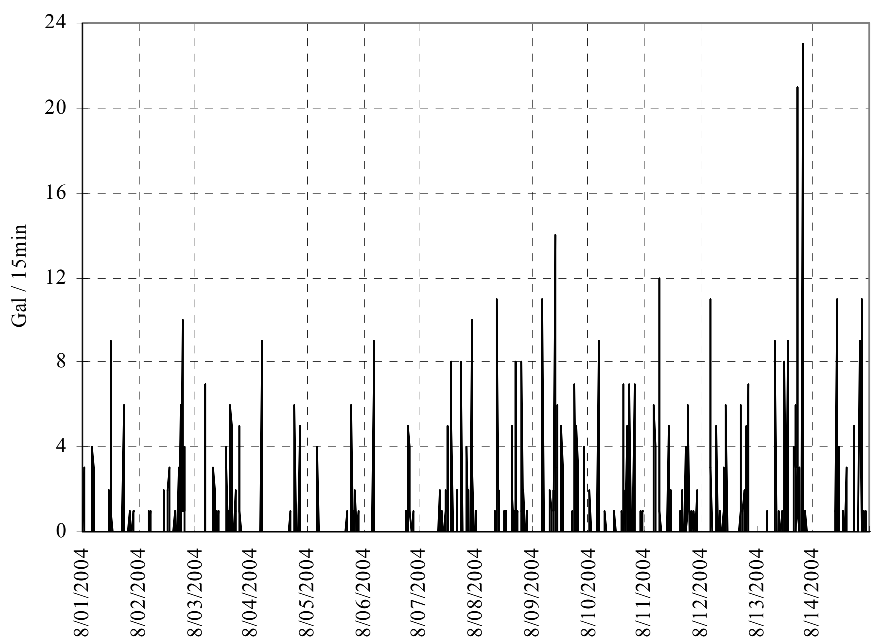


Figure 4.26 DHW flow meter (CH3813)

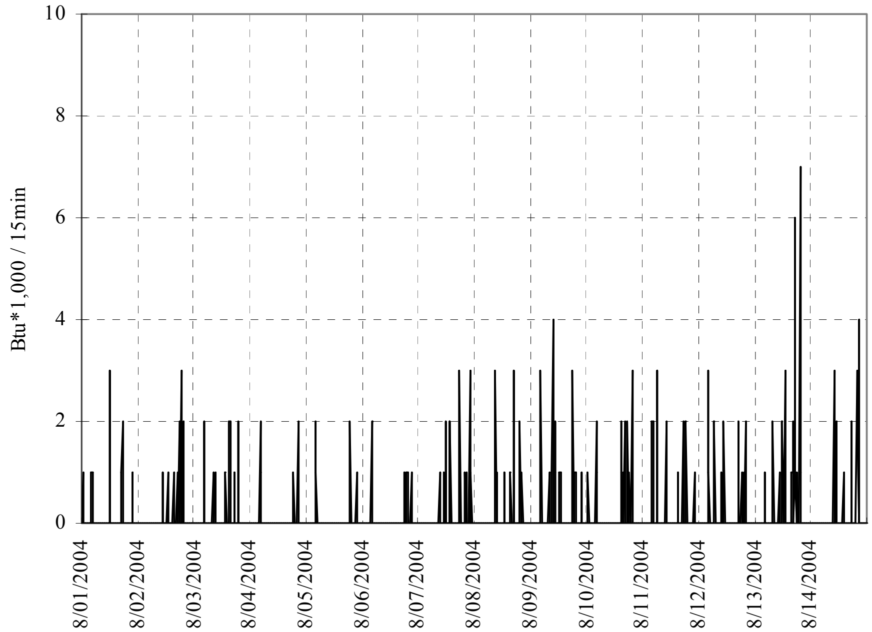


Figure 4.27   Btu meter for domestic water heater (CH3814)

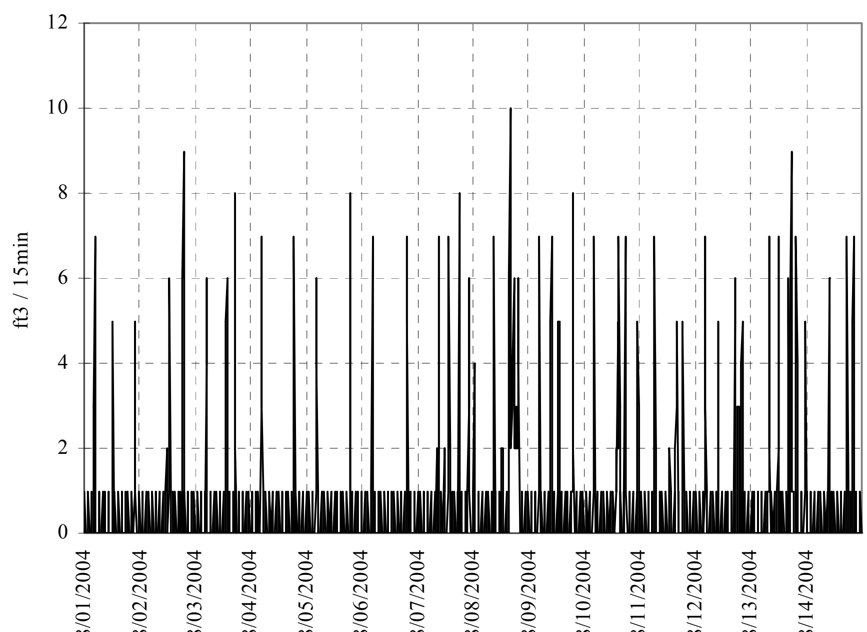


Figure 4.28   Gas meter for the house (CH3815)

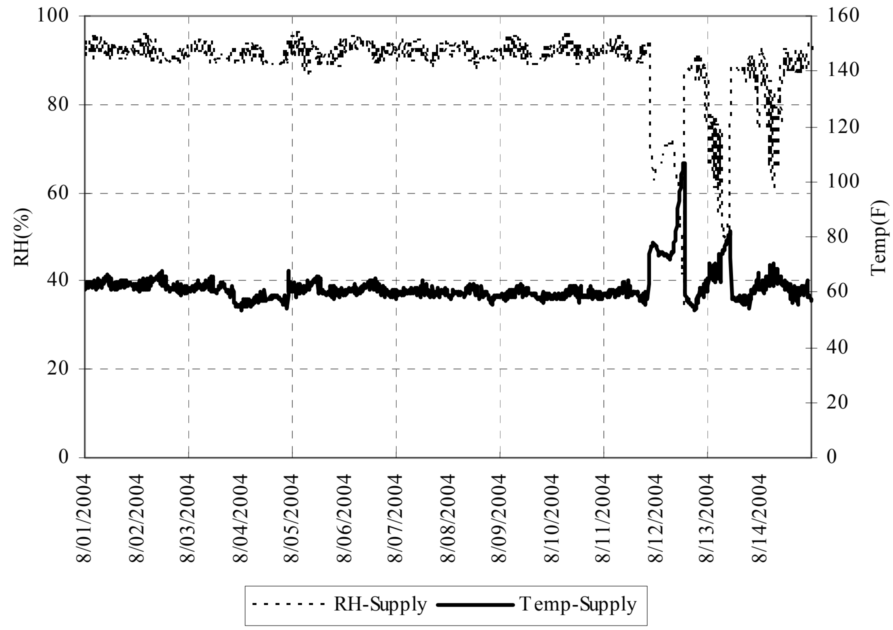


Figure 4.29 Supply relative humidity and temperature (CH3801, CH3802)

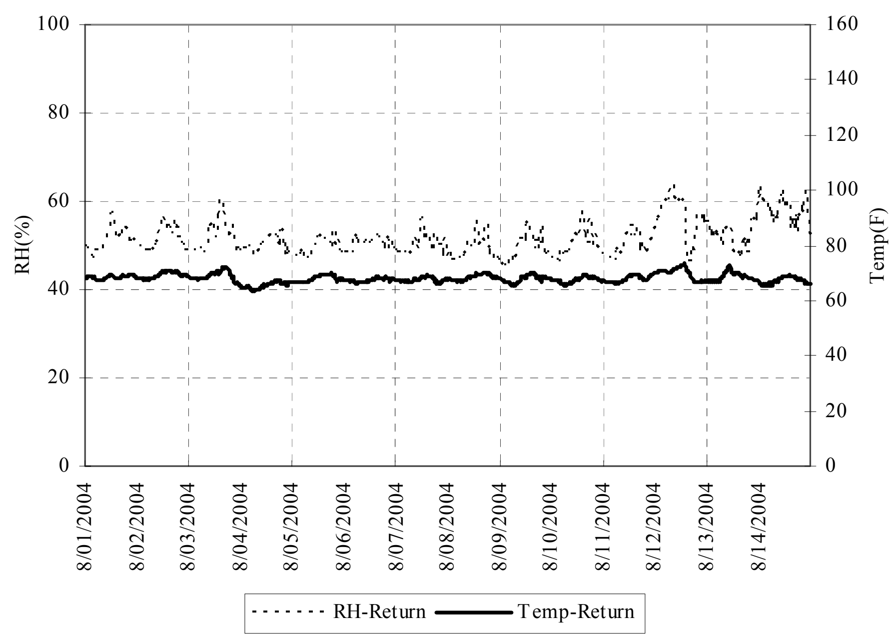


Figure 4.30 Return relative humidity and temperature (CH3803, CH3804)

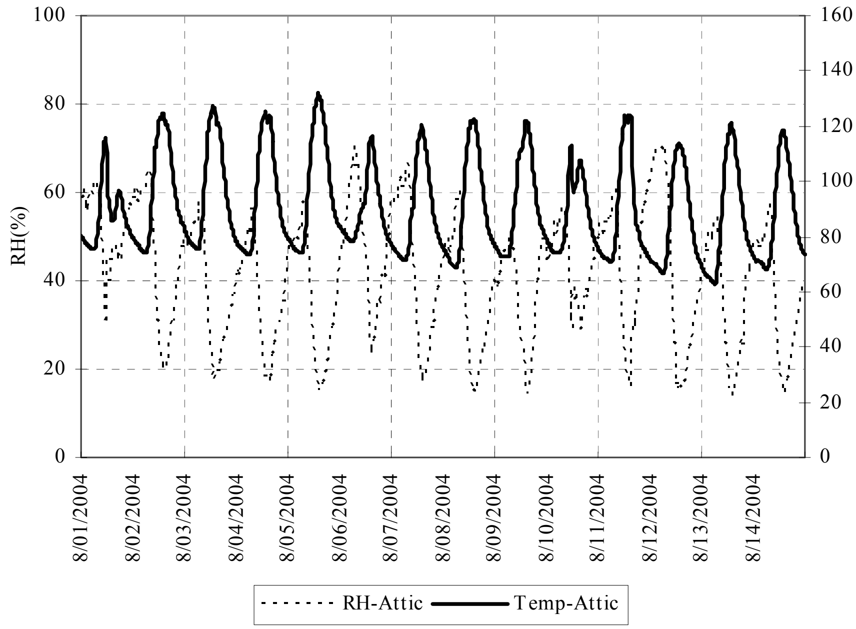


Figure 4.31 Attic relative humidity and temperature (CH3811, CH3812)

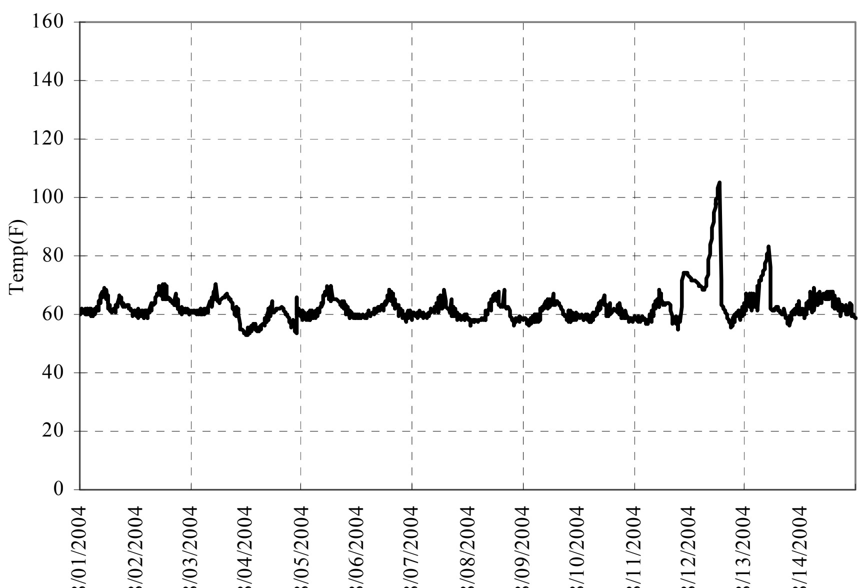


Figure 4.32 Duct temperature (CH3806)

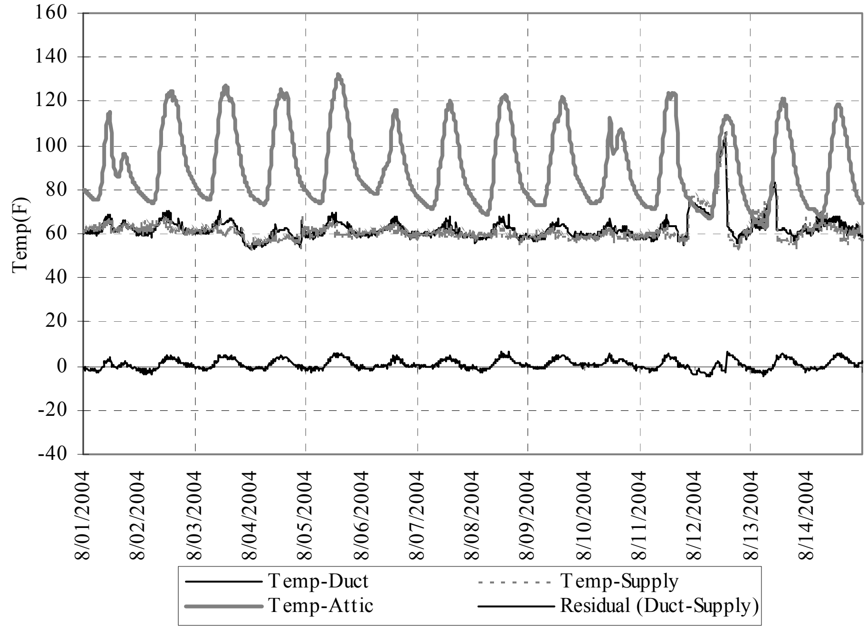


Figure 4.33 Supply, attic and duct temperature (CH3802, CH3812, CH3806)

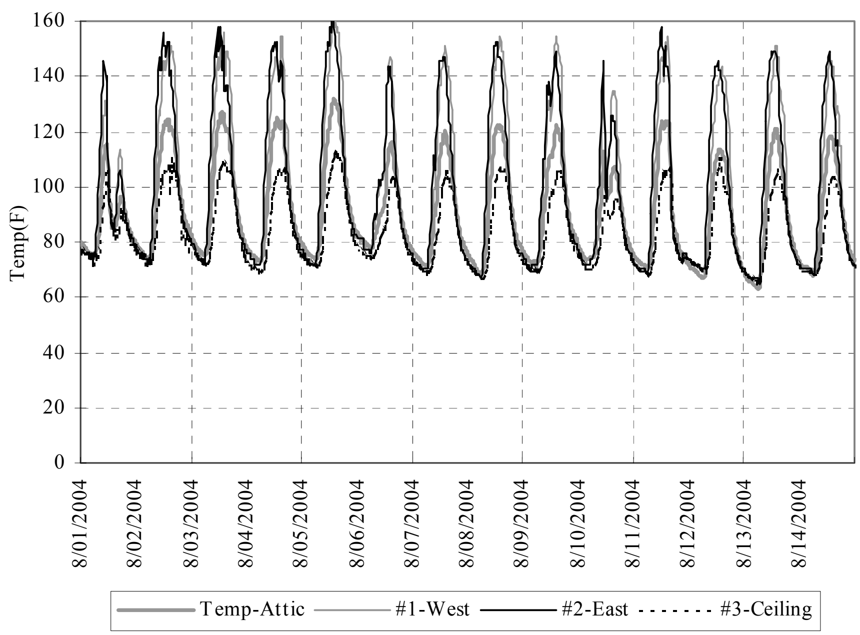


Figure 4.34 Attic temperature and roof surface temperatures

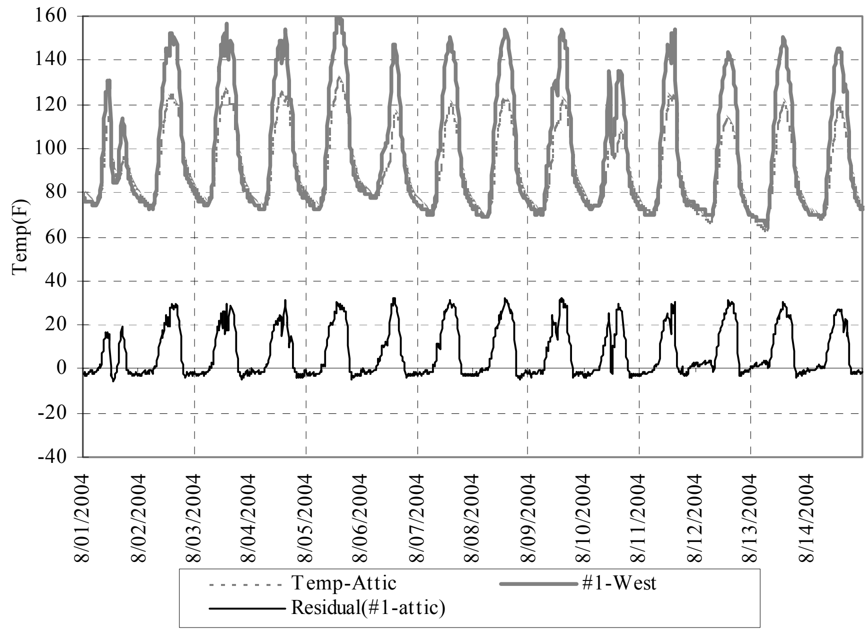


Figure 4.35 West side of inside roof surface temperature

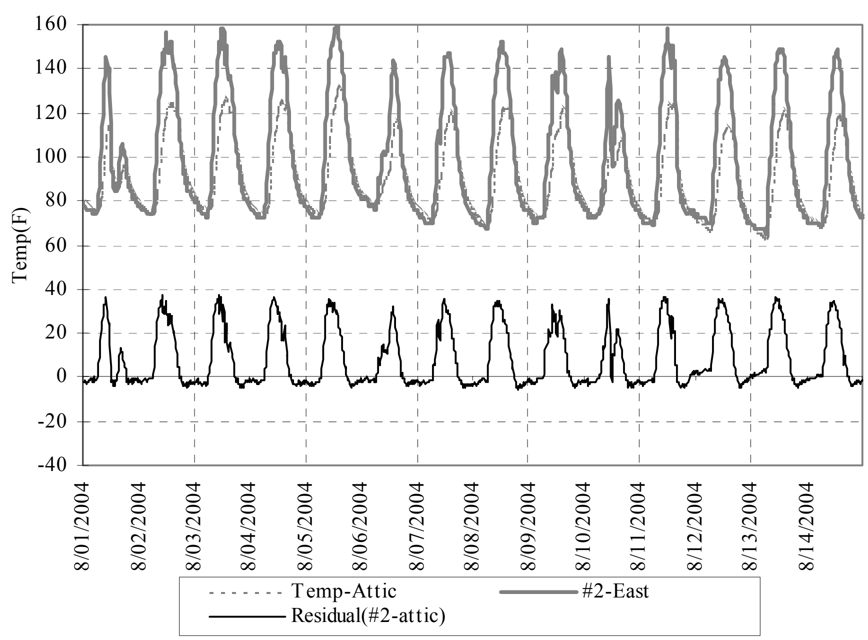


Figure 4.36 East side of inside roof surface temperature

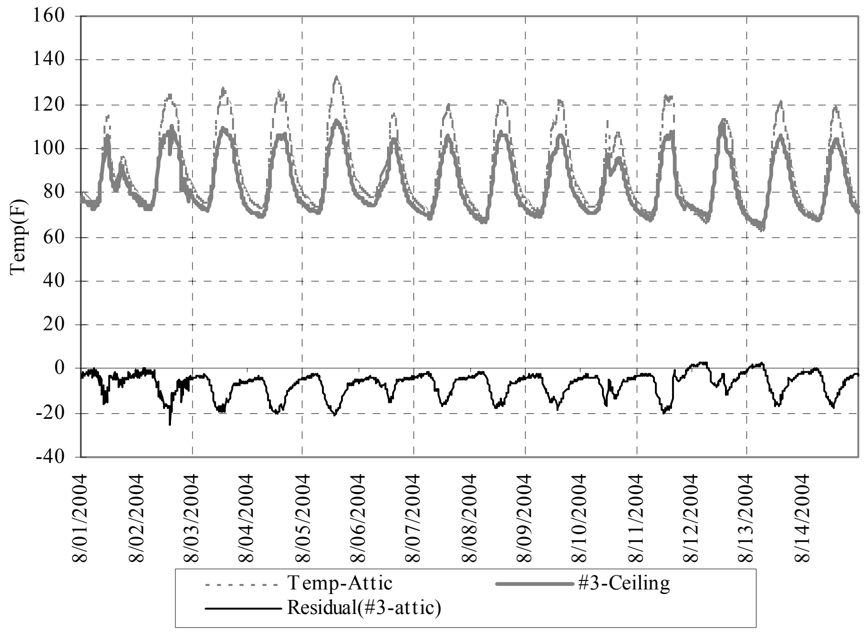


Figure 4.37 Ceiling surface temperature in the attic

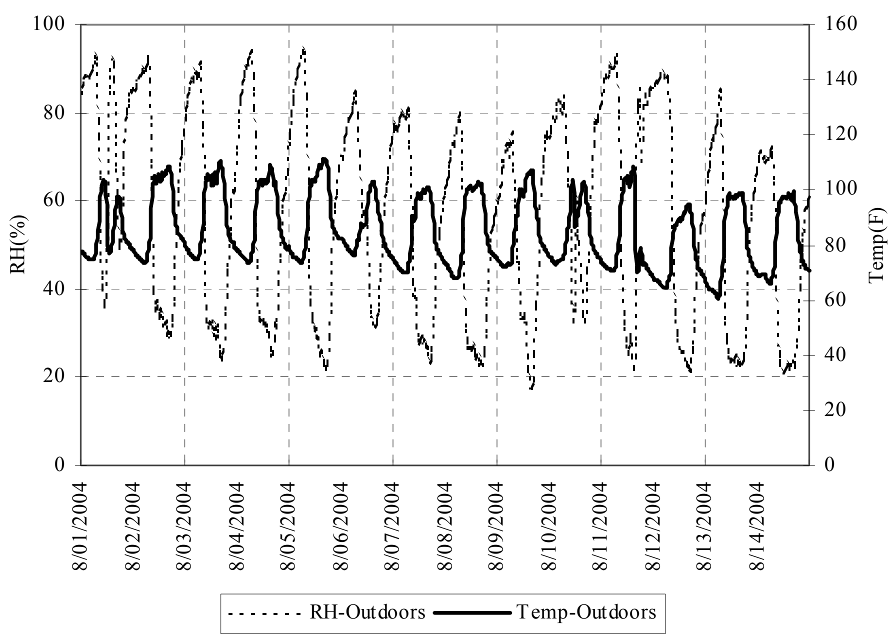


Figure 4.38 Outside air relative humidity and temperature (CH3809, CH3810)

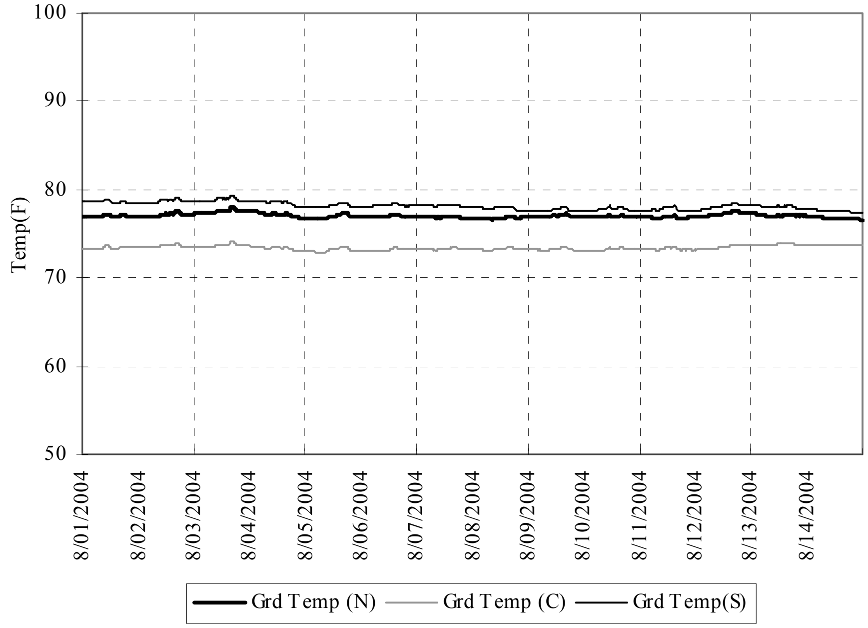


Figure 4.39 Ground temperature (north, center and south) (CH3798, CH3799, CH3800)

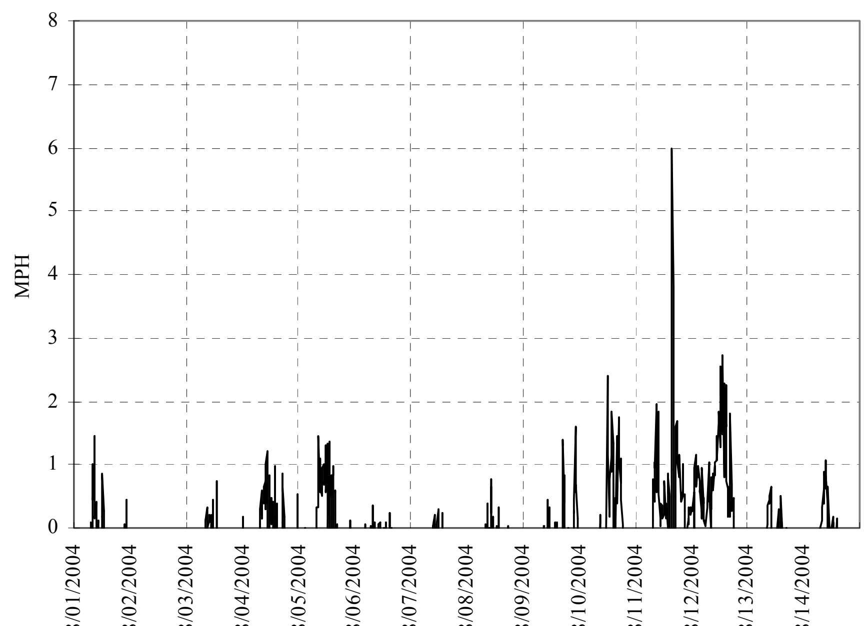


Figure 4.40 Wind speed (CH3808)

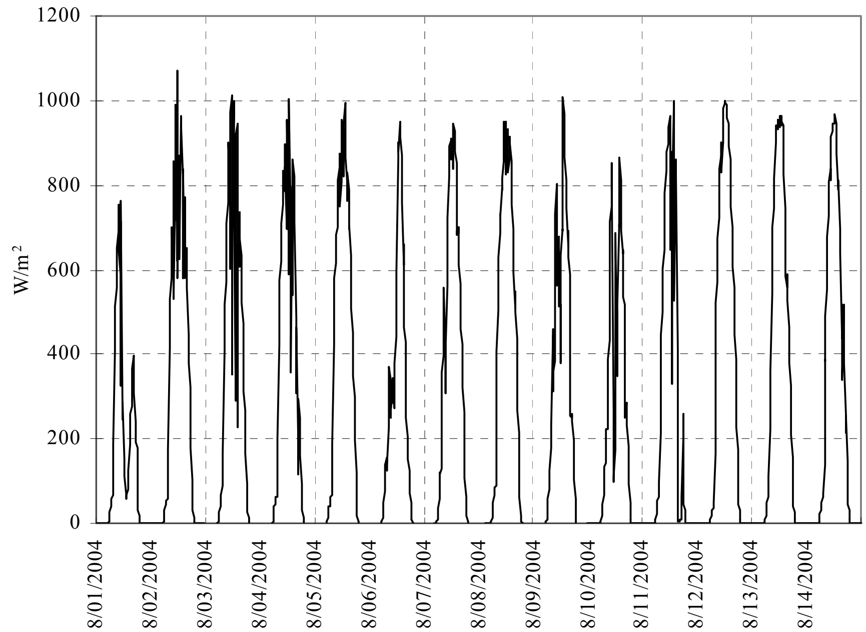


Figure 4.41 Global horizontal solar radiation (CH3807)

4.2.2.5 Comparison of IECC-Compliant Model with the Case-Study House Using ASHRAE Inverse Modeling Toolkit (IMT)

The IMT was used to examine the pattern of electricity and natural gas energy use of the as-built case-study house and to compare with the code-compliant IECC simulation model. The IMT is a FORTRAN 90 application of calculating linear, change-point linear, variable-based degree-day, multilinear and combined regression models.

4.2.2.5.1 IMT Input Files

In order to run IMT, two files are required: a data file and an instruction file. The IMT is provided with two sample data files, DAILY2.DAT and NONUNIPP.DAT. DAILY2.DAT is a uniform time-scale data file which contains daily ambient temperatures and energy consumption data. The DAILY2.DAT file format can be used to run the mean (1P), linear (2P), three-perimeter (3P), four-parameter (4P), five-parameter (5P), and multi-variable regression (MVR) models. The second sample is a nonuniform time-scale data file called NONUNIPP.DAT. This file format includes monthly energy use and other data and daily ambient temperatures. This file can be used to run the variable-based degree-day (VBDD) and combined VBDD-MVR models.

Using the IMT instruction file, the user identifies the input data file, the desired fields and record in the input data file, and can select the proper regression model. Figure 4.42 shows an example of a data file. Each column contains the following information:

Column 1: Site Number

Column 2: Month

Column 3: Day

Column 4: Year

Column 5: Group field (1 for pre-retrofit period and 2 for post-retrofit period)

Column 6: Cooling energy use (mBtu/day)

Column 7: Heating energy use (mBtu/day)

Column 8: Whole energy use (mBtu/day)

Column 9: Daily average ambient temperature (°F)

114	10	16	90	1	61.8	27.23	-99	76
114	10	17	90	1	65.2	25.68	-99	79
114	10	18	90	1	44.2	35.21	-99	64
114	10	19	90	1	42.6	38.66	-99	62
114	10	20	90	1	52	32.76	-99	70
114	10	21	90	1	44.8	41.29	-99	63
114	10	22	90	1	36.8	44.2	-99	57
114	10	23	90	1	-99	-99	-99	58
114	10	24	90	1	41	39.66	-99	63
114	10	25	90	1	41.8	37.66	-99	64
114	10	26	90	1	43.2	37.39	-99	62
114	10	27	90	1	45.2	33.49	-99	65
114	10	28	90	1	46.8	32.49	-99	68
114	10	29	90	1	48.4	34.21	-99	68
114	10	30	90	1	52.8	33.85	-99	67
114	10	31	90	1	55.6	33.31	-99	68
114	11	1	90	1	53.2	32.13	-99	68
114	11	2	90	1	57.2	31.67	-99	70
114	11	3	90	1	61	29.86	-99	75
114	11	4	90	1	40.4	43.02	-99	57
114	11	5	90	1	37.2	47.01	-99	51
114	11	6	90	1	40.2	41.02	-99	57
114	11	7	90	1	41.2	38.84	-99	60
114	11	8	90	1	37	44.56	-99	53
114	11	9	90	1	37	44.65	-99	57

Figure 4.42 Sample DAILY2.DAT file

For the IMT instruction file, the user gives the IMT instructions about the locations of the input data file, the specific fields in the data file that are being used for analysis, and regression model which is to be used. Figure 4.43 shows the DAILY2INS.TXT instruction file to generate a multivariable regression (MVR) model of cooling energy use as a function of building electricity use and ambient temperature. The instruction file consists of 14 lines of a single field. The first line is for the path and name of the input data file. The second line is for the value of the no-data flag. In this sample file, “-99” was used for the no-data flag. The third and fourth line is for the column number of group field and the value of valid group field. The fifth line is for residential file. If the user needs the residual file, this option will be input as 1. From the sixth line, the appropriate model is selected from the list shown. In this model, the MVR model (7) is selected. The seventh line is for the column number of dependent variable Y. The value in this record indicates the column number for the dependent variable such as the cooling or heating energy consumption. The eighth line indicates the number of independent variables. In this sample file, two independent variables are used. The corresponding column numbers of independent variables are indicated from the ninth to the fourteenth lines. Since this sample file has two independent variables, the ninth and the tenth lines show the corresponding numbers 8, 9, which are the eighth and ninth columns in the input file.

```
Line 1: Path and name of input data file = daily2.dat
Line 2: Value of no-data flag = -99
Line 3: Column number of group field = 5
Line 4: Value of valid group field = 1
Line 5: Residual file needed (1 yes, 0 no) = 1
Line 6: Model type (1:Mean,2:2p,3:3pc,4:3ph,5:4p,6:5p,7:MVR,8:HDD,9:CDD) = 7
Line 7: Column number of dependent Y variable = 6
Line 8: Number of independent X variables (0 to 6)  = 2
Line 9: Column number of independent variable X1 = 8
Line 10: Column number of independent variable X2 = 9
Line 11: Column number of independent variable X3 = 0
Line 12: Column number of independent variable X4 = 0
Line 13: Column number of independent variable X5 = 0
Line 14: Column number of independent variable X6 = 0
```

Figure 4.43 Sample instruction file

4.2.2.5.2 IMT Output Files

Model coefficients and goodness of fit parameters are reported in the ASCII output file IMT.OUT. This output can be viewed from any text editor. Figure 4.44 shows an example of an IMT.OUT file. As mentioned previously, the IMT also creates a residual file that includes all the input data, predicted values of the dependent variable, and the difference between predicted and measured values of the dependent variable (i.e., the residual). This is named IMT.RES. It can be used to create plots using the Microsoft EXCEL program. It is also used to calculate average billing-period temperatures as a preprocessor to linear and change-point linear models, which are run with monthly utility billing data.

```
*******************************************
 ASHRAE INVERSE MODELING TOOLKIT (1.9)
*******************************************
  Output file name = IMT.Out
*******************************************
  Input data file name =  daily2.dat
  Model type =          MVR
  Grouping column No =    5
  Value for grouping =    1
  Residual mode =         1
  # of X(Indep.) Var =    2
  Y1 column number =      6
  X1 column number =    8
  X2 column number =    9
  X3 column number =    0 (unused)
  X4 column number =    0 (unused)
  X5 column number =    0 (unused)
  X6 column number =    0 (unused)
*******************************************
  Regression Results
 -------------------------------------
       N =    167
 -------------------------------------
      R2 =     0.845
 -------------------------------------
   AdjR2 =     0.845
 -------------------------------------
    RMSE =      6.4314
 -------------------------------------
 CV-RMSE =    11.328%
 -------------------------------------
       p =     0.627
 -------------------------------------
      DW =     0.740 (p>0)
 -------------------------------------
       a =    -50.6026 (      5.8082)
 -------------------------------------
      X1 =      0.0035 (      0.0007)
 -------------------------------------
      X2 =      1.2576 (      0.0421)
 -------------------------------------
```

Figure 4.44   Sample IMT output file

4.2.2.5.3 Three Parameter Change-Point Models

In general, 3P models are used for modeling residential building energy use that is constant over one portion of the temperature range and varies linearly with temperature over the other portion (Kissock et al. 2001). For this research, two 3P models were selected (Figure 4.45): 3PC for cooling and 3PH for heating. The 3PC model uses ambient temperature as a independent variable and cooling energy use as a dependent variable above a certain change-point. The 3PH model uses ambient temperature as an independent variable and heating energy use as a dependent variable below a certain change-point. After running the IMT for the 3PC and 3PH models, weather-normalized IMT coefficients were identified from the IMT.OUT, which includes a constant term, a slope, and a change point. The following formula explains the typical three-parameter change-point model.

$$Y_c = \beta_1 + \beta_2(X_1 - \beta_3)^+ \tag{4.1}$$

$$Y_h = \beta_1 + \beta_2(\beta_3 - X_1)^+ \tag{4.2}$$

where, β_1 is the constant term, β_2 is the slope term, and β_3 is the change point. The $(\ )^+$ indicates that the value of the parenthetic term should be zero when they are negative.

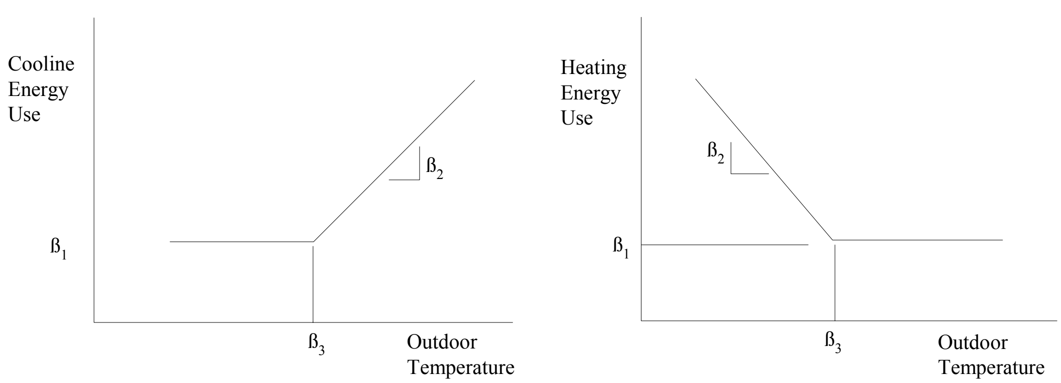


Figure 4.45 IMT three parameter change-point models

4.2.3 Analysis of the As-built Case-Study House Using the DOE-2.1e Building Energy Simulation Program

The DOE-2.1e (ver.119) building energy simulation program was used to perform this study. The DOE-2 program was selected because of its ability to simulate the overall thermal performance of a building using specially prepared hourly weather file that were measured from the case-study house for the 2004 period in Bryan, Texas.

4.2.3.1 Development of the On-Site Weather File

Figure 4.46 shows a flowchart diagram for the DOE-2 weather processing. The DOE-2 program was designed to calculate hourly building energy consumptions by using hourly weather data available in several file formats. The available types of weather files include the Test Reference Year (TRY or TRY2), the Typical Meteorological Year (TMY or TMY2), the California Climate Zone (CTZ), and the Weather Year for Energy Consumption (WYEC and WYEC2). However, users need to convert ASCII files into binary files recognized by DOE-2 program before running the DOE-2 program.

In order to pack the actual case-study weather data into DOE-2 weather file, the hourly weather data from the case-study house must be in the TRY, TRY2, TMY, TMY2, CTZ or WYEC file formats. Since the TRY format contains all necessary data for this research, TRY format was used to pack the weather file. The flowchart in Figure 4.46 demonstrates how the raw hourly weather data obtained from the on-site weather station were converted into the TRY file needed by the DOE-2 weather packer.

In this study, packing the weather file included combining the hourly outdoor dry bulb temperature, outdoor relative humidity, wind speed and beam and diffuse solar radiation into a data file. The hourly outdoor temperature, relative humidity, wind speed and global horizontal solar radiation were obtained from the on-site weather station. These were then combined into a data file and processed by Bronson's LS2TRY (1992) packing routine that converts global horizontal solar radiation into beam and diffuse radiation using the method developed by Erbs et al. (1982). This can be passed to the DOE-2 weather packing routine (LBNL 1993).

$$\frac{I_{df}}{I} = 1.0 - 0.09k_T \qquad \text{for } 0 \le k_T \le 0.22 \qquad (4.3)$$

$$\frac{I_{df}}{I} = 0.9511 - 0.16404k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 \qquad \text{for } 0.22 \le k_T \le 0.80 \qquad (4.4)$$

$$\frac{I_{df}}{I} = 0.165 \qquad \text{for } k_T > 0.80 \qquad (4.5)$$

Where I_{df} is the hourly diffuse solar radiation, I is the hourly horizontal solar radiation, and k_T is the hourly clearness index (the ratio of the terrestrial and extraterrestrial solar radiation) that is calculated by the formula:

$$k_T = \frac{I}{I_0 \cos\theta_s} \qquad (4.6)$$

In the equation θ_s is the zenith angle of the sun. I_0 is the extraterrestrial solar radiation, which is calculated by the following formulae:

$$I_0 = \frac{(1 + 0.033 \times \cos 360° \times n)}{365.25} \times 435.2 \quad \text{(Btu/hr-ft}^2\text{) (IP)} \qquad (4.7)$$

$$I_0 = \frac{(1 + 0.033 \times \cos 360° \times n)}{365.25} \times 1373 \quad \text{(W/m}^2\text{) (SI)} \qquad (4.8)$$

Where n is the day of the year

The packed on-site weather file, once prepared, was ready to be converted to binary format by the DOE-2 weather processor and used in the simulation.

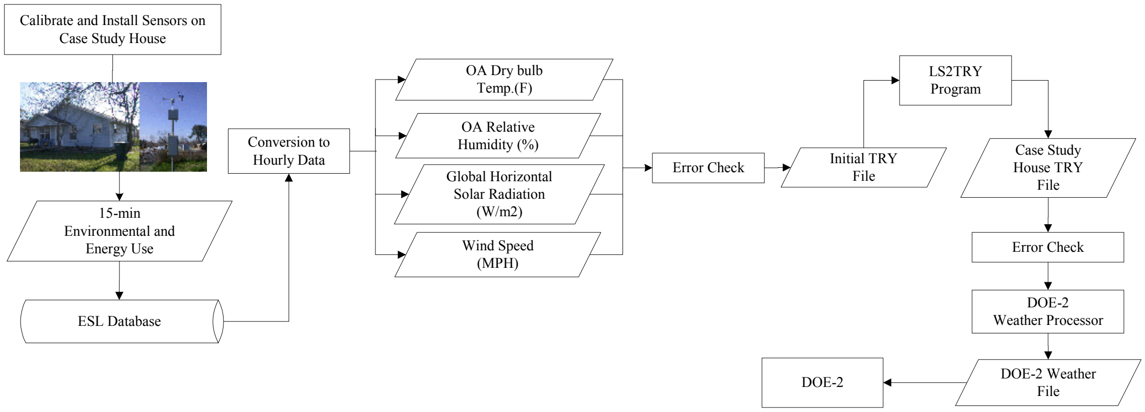


Figure 4.46 Flowchart of the DOE-2 weather data processing

4.2.3.2 Development of the DOE-2.1 Input File for the Case-Study House

A computer model of the as-built case-study house was constructed using the DOE-2 program (LBNL 1981). The building dimensions and installed equipment were obtained from the architectural drawings of the case-study house and documentation from the manufacturer and thesis by Kootin-Sanwu (2004).

The DrawBDL architectural rendering program (Huang and Associates 2000) was used to check the accuracy of the building's geometry in the DOE-2 model. The output of the DOE-2.1e program provides an annual energy use for a building in a Building Energy Summary Report (BEPS), monthly energy use, and hourly energy use depending on the specific requirements made for reports in the input file.

A DOE-2 input file generally contains a series of input variables assigned to four major DOE-2 sub-programs: LOADS, SYSTEM, PLANT and ECONOMICS. However, this research used only LOADS and SYSTEM sub-programs. These contain the building's location, materials, general space definition, building zones, and building systems. The modeling of case-study house is divided into an attic zone (unconditioned space) and room zone (conditioned space) (Figure 4.47).

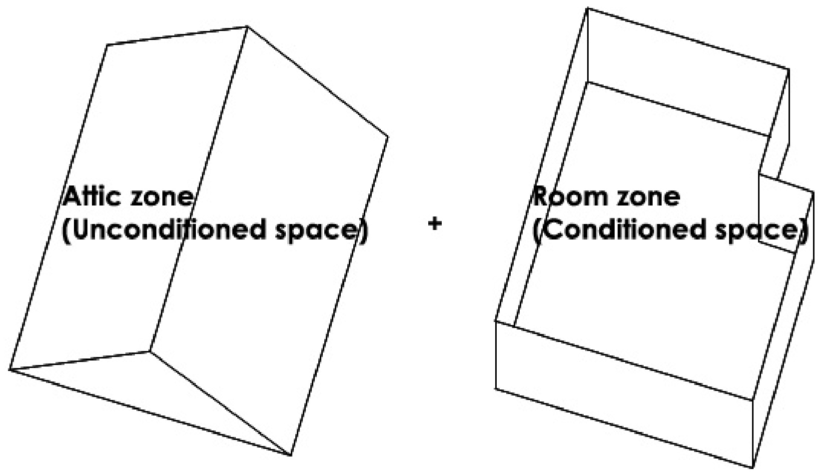


Figure 4.47 Zones of the as-built base-case house

The following figures (Figures 4.48 to 4.50) describe how the building's materials were used in the construction of the input file. Tables 4.3 to 4.5 specify thermal properties of the materials to develop DOE-2.1e simulation model. Figure 4.51 shows the 3-dimensional geometry of the building created by the DrawBDL program.

Since DOE-2 calculates the weight of building materials to find out custom-weighting factor, it was important to put the proper materials into the DOE-2 simulation model. To simplify the DOE-2 input model, the wall of the case-study house simulation input file was modeled with two different constructions, one presenting the framed area of 12.6% of the wall area, and another presenting the insulated area of 87.4% of the wall area. The roof of the case-study house input file was also modeled with two different constructions, one presenting the frame area of 18.9% of the roof area and another presenting non-frame area of 81.1% of the roof area.

The walls of the case-study house were constructed with 2x4 studs placed 24 inches on center. These walls had 3 ½ inches of cellular insulation blown into the cavity between the studs. The exterior of the house was vinyl sheathing over plywood with a TYVEK moisture barrier. The interior of the walls were ½ inch gypsum board. The windows were double-pane clear glazing with aluminum frame without thermal break. The ceilings were 5/8" gypsum board on 2 x 6" trusses with fiberglass insulation. The roof construction consisted of composite shingles on 5/8" plywood deck placed on 2x6" trusses set at 24" centers. Attic ventilation was provided by a continuous perforated vinyl soffit on all sides of the house.

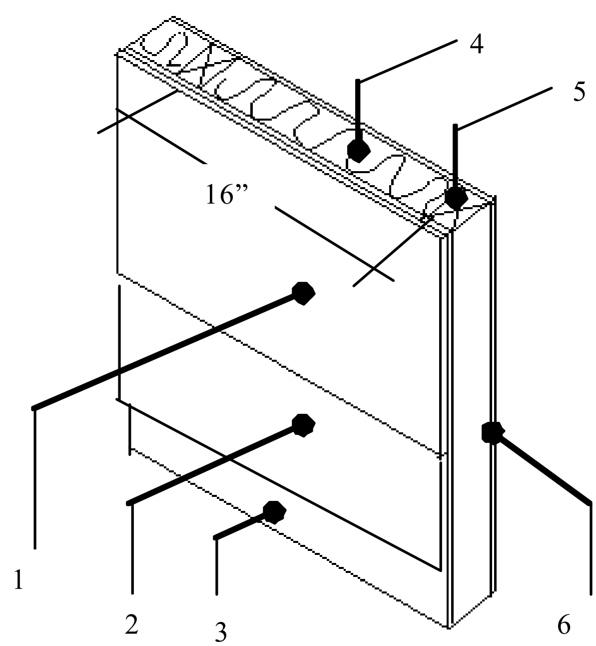


Figure 4.48 Details of wall construction

Table 4.3 Details of wall thermal properties and DOE-2 code-word

No.	Description	Thickness	Conductivity	Density	Specific heat	Resistance	DOE-2 code-word
		ft	Btu-ft/hr-ft^2-°F	lb/ft^3	Btu/lb-°F	hr-ft^2-°F/Btu	
1	VINYL-TILE				0.3	0.050	AV01
2	TYBEK MOISTURE PAPER					0.060	BP01
3	PLYWOOD-1/2IN	0.0417	0.0667	34	0.29	0.625	PW03
4	CELLULOSE-R13	0.2917	0.0225	3	0.33	12.964	IN13
5	STUD - 4INCH	0.3333	0.0667	32	0.33	4.997	WD05
6	GYPSUM-BOARD-1/2IN	0.0417	0.0926	50	0.2	0.450	GP01

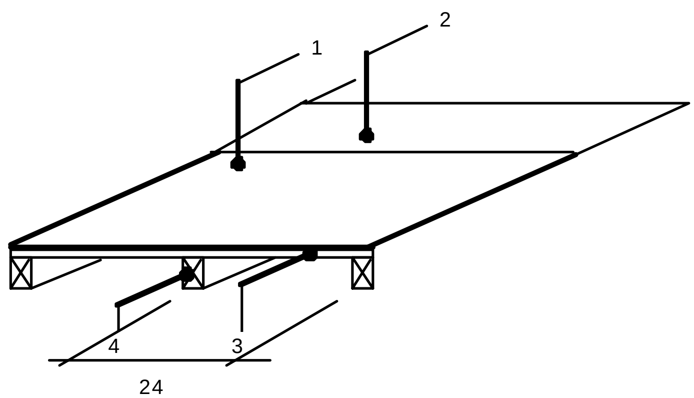


Figure 4.49 Details of roof construction

Table 4.4 Details of roof thermal properties and DOE-2 code-word

No.	Description	Thickness	Conductivity	Density	Specific heat	Resistance	DOE-2 code-word
		ft	Btu-ft/hr-ft^2-°F	lb/ft^3	Btu/lb-°F	hr-ft^2-°F/Btu	
1	SHINGLE-SIDING			70.00	0.35	0.44	AR02
2	PLASTIC-FILM-SEAL					0.01	BP03
3	PLYWOOD-3/8IN	0.05	0.07	34.00	0.29	0.71	PW04
4	STUD-6IN	0.50	0.07	32.00	0.33	7.14	

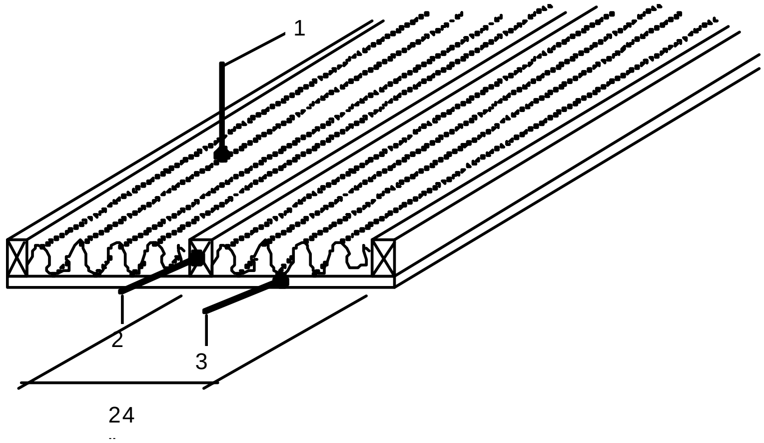


Figure 4.50   Details of ceiling construction

Table 4.5   Details of ceiling thermal properties and DOE-2 code-word

No.	Description	Thickness	Conductivity	Density	Specific heat	Resistance	DOE-2 code-word
		ft	Btu-ft/hr-ft^2-°F	lb/ft^3	Btu/lb-°F	hr-ft^2-°F/Btu	
1	WOOL-FIBER-R19	0.45	0.03	0.63	0.20	16.81	IN12
2	STUD-6IN	0.50	0.07	32.00	0.33	7.50	
3	GYPSUM-BOARD-5/8IN	0.05	0.09	50.00	0.20	0.56	GP02

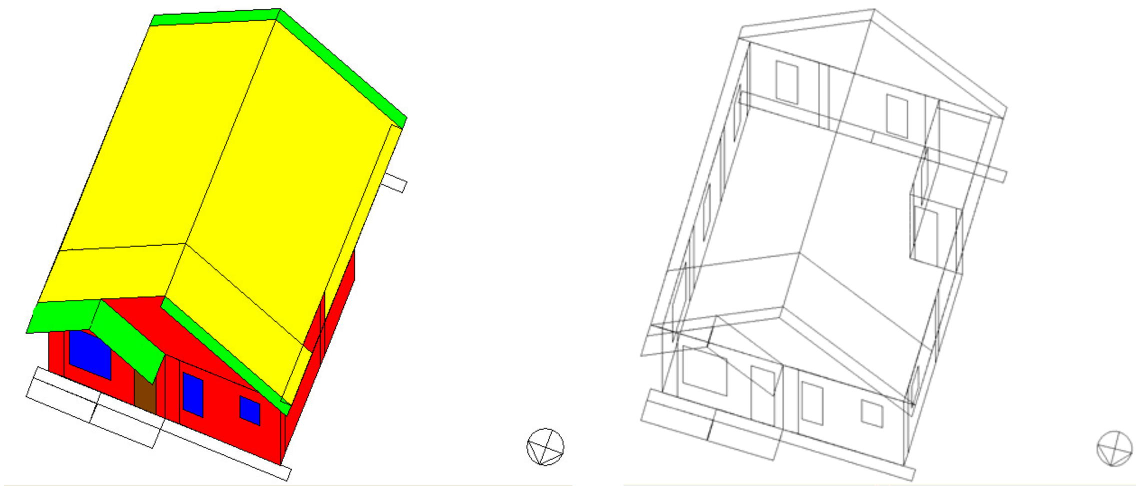


Figure 4.51 Image of the as-built case-study house simulation input using the DrawBDL program

4.2.3.3 Incorporating Duct Model

As mentioned at Chapter 2.3.5, ASHRAE developed ASHRAE Standard 152-2004 - Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems (ASHRAE 2004) to estimate design and seasonal efficiency for residential building systems. This calculation considers the impacts of duct leakage, location (i.e., attic space, crawl space, etc.), insulation level, climate, etc.

Figure 4.52 shows the concept of duct works which are located in two buffer zones, one for return side and one for the supply side (Palmiter and Francisco 1996) and this concept was applied to DOE-2.1e simulation program using DOE-2 FUNCTION commands.

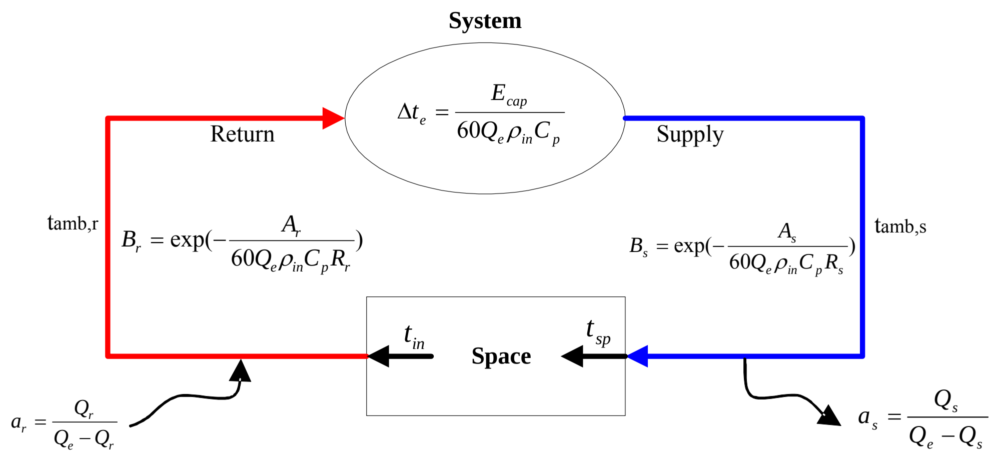


Figure 4.52 Schematic diagram of duct model (ASHRAE 152-2004)

Duct leakage rates of supply and return side of the case-study house were assumed as 10% for supply and return sides based on the research by Cummings (1991).

Supply air flow (cfm) was 992cfm obtained from the previous research by Kootin-Sanwoo (2004). For the supply cfm measurement, air-handler fan flow measurement using an Alnor air flow meter was performed. By placing the air flow plate over a return grill and turning on the air-handler fan, the air-flow cfm going through the flow meter was measured (Kootin-Sanwu 2004). To assure maximum accuracy, the foam gasket along the top of the frame should be firmly in contact with the surface all around the return grill and ensure that other materials were not accidentally affecting the reading by blocking or diverting the air flow at the return grill. According to manufacturer manual (Alnor 2002), the accuracy range is ±3%.

Following equations show the procedure of calculation of the delivery efficiency of the heating and cooling systems considering conduction loss and air leakage of supply duct and return duct side.

$$DE_{heating} = a_s B_s - a_s B_s (1 - B_r a_r) \frac{\Delta t_r}{\Delta t_e} - a_s (1 - B_s) \frac{\Delta t_s}{\Delta t_e} \tag{4.9}$$

$$DE_{cooling} = \frac{a_s Q_e \rho_{in}}{E_{cap}} \left(\frac{E_{cap}}{60 Q_e \rho_{in}} + (1 - a_r)(h_{amb,r} - h_{in}) + a_r C_p (B_r - 1)\Delta t_r + C_p (B_s - 1)(t_{sp} - t_{amb,s}) \right) \tag{4.10}$$

where,

B_s = conduction efficiency of supply duct = $\exp\left(\frac{-A_s}{60 Q_e \rho_{in} C_p R_s}\right)$, (4.11)

B_r = conduction efficiency of return duct = $\exp\left(\frac{-A_r}{60 Q_e \rho_{in} C_p R_r}\right)$, (4.12)

a_s = air leakage efficiency of the duct of supply duct = $\left(\frac{Q_e - Q_s}{Q_e}\right)$, (4.13)

a_r = air leakage efficiency of the duct of return duct = $\left(\frac{Q_e - Q_r}{Q_e}\right)$, (4.14)

E_{cap} = capacity of the equipment (Btu/hr),

Q_e = system air flow (CFM),

C_p = specific heat (Btu/(lb$_m$·°F)),

Δt_e = temperature rise across the equipment (°F) = $\frac{E_{cap}}{60 Q_e \rho_{in} C_p}$, (4.15)

Δt_s = temperature difference between the building and the ambient temperature surrounding the supply (°F) $= t_{in} - t_{amb,s}$, (4.16)

Δt_r = temperature difference between the building and the ambient temperature surrounding the return (°F) $= t_{in} - t_{amb,r}$, (4.17)

t_{in} = temperature of indoor air (°F),

t_{sp} = supply plenum air temperature (°F),

$t_{amb,s}$ = ambient temperature for supply ducts (°F),

$t_{amb,r}$ = ambient temperature for return ducts (°F),

$h_{amb,r}$ = enthalpy of ambient air for return (Btu/hr),

h_{in} = enthalpy of air inside conditioned space (Btu/hr),

A_s = supply duct area (ft^2),

A_r = return duct area (ft^2),

ρ_{in} = density of air (lb/ft^3),

R_s = thermal resistance of supply duct ($hr\text{-}ft^2\text{-}^{o}F$ /Btu),

R_r = thermal resistance of return duct ($hr\text{-}ft^2\text{-}^{o}F$ /Btu).

Figures 4.53 and 4.54 show the procedures of the function method developed for the DOE-2.1e to apply the duct model using concepts of ASHRAE 152-2004. Three function methods (SAVETEMP, DUCT, and DUCT 2) are used. 1) The SAVETEMP function saves the buffer zone temperature and conditioned space temperature to send these temperature data to the next function. 2) The DUCT function calculates the delivery efficiency using temperature. Data from the hourly report and user inputs, and it modifies the Energy Input Ratio (EIR) every hour in proportion to the losses. The concept for this EIR modification came from Huang (personal communication, October 2001), 3) the DUCT2 function changes the modified EIR to the original value for the next calculation. The duct model on DOE-2.1e program was presented at Appendix B.

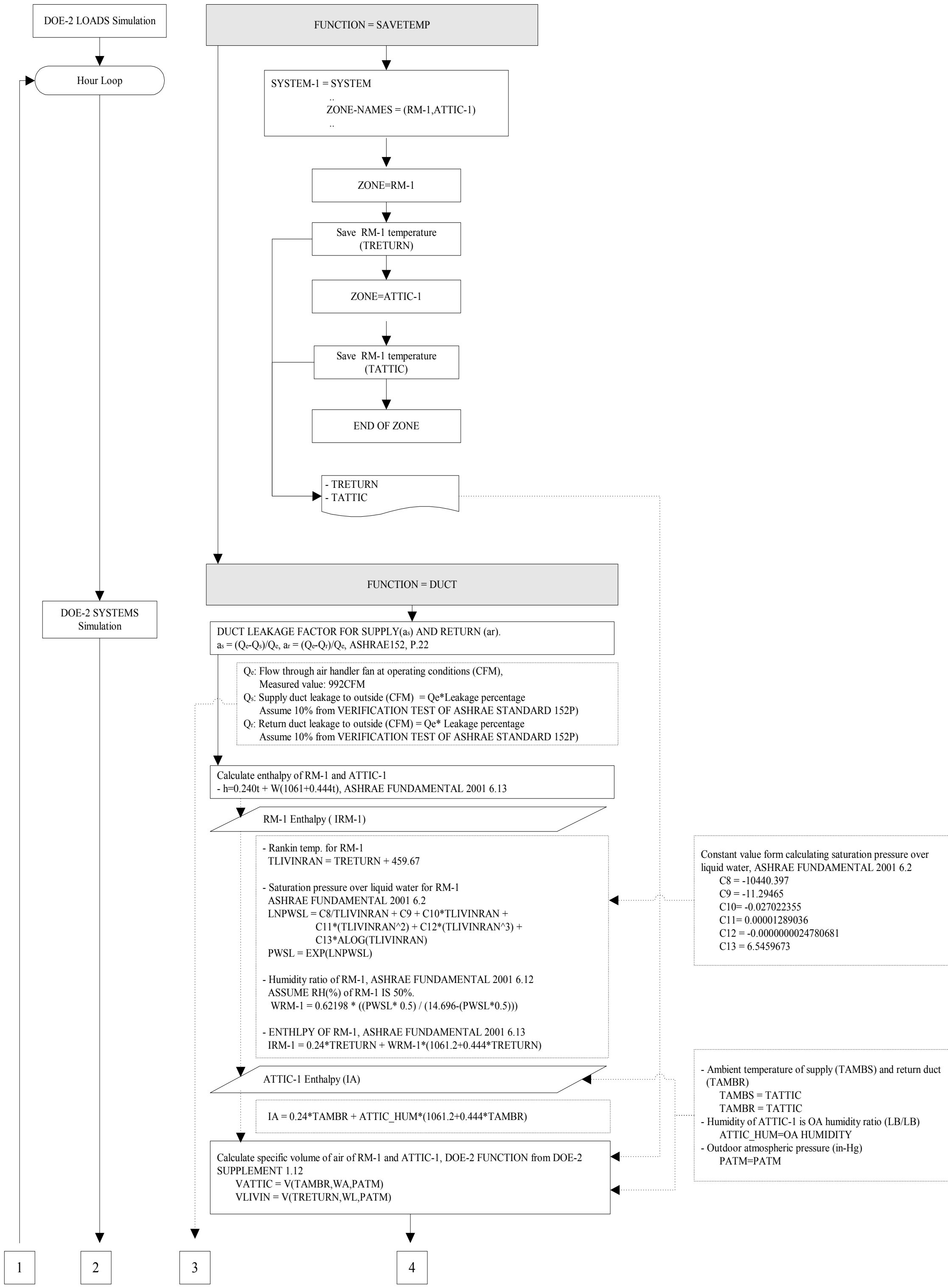


Figure 4.53 Diagram of DOE-2 FUNCTION command for ASHRAE 152-2004 duct loss model (a)

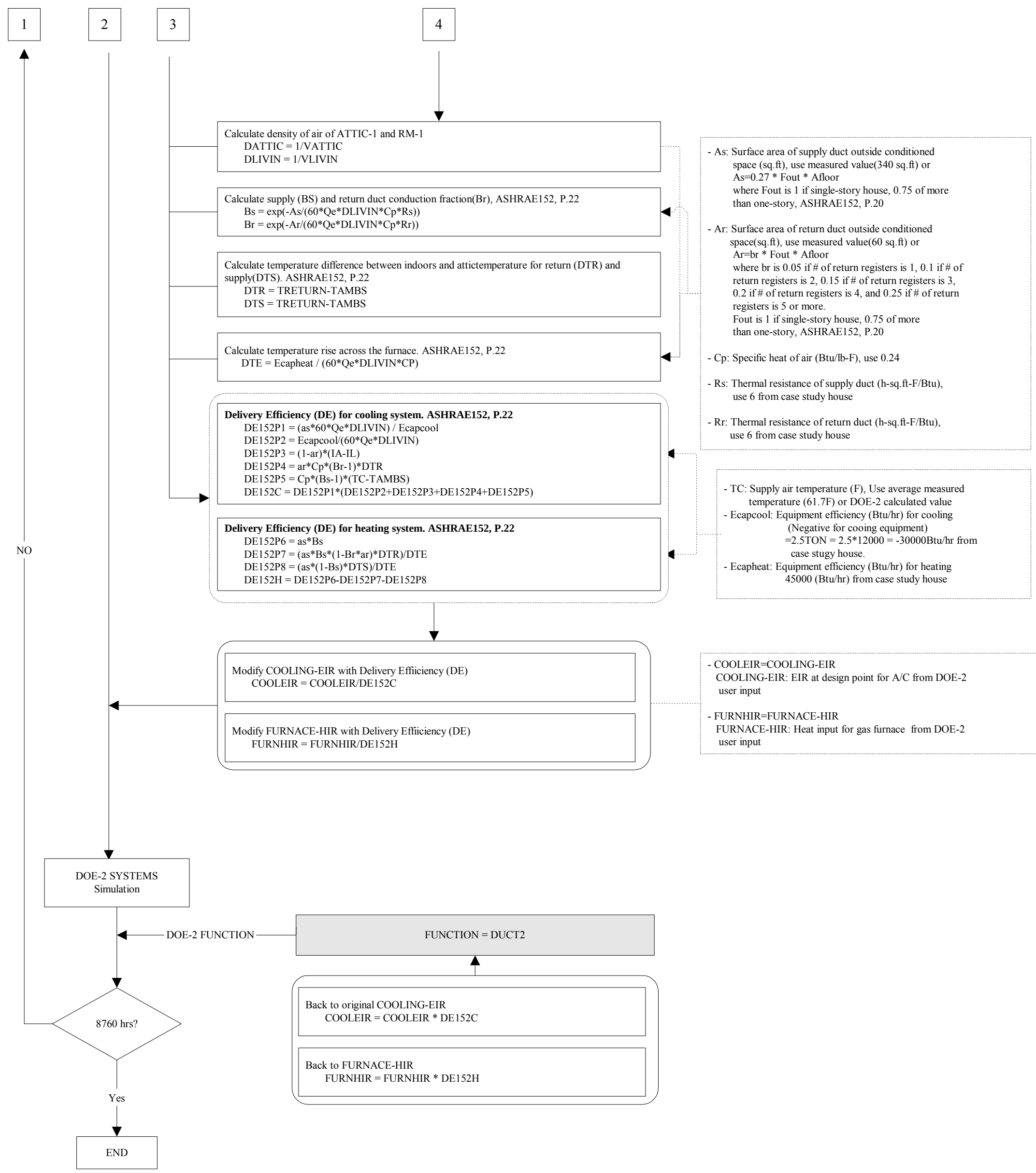


Figure 4.54 Diagram of DOE-2 FUNCTION command for ASHRAE 152-2004 duct loss model (b)

4.2.3.4 New Air Conditioning System Curves

It is important to accurately predict the performance of air conditioning systems over a range of full and part load operating conditions in hourly energy simulations. Henderson et al. (2000) presented new approaches to account for the part load performance of residential and light commercial air conditioning system in DOE-2 simulation program. They provided three different air conditioner curves of typical, good and poor conditions and Figure 4.55 shows curves for a residential cooling system from Henderson et al.'s and DOE-2 default curves. Table 4.6 lists the corresponding Energy Input Ratio (EIR) coefficients for testing each curve using DOE-2 program.

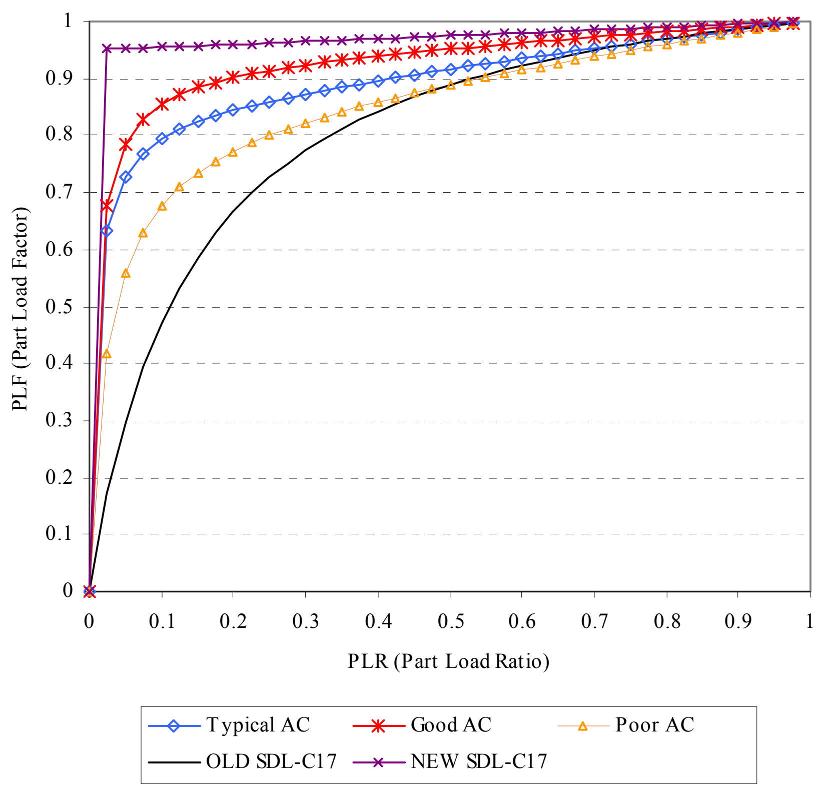


Figure 4.55 AC system curves for DOE-2 program (Henderson et al. 2000)

Table 4.6 Coefficients for DOE-2 program

	Coefficients for DOE-2 input (EIR-FPLR = a + b*PLR + c*PLR^2 + d*PLR^3)			
	a	b	c	d
Typical AC (Henderson et al.)	0.0101858	1.18131	-0.246748	0.0555745
Good AC (Henderson et al.)	0.00988125	1.08033	-0.105267	0.0151403
Poor AC (Henderson et al.)	0.0300924	1.20211	-0.311465	0.0798283
OLD SDL-C17 (Old DOE-2 default curve)	0.125	0.875		
NEW SDL-C17 (New DOE-2 default curve)	0.00000273404	1.05259	-0.0552087	0.00262236

In order to implement new curves in DOE-2 program, the following DOE-2 commands (Figure 4.56) were used.

```
NEWACPLR = CURVE-FIT
           TYPE = LINEAR OR CUBIC
           COEFFICIENTS = (a,b,c,d)  ..

           COOL-EIR-FPLR = NEWACPLR  ..
```

Figure 4.56 DOE-2 code for new system curves

For this study, the five different air conditioning system curves were tested using the DOE-2 simulation model of the base-case house and compared with measured data from the case-study house. Then, the best curve, which was matched with the measured data, was selected.

4.2.3.5 New Domestic Hot Water Curves

The efficiency specification of hot-water systems is the Energy Factor (EF), which accounts for the annual average burner efficiency and tank losses. The 2000/2001 IECC uses an Energy Factor (EF) to describe the efficiency of a domestic hot water system. Therefore, the EF will be used for the simulation of the domestic hot water heater in this effort. The EF is determined from the following equation: (Section 504.2.1 of the 2000/2001 IECC)

Minimum Performance of Storage Type Gas Water Heating Equipment = 0.62 – 0.0019V (4.18)

where, V=Rated Storage Volume in Gallon, 40 gallon for base-case house.

NREL (2001) has developed an improved DOE-2 part-load performance curve (Figure 4.57) for simulating domestic hot water equipment, which eliminates inefficiencies due to partial loads. Figure 4.58 shows the DOE-2 commands for simulating a domestic hot water system with the new NREL commands.

Before applying NREL method to the domestic hot water energy use calculations, 0.76 of the gas water heater efficiency from DOE-2 was used with 3% of the domestic hot water tank loss (DOE-2 keyword: DHW-LOSS). In order to investigate the reasonable method for the domestic hot water, the four different results of 1) the measured data from the case-study house, 2) the simple calculation using ASHRAE 90.2 (2001a), 3) the simulation results using NREL suggested method, and 4) the simulation results using previous method with DHW-LOSS were compared.

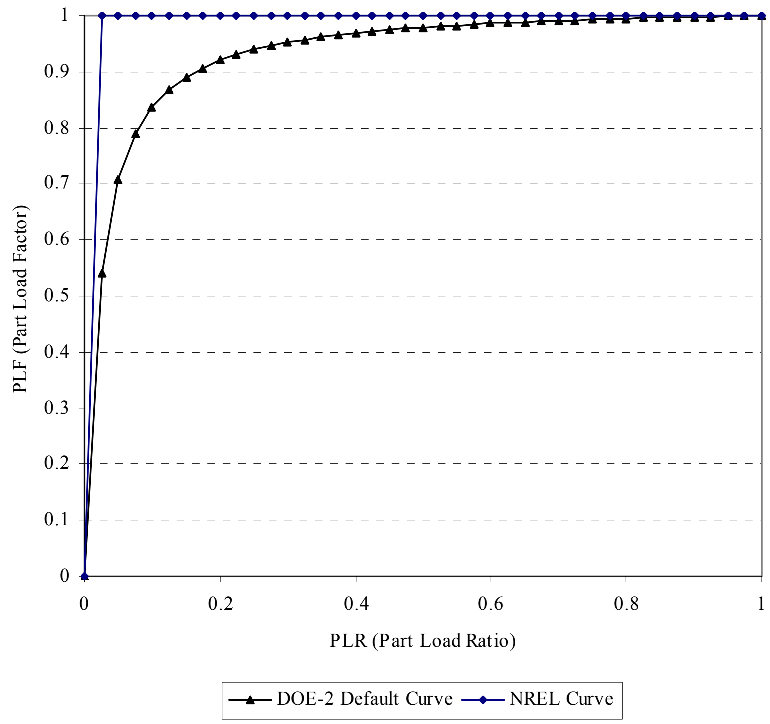


Figure 4.57 Domestic hot water efficiency curves for the DOE-2 program (NREL 2001)

Table 4.7 DHW coefficients for DOE-2 program

	Coefficients for DOE-2 input			
	a	b	c	Equation
DOE-2 default curve	0.021826	0.97763	0.000543	$PLF=0.021826+0.97763xPLR+0.000543PLR^2$
NEW NREL curve	0	1		PLF=PLR

```
NEWDHW =   CURVE-FIT
           TYPE = LINEAR
           COEFFICIENTS = (0,1)  ..

            DHW-EIR = 1.85                 $=1/ENERGY FACTOR=1/0.54=1.85
           DHW-EIR-FPLR = NEWDHW
           DHW-LOSS = 0   ..
```

Figure 4.58 DOE-2 code for domestic hot water

For the verification of this simulation, the domestic hot water load is calculated from the following equation in ASHRAE 90.2 (2001a) Section 8.9.2 and 8.9.2. Then, calculation results will be compared with simulation results using NREL suggested method.

Domestic Hot Water Load (DHWL) = ((30*Units)+(10*Bedrooms))*8.28*(135-T_{inlet}) (4.19)

DHW Gas Use (DHW_G) = (DHWL/E_r +Heaters*(41,000/EF-41,000/E_r))/100,000 (4.20)

where,

DHWL = domestic hot water load for the building (Btu/day),

Units = number of living units in the proposed design,

Bedrooms = total number of bedroom in the all the living units in the proposed design,

T_{inlet} = inlet mean water temperature, which may be assumed to be equal to the average annual outdoor dry-bulb air temperature for the location or 40F, whichever is higher (College station: 68ºF),

DHW_G = domestic hot water gas use (therms/day),

Heaters = number of water heaters in the proposed design,

EF = Energy Factor,

E_r = recovery efficiency (if E, is not known, use 0.76).

From these equations, the outlet temperature (135°F) can be replaced by 120°F, since the 2000/2001 IECC (402.1.3.7) provides the domestic hot water set point temperature as 120°F. Therefore,

Domestic Hot Water Load (DHWL) = ((30*1)+(10*3))*8.28*(120-68)

= 25833.6 Btu/day

DHW Gas Use (DHW_G) = (DHWL/E_r +Heaters*(41,000/EF-41,000/E_r))/100,000

= 25833.6/0.76 + 1*(41000/0.56-41000/0.76))/100000

= 0.53 therms/day * 365

= 194.39 therms/year

This value will be used for the comparison and verification of the domestic hot water calculation methods.

4.2.3.6 Underground Surface Heat Transfer

Winkelmann (1998) reported corrections and bug fixes in calculating the heat transfer through underground surfaces in DOE-2.1e. Since the program calculates the thermal mass of the underground surfaces according to custom weighting factors (CWFs) by multiplying the U-value with the surface area, and the temperature differences between zone temperature and ground temperature, the results of heat transfer are grossly overcalculated. Therefore, he suggested the use of U-EFFECTIVE and a procedure for defining the underground surface construction using a perimeter conduction factor. Table 4.8 shows the thermal properties and shape of a slab on grade construction at the base-case house. The case-study house has a 4” concrete slab and 30”x12” ground beams approximately 12ft center (Figure 4.59).

Table 4.8 Thermal properties of slab on grade at base-case house

No	Name	Conductivity	R	Thickness	DOE code
		Btu-ft/hr-ft^2-°F	ft^2-hr-°F/Btu	ft	
1	Concrete Slab	1.0417	0.32	0.3333	CC14
2	Ground Beam	1.0417	2.40	2.5	CC14

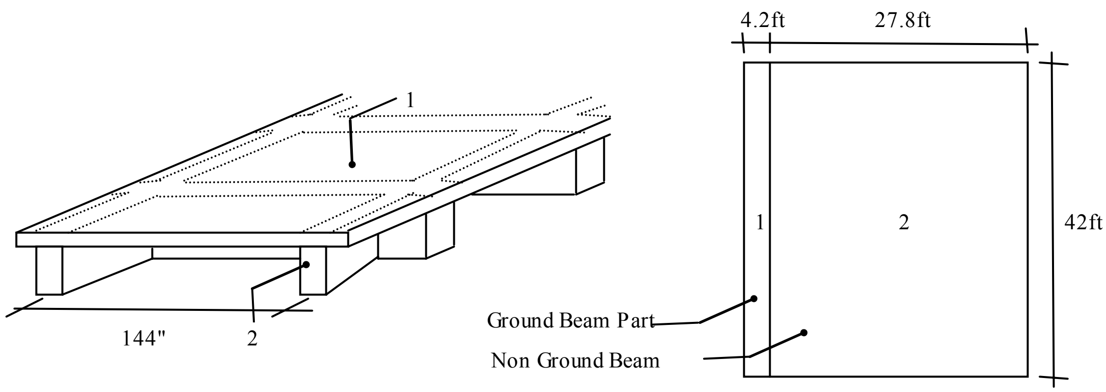


Figure 4.59 Draw of the slab

The following procedure presents how Winkelmann's method was applied to the base-case simulation input file. The value and procedure used for this procedure are from the "Underground Surface: How to get a Better Underground Surface Heat Transfer Calculation in DOE-2.1E" by Fred Winkelmann (1998).

1. Choose a value of the perimeter conduction factor, F2 for the configuration that best matches the type of surface.

- For the case-study house, a value of F2=0.77, was chosen.

2. Using F2, calculating R_{eff}, the effective resistance of the underground surface.

- $R_{eff} = A / (F2*P_{exp})$ (4.21)
- $R_{eff-1} = (42*4.2) / (0.77 * (42+4.2*2)) = 4.55$

- $R_{eff\text{-}2}$ = (42*27.8) / (0.77 * (42+27.8*2)) = 15.54

3. Set U-EFFECTIVE = 1 / R_{eff} (4.22)

- U_1 = 1 / 4.55 = 0.22
- U_2 = 1 / 15.54 = 0.064

4. Define a construction

$$R_{eff} = R_{us} + R_{soil} + R_{fic} \tag{4.23}$$

$$R_{fic} = R_{eff} - R_{us} - R_{soil} \tag{4.24}$$

- Actual slab resistance: R_{us1} = 2.4 + 0.77 = 3.17

  R_{us2} = 0.32 + 0.77 = 1.09

- Rfic1 = $R_{eff1} - R_{us1} - R_{soil}$ = 4.55 – 3.17 – 1.0 = 0.38
- Rfic2 = $R_{eff2} - R_{us2} - R_{soil}$ = 15.54 – 1.09 – 1.0 = 13.45

where,

F2 = perimeter conduction for concrete slab on-grade from Table 1 (Winkelmann 1998),

R_{eff} = the effective resistance of the underground surface,

U_1 and U_2 = U-effective,

A = area of the surface (ft^2),

P_{exp} = length of the surface's perimeter that is exposed to the outside air (ft),

R_{us} = overall resistance of the underground wall or floor and inside film resistance,

R_{soil} = resistance of a 1-ft layer of soil,

R_{fic} = resistance of a fictitious insulating layer.

This study examined: 1) the use of raw U-value without U-effective method, 2) U-effective method with ground temperature from TRY weather file, and 3) U-effective method with the measured ground temperature from the case-study house for the underground surface. Figure 4.60 shows the DOE-2 input of underground surface heat transfer.

```
CONCRETE-SLAB        = MATERIAL                    $DOE2.1E(MATERIALS LIBRARY)
                     THICKNESS    = 0.3333         $(FT)
                     CONDUCTIVITY = 1.0417         $(BTU.FT/HR.FT^2.F)
                     DENSITY      = 140            $(LB/FT^3)
                     SPECIFIC-HEAT= .20  ..        $(BTU/LB.F)

GROUND-BEAM          = MATERIAL                    $DOE2.1E(MATERIALS LIBRARY)
                     THICKNESS    = 2.40           $(FT)
                     CONDUCTIVITY = 1.0417         $(BTU.FT/HR.FT^2.F)
                     DENSITY      = 140            $(LB/FT^3)
                     SPECIFIC-HEAT= .20  ..        $(BTU/LB.F)

MAT-FIC-1            = MATERIAL
                     RESISTANCE = 0.38   ..        $THE Rfic VALUE

MAT-FIC-2            = MATERIAL
                     RESISTANCE = 13.45   ..       $THE Rfic VALUE

SOIL-12IN            =  MATERIAL
                     THICKNESS = 1.0
                     CONDUCTIVITY = 1.0
                     DENSITY = 115
                     SPECIFIC-HEAT = 0.1   ..

FL-1 = LAYERS
       MATERIAL = (MAT-FIC-2, SOIL-12IN, CONCRETE-SLAB)  ..
              $ Non Ground-beam Part of Slab
              $ CONCRETE-SLAB = 4" Concrete, Heavy weight
              $ The percentage of FL-1 = 87 %

FL-2 = LAYERS
       MATERIAL = (MAT-FIC-1, SOIL-12IN, GROUND-BEAM, CONCRETE-SLAB)  ..
              $ Ground-beam Part of Slab
              $ CONCRETE-SLAB = 4" Concrete, Heavy Weight
              $ GROUND-BEAM = 26" Concrete, Heavy Weight
              $ The percentage of FL-2 = 13 %

FLOR-1    = CONSTRUCTION
            LAYERS = FL-1   ..

FLOR-2    = CONSTRUCTION
            LAYERS = FL-2   ..

FLOOR-R1 = UNDERGROUND-FLOOR                  $NON-GROUND BEAM PART
           AREA = 176.4
           CONSTRUCTION = FLOR-1
           TILT = 0
           U-EFFECTIVE = 0.22       ..

FLOOR-R2 = UNDERGROUND-FLOOR                  $GROUND BEAM PART
           AREA = 1167.6
           CONSTRUCTION = FLOR-2
           TILT = 0
           U-EFFECTIVE = 0.064       ..
```

Figure 4.60 DOE-2 input of underground surface heat transfer

4.2.3.7 Calibrated Simulation Model to the Case-Study House

A two-week period of summer and winter was selected for the calibration of the simulation model for this study. The calibration of the two week period for the summer was performed using monitored hourly data from August 1 to August 14, 2004, which shows continuous running of the air conditioner. The calibration of the two week period for the winter was performed from December 18 through December 31, 2004, which shows a regular use of natural gas. The calibration of the model was performed using the attic temperature, indoor temperature, building electricity use, and gas energy use for both summer and winter two-week periods. The statistic methods include the hourly coefficient of root mean square error (RMSE) and the mean bias error (MBE), which were used for comparison between simulated results and measured results.

4.2.3.8 Statistical Evaluation of the Calibration Results

After the calibration process, the Mean Bias Error (MBE) and the coefficient of variation of the root Mean Square Error (CV (RMSE)) were calculated. The Mean Bias Error, MBE (%) (Kreider and Haberl 1994a, b; Haberl and Thamilseran 1996) determines the non-dimensional bias measure (the sum of errors) between the simulated data and the measured data.

$$MBE = \left[\left(\sum y_{pred,i} - \sum y_{data,i}\right)/(n-p)\right] / \bar{y}_{data} \times 100 \tag{4.25}$$

The coefficients of variation of the root mean squared error, CV (RMSE) (%) (Draper and Smith 1981) is essentially the root mean squared error divided by the measured mean of all the data, which is a convenient way of reporting a non-dimensional result. CV (RMSE) allows one to determine how well a model fits the data; the lower the CV (RMSE), the better the calibration.

$$CV(RMSE)(\%) = \left[\left(\sum y_{pred,i} - \sum y_{data,i}\right)^2 /(n-p)\right]^{1/2} / \bar{y}_{data} \times 100 \tag{4.26}$$

where,

$y_{pred,i}$ is a predicted dependent variable value for the same set of independent varialbles,

$y_{data,i}$ is a data value of the dependent variable corresponding to a particular set of the independent varialbles,

$\bar{y}_{data}$ is the mean value of the dependent variable of the data set,

n is the number of data points in the data set,

p is the total number of regression parameters in the model (arbitrarily assigned as 1 for all models).

4.3 The International Energy Conservation Code (IECC)

The building characteristics required in the 2000/2001 IECC (ICC 1999, 2001) were reviewed to develop a initial input file for a single-family residential building. Chapter 3 of the 2000/2001 IECC presents the climate zones for the United States, and Chapter 5 contains prescriptive tables to determine the building envelope requirements, and the requirement of the building mechanical systems and other equipment.

4.3.1 Climate Zone

In Chapter 3 of the 2000/2001 IECC, climate zones are classified by Heating Degree Days (HDD) and building envelope requirements are specified based on climate zones. Table 4.9 explains the classification of 41 non-attainment and affected counties in Texas by climate zones.

Table 4.9 Texas counties by climate zones

HDD	Climate Zone	Counties
2500 – 2999	6	Collin , Denton, El Paso, Gregg, Harrison, Hunt, Kaufman, Parker, Rockwall, Upshur
2000 – 2499	5	Dallas, Ellis, Hays, Henderson, Hood, Johnson, Rusk, Smith, Tarrant, Travis, Williamson
1500 – 1999	4	Bastrop, Bexar, Caldwell, Chambers, Comal, Fort Bend, Guadalupe, Hardin, Harris, Jefferson, Liberty, Montgomery, Orange, Waller, Wilson
1000 – 1499	3	Brazoria, Galveston, Nueces, San Patricio, Victoria

4.3.2 Prescriptive Building Envelope Requirement

Chapter 5 of the 2000/2001 IECC provides prescriptive tables to determine the building envelope requirements. In order to decide the envelope requirement, the type of house (i.e., Type A-1 is single-family house and Type A-2 is multi-family house) and the window-to-wall ratio should be identified. The proper insulation level of the ceiling, exterior, floor, basement, slab perimeter, crawl space and glazing properties are determined according to the Heating Degree Days (HDD) based on the type of house, window-to-wall ratio and other features. This chapter also provides alternative table for high-mass wall construction whose heating capacity is greater than or equal to 6 Btu / ft^2-°F.

4.3.3 Building Mechanical Systems and Equipment

Chapter 5 of the 2000/2001 IECC also describes the requirements of the building mechanical systems and other equipment. In this chapter, the minimum efficiency of air conditioning system, heat pump, furnace, boiler and domestic hot water system is defined. The minimum duct insulation is also specified in this chapter.

4.3.4 Procedure to Determine Building Envelope Requirements

The procedure to determine the building envelope requirements is shown on Figure 4.61. In order to determine the building envelope requirements, the type (i.e., single-family or multi-family) and the location of the building should be decided. Heating Degree Days (HDD) is selected based on the location from Chapter 3 of the 2000/2001 IECC. Then, building envelope requirements are determined according to the window-to-wall ratio of the building from Chapter 5. Minimum equipment performances are also determined according to the type and size of equipment.

4.3.5 Simulation of the IECC-Compliant House with DOE-2 program

The DOE-2.1e (Version 119) program was selected as the simulation program to be used for this study. The characteristics of this simulation program were already explained in section 4.2.3.2. For the IECC simulations, specially prepared programs such as the Input Macro Method, Batch DOE Input (BDI), and GAWK (Aho et al. 1988) are used. These procedures are explained in the next section. Appendix C presented the examples of working with BDI and GAWK programs.

The DOE-2 simulation model for this study was adopted from the input file (SNGFAM2ST.INP version 1.20), developed by the Energy Systems Laboratory (ESL). This input file was developed and used to evaluate amendments of the building energy codes for single-family house, and to quantify the resulting energy savings and emission reductions for the Senate Bill 5 (SB5 2004). This DOE-2 input file uses DOE-2 PARAMETERS instead of fixed values for various building characteristics that include the building geometry, location, building envelope components, HVAC and DHW system, lighting, equipment, and occupancy.

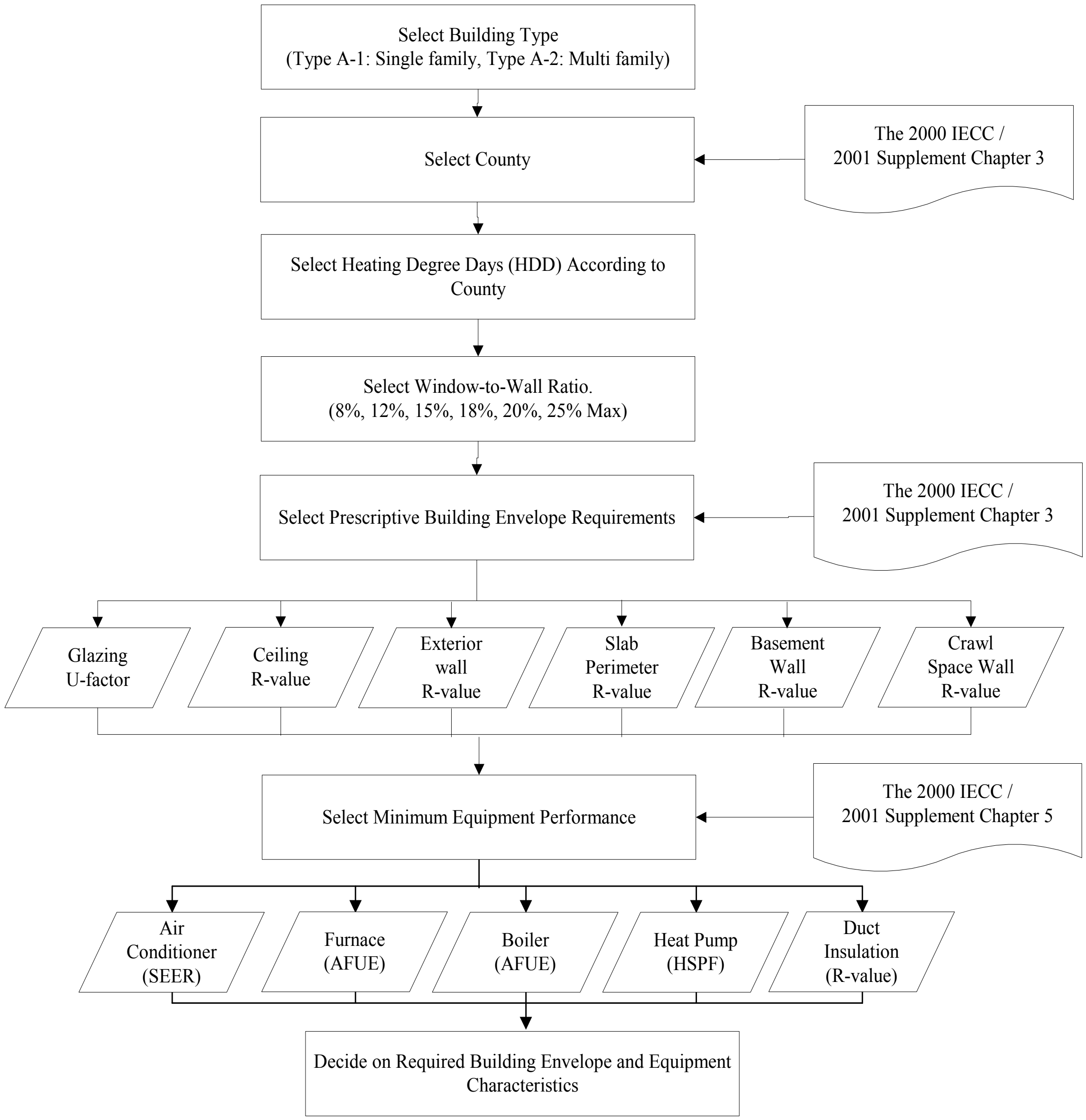


Figure 4.61 Procedure to determine the building envelope and equipment characteristics

Figures 4.62 to 4.64 show the parameters used to generate a single-family simulation model. The parameters are divided into two major categories: LOADS and SYSTEMS. The LOADS are then further divided into building, construction, space and shading PARAMETERS (Ahmad et al. 2005).

In the ESL's input file, the building parameters are used to define the location, orientation, basic dimensions and layout of the building. The current ESL simulation model has the provision of either one or two stories with a crawlspace or a slab on grade. There is also switch between quick (i.e., pre-calculated ASHRAE weighting factors with the floor-weight equal to 11.5 lb/ft^2, as required by Chapter 4 of the 2000/2001 IECC, section 402.1.3.3) and thermal mass (i.e., DOE-2's custom weighting factors) mode. The construction PARAMETERS are divided into two categories: construction I and construction II. The construction I PARAMETERS include the material properties and U-values of the different components usually for quick construction mode and the glazing properties and the window-to-wall area ratio. The user has the option of changing the window areas for the different orientations. The construction II PARAMETERS include the material properties of the different components for the thermal mass construction mode. The space PARAMETERS are currently fixed at 2 occupants and 3 bedrooms per house. The number of bedrooms is used to calculate the daily domestic hot water consumption, which in turn is used to size the domestic hot water heater according to the section 420.1.3.7 of the 2000/2001 IECC, including the 2001 Supplement.

In this study, the shade PARAMETERS were fixed to no-shading. For the simulation of the impact of different tree shading types (live oak, deciduous and evergreen), two new parameters were added to the existing PARAMETERS of SNGFAM2ST.INP version 1.20: 1) tree shade (no shading, east side, west side and both sides, s05) and 2) shading types (live oak, deciduous and evergreen, s06).

The system PARAMETERS include the type of systems, the system capacity and the efficiencies of the system selected. The user can choose from three kinds of systems; 1) gas heating, gas DHW and electric cooling, 2) electric heating, electric DHW and electric cooling, and 3) electric heat pump heating, electric DHW and electric cooling.

Currently, the ESL's heating and cooling system is auto-sized by DOE-2 according to the heating/cooling loads entered in DOE-2's LOADS sub-program. The user can define the system efficiencies according to the system type that is selected. For the additional analysis for the duct system, new PARAMETERS were added to existing PARAMETERS since the current version of the ESL's input file did not include a duct model, which was already explained in section 4.2.3.3. The new parameters for the duct analysis in this study are: 1) supply air (CFM, sy12), 2) supply leakage fraction (sy13), 3) return leakage fraction (sy14), 4) supply duct area (ft^2, sy15), 5) return duct area (ft^2, sy16), 6) R-value for supply duct (sy17), 7) R-value for return duct (sy18), 8) cooling system capacity (Btu/hr, sy19), 9) heating system capacity (Btu/hr, sy20), and 10) duct location (attic or room, sy21). The highlighted rows in Figure 4.64 show the new PARAMETERS for tree shades and duct system analyses.

Figure 4.65 presents three DrawBDL views to show the development procedures of the single-family residential house for simulations. Figure 4.65a is the initial input model which is a 1-story residence with flat roof. This input file includes only the quick mode of construction and does not contain an attic or duct model. Figure 4.65b has the option for one and two-story residence, and crawl space or slab-on-grade with flat roof. This input file also does not consider the thermal mass construction mode, attic space and duct model. Figure 4.65c was developed for this simulation and has all the PARAMETERS of Figures 4.62 to 4.64. This input file can analyze the thermal mass construction mode, pitched roof with attic space, tree shading, and duct model.

PARAMETER	NO	DESCRIPTION	DEFAULT	STATUS	COMMENTS
BUILDING	b01	Quick or thermal mode (Q or T)	T	User defined	Q simulates the building as massless, T simulates thermal mass
	b02	Location	HAR	User defined	41 Counties, ( ): DOE WEATHER FILE
	b03	Azimuth of building (degree)	0	User defined	Orientation of the building
	b04	Width of building (ft)	49.87	User defined	From NAHB survey (2002)
	b05	Depth of building (ft)	49.87	User defined	From NAHB survey (2002)
	b06	Height of wall (ft)	9	User defined	From NAHB survey (2002)
	b07	Door height (ft)	6.67	Fixed	From survey of manufactured doors
	b08	Door width (ft)	3	Fixed	From survey of manufactured doors
	b09	Run year	2001	Fixed	
	b10	Option of second floor (1 or 2)	1	User defined	Control activation/deactivation of one and two story portions of BDL input
	b11	Activation/ Deactivation of crawl (C or S)	S	User defined	Control activation/deactivation of crawl space and slab on grade floor types for the residence
	b12	Height of crawl space wall above ground(ft)	1.5	User defined	
	b13	Height of crawl space walll under ground(ft)	1	User defined	
	b14	Pitch of roof	23	User defined	Measured from the case study house
CONSTRUCTION I	c01	Roof outside emissivity	0.90	User defined	c01 and c02 are used to define "Roof Color"
	c02	Roof absorptance	0.50	User defined	
	c03	Roof roughness	1	Fixed	This is used to calculate the outside film coefficienct for heat transfer calculations, DOE-2 allows values from 1 to 6 increasing in smoothness
	c04	Roof R-value (Hr-sq.ft-F/Btu)	26	User defined	
	c05	Wall absorptance	0.55	User defined	c05 and c07 are used to define "Wall Color"
	c06	Wall roughness	2	User defined	This is used to calculate the outside film coefficienct for heat transfer calculations, DOE-2 allows values from 1 to 6 increasing in smoothness
	c07	Wall outside emissivity	0.90	User defined	c05 and c07 are used to define "Wall Color"
	c08	Wall R-value (Hr-sq.ft-F/Btu)	13	User defined	
	c09	Ground reflectance	0.24	Fixwd	This defines the fraction of sunlight reflected from the ground
	c10	Window option (S or D)	S (Same)	User defined	S: Same widow ratio for all side, D: Different winow ratio for each side. Activate from c21 to c25
	c11	U-Factor of glazing (Btu/hr-sq.ft-F)	0.75	User defined	
	c12	Solar Heat Gain Coefficient(SHGC)	0.40	User defined	
	c13	Number of panes of glazing	2	Fixed	
	c14	Frame absorptance of glazing	0.7	Fixed	
	c15	Frame type - A,B,C,D,E	A (Aluminum without thermal break)	User defined	5 kinds of window frames
	c16	VOID			
	c17	Floor weight (lb/sq-ft)	11.50	Fixed	Activated if b01 is Q (Quick mode), from IECC2000 p.64 (If T:themal mass mode), Floor weight = 0), DOE Default 30=light; 70 = medium; 130 = heavy
	c18	VOID			
	c19	R-value of concrete slab (hr-sq.ft-F/Btu)	0.44	Fixed	R-value of concrete slab, Now 4" heavy weight concrete(CC03 in DOE Library). For Winkelmann calculation
	c20	Air film resistance (hr-sq.ft-F/Btu)	0.77	Fixed	The average of the air film resistance, Current heat flow up from article by Winkelmann. For Winkelmann calculation
	c21	Percentage of window area (%) for whole area or front side wall	15.00	User defined	If c10 is S, then this percentage is applied to all window area. Or If c21 is D, then this percentage is applied only to front side wall.
	c22	Percentage of window area (%) for back side wall	15.00	User defined	Only when c10 is D, this percentage is applied to back side wall.
	c23	Percentage of window area (%) for right side wall	15.00	User defined	Only when c10 is D, this percentage is applied to right side wall.
	c24	Percentage of window area (%) for left side wall	15.00	User defined	Only when c10 is D, this percentage is applied to left side wall.
	c25	Percentage of window area (%) for 2nd floor left side wall	15.00	User defined	Only when c10 is D, this percentage is applied to 2nd floor left side wall.
	c26	Floor R-Value (hr-sq.ft-F/Btu)	11	User defined	Default from IECC2000, page 81 (Window 15%, R-11). Crawl space only
	c27	Crawl space wall R-value (hr-sq.ft-F/Btu)	F (R-5)	User defined	Option (A, B, C, D, E, F, G, H, I, J, K, L, M, N). Default from IECC2000, page 81 (Window 15%, R-5). Crawl space only
	c28	Slab perimeter R-value and depth	A (R-0)	User defined	Option (A, B, C, D, E, F, G, H, I, J, K). Default from IECC2000, page 81 (Window 15%, R-0). Slab only
CONSTRUCTION II	cc01	Wall type selection	A	User defined	A: Wood frame B: Metal C: Masonary
	cc02	Wall stud type	a	User defined	a: 2 x4" stud dimensions b: 2 x 6" stud dimensions
	cc03	Wall stud position	WSPA	User defined	Fixed at WSPA: Postion of studs at 16" c/c
	cc04	Wall cavity insulation	CIA	User defined	Corresponding insulation values in the DOE-2 material library: CIA: R-11 CIB: R-13 CIC: R-15 CID: R-19 CIE: R-20

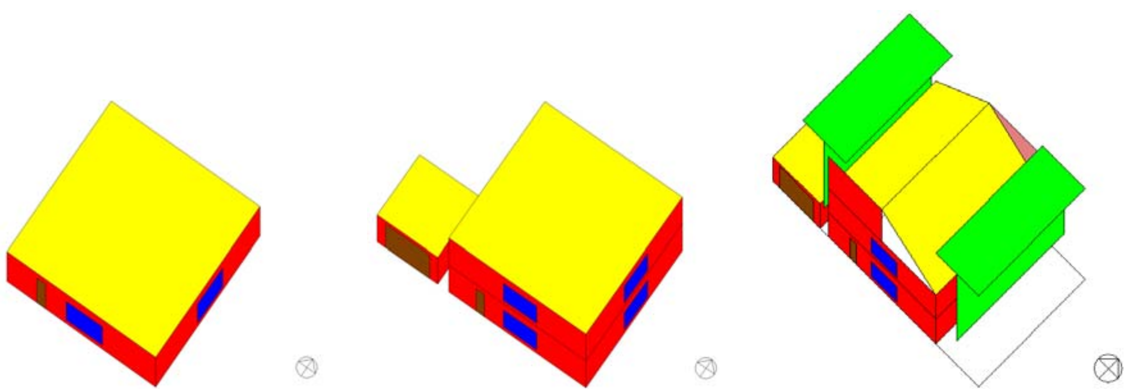
Figure 4.62 Single-Family input parameters (a)

PARAMETER	NO	DESCRIPTION	DEFAULT	STATUS	COMMENTS
CONSTRUCTION II	cc05	Wall exterior Insulation	EIB	User defined	Corresponding Exterior insulation/ sheathing values from DOE-2 material library:
					EIA: R-0
					EIB: R-5
					EIC: R-7.5
					EID: R-10
					EIE: Polyisocyanurate R 3.6
	cc06	Exterior finish	EFA	User defined	Corresponding finishing values from DOE-2 material library:
					EFA: Stucco R 0.2
					EFB: Vinyl Siding R 0.045
					EFC: Brick Siding R 0.33
					EFD: Hardi-Plank R 0.24
					EFE: Wood-Siding R 0.494
	cc07	Void			
	cc08	Void			
	cc09	Void			
	cc10	Roof type selection	WOODFRAME	User defined	WOODFRAME: Custom made frame for both ceiling and roof
					TRUSS: Pre-designed/Engineered truss
	cc11	Roof stud selection	a	User defined	a: 2 x 6" stud dimensions
					b: 2 x 8" stud dimensions
	cc12	Ceiling stud selection	a	User defined	a: 2 x 6" stud dimensions
					b: 2 x 8" stud dimensions
	cc13	Roof truss size	a	User defined	a: 2 x 4" stud dimensions
					b: 2 x 6" stud dimensions
	cc14	Placement of cavity insulation in roof	no	User defined	Roof insulation: No Ceiling insulation: yes
					Roof insulation: No Ceiling insulation: No
	cc15	Placement of cavity insulation in ceiling	yes	User defined	Roof insulation: yes Ceiling insulation: no
					Roof insulation: yes Ceiling insulation: yes
	cc16	Choice of cavity insulation	CCIA	User defined	Corresponding exterior finish values from DOE-2 material library:
					CCIA: R-19
					CCIB: R-26
					CCIC: R-28
					CCID: R-30
	cc17	Stud position for roof and ceiling	RSPA	User defined	Fixed at RSPA: Postion of studs at 16" c/c
	cc18	Choice of exterior insulation for roof			Place holder
	cc19	Choice of exterior finish for roof	Asphalt shingles	User defined	Fixed value obtained from DOE-2 library: Asphalt shingles
	cc20	Ceiling finish	Fixed at GP01	Fixed	Fixed value obtained from DOE-2 library: GP01 (1/2 " thick Gypsum or Plaster Board)
	cc21	Interior floor structure	a	User defined	a: 2 x 10" stud dimensions
					b: 2 x 12" stud dimensions
					TRUSS: Engineered Truss
	cc22	Interior floor stud position	IFSPA	User defined	IFSPA: Postion of studs at 16" o.c.
					IFSPB: Position of studs at 24" o.c.
					IFSPC: Position of studs at 16" o.c.
	cc23	Interior floor finish	FIFA	User defined	Corresponding floor finish values from DOE-2 material library. Activated when second story present:
					FIFA: CP01 (Carpet finish) R 2.08
					FIFB: ST01 (Stone finish) R .08
					FIFC: Hardwood R 0.68
	cc24	Floor slab structure	Fixed at 4" concrete	Fixed	Fixed value obtained from DOE-2 library: CC14
	cc25	Choice of studs for floor over crawl space	a	User defined	a: 2 x 10" stud dimensions
					b: 2 x 12" stud dimensions
					c: 3"x2" chord size wirh 11 7/8" truss
					d: 3"x4" chord size wirh 16" truss
	cc26	Crawl space stud position	FSPA	User defined	FSPA: Postion of studs at 16"
					FSPB: Position of studs at 24"
	cc27	Type of crawlspace	Vented	User defined	Vented
					Unvented
	cc28	Crawl space insulation	FCIA	User defined	Corresponding insulation values from DOE-2 material library:
					FCIA: R-11
					FCIB: R-13
					FCIC: R-15
					FCID: R-19
					FCIE: R-4
					FCIF: R-5
					FCIG: R-6
					FCIH: R-10
					FCII: R-12
	cc29	Crawl space floor finish	FFA	User defined	Corresponding floor finish values from DOE-2 material library:
					FFA: CP01 (Carpet finish) R-2.08
					FFB: ST01 (Stone finish) R-0.08
					FFC: Hard wood R-0.68
	cc30	Crawlspace wall finish	CSWA	User defined	Corresponding floor finish values from DOE-2 material library:
					CSWA: CB31 (Concrete block, 8" medium weight, hollow) R 1.72
					CSWB: CB32 (Concrete block, 8" medium weight, concrete filled) R 1.34
					CSWC: CB33 (Concrete block, 8" medium weight perelite filled) R 5.84

Figure 4.63   Single-Family input parameters (b)

PARAMETER	NO	DESCRIPTION	DEFAULT	STATUS	COMMENTS
SPACE	sp01	Number of people	2		
	sp02	Number of bedroom	3		Default calculated from IECC 2001(402.1.3.7) HOT WATER CONSUMPTION/MIN = ((30*a)+(10*b))/1440, a=living unit, b=# of bedroom
SHADE	s01	Front eave shade (ft)	0	User defined	Front eave shade (ft)
	s02	Back eave shade (ft)	0	User defined	Back eave shade (ft)
	s03	Left eave shade (ft)	0	User defined	Left eave shade (ft)
	s04	Right eave shade (ft)	0	User defined	Right eave shade (ft)
	s05	Tree shade	NO	User defined	NO: No shading
					E: East side of the house
					W: West of the house
					EW: East and west side of house
	s06	Shading type	Liveoak	User defined	Activated only when s05 has shade
					Liveoak
					Deciduous
					Evergreen
SYSTEM	sy01	Mode of system: 1, 2, 3	1	User defined	Allows user to select all-electric, gas/electric or heat pump for HVAC
	sy02	Cooling capacity of cooling system (Btu/hr)	0	User defined	0: Let DOE2 calculate
	sy03	Heating capacity of heating system (Btu/hr)	0	User defined	0: Let DOE2 calculate
	sy04	Seasonal Energy Efficiency Ratio (SEER)	10	User defined	C-EIR: 0.1-1 (3.41/SEER = C-EIR)
	sy05	Annual Fuel Utilization Efficiency (AFUE)	0.78	User defined	F-HIR: 1-1.75 (1/AFUE = F-HIR)
	sy06	Heating Seasonal Performance Factor (HSPF)	6.8	User defined	H-EIR: 0.1-2 (3.41/HSPF = H-EIR) (ResCheck HSPF: 6.6 - 12)
	sy07	The number of pilot lights of DHW	1	User defined	Each pilot light is 500 BTU/HR
	sy08	The number of pilot lights of Furnace	0	User defined	Each pilot light is 500 BTU/HR
	sy09	The number of pilot lights of others	0	User defined	Each pilot light is 500 BTU/HR
	sy10	Switch for Energy Factor for Domestic Hot Water consumption	A	User defined	If "A", then macro in DOE-2 calculates the Energy Factor, if S then the EF is calculated using values input by the user in sys11 parameter.
	sy11	Energy Factor (%) for Domestic Hot Water	0.55	User defined	MIN MAX values available only when sy10 = S. If fuel is Electric, EF(Energy Factor) is calculated by 0.93-0.00132*DHW-SIZE(Gallon), or if fuel is Gas, EF(Energy Factor) is calculated by 0.62-0.0019*DHW-SIZE(Gallon). DHW-SIZE in Gallon = (30*a) + (10*b) (a: Number of living units, b: Number of bedrooms). IECC2000(p.65) 402.1.3.7. The criteria listed in section 504.2.1 decribing the efficiency is overruled as the EF is calculated per DHW heater which is installed per unit.
	sy12	Supply air (CFM)	2487	User defined	1CFM/ft^2
	sy13	Supply leakage fraction	0	User defined	
	sy14	Return leakage fraction	0	User defined	
	sy15	Supply duct area (ft^2)	746.17	User defined	From ASHRAE 152-2004, 30% of Building Area
	sy16	Return duct area(ft^2)	124.36	User defined	From ASHRAE 152-2004, 5% of Building Area
	sy17	R-value for supply duct	8	User defined	From IECC 2000/2001
	sy18	R-value for return duct	4	User defined	From IECC 2000/2002
	sy19	Cooling system capacity (Btu/hr)		User defined	From DOE-2 calculation (SV-A report)
	sy20	Heating system capacity (Btu/hr)		User defined	From DOE-2 calculation (SV-A report)
	sy21	Duct location	Attic	User defined	Attic or Room

Figure 4.64 Single-Family input parameters (c)



(a) ***(b)*** ***(c)***

Figure 4.65 DrawBDL views of the development procedure of the code compliant house

4.3.5.1 DOE-2 Input Macro Method

According to LBNL (1993), the Input Macro feature was added to the Building Description Language (BDL) in DOE-2.1d to increase the flexibility of BDL. The Input Macro allows DOE-2 users to 1) incorporate external files containing pieces of BDL into the main BDL input stream, 2) selectively accept or skip portions of the input, 3) define a block of input with parameters and later reference this block and 4) perform arithmetic and logical HVAC and DHW systems. The input file for this research (SNGFAM2ST.INP) calculates PARAMETERS using data from the external INCLUDE file and assigns values to LOADS and SYSTEMS part for DOE-2 simulation.

4.3.5.2 DOE-2 Input Function Method

The Input Function feature allows DOE-2 users to modify DOE-2 LOADS or SYSTEMS calculations without recompiling the DOE-2 program. According to LBNL (1993), there are three types of applications for Input Functions: 1) calculation of variables that influence the simulation results, thus allowing users to modify or replace the algorithms used by the program without recompiling the program, 2) calculation of variables for reporting or debugging purposes, 3) reading in data files for use in the simulation. Input Functions are written as FORTRAN routines that are included in regular DOE-2 input file.

For this research, ASHRAE 152-2004 (Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems)(ASHRAE 2004) was applied to the SYSTEMS part of the DOE-2 simulation using the Input Function method for DOE-2.1e (Figure 4.66) to incorporate a duct model. This function calculates duct loss or gain in a conditioned space or unconditioned space because the current DOE-2-1e doesn't consider a variable duct loss or gain. The detailed procedure was explained on section 4.2.3.3.

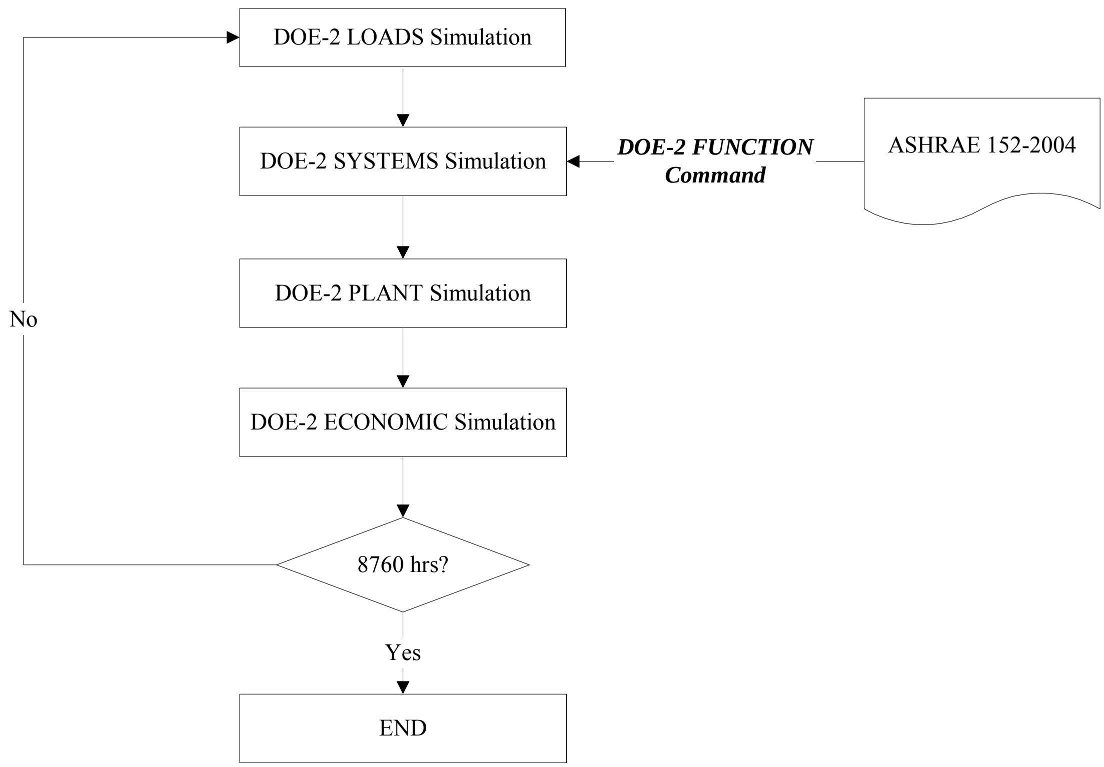


Figure 4.66 DOE-2 input function method for ASHRAE 152-2004

4.3.5.3 Batch DOE-2 Input (BDI)

The BDI program (version 1.08) was developed by ESL to perform the DOE-2 simulation in the batch mode. In order to use the BDI, a specially prepared spreadsheet (SNGFAM2ST.XLS) is utilized to assign values to all the PARAMETERS that are specified in the input file. In this spreadsheet, each row has information for the PARAMETERS for the DOE-2 INCLUDE file which is used with the input file (SNGFAM2ST.INP) for different runs. Using this spreadsheet, the BDI makes the INCLUDE files that correspond to the rows of spreadsheet, runs the DOE-2 simulation using SNGFAM2ST.INP in the batch mode, generates and saves output files. Figure 4.67 explains the steps of the BDI. Appendix C shows the examples of working with BDI and GAWK programs.

4.3.6 The Development of IECC-Compliant Simulation Model

Figure 4.68 represents the initial views of the building model constructed in the DOE-2.1e input file using the DrawBDL program. The initial input file has equal percentage of windows on all orientations as section 402.1.3.1.1 of the 2000/2001 IECC requires. The default model is a single-storied structure without garage, and the size is 50 ft by 50 ft (2500ft^2) with 15% of window-to-wall ratio. The default value for envelope components, space conditions, and system efficiency are based on Houston (HDD 1500 – 1999) for initial test. In addition, the input file provides options to incorporate a second story, crawl space, attic space, flexible house size, and different window-to-wall area ratios on each orientation.

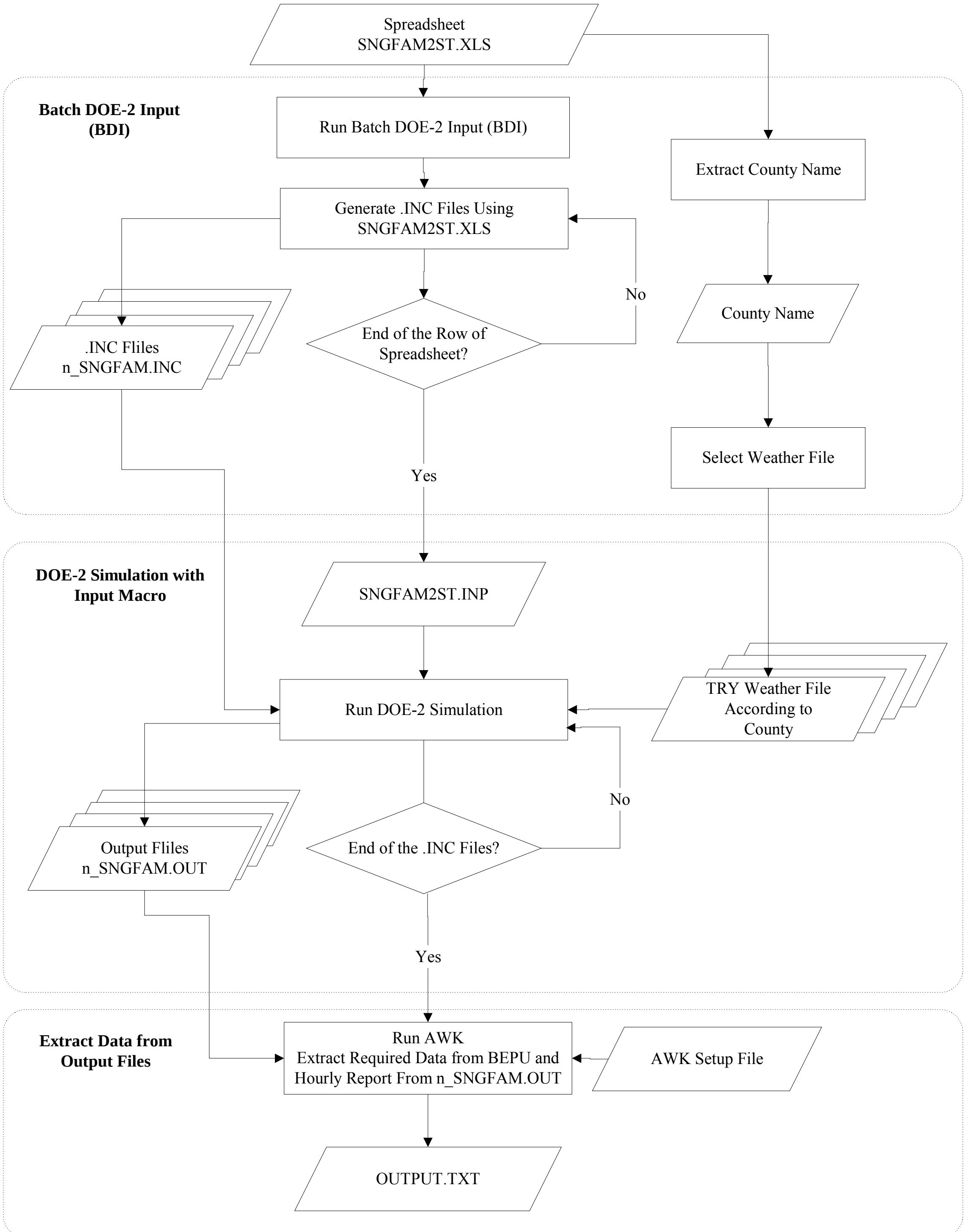


Figure 4.67   Procedure for using the BDI

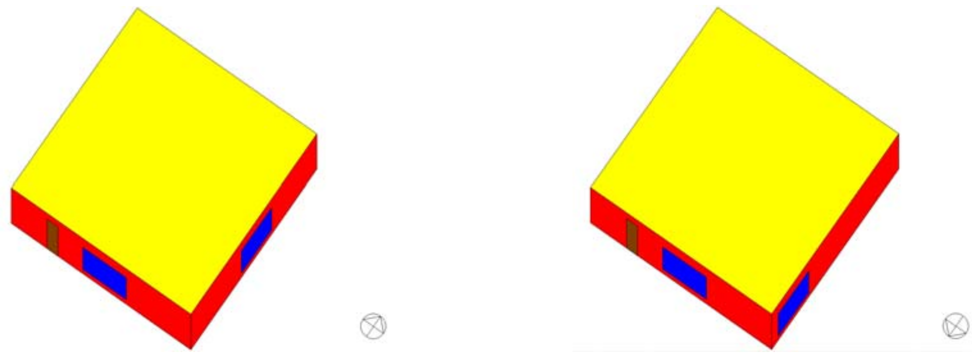


Figure 4.68 DrawBDL views of the code compliant initial input model

4.3.6.1 Shape

In order to analyze different types of residential houses according to the IECC model, various shapes were developed including: detached garage, second story, attic space and crawl space. Different shapes and sizes can be achieved automatically using DOE-2 MACRO method. Figures 4.69 and 4.70 show the DrawBDL views of different shapes of input file.

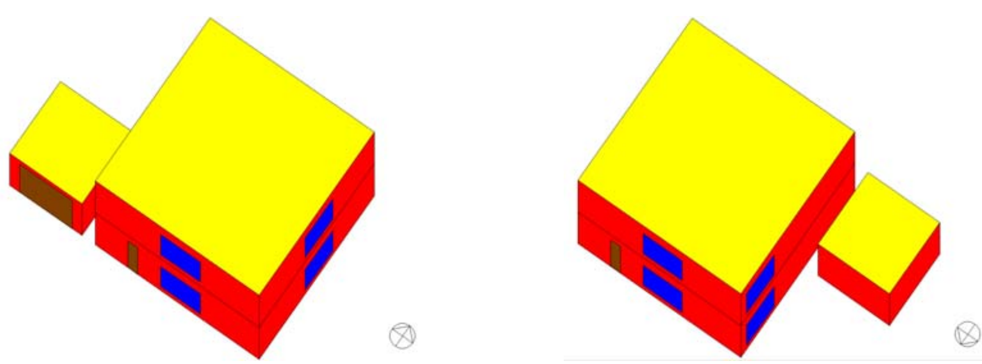


Figure 4.69 DrawBDL views of the code compliant two-story house with detached garage

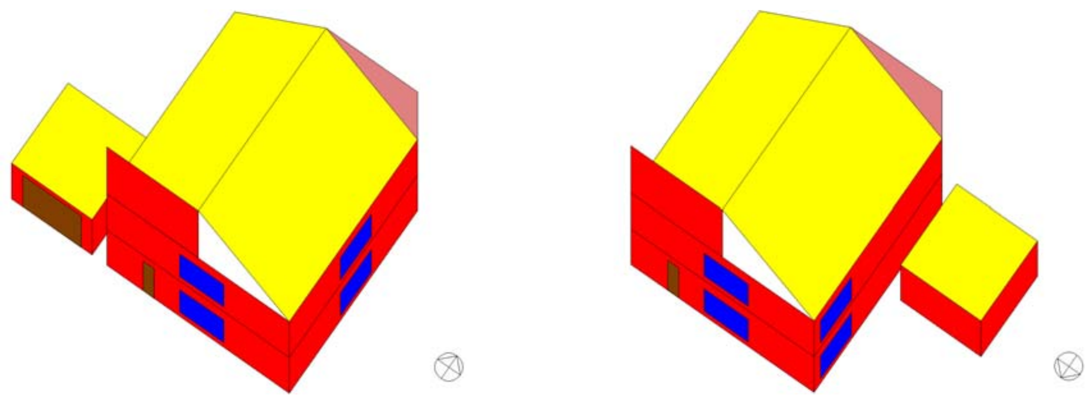


Figure 4.70 DrawBDL views of the code compliant two-story house with detached garage and attic space

4.3.6.2 Building Location Specifications

For this analysis, nine TMY2 weather files were used to represent the 41 non-attainment and affected counties. These are: 1) Austin, 2) Corpus Christi, 3) El Paso, 4) Fort Worth, 5) Houston, 6) Lufkin, 7) Port Arthur, 8) San Antonio and 9) Victoria. These 9 weather files represent 41 counties based on the location of county. Figure 4.71 and Table 4.10 show the climate zone of each county and the corresponding location of the weather data source for each county, including the Typical Meteorological Year (TMY2) stations, the Weather Year for Energy Calculations (WYEC2) weather stations, and the National Weather Service weather stations (NWS). Counties in the bold dash line on Figure 4.71 are 41 non-attainment and affected counties.

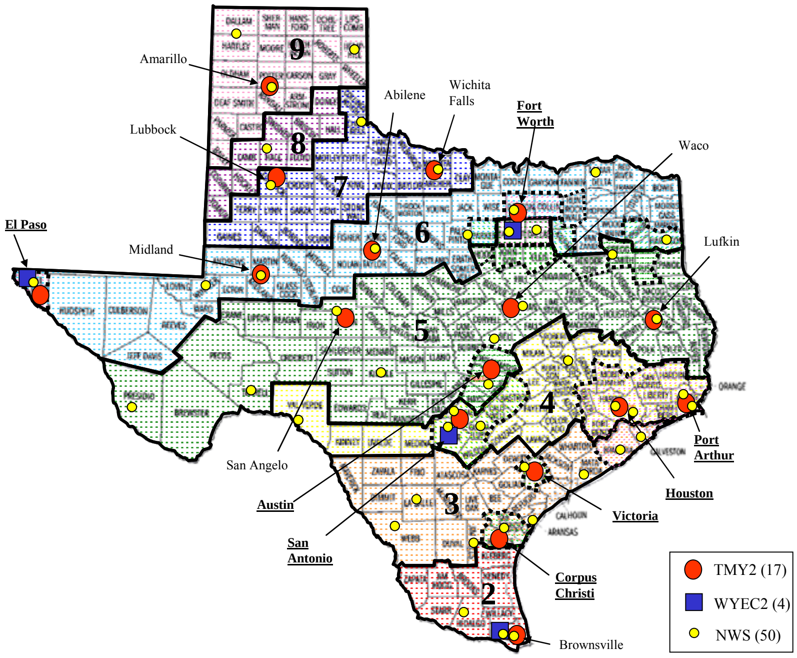


Figure 4.71   Map of climate zone (Haberl et al. 2004)

Table 4.10 TMY2 weather files according to counties

No.	County	Assigned TMY2 Weather File
1	Bastrop	Austin
2	Caldwell	
3	Hays	
4	Travis	
5	Williamson	
6	Nueces	Corpus Christi
7	San Patricio	
8	El Paso	El Paso
9	Ellis	Fort Worth
10	Johnson	
11	Kaufman	
12	Parker	
13	Rockwall	
14	Collin	
15	Dallas	
16	Denton	
17	Tarrant	
18	Hood	
19	Henderson	
20	Hunt	
21	Brazoria	Houston
22	Fort Bend	
23	Galveston	
24	Harris	
25	Montgomery	
26	Waller	
27	Gregg	Lufkin
28	Harrison	
29	Rusk	
30	Smith	
31	Upshur	
32	Chambers	Port Arthur
33	Hardin	
34	Jefferson	
35	Liberty	
36	Orange	
37	Bexar	San Antonio
38	Comal	
39	Guadalupe	
40	Wilson	
41	Victoria	Victoria

4.3.6.3 Envelope Components Options

Table 4.11 shows excerpts from the prescriptive building envelope requirement table in the Chapter 5 of the 2000/2001 IECC (ICC 1999, 2001). The specifications provided for the envelope components correspond to a range of Heating Degree Days (HDD) identified by the 2000/2001 IECC for Texas. Climate zone 3 to 6 include the 41 non-attainment and affected counties. The specifications for the envelope requirements vary based on the climate zone.

Table 4.11 Table of prescriptive building envelope requirements of climate zones 3, 4, 5 and 6 as specified by the 2000/2001 IECC

Climate Zone	HDD	Path	Glazing and Insulation					Foundation Type			
			Area %	U-Factor	SHGC	Ceiling	Wall	Floor	Basement	Slab Perimeter	Crawl Space
6	2500 – 2999	1	15	.60	.40	R-30	R-13	R-19	R-6	R-4, 2ft	R-7
		2	20	.50	.40	R-38	R-13	R-19	R-6	R-0	R-7
		3	25	.46	.40	R-38	R-16	R-19	R-6	R-0	R-7
5	2000 – 2499	1	15	.65	.40	R-30	R-13	R-11	R-5	R-0	R-6
		2	20	.52	.40	R-38	R-13	R-11	R-5	R-0	R-6
		3	25	.50	.40	R-38	R-13	R-19	R-8	R-0	R-10
4	1500 – 1999	1	15	.75	.40	R-26	R-13	R-11	R-5	R-0	R-5
		2	20	.60	.40	R-30	R-13	R-11	R-5	R-0	R-5
		3	25	.52	.40	R-30	R-13	R-13	R-6	R-0	R-6
3	1000 - 1499	1	15	.75	.40	R-19	R-11	R-11	R-0	R-0	R-5
		2	20	.70	.40	R-30	R-13	R-11	R-0	R-0	R-5
		3	25	.55	.40	R-30	R-13	R-11	R-0	R-0	R-5

4.3.6.4 Space Conditions

Table 4.12 shows the space conditions for the IECC-compliant, DOE-2 simulation input file. Most values were taken from the 2000/2001 IECC specifications. For sensible and latent heat gain from the occupants, Chapter 26 of the ASHRAE Handbook of Fundamentals (ASHRAE 2001b) was used for the nominal heat gain values from occupants. For weather factor to calculate air-change, ASHRAE Standard 136 (ASHRAE 1993) presents different weather factor according to different location.

Table 4.12 Space conditions on DOE-2 input file

Space Conditions on DOE-2 Input File	Default Value	Description
TEMPERATURE	73ºF	Average value of winter and summer set points which are taken from table 402.1.3.5 of IECC 2001. Winter set point = 68 Summer set point = 78
NUMBER-OF-PEOPLE	2	Assume that there are 2 people because of no specification on the IECC
PEOPLE-HG-LAT	200 Btu/hr	ASHRAE handbook of fundamentals 2001 Chapter 29
PEOPLE-HG-SENS	200 Btu/hr	ASHRAE handbook of fundamentals 2001 Chapter 29
LIGHTING-TYPE	INCAND	Assume that house uses incandescent light because of no specification on the 2000/2001 IECC
LIGHTING-KW	0.44 or 0.22 kW	Fraction of 879 watts constant internal heat gain of a type A1 house according to the 2000/2001 IECC, section 402.1.3.6. 1-stoty: 0.44kW 2-story: 0.22kW
EQUIPMENT-KW	0.44 or 0.22 kW	Fraction of 879 watts constant internal heat gain of a type A1 house according to the 2000/2001 IECC, section 402.1.3.6. 1-stoty: 0.44kW 2-story: 0.22kW
INF-METHOD	AIR-CHANGE	The 2000/2001 IECC, section 402.1.3.3
AIR-CHANGES/HR	0.46 (Houston)	ACH = Normalized Leakage x Weather Factor. Where Normalized Leakage is 0.57 from section 402.1.3.3 on IECC 2000 and Weather Factor is determined in accordance with the weather factors given by ASHRAE standard 136, as taken from the weather station nearest the building site. Abilene: 1.05, Amarillo: 1.14, Austin: 0.8 Brownsville: 0.9, Corpus Christi: 0.86 El Paso: 0.76 , Fort Worth: 0.89 Houston: 0.81, Kingsville: 0.72 Laredo: 0.91, Lubbock: 1.00 Lufkin: 0.64, Midland: 0.96 Port Arthur: 0.79, San Angelo: 0.84 San Antonio: 0.83, Sherman: 0.80 Waco: 0.92, Wichita Falls: 0.99
FLOOR-WEIGHT	11.5 lb/ft^2	2000/2001 IECC, section 402.1.3.3

4.3.6.5 HVAC and DHW Systems

In order to simulate the HVAC system in the IECC-compliant input file, the RESYS option was used. Table 4.13 presents the specifications used for the system simulation, and Figure 4.72 shows the procedure to decide HVAC and DHW system characteristics. Most values for the system simulation were taken from the 2000/2001 IECC.

The method to simulate DHW using the Energy Factor (EF) on DOE-2.1e is based on NREL REPORT (NREL/TP-550-27754) "Building America House Performance Analysis Procedures" (NREL 2001). For the DHW-EIR, the EF (Energy Factor) was calculated from the 2000/2001 IECC, Table 504.2. If electricity is used, the EF (Energy Factor) was calculated as 0.93-0.00132*DHW-SIZE (Gallon), and if gas is used, the EF (Energy Factor) was calculated by 0.62-0.0019*DHW-SIZE (Gallon). The DHW-SIZE is from the 2000/2001 IECC 402.1.3.7, which states that the DHW-SIZE (Gallon per day) = (30*a) + (10*b) (a: Number of living units, b: Number of bedrooms). In order to change gallon per day to gallon per minute for DOE-2 input, gallon per day was divided by 1440 (= 24hr/day * 60mim/hr). The DHW-GAL (Gal/min) was DHW-SIZE (Gallon per day) / 1440.

Table 4.13 System characteristics for the DOE-2 input file

Specification on DOE-2 Input File		Default Value	Description
ZONE-CONTROL	DESIGN-HEAT-T	68 ºF	Values are taken from table 402.1.3.5 of the 2000/2001 IECC.
	DESIGN-COOL-T	78 ºF	
	THROTTLING-RANGE	5 ºF	
	THERMOSTAT-TYPE	PROPORTIONAL	Default for residential building
SYSTEM FANS	SUPPLY-STATIC	2 INCH W.G.	Typical value for residential building
	SUPPLY-EFF	0.75	
SYSTEM-EQUIPMENT	COOLING-EIR	0.341	Refer to Figure 4.72 for calculation.
	HEATING-EIR	0.50	
	FURNACE-HIR	1.25	
SYSTEM	SYSTEM-TYPE	RESYS	Residential System in DOE-2.1e
	HEAT-SOURCE	GAS	Options given in the 2000/2001 IECC: Gas Furnace, Heat-Pump, Electric Heating
PLANT-ASSIGNMENT	DHW-TYPE	GAS	Options given in the 2000/2001 IECC: Electric, Gas
	DHW-SUPPLY-T	120ºF	Value is taken from section 402.1.3.7 of the 2000/2001 IECC
	DHW-EIR	1.83 (EF=0.55)	Refer to Figure 4.72 for calculation.
	DHW-SIZE	40 Gal	Calculated by equation specified in section 402.1.3.7 of the 2000/2001 IECC
	DHW-GAL	0.027 Gal/min	
	DHW-EIR-FPLR	NEWDHW	NREL Report (NREL/TP-550-27754) (NREL 2001)

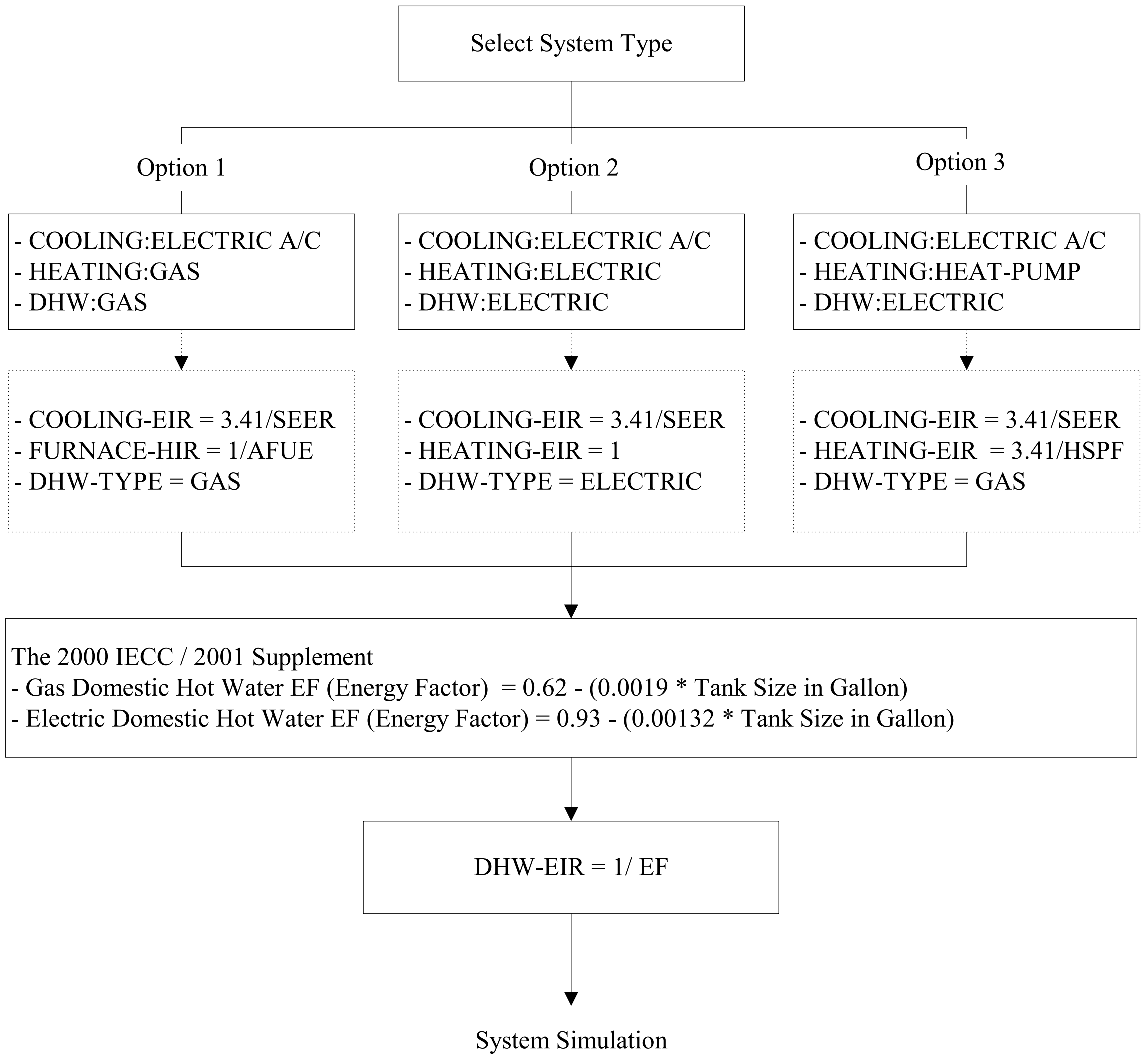


Figure 4.72 Procedure to decide HVAC and DHW system characteristics

4.3.6.6 Quick and Delayed Construction Modes

There are two methods to specify the construction of the DOE-2 simulation input file: 1) the "quick" mode option, which uses U-values for the walls and roofs and pre-calculated ASHRAE weighting factors for building components (III.A.3, LBNL 1981), and 2) delayed mode option which uses layered construction and DOE-2's Custom Weighting Factors (CWFs) to calculate heat transfer through the building components in a space (III.A.3, LBNL 1981). Therefore, this study evaluated both the quick and the delayed methods since the 2000/2001 IECC specifies the thermal properties of the wall and roof for normal and thermal mass walls.

According to the 2000/2001 IECC, exterior walls that are constructed with high-mass materials having heat-capacity greater than or equal to 6 Btu/ft^2-°F shall meet the equivalent insulation R-values in Table 502.2.1.1.2(1) or 502.2.1.1.2(2) (Table 4.14). Therefore, each wall type for the simulations was matched to the recommended overall U-value of the 2000/2001 IECC.

Table 4.14 Recommended overall U-value of high-mass materials

Wood framed wall R-value	HDD: 0 - 1,999	
	Table 502.2.4.17(1)	Table 502.2.4.17(2)
R-13 (U_w=0.076)	Exterior insulation (U_w)	Interior insulation (U_w)
	U_w = 0.130	U_w = 0.090

The building model used for the DOE-2.1e input file was based on the 2000/2001 IECC specifications for a single-family building of 2500 ft^2 gross floor area. The version of the model used for this analysis was the 'SNGFAM2ST.INP', which was developed by the Energy Systems Laboratory, Texas A&M University as part of the Texas Emission Reduction Plan (TERP) (Haberl et al. 2003a, 2003b, 2004a, 2004b, 2004c and 2004d). Houston was chosen as the building location for this analysis and the TMY2 weather file for Houston was used to carry out the simulations. The size of base-case model for the simulation was an average house as specified by the National Association of Home Builders (NAHB) with HVAC equipment efficiencies meeting the 2000/2001 International Energy Conservation Code (IECC). Figure 4.73 and Table 4.15 show the single-story simulation model of the base-case house. Shape of the roof side is created using rectangular shape for simplicity because DOE-2 usually considers the area instead of shape to calculate heat transfer and the area of rectangular shape of the roof side is equivalent to the area of the roof side.

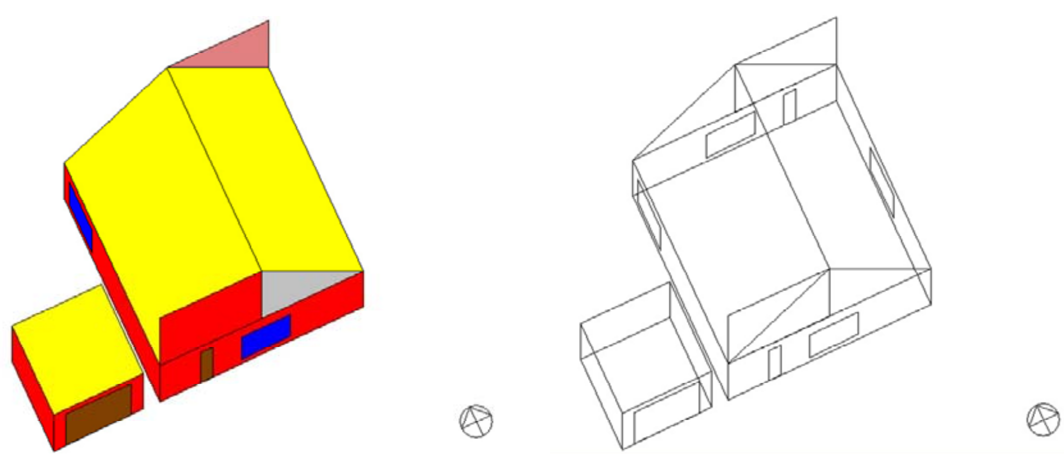


Figure 4.73 DrawBDL view of base-case model

Table 4.15 House description for analysis

Location	Climate Zone	HDD Range	Floor Area (sq.ft)	Wall Height (ft)	Wall R-Value	Ceiling R-value	Window to Wall Ratio	Glazing U-factor	SHGC	Duct Insulation	SEER	AFUE(%)	DHW PILOT LIGHT (500 BTU/HR)	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%
			NAHB 2002	NAHB 2002	IECC 2000	IECC 2000		IECC 2000	IECC 2000	IECC 2000	IECC 2000	IECC 2000		ASHRAE 152-2004	ASHRAE 152-2004
Houston	4	1500-1999	2487.22 (49.87ft* 49.87ft)	9	13	26	15%	0.75	0.4	SR-8,RR-4	10	0.78	Y	746.17	124.36

The effect of different construction types was analyzed for different building configurations to find the effect of high thermal materials in the IECC. Besides the base-case construction type of quick mode, several different wall types of thermal mass mode were investigated including: 1) a quick mode wall that uses U-values instead of the layered materials, 2) a 2x4, wood-framed wall with studs 16” O.C. with insulation between the studs, 3) a 3” facia brick wall with 2x4 wood-framed with studs 16” O.C. with insulation between the studs, 4) an 8” concrete block wall with perlite fill in the cells of the block and insulation between the block and the interior gypsum board, 5) an 8” concrete block wall with perlite and concrete fill in the cells of the block and insulation between the block and the interior gypsum board, 6) an 8” concrete block wall with perlite fill in the cells of the block and insulation outside the block, covered by stucco, and 7) an 8” concrete block with perlite and concrete fill in the cells of the block and insulation outside the block, covered by stucco.

The details of different construction types of exterior walls and their overall R-values are summarized in Table 4.16. DOE-2 commands of these wall types were shown at Appendix D.

Table 4.16 Summary of wall description of each simulation

No	R-value hr- ft^2-°F/Btu	Uw Btu/ hr-ft^2-°F	Heat Capacity Btu/ft^2-°F	Insulation	Description
1	13.0	0.076	N/A	N/A	Quick construction mode
2	13.0	0.077	4.39	Center	Asbestos-vinyl tile + Plywood + Insulation + Stud + Gypsum board
3	11.0	0.091	8.05	Inside	3" Face Brick + Plywood + Insulation + Gypsum board
4	11.1	0.090	7.94	Inside	8" Block with perlite filled + Insulation + Gypsum board
5	11.1	0.090	10.77	Inside	8" Block with perlite and concrete filled + Insulation + Gypsum board
6	7.8	0.129	10.87	Outside	Stucco + Insulation + 8" Block with perlite filled + Stud + Air + Gypsum board
7	7.7	0.130	13.68	Outside	Stucco + Insulation + 8" Block with perlite and concrete filled + Stud + Air + Gypsum board

4.3.6.6.1 Base-Case Model (Quick Construction Mode)

The values that were used to develop base-case model are from a Type A-1 Residential Buildings of the 2000/2001 IECC. The base-case house had an R-13 for wall, R-26 for roof insulation and floor-weight of 11.5 lb/ft^2 as specified in the 2000/2001 IECC for a standard design with 15% window-to-wall ratio (Table 4.17). Figure 4.74 shows the DOE-2 code of quick construction wall

Table 4.17 Base-case house according to the 2000/2001 IECC

Heating Degree Days	Maximum		Minimum			
	Glazing U-factor	SHGC	Ceiling R-value	Exterior wall R-value	Floor U-value	Floor weight (Lb/ft^2)
1,500-1,999	0.75	0.40	R-26	R-13	Slab	11.5

* Table 502.2.4(3) of the 2000/2001 IECC Type A-1 Residential Buildings and window area 15 percent of gross exterior wall area

```
P-WALLUVALUE = 0.0769                          $ U-value = 1/R = 1/13

WALL-CON1 = CONSTRUCTION
           ABSORPTANCE = P-WALLABSORPTANCE
           ROUGHNESS = P-WALLROUGHNESS
           U = P-WALLUVALUE ..
```

Figure 4.74 DOE-2 code of quick construction wall

4.3.6.6.2 2x4, Wood-Framed Wall with Studs 16" O.C. with Insulation between the Studs (Delayed Construction Mode)

Several changes were applied to the base-case model such as a layered roof, wall and the new method for ground surface (Winkelmann 1998) to perform the delayed construction mode simulation. The R-value of the layered materials that were applied to wood frame wall construction was identical to the recommended R-value of Table 502.2.4(3) (Table 4.14). The material used in this wall type included vinyl siding on ½" plywood. The interiors of the walls were ½" gypsum board on 2x4" stud construction set at 16" centers with insulation (Table 4.18). Figure 4.75 shows the wood frame wall dimension and calculated R-value.

Table 4.18 Thermal properties of wood frame wall

No	Name	Thickness (ft)	Conductivity	R (Ft^2-hr-ºF/Btu)		Density (lb/ft^3)	Specific Heat (Btu/Lb-ºF)	DOE-2 Code
			(Btu-ft/hr-ft^{2}-ºF)	Insulation Section	Stud Section			
1	Vinyl Siding			0.05			0.30	AV01
2	Plywood ½”	0.0417	0.0667	0.63		34.00	0.29	PW03
3	Mineral wool / fiber Insulation	0.4050	0.0270		15.00	0.60	0.20	IN
4	2*4” stud	0.3333	0.0667	4.37		32.00	0.33	WD05
5	Gypsum board ½”	0.0417	0.0926	0.45		50.00	0.20	GP01
Tot				13.00 (U_w=0.077)				

	Insulation Section	Frame Section
1	0.05	0.05
2	0.63	0.63
3	15	
4		4.37
5	0.45	0.45
Tot	16.13	5.5

A_{tot} (16”*12”): 192 in^2
A_{ins} (14”*12”): 168 in^2
Astud (2”*12”): 18in^2

$U_t = 1/R_t = (1/A_t) * ((A_{stud}/R_{stud})+(A_{ins}/R_{ins}))$
$= (1/192)*((24/5.5)+(168/16.13))$
$= 0.077$ Btu/hr-ft^2-°F

R_{tot}= 13.0 hr-ft^2 -ºF/Btu

The required R-value of wall of the 2000/2001 IECC code is R-13

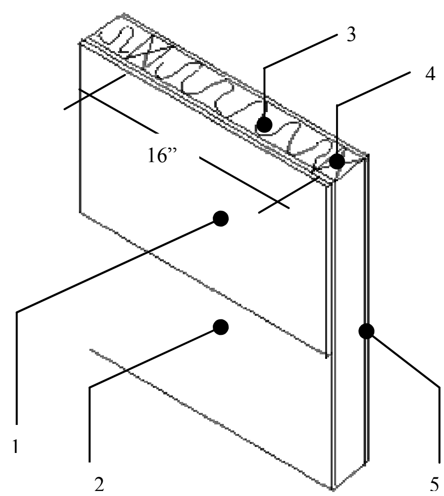


Figure 4.75 Wood frame wall dimension and calculated R-value

While the original base-case uses U-value of the wall, the wood frame wall construction uses real layout to investigate thermal mass effects. DOE-2 commands were shown at Appendix D.

4.3.6.6.3 3" Facia Brick Wall with 2x4 Wood-Framed with Studs 16" O.C. with Insulation between the Studs

The following table (Table 4.19) describes the thermal properties and other dimensions which are used for face brick wall. The material used in this wall type included face brick on ½" plywood. The interiors of the walls were ½" gypsum board on 2x4" stud construction set at 16" centers with insulation. DOE-2 commands were shown at Appendix D.

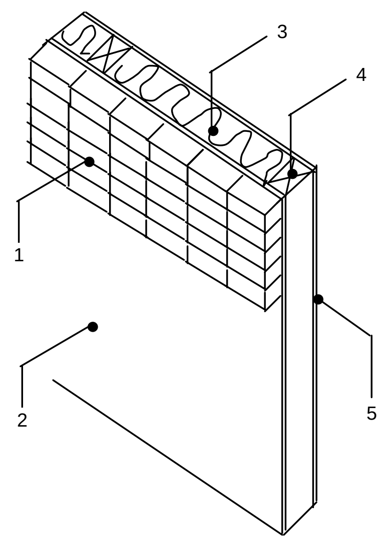
Table 4.19 Thermal properties of face brick wall

No	Name	Thickness (ft)	Conductivity (Btu-ft/hr-ft^2-°F)	R (Ft^2-hr-°F/Btu)		Density (lb/ft^3)	Specific Heat (Btu/Lb-°F)	DOE-2 Code
				Insulation Section	Stud Section			
1	Face Brick	0.2500	0.7600	0.33	0.33	130.00	0.22	BK04
2	Plywood	0.0400	0.0700	0.63	0.63	34.00	0.29	PW03
3	Insulation	0.2900	0.0300	10.80		6.00	0.20	IN11
4	2*4 Stud	0.3300	0.0700		5.00	32.00	0.33	WD05
5	Gypsum Board	0.0400	0.0900	0.45	0.45	50.00	0.20	GP01
Tot				11.00 (U_w=0.091)				

* The insulation is located at the interior side.

In order to check whether the R-value and the heat capacity of the brick wall agree with the 2000/2001 IECC, the following calculation procedures (Figure 4.76) are performed.

No	Insulation Section	Frame Section
1	0.33	0.33
2	0.63	0.63
3	10.80	
4		5.00
5	0.45	0.45
Tot	12.21	6.41



tot (16"*12"): 192 in^2
A_{ins} (14"*12"): 168 in^2
A_{stud} (2"*12"): 24in^2
$U_t = 1/R_t = (1/A_t) * ((A_{stud}/R_{stud})+(A_{ins}/R_{ins}))$
$= (1/192)*((24/6.41)+(168/12.21))$
$= 0.091$ Btu/hr-ft^2-°F

R_{tot}= 11.0 hr-ft^2-ºF/Btu, Uw=0.091 Btu/ hr-ft^2-ºF

The required U of wall of the 2000/2001 IECC is 0.09 (Table 502.2.1.1.1.2(2) Interior Insulation)

Heat Capacity =
0.25*130*0.22+0.04*34*0.29+0.29*6*0.2+0.33*3
2*0.33+0.04*50*0.2 = 8.05 Btu/ft^2-°F
(>6 Btu/ft^2-°F: High mass material)

Figure 4.76   Facia brick wall dimension and calculated R-Value

4.3.6.6.4 8” Concrete Block Wall with Perlite Fill in the Cells of the Block and Insulation between the Block and the Interior Gypsum Board (I)

The following table (Table 4.20) and figure (Figure 4.77) describe the thermal properties and other dimensions which are used for 8” block with perlite fill. The material used in this wall type included 8” concrete block with perlite fill and the interiors of the walls were ½” gypsum board with insulation. DOE-2 commands were shown at Appendix D.

Table 4.20 Thermal properties of 8" block with perlite fill

No	Name	Thickness (ft)	Conductivity (Btu-ft/hr-ft^2-°F)	R (Ft^2-hr-°F/Btu)	Density (lb/ft^3)	Specific Heat (Btu/Lb-°F)	DOE-2 Code
1	Block	0.6667	0.1140	5.84	56.00	0.20	CB33
2	Insulation	0.096	0.0200	4.80	1.80	0.29	IN34
3	Gypsum Board	0.0417	0.0930	0.45	50.00	0.20	GP01
Tot				11.10 (Uw=0.090)			

* The insulation is located at the interior side.

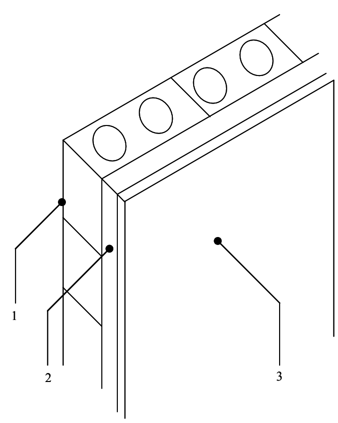


Figure 4.77 8" concrete block wall with perlite fill

The calculated R-value was 11.10 hr-ºF-ft^2 /Btu, and the U_w was 0.090 Btu/hr-ft^2-ºF, which the U_w agrees with the required U_w-value of wall of Table 502.2.1.1.2(2) on the 2000/2001 IECC (U_w = 0.09). The heat capacity is 7.94 Btu/ft^2-ºF. This value also agrees with high mass material (6 Btu/ft^2-°F).

4.3.6.6.5 8” Concrete Block Wall with Perlite and Concrete Fill in the Cells of the Block and Insulation between the Block and the Interior Gypsum Board(II)

The following table (Table 4.21) and the figure (Figure 4.78) describe the thermal properties and other dimensions which are used for 8” block with perlite and concrete fill. The material used in this wall type included 8” concrete block with perlite and concrete fill and the interiors of the walls were ½” gypsum board with insulation. DOE-2 commands were shown at Appendix D.

Table 4.21 Thermal properties of 8" block with perlite and concrete fill

No	Name	Thickness (ft)	Conductivity (Btu-ft/hr-ft^2-ºF)	R (Ft^2-hr-ºF/Btu)	Density (lb/ft^3)	Specific Heat (Btu/Lb-ºF)	DOE-2 Code
1	Block	0.6667	0.2410	2.77	77.00	0.20	CB35
2	Insulation	0.1580	0.0200	8.34	1.80	0.29	IN34
3	Gypsum Board	0.0417	0.0930	0.45	50.00	0.20	GP01
Tot				11.12 (Uw=0.090)			

* The insulation is located at the interior side.

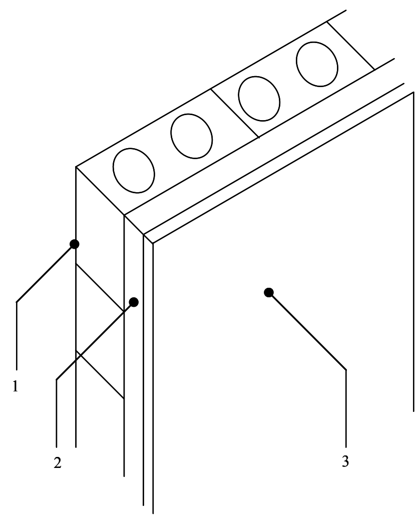


Figure 4.78   8" concrete block wall with perlite and concrete fill

The calculated R-value was 11.12 hr-ºF-ft^2 /Btu, and the U_w was 0.090 Btu/hr-ft^2-ºF, which the U_w agrees with the required U_w-value of wall of Table 502.2.1.1.2(2) on the 2000/2001 IECC (U_w = 0.09). The heat capacity is 10.77 Btu/ft^2-ºF, and this value also agrees with high mass material (6 Btu/ft^2-°F).

4.3.6.6.6 8" Concrete Block Wall with Perlite Fill in the Cells of the Block and Insulation Outside the Block, Covered by Stucco (III)

The following table (Table 4.22) and figure (Figure 4.79) describe the thermal properties and other dimensions which are used for 8" block with perlite fill. The material used in this wall type included 1" stucco and insulation on 8" block with perlite fill. The interiors of the walls were ½" gypsum board on 2x4" stud construction set at 16" centers with air layer. DOE-2 commands were shown at Appendix D.

Table 4.22 Thermal properties of 8" block with perlite fill

No	Name	Thickness (ft)	Conductivity (Btu-ft/hr-ft^2-°F)	R (Ft^2-hr-°F/Btu) Air Section	Stud Section	Density (lb/ft^3)	Specific Heat (Btu/Lb-°F)	DOE-2 Code
1	Stucco	0.0833	1.0420	0.08	0.08	166.00	0.20	SC01
2	Insulation	0.0081	0.0270	0.30	0.30	0.60	0.20	IN11
3	Block	0.6667	0.1140	5.84	5.84	56.00	0.20	CB33
4	Stud	0.1670	0.0670		2.50	32.00	0.33	WD05
5	Air	0.0167		0.89				AL21
6	Gypsum Board	0.0417	0.0926	0.45	0.45	50.00	0.20	GP01
Tot				7.73 (Uw=0.130)				

* The insulation is located at the exterior side.

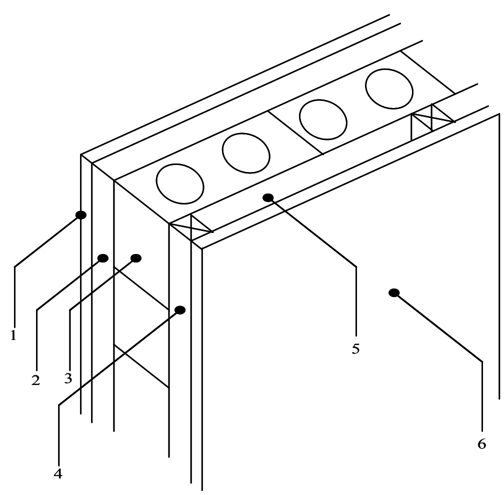


Figure 4.79 8" concrete block wall with perlite fill

The calculated R-value was 7.73 hr-ºF-ft^2 /Btu, and the U_w was 0.13 Btu/hr-ft^2-ºF, which the U_w agrees with the required U_w-value of wall of Table 502.2.1.1.2(1) on the 2000/2001 IECC (U_w = 0.13). The heat capacity is 10.88 Btu/ft^2-ºF, and this value also agrees with high mass material (6 Btu/ft^2-°F).

4.3.6.6.7 8” Concrete Block with Perlite and Concrete Fill in the Cells of the Block and Insulation Outside the Block, Covered by Stucco (IV)

The following table (Table 4.23) and picture (Figure 4.80) describe the thermal properties and other dimensions which are used for 8” block with perlite and concrete fill. The material used in this wall type included 1” stucco and insulation on 8” block with perlite and concrete fill. The interiors of the walls were ½” gypsum board on 2x4” stud construction set at 16” centers with air layer. DOE-2 commands were shown at Appendix D.

Table 4.23 Thermal properties of 8" block with perlite and concrete filled

No	Name	Thickness (ft)	Conductivity (Btu-ft/hr-ft^2-ºF)	R (Ft^2-hr-ºF/Btu) Air Section	R (Ft^2-hr-ºF/Btu) Stud Section	Density (lb/ft^3)	Specific Heat (Btu/Lb-ºF)	DOE-2 Code
1	Stucco	0.0833	1.0420	0.08	0.08	166.00	0.20	SC01
2	Insulation	0.0900	0.0270	3.33	3.33	0.60	0.20	IN11
3	Block	0.6667	0.2410	2.76	2.76	77.00	0.20	CB35
4	Stud	0.1670	0.0670		2.50	32.00	0.33	WD05
5	Air	0.0167		0.89				AL21
6	Gypsum Board	0.0417	0.0926	0.45	0.45	50.00	0.20	GP01
Tot				7.68 (Uw=0.130)				

* The insulation is located at the exterior side.

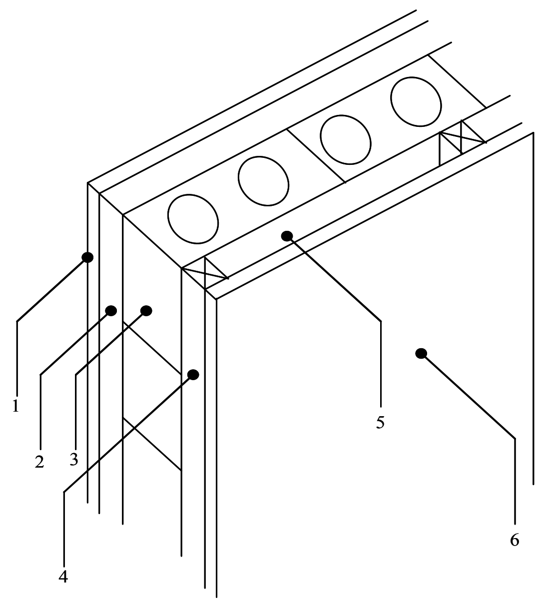


Figure 4.80 8" concrete block wall with perlite and concrete filled

The calculated R-value was 7.68 hr-ºF-ft^2 /Btu, and the U_w was 0.13 Btu/hr-ft^2-ºF, which U_w agrees with the required U_w-value of wall of Table 502.2.1.1.2(1) on the 2000/2001 IECC (U_w = 0.13). The heat capacity is 13.68 Btu/ft^2-ºF, and this value agrees with high mass material (6 Btu/ft^2-°F).

4.3.6.8 Window Input Mode (Window-5 vs. SC Method)

In this study, two methods were investigated for modeling windows in the DOE-2 program: The Window-5 method which requires the Window-5 program, which can be modified by the user and incorporated into a DOE-2 window library, and the Shading Coefficient (SC) method which needs simple input information about the shading coefficient and the glass conductance.

The SC method calculates solar heat gain and loads using algorithms developed for single pane clear glass (ASHRAE 1975 and 1989). In Shading Coefficient (SC) method, the solar gain was first determined for a reference glazing consisting of 1/8 inch clear glass under ASHRAE standard summer conditions (95ºF outside temperature, 75ºF inside temperature, 7.5mph wind speed, and near-normal irradiance of 248 Btu/hr-ft^2). The reference glazing had a solar transmittance of 86% and an absorptance of 8.8% at normal incidence (0°). The solar gain for the selected glazing was then determined each hour by multiplying the solar gain of the reference glazing by the shading coefficient of the selected glazing. However, DOE-2.1e window library developed by the Window-5 program contained detailed information on the window system. The information included the solar and visible optical properties, and the solar heat gain coefficient for the glazing system at 10° increments from 0° to 90°. The infrared hemispherical transmittance and emittances, the thickness, the conductivity for each glazing layer, the gas properties and gap width for the individual gas layers were also included. This window information converted to WIN.DAT library which is required in the DOE-2 program.

In order to investigate the difference between two methods, the window simulation tests were performed using single-pane, double-pane, and low-e glass on two standard IECC single-family houses which have the same characteristics for analysis on the Chapter 4.3.6.6: 1) A model which has just an R-value for the wall, roof and floor according to the 2000/2001 IECC (i.e., pre-calculated ASHRAE weighting factors or the “quick” mode), 2) the model which has a layered wood frame wall with the same R-value as the first one (i.e., custom-weighting factors or the “thermal mass” mode). The objective of this analysis was to test the differences in the results from the modeling of different window types using the Window-5 options against the SC options in the DOE-2 input file. A detailed simulation scheme for this comparison is presented in Table 4.24.

Table 4.24 Simulation scheme for window analysis

	Single Pane	Double Pane	Double Pane Low-e
"Quick" construction mode	Shading Coefficient	Shading Coefficient	Shading Coefficient
	Window-Library	Window-Library	Window-Library
"Thermal mass" construction mode	Shading Coefficient	Shading Coefficient	Shading Coefficient
	Window-Library	Window-Library	Window-Library

In order to compare the differences between the two methods, a two-step test was adopted. The first step looked at the properties of the glazing using the DOE-2 LV-H report to check that the same window shapes and thermal properties were being used, including: the glass area, the shading coefficient, the number of panes and the glass U-value. The second step examined the impact of using each of these options on the annual energy consumption, including heating and cooling energy use. The Window-5 output files of three window types (single-pane clear, double-pane clear and double-pane low-e glass) from the Window-5 program simulations can be found in the Appendix E. These Window-5 output files were incorporated to the window library of DOE-2 program for the simulations. The LV-H report of DOE-2 from the different window type can be found in the Appendix F.

4.4 Analysis of an IECC-Compliant Simulation Model

In this section, an efficiency analysis of an IECC-compliant residence was performed that compared a base-case building with the same building modified by an energy efficiency strategy. To perform this analysis, the following programs and files were used: 1) a thermal mass wood frame wall of an IECC-compliant DOE-2 simulation model (SNGFAM2ST.inp version 1.20), 2) the ESL's Batch DOE-2 Input (BDI) program (version 1.13), 3) the GAWK program, which was described at Chapter 4.3.5.3, and 4) the TMY2 weather data for Amarillo, Fort Worth, Houston, and Brownsville, Texas. The primary input model had the same thermal properties for the window and building envelopes, and HVAC system efficiencies shown in Tables 4.12 and 4.13. Table 4.25 presents the primary input model information about the building envelope, fenestration, duct properties, HVAC systems, etc. HVAC and duct systems were located at the attic space where it was unconditioned.

Table 4.25 Primary input model for the efficiency analysis

Climate Zone	Weather file (TMY2)	Floor Area (sq.ft)	Wall Height (ft)	Wall R-Value	Ceiling R-value	Window Area (%)	Glazing U-value	SHGC
		NAHB	NAHB	IECC 2000	IECC 2000	IECC 2000	IECC 2000	IECC 2000
9	Amarillo	2487.22	9	13	38	15	0.45	0.66
5	Fort Worth	2487.22	9	13	30	15	0.65	0.40
4	Houston	2487.22	9	13	26	15	0.75	0.40
2	Brownsville	2487.22	9	11	19	15	0.90	0.40

Duct Insulation	ACH	SEER	AFUE(%)	DHW PILOT LIGHT (500 BTU/HR)	AC Size (TON)	Heating Size (Bru/hr)	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%
	ASHRAE 136-1993	IECC 2000	IECC 2000		Manual	Manual	ASHRAE 152-2004	ASHRAE 152-2004
SR-8, RR-4	0.65	10	78	Y	5.0	75000	746.17	124.36
SR-8, RR-4	0.51	10	78	Y	5.0	75000	746.17	124.36
SR-8, RR-4	0.46	10	78	Y	5.0	75000	746.17	124.36
SR-8, RR-4	0.51	10	78	Y	5.0	75000	746.17	124.36

The 2000/2001 IECC provides the different levels of insulation for the wall and ceiling, and fenestration properties according to the climate zones. The wall insulation level is R-13 and the ceiling insulation level is R-38 for the climate zone 9, while the wall insulation level is R-11 and the ceiling insulation level is R-19 for the climate zone 2. Because of the different levels of insulation, the insulation levels of the wall and ceiling were adjusted using the thickness variable in the DOE-2 input (SNGFAM2ST.INP) to perform the simulations. Tables 4.26 to 4.28 and Figures 4.81 to 4.83 show the details of the construction for exterior wall and roof and ceiling, and their thermal properties of each component. The walls of the base-case house were constructed with 2x4 studs placed 24 inches on center. These walls had insulation in the cavity between the studs. The exterior of the house was vinyl sheathing over plywood and the interior of the walls was ½ inch gypsum board. The roof construction consisted of composite shingles on 5/8” plywood deck placed on 2x6” trusses set at 24” centers. The ceilings were 5/8” gypsum board on 2 x 6” trusses set at 24” centers with insulation.

Table 4.26 Wall thermal properties of the primary input file

No.	Description	Thickness	Conductivity	Density	Specific heat
		ft	Btu-ft/hr-ft2-F	lb/ft3	Btu/lb-F
1	VINYL-SIDING	0.0036	0.08	79.48	0.33
2	PLYWOOD-1/2IN	0.0417	0.0667	34	0.29
3	INSULATION	Depend on location	0.0225	3	0.33
4	STUD - 4INCH	0.3333	0.0667	32	0.33
5	GYPSUM-BOARD-1/2IN	0.0417	0.0926	50	0.2

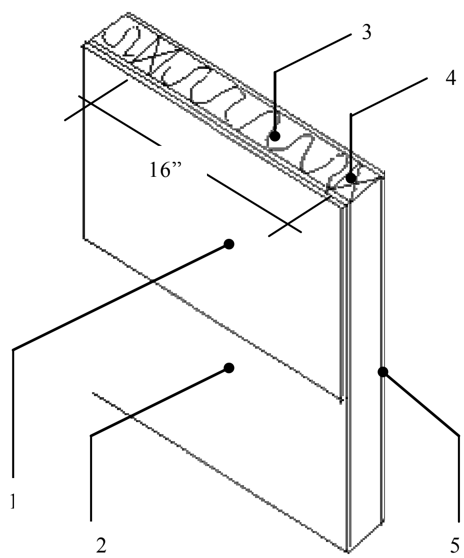


Figure 4.81 Wall dimensions of the primary input file

Table 4.27 Roof thermal properties of the primary input file

No.	Description	Thickness	Conductivity	Density	Specific heat
		ft	Btu-ft/hr-ft2-F	lb/ft3	Btu/lb-F
1	ASPHALT SHINGLE-SIDING			70	0.35
2	PLYWOOD-5/8IN	0.0417	0.0667	34	0.29
3	STUD-6IN	0.5	0.07	32	0.33

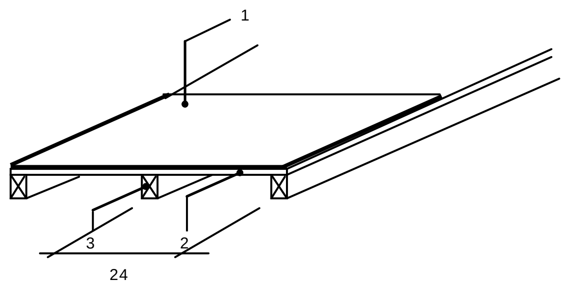


Figure 4.82 Roof dimensions of the primary input file

Table 4.28 Ceiling thermal properties of the primary input file

No.	Description	Thickness	Conductivity	Density	Specific heat
		ft	Btu-ft/hr-ft2-F	lb/ft3	Btu/lb-F
1	INSULATION	Depend on location	0.03	0.63	0.2
2	STUD-6IN	0.5	0.0667	32	0.33
3	GYPSUM-BOARD-1/2IN	0.0417	0.0926	50	0.2

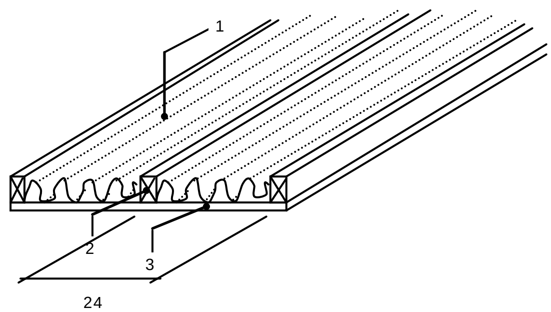


Figure 4.83 Ceiling dimensions of the primary input file

In order to investigate the efficiency analysis of the IECC-compliant simulation model, several different elements were tested: 1) the fenestration properties such as the U-value and Solar Heat Gain Coefficient (SHGC), 2) duct insulation levels and leakage, 3) the Seasonal Energy Efficiency Ratio (SEER) for the air conditioner system, 4) the Annual Fuel Utilization Efficiency (AFUE) for the gas furnace, 5) the Heating Seasonal Performance Factor (HSPF) for the heat pump, 6) the Energy Factor (EF) for the domestic hot water, 7) the different locations of HVAC system and ductwork including the attic space and conditioned space, and 8) the different types of tree shading, including: all year (Live Oak), a deciduous tree, and an evergreen tree with different shading schedules.

4.4.1 Fenestration Properties

The effect of improving the fenestration properties on annual energy use was analyzed to investigate the individual performance and to find the optimum combinations of fenestration properties that could result in the minimum energy use. The simulation scheme for fenestration properties is presented in Table 4.29.

The base-case U-value (Btu/hr-ft^2-ºF) was 0.45 for the climate zone 9, 0.65 for the climate zone 5, 0.75 for climate zone 4, and 0.90 for the climate zone 2. The SHGC of the base case was fixed to 0.40 for the entire climate zone except for the climate zone 8 and 9. Therefore, in the case of the climate zone 8 and 9, the SHGC of the double pane clear glass (0.66) was used according to the table 102.5.2(3) of the 2000/2001 IECC. The locations of analysis were the climate zone 2 (Brownsville), 4(Houston), 5(Fort Worth) and 9 (Amarillo), and the window distribution was 15% for all four sides of the house. HVAC and duct systems were located at the attic space where it was unconditioned.

In the analysis, the U-value was changed up to 20% in decrements of 5% from the base case. The SHGC was changed from 0.40 to 0.36 in decrements of 0.02 for climate zones 5, 4 and

2; and was changed from 0.66 to 0.62 in increments of 0.02 for climate zone 9. Table 4.29 presents the simulation plan for the fenestration types.

Table 4.29 Simulation plan for the fenestration types

Location	U-value (Btu/hr-ft^2-ºF)	SHGC
Climate zone 9	0.450 (Base case)	1) 0.66 (Base case), 2) 0.64, 3) 0.62
	0.428	1) 0.66, 2) 0.64, 3) 0.62
	0.405	1) 0.66, 2) 0.64, 3) 0.62
	0.383	1) 0.66, 2) 0.64, 3) 0.62
	0.360	1) 0.66, 2) 0.64, 3) 0.62
Climate zone 5	0.650 (Base case)	1) 0.40 (Base case), 2) 0.38, 3) 0.36
	0.618	1) 0.40, 2) 0.38, 3) 0.36
	0.585	1) 0.40, 2) 0.38, 3) 0.36
	0.555	1) 0.40, 2) 0.38, 3) 0.36
	0.520	1) 0.40, 2) 0.38, 3) 0.36
Climate zone 4	0.750 (Base case)	1) 0.40 (Base case), 2) 0.38, 3) 0.36
	0.713	1) 0.40, 2) 0.38, 3) 0.36
	0.675	1) 0.40, 2) 0.38, 3) 0.36
	0.638	1) 0.40, 2) 0.38, 3) 0.36
	0.600	1) 0.40, 2) 0.38, 3) 0.36
Climate zone 2	0.90 (Base case)	1) 0.40 (Base case), 2) 0.38, 3) 0.36
	0.855	1) 0.40, 2) 0.38, 3) 0.36
	0.810	1) 0.40, 2) 0.38, 3) 0.36
	0.765	1) 0.40, 2) 0.38, 3) 0.36
	0.720	1) 0.40, 2) 0.38, 3) 0.36

4.4.2 Duct insulation level and leakage rate

In order to investigate the energy impact of varying duct insulation levels and leakage rates, simulations were performed for different insulation R-values and duct leakage rate. For this analysis, the duct R-values of the supply and return side were changed from R-8 for the supply duct and R-4 for the return duct (which is same as the base case) to R-12 for the supply duct and the return duct in increments of 2 for 4 different climate zones. For the simulations, the different levels of the duct R-value and duct leakages were simulated from 0 % to 20 % in increments of 5%. Since the 2000/2001 IECC does not define the duct leakages, the duct leakage for the base-case house was set at 0%. Duct systems were located in the attic space where it was unconditioned. Table 4.30 shows the simulation plan of variations in the duct insulation levels and duct leakages of the different climate zones for the analysis.

Table 4.30 Simulation plan for duct insulation level and leakage

Location	Duct R-value		Duct Leakage (%)
	Supply	Return	
Climate zone 9	8 (Base case)	4 (Base case)	1) 0 (Base case), 2) 5, 3) 10, 4) 15, 5)20
	6	6	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	8	8	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	10	10	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	12	12	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
Climate zone 5	8 (Base case)	4 (Base case)	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	6	6	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	10	10	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	8	8	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	12	12	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
Climate zone 4	8 (Base case)	4 (Base case)	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	6	6	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	10	10	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	8	8	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	12	12	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
Climate zone 2	8 (Base case)	4 (Base case)	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	6	6	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	8	8	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	10	10	1) 0, 2) 5, 3) 10, 4) 15, 5) 20
	12	12	1) 0, 2) 5, 3) 10, 4) 15, 5) 20

4.4.3 HVAC and DHW systems

Table 4.31 shows the simulation plan of the air conditioner, the gas furnace, the heat pump and the domestic hot water heater for the analysis. Simulations with systems of different efficiencies were performed to analyze the effect of using more efficient systems on reducing energy use. In addition, simulations were performed for different climate zones.

Table 4.31 Simulation plan for HVAC and DHW systems

Location	Air conditioner	Gas Furnace	Heat Pump	Domestic Hot Water
	SEER	AFUE (%)	HSPF	EF
Climate zone 9	10 (Base case)	0.78 (Base case)	6.8 (Base case)	0.55 (Base case)
	11	0.80	7.0	0.60
	12	0.85	7.5	0.65
	13	0.90	8.0	0.70
	14			0.75
	15			0.80
	16			
	17			
Climate zone 5	10 (Base case)	0.78 (Base case)	6.8 (Base case)	0.55 (Base case)
	11	0.80	7.0	0.60
	12	0.85	7.5	0.65
	13	0.90	8.0	0.70
	14			0.75
	15			0.80
	16			
	17			
Climate zone 4	10 (Base case)	0.78 (Base case)	6.8 (Base case)	0.55 (Base case)
	11	0.80	7.0	0.60
	12	0.85	7.5	0.65
	13	0.90	8.0	0.70
	14			0.75
	15			0.80
	16			
	17			
Climate zone 2	10 (Base case)	0.78 (Base case)	6.8 (Base case)	0.55 (Base case)
	11	0.80	7.0	0.60
	12	0.85	7.5	0.65
	13	0.90	8.0	0.70
	14			0.75
	15			0.80
	16			
	17			

4.4.4 The Locations of the HVAC systems

Table 4.32 shows the simulation plans for the analysis of the locations of the HVAC system. Simulations were performed for the different locations (i.e., the attic space and the conditioned space) of the HVAC systems which were provided by the current simulation input file (SNGFAM2ST.INP). Duct leakage rates were changed from 0% to 20% in increments of 5% for both locations, including the attic and conditioned space. For the system efficiency, a 10 SEER air conditioner and a 78% AFUE for the gas furnace (base case) were used for the simulation.

Table 4.32 Simulation plan for the location of the HVAC system

Location	Air conditioner	Gas furnace	Duct leakage	Location
	SEER	AFUE (%)		
Climate zone 9	10 (Base case)	78 (Base case)	1) 0% (Base case), 2) 5%, 3) 10%, 4) 15%, 5) 20%	Attic space
			1) 0% (Base case), 2) 5%, 3) 10%, 4) 15%, 5) 20%	Conditioned space
Climate zone 5			1) 0% (Base case), 2) 5%, 3) 10%, 4) 15%, 5) 20%	Attic space
			1) 0% (Base case), 2) 5%, 3) 10%, 4) 15%, 5) 20%	Conditioned space
Climate zone 4			1) 0% (Base case), 2) 5%, 3) 10%, 4) 15%, 5) 20%	Attic space
			1) 0% (Base case), 2) 5%, 3) 10%, 4) 15%, 5) 20%	Conditioned space
Climate zone 2			1) 0% (Base case), 2) 5%, 3) 10%, 4) 15%, 5) 20%	Attic space
			1) 0% (Base case), 2) 5%, 3) 10%, 4) 15%, 5) 20%	Conditioned space

4.4.5 Tree shading

In order to investigate the shading effects from trees, the simulations were performed on three tree types at 4 different climate zones. In this analysis, it was assumed that the height of tree was a 30 ft with 20 ft branches, and the trees were directly next to the house (Figures 4.84 to 4.86).

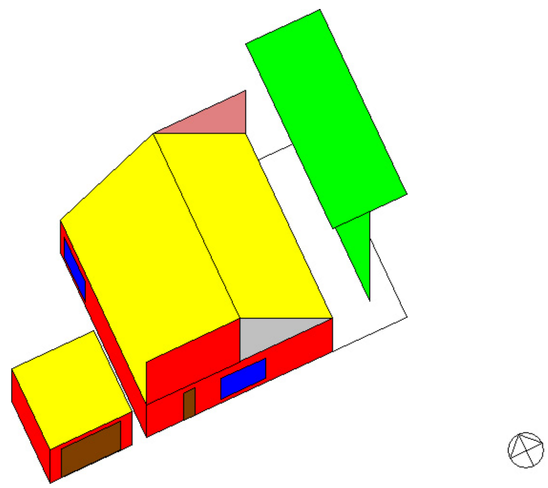


Figure 4.84 DrawBDL view of base-case model (east side shade)

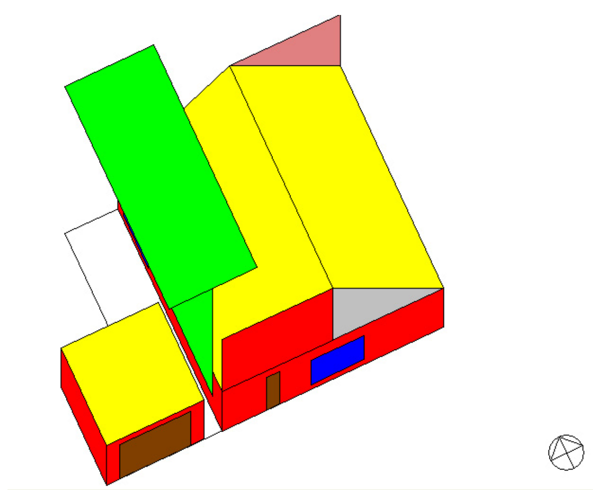


Figure 4.85 DrawBDL view of base-case model (west side shade)

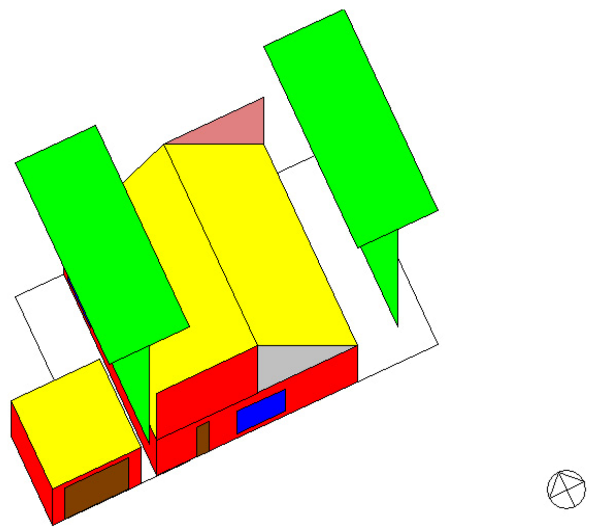


Figure 4.86 DrawBDL view of base-case model (both side shade)

Tree types include: 1) leaves all year (Live Oak), 2) a deciduous tree, 3) and an evergreen tree. The shading effects according to the tree types, the different shading schedule were used using DOE-2's SCHEDULE command. Figure 4.87 shows the DOE-2 commands for this analysis. Table 4.33 presents the simulation plans for the tree shadings.

```
##IF #[TREESHAPE[] EQS "LIVEOAK"]

B-SH-1 = SCHEDULE
          THRU MAR 31 (ALL) (1,24)  (0.1)
          THRU APR 30 (ALL) (1,24)  (0.7)
          THRU DEC 31 (ALL) (1,24)  (0.1)   ..

##ELSEIF #[TREESHAPE[] EQS "DECIDUOUS"]

B-SH-1 = SCHEDULE
          THRU MAR 31 (ALL) (1,24)  (0.7)
          THRU OCT 31 (ALL) (1,24)  (0.1)
          THRU DEC 31 (ALL) (1,24)  (0.7)   ..

##ELSEIF #[TREESHAPE[] EQS "EVERGREEN"]

B-SH-1 = SCHEDULE
          THRU DEC 31 (ALL) (1,24)  (0.1)   ..
##ENDIF
```

Figure 4.87   Shading schedules according to tree types

Table 4.33   Simulation plan for the tree shadings

Location	Tree	Shading side
Climate zone 9	leaves all year (Live Oak)	1) East, 2) West, 3) Both
	a deciduous tree	1) East, 2) West, 3) Both
	evergreen tree	1) East, 2) West, 3) Both
Climate zone 5	leaves all year (Live Oak)	1) East, 2) West, 3) Both
	a deciduous tree	1) East, 2) West, 3) Both
	evergreen tree	1) East, 2) West, 3) Both
Climate zone 4	leaves all year (Live Oak)	1) East, 2) West, 3) Both
	a deciduous tree	1) East, 2) West, 3) Both
	evergreen tree	1) East, 2) West, 3) Both
Climate zone 2	leaves all year (Live Oak)	1) East, 2) West, 3) Both
	a deciduous tree	1) East, 2) West, 3) Both
	evergreen tree	1) East, 2) West, 3) Both

4.5 Summary

In summary, this chapter has discussed the methodology used for the installation of sensors, polling and archiving measured data from the case-study house. It explained the plan for analyzing the energy use of the house. This chapter discussed the methodologies for analyzing the case house using the DOE-2 building energy simulation program beginning with the development of an on-site weather file, creating the input files for the house, and calibrating the input files for the two representative periods. This chapter also discussed improved simulation methods for the as-built and code complaint simulation model.

In addition, this chapter explained the development of the DOE-2 simulation model using the characteristics of the code-compliant, base-case house which include size, envelope, HVAC and DHW systems based on the 2000/2001 International Energy Conservation Code (IECC) as well as verification of the new simulation methods from the as-built base-case simulation model. It also explained the analysis methodology for studying thermal mass effects based on the 2000/2001 IECC and the different window input methods.

Finally, it ends with an efficiency analysis, including: 1) the fenestration properties such as the U-value and Solar Heat Gain Coefficient (SHGC), 2) duct insulation levels and leakage, 3) the Seasonal Energy Efficiency Ratio (SEER) for the air conditioner system, 4) the Annual Fuel Utilization Efficiency (AFUE) for the gas furnace, 5) the Heating Seasonal Performance Factor (HSPF) for the heat pump, 6) the Energy Factor (EF) for the domestic hot water, 7) the different locations of HVAC system and ductwork including the attic space and conditioned space, and 8) the different types of tree shading as varying the possible conditions affecting the energy performances of the residential buildings.

CHAPTER V

RESULTS OF THE SIMULATIONS OF THE CASE-STUDY HOUSE

This chapter presents the results of the data collection and calibration procedures of the simulation model of the case-study house DOE-2 program. This chapter contains data analysis of the case-study house, calibration of the simulation model of the case-study house using a two-week period for the summer and winter, and analysis of the results, including the duct model, application of new A/C curves, National Renewable Energy Laboratory (NREL)'s domestic hot water heater method and new heat flow method for underground surface.

5.1 Data Analysis of the Case-Study House

5.1.1 Comparison Results of IECC-Compliant Model with the Case-Study House Using ASHRAE Inverse Modeling Toolkit (IMT)

In order to compare the annual electricity and natural gas of the case-study house with a similarly sized (1,333 ft^2) IECC-compliant house, three-parameter change-point (3P) cooling and heating models were developed using the ASHRAE Inverse Model Toolkit (IMT). Detailed modeling procedures using the IMT were described in Chapter IV. Tables 5.1 and 5.2 show the monthly average temperature and natural gas use from case-studuy house and IECC-code compliant house, respectively. Figure 5.1 shows the output files of three-parameter change-point (3P) cooling and heating models of the base-case house and IECC-compliant house.

For the analysis of the natural gas, the adjusted R^2 value for the case-study house and IECC-compliant house were 99.0% and 93.7% respectively, which were considered statistically significant. The CV (RMSE) values for the case-study house and IECC-compliant house are 7.2% and 8.7%, which are also considered statistically acceptable (Haberl et al. 1998). The Ycp is the baseline heating energy use below the change point, where RS is the slope of the model, and Xcp is the change point of the model. As shown, the baseline use of the IECC-compliant house (54.2 kBtu/day) was slightly lower than that of the case-study house (58.2 kBtu/day). The change-point temperature of the case-study and IECC-compliant house were 62.3ºF and 64.5ºF, respectively. Using the IMT coefficients, Figure 5.2 can be plotted to show the monthly electricity use and the IMT model.

Since the case-study house does not have the garage space and the IECC-code complaint house has the garage space, the comparison of with and without garage space of the IECC-code compliant model was performed and Appendix J showed the comparison results.

Table 5.1 Monthly average temperature and natural gas use from case-study house

Month	Date	Number of Days	Average Temperature (F)	Monthly mBtu	Daily kBtu
Jan	01/07/2004 – 02/05/2004	30	51.2	6.8	226.7
Feb	02/06/2004 – 03/05/2004	29	51.6	6.0	206.9
Mar	03/06/2004 – 04/06/2004	32	67.6	1.8	56.3
Apr	04/07/2004 – 05/07/2004	31	71.9	1.7	54.8
May	05/08/2004 – 06/08/2004	32	73.4	1.5	46.9
Jun	06/09/2004 – 07/08/2004	30	80.0	1.6	53.3
Jul	07/09/2004 – 08/06/2004	29	85.9	1.6	55.2
Aug	08/07/2004 – 09/07/2004	32	82.3	2.2	68.8
Sep	09/08/2004 – 10/06/2004	29	81.2	2.0	69.0
Oct	10/07/2004 – 11/04/2004	29	74.3	1.8	62.1
Nov	11/05/2004 – 12/06/2004	32	59.7	3.1	96.9
Dec	12/07/2004 – 01/06/2005	31	52.4	6.4	206.5

Table 5.2 Monthly average temperature and natural gas use from IECC simulation

Month	Date	Number of Days	Average Temperature (F)	Monthly mBtu	Daily kBtu
Jan	01/01/2004 – 01/31/2004	31	53.4	3.5	112.9
Feb	02/01/2004 – 02/28/2004	28	51.6	3.0	107.1
Mar	03/01/2004 – 03/31/2004	31	61.2	2.1	67.7
Apr	04/01/2004 – 04/30/2004	30	68.9	1.8	60.0
May	05/01/2004 – 05/31/2004	31	75.1	1.8	58.1
Jun	06/01/2004 – 06/30/2004	30	79.8	1.7	56.7
Jul	07/01/2004 – 07/31/2004	31	82.4	1.6	51.6
Aug	08/01/2004 – 08/31/2004	31	81.1	1.6	51.6
Sep	09/01/2004 – 09/30/2004	30	77.5	1.5	50.0
Oct	10/01/2004 – 10/31/2004	31	69.7	1.6	51.6
Nov	11/01/2004 – 11/30/2004	30	62.8	1.8	60.0
Dec	12/01/2004 – 12/31/2004	31	52.6	2.9	93.5

```
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Input data file name=HABITAT_HEATING_DAILY.dat
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Value for grouping =    1
Residual mode =        1
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Y1 column number =     4
X1 column number =   9
X2 column number =   0 (unused)
X3 column number =   0 (unused)
X4 column number =   0 (unused)
X5 column number =   0 (unused)
X6 column number =   0 (unused)
********************************************
  Regression Results
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      N =     12
  -------------------------------------
     R2 =     0.990
  -------------------------------------
   AdjR2 =     0.990
  -------------------------------------
    RMSE =      7.2641
  -------------------------------------
  CV-RMSE =     7.244%
  -------------------------------------
      p =     0.415
  -------------------------------------
     DW =     1.147 (p>0)
  -------------------------------------
     N1 =      4
  -------------------------------------
     N2 =      8
  -------------------------------------
    Ycp =    58.2466 (      2.4837)
  -------------------------------------
     LS =   -14.6572 (      0.4641)
  -------------------------------------
     RS =     0.0000 (      0.0000)
  -------------------------------------
    Xcp =    62.3340 (      0.6940)
  -------------------------------------
```

```
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  Value for grouping =    1
  Residual mode =        1
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  X3 column number =   0 (unused)
  X4 column number =   0 (unused)
  X5 column number =   0 (unused)
  X6 column number =   0 (unused)
********************************************
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      N =     12
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     R2 =     0.937
  -------------------------------------
   AdjR2 =     0.937
  -------------------------------------
    RMSE =      5.9693
  -------------------------------------
  CV-RMSE =     8.727%
  -------------------------------------
      p =     0.294
  -------------------------------------
     DW =     0.935 (p>0)
  -------------------------------------
     N1 =      5
  -------------------------------------
     N2 =      7
  -------------------------------------
    Ycp =    54.1550 (      2.0804)
  -------------------------------------
     LS =    -4.1612 (      0.3405)
  -------------------------------------
     RS =     0.0000 (      0.0000)
  -------------------------------------
    Xcp =    64.5360 (      0.6160)
  -------------------------------------
```
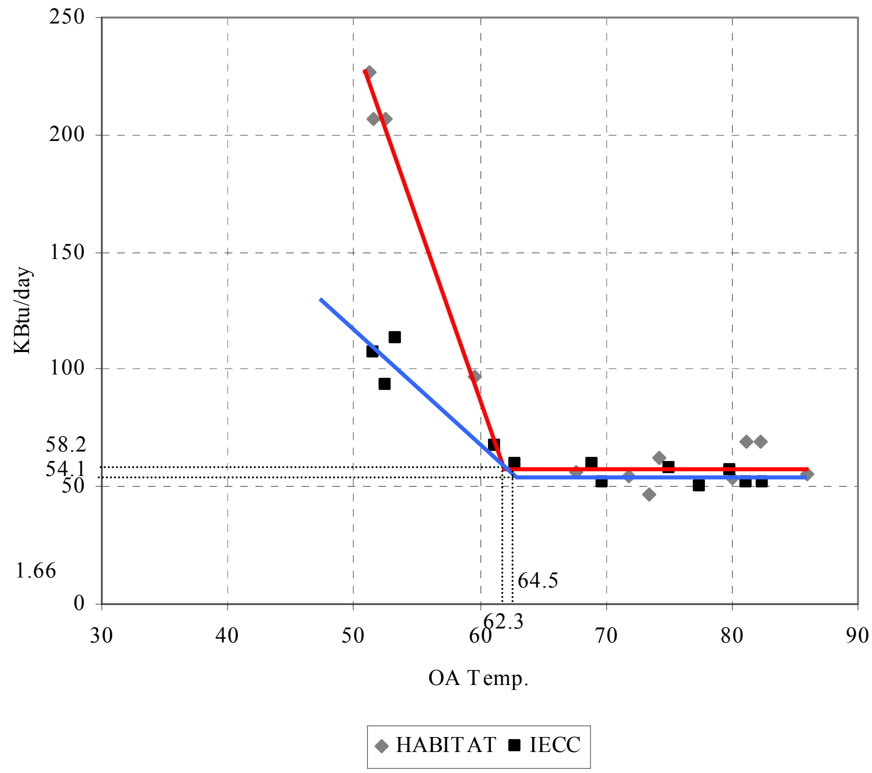

Figure 5.1 Three-parameter change-point natural gas models (Left: case-study house, Right: IECC model)



	Month	Average Temperature (F)	Daily mBtu	Modeled Use kBtu	Residual
Case-study house	Jan	51.23	226.70	220.98	5.72
	Feb	51.63	206.90	215.11	-8.21
	Mar	67.60	56.30	58.25	-1.95
	Apr	71.88	54.80	58.25	-3.45
	May	73.36	46.90	58.25	-11.35
	Jun	79.96	53.30	58.25	-4.95
	Jul	85.93	55.20	58.25	-3.05
	Aug	82.28	68.80	58.25	10.55
	Sep	81.15	69.00	58.25	10.75
	Oct	74.28	62.10	58.25	3.85
	Nov	59.66	96.90	97.39	-0.49
	Dec	52.44	206.50	203.24	3.26
IECC-compliant	Jan	53.40	112.90	100.50	12.40
	Feb	51.60	107.14	107.99	-0.85
	Mar	61.20	67.74	68.05	-0.31
	Apr	68.90	60.00	54.20	5.80
	May	75.10	58.06	54.20	3.86
	Jun	79.80	56.67	54.20	2.47
	Jul	82.40	51.61	54.20	-2.59
	Aug	81.10	51.61	54.20	-2.59
	Sep	77.50	50.00	54.20	-4.20
	Oct	69.70	51.61	54.20	-2.59
	Nov	62.80	60.00	61.40	-1.40
	Dec	52.60	93.55	103.83	-10.28

Figure 5.2 Three parameter change-point natural gas models for the base-case house and IECC-compliant house

A similar procedure was used to model the electricity use for the case-study house and IECC-compliant house. Tables 5.3 and 5.4 show the monthly average temperature and electricity use from case-studuy house and IECC-code compliant house, respectively. Figure 5.3 shows the output file of the 3P cooling model. The results show that the baseline use of the case-study house (14.8 kWh/day) is significantly lower than that of the IECC-compliant house (23.7 kWh/day). The change points of temperature of the base case-study house and the IECC-compliant house are 68.5ºF and 59.6ºF respectively. Using the IMT coefficients, the model can be plotted as shown in Figure 5.4. In this figure, the monthly electricity use is also shown.

Table 5.3 Monthly average temperature and electricity use from case-study house

Month	Date	Number of Days	Average Temperature (F)	Monthly Electricity Use (kWh)	Daily Electricity Use (kWh)
Jan	01/01/2004 – 0/31/2004	31	52.7	450	14.5
Feb	02/01/2004 – 2/29/2004	29	48.0	441	15.2
Mar	03/01/2004 – 3/31/2004	31	65.7	397	12.8
Apr	04/01/2004 – 4/30/2004	30	68.5	381	12.7
May	05/01/2004 – 5/31/2004	31	75.4	1080	34.8
Jun	06/01/2004 – 6/30/2004	30	79.4	1340	44.7
Jul	07/01/2004 – 7/31/2004	31	82.1	1719	55.5
Aug	08/01/2004 – 8/31/2004	31	81.5	1850	59.7
Sep	09/01/2004 – 9/30/2004	30	79.7	1686	56.2
Oct	10/01/2004 – 0/31/2004	31	75.6	1234	39.8
Nov	11/01/2004 – 1/30/2004	30	60.3	514	17.1
Dec	12/01/2004 – 2/31/2004	31	68.5	524	16.9

Table 5.4 Monthly average temperature and electricity use from IECC simulation

Month	Date	Number of Days	Average Temperature (F)	Monthly Electricity Use (kWh)	Daily Electricity Use (kWh)
Jan	01/012004 – 1/31/2004	31	53.4	742	23.9
Feb	02/01/2004 – 2/28/2004	28	51.6	667	23.8
Mar	03/01/2004 – 3/31/2004	31	61.2	788	25.4
Apr	04/01/2004 – 4/30/2004	30	68.9	872	29.1
May	05/01/2004 – 5/31/2004	31	75.1	1046	33.7
Jun	06/01/2004 – 6/30/2004	30	79.8	1148	38.3
Jul	07/01/2004 – 7/31/2004	31	82.4	1262	40.7
Aug	08/01/2004 – 8/31/2004	31	81.1	1222	39.4
Sep	09/01/2004 – 9/30/2004	30	77.5	1078	35.9
Oct	10/01/2004 – 0/31/2004	31	69.7	963	31.1
Nov	11/01/2004 – 1/30/2004	30	62.8	804	26.8
Dec	12/01/2004 – 2/31/2004	31	52.6	726	23.4

```
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 ASHRAE INVERSE MODELING TOOLKIT (1.9)
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********************************************
Input data file name=HABITAT_COOLING_DAILY.dat
Model type =          3P Cooling
Grouping column No =    5
Value for grouping =    1
Residual mode =         1
# of X(Indep.) Var =    1
Y1 column number =      4
X1 column number =    9
X2 column number =    0 (unused)
X3 column number =    0 (unused)
X4 column number =    0 (unused)
X5 column number =    0 (unused)
X6 column number =    0 (unused)
********************************************
  Regression Results
  --------------------------------------
       N =     12
  --------------------------------------
      R2 =     0.974
  --------------------------------------
   AdjR2 =     0.974
  --------------------------------------
    RMSE =     3.1967
  --------------------------------------
 CV-RMSE =    10.098%
  --------------------------------------
       p =     0.625
  --------------------------------------
      DW =     0.713 (p>0)
  --------------------------------------
      N1 =     4
  --------------------------------------
      N2 =     8
  --------------------------------------
     Ycp =     14.8102 (      1.2699)
  --------------------------------------
      LS =      0.0000 (      0.0000)
  --------------------------------------
      RS =      3.2082 (      0.1661)
  --------------------------------------
     Xcp =     68.4600 (      0.6820)
  --------------------------------------
```

```
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 ASHRAE INVERSE MODELING TOOLKIT (1.9)
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********************************************
  Input data file name =  IECC_COOLING_DAILY.dat
  Model type =          3P Cooling
  Grouping column No =    5
  Value for grouping =    1
  Residual mode =         1
  # of X(Indep.) Var =    1
  Y1 column number =      4
  X1 column number =    9
  X2 column number =    0 (unused)
  X3 column number =    0 (unused)
  X4 column number =    0 (unused)
  X5 column number =    0 (unused)
  X6 column number =    0 (unused)
********************************************
  Regression Results
  --------------------------------------
       N =     12
  --------------------------------------
      R2 =     0.990
  --------------------------------------
   AdjR2 =     0.990
  --------------------------------------
    RMSE =     0.6938
  --------------------------------------
 CV-RMSE =     2.241%
  --------------------------------------
       p =     0.102
  --------------------------------------
      DW =     1.766 (p>0)
  --------------------------------------
      N1 =     3
  --------------------------------------
      N2 =     9
  --------------------------------------
     Ycp =     23.7487 (      0.3080)
  --------------------------------------
      LS =      0.0000 (      0.0000)
  --------------------------------------
      RS =      0.7090 (      0.0230)
  --------------------------------------
     Xcp =     59.6080 (      0.6160)
  --------------------------------------
```
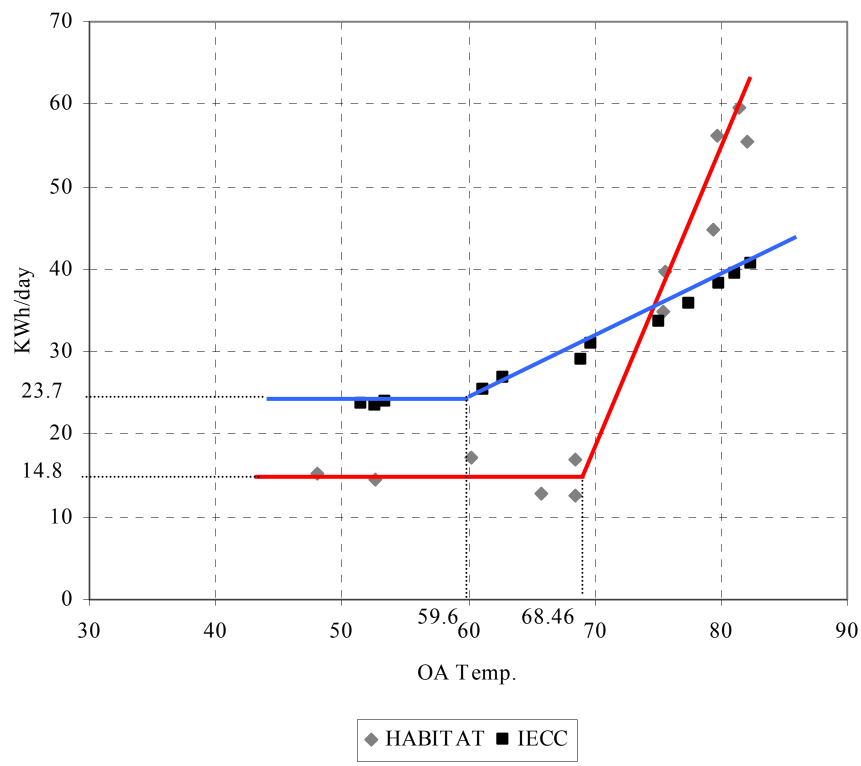

Figure 5.3 Three-parameter change-point electricity models(Left: case-study house, Right: IECC model)



	Month	Average Temperature (F)	Daily Electricity Use (kWh)	Modeled Use kWh	Residual
Case-study house	Jan	52.7	14.5	14.80	-0.30
	Feb	48	15.2	14.80	0.40
	Mar	65.7	12.8	14.80	-2.00
	Apr	68.5	12.7	14.93	-2.23
	May	75.4	34.8	37.01	-2.21
	Jun	79.4	44.7	49.81	-5.11
	Jul	82.1	55.5	58.45	-2.95
	Aug	81.5	59.7	56.53	3.17
	Sep	79.7	56.2	50.77	5.43
	Oct	75.6	39.8	37.65	2.15
	Nov	60.3	17.1	14.80	2.30
	Dec	68.5	16.9	14.93	1.97
IECC-compliant	Jan	53.4	23.9	23.70	0.20
	Feb	51.6	23.8	23.70	0.10
	Mar	61.2	25.4	24.84	0.56
	Apr	68.9	29.1	30.30	-1.20
	May	75.1	33.7	34.71	-1.00
	Jun	79.8	38.3	38.04	0.26
	Jul	82.4	40.7	39.89	0.81
	Aug	81.1	39.4	38.97	0.44
	Sep	77.5	35.9	36.41	-0.51
	Oct	69.7	31.1	30.87	0.23
	Nov	62.8	26.8	25.97	0.83
	Dec	52.6	23.4	23.70	-0.30

Figure 5.4 Three parameter change-point electricity models for the base-case house and IECC-compliant house

5.1.2 Investigation of Applying the IECC Strategies and Results

Once the base-case simulation model was calibrated against the measured data from the case-study house, 6 strategies that are compliant with the 2000/2001 IECC were applied to the base-case simulation model to determine the most effective strategy from the 2000/2001 IECC. The calibration procedures of the base-case simulation input were presented in Chapter 5.3. Descriptions of these IECC strategies and combinations are shown in Table 5.5.

Table 5.5 Summary of the IECC Strategies

Strategy	IECC Strategy	Description	
		Base Case	Modified Base Case
1	Use Houston weather file	On-site weather	Houston weather
2	Strategy 1 + SEER 13	SEER 10.5	SEER 13
3	Strategy 2 + Duct insulation	R-6 of the supply and return duct	R-8 for the supply duct and R-4 for the return duct
4	Strategy 3 + Low-e window	Double pane clear glass	Double pane low-e glass
5	Strategy 4 + Setting temperature	74ºF for summer and winter setting temperature	68 ºF for winter and 78 ºF for summer with 5 ºF set back temperature from 1 to 6 in the morning
6	Strategy 5 + Internal Load	LIGHTING-W/SQFT = 0.892 and EQUIPMENT-W/SQFT = 0.552 with different schedule	LIGHTING-KW = 0.44 and EQUIPMENT-KW = 0.44

Figures 5.5 and 5.6 shows the calibrated simulation and measured results from the case-study house, and the IECC-compliant simulation results.

Since the IECC-compliant house simulation is performed using Houston TMY2 weather file and the case-study house simulation uses the on-site measured weather file, strategy 1 starts from changing weather file from on-site measured weather file to Houston TMY2 weather file (Figure 5.7 for electricity use and Figure 5.8 for natural gas use). This change results in an increase of the total electricity consumption by 2.6 percent and a decrease of total natural gas consumption by 6.2 percent. Strategy 2 aims to increase the SEER of air conditioner from 10.5 to 13, since the 2000/2001 IECC provides 13 as a SEER of the air conditioner (Figure 5.9 for electricity use and Figure 5.10 for natural gas use). The results show a decrease in the total electricity consumption by 5.9 percent but no change of total natural gas consumption because SEER affects only cooling electricity energy use.

Strategy 3 adds the duct insulation level on the strategy 2 by changing the supply and return duct of R-6 to the supply duct of R-8 and the return duct of R-4 (Figure 5.11 for electricity use and Figure 5.12 for natural gas use). The results show a decrease of the electricity consumption by 0.5 percent and accumulated decrease of 6.4 percent from the strategy 2. For natural gas, there were a 0.3 percent of decreases in the natural gas consumption and 6.5 percent of accumulated natural gas consumption from the strategy 2. Changing insulation level (from R-6 for supply and return to R-8 for supply and R-4 for return) to the IECC level doesn't significantly reduce the energy consumption.

In the strategy 4, there was a change in window thermal properties from the double pane clear glass to the double pane low-e glass (Figure 5.13 for electricity use and Figure 5.14 for natural gas use). This change decreases 3.5 percent from strategy 3 results and accumulates 10 percent decrease of the electricity use. For the natural gas use, the window property increases the gas usage by 5.1 percent on the strategy 3 and accumulates 1.4 percent increase. Since the double pane low-e window blocks the heat gain from solar energy, it is helpful in decreasing the cooling loads. However, it also has the negative effect of increasing heating loads.

Strategy 5 changes the set point temperature for cooling and heating (Figure 5.15 for electricity use and Figure 5.16 for natural gas use). According to the 2000/2001 IECC, 68 ºF for winter and 78 ºF for summer with 5 ºF set back temperature are recommended, while the case-study house sets to 72 ºF for the cooling and heating set point temperature. This change results in significant decrease for the electricity and natural gas use. For the electricity, this change adds 14.5 percent of decrease on the strategy 4 results and the total decrease shows 24.7 percent. For the natural gas use, this change also adds 14.6 percent of decrease on the strategy 4 and 16 percent of the total decrease. It is found that the set point temperature of the heating and cooling is the most effective strategy for the case-study house.

Strategy 6 changes internal loads to match the IECC (LIGHTING-KW = 0.44 and EQUIPMENT-KW = 0.44). This modification increases the electricity consumptions due to increase in the internal load, while decrease natural gas consumption (Figure 5.17 for electiricy use and Figure 5.18 for natural gas use). Figures 5.19 and 5.20 show the total results due to each strategy. From this figure, 'IECC' refers to IECC-compliant house simulation and 'Habitat' is the calibrated simulation result of the base-case house.

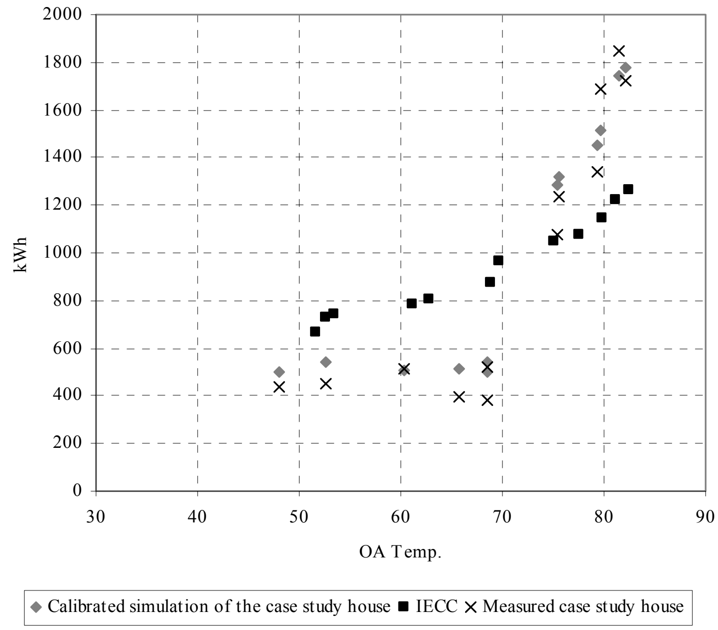


Figure 5.5 Measurement and calibration results of the electricity

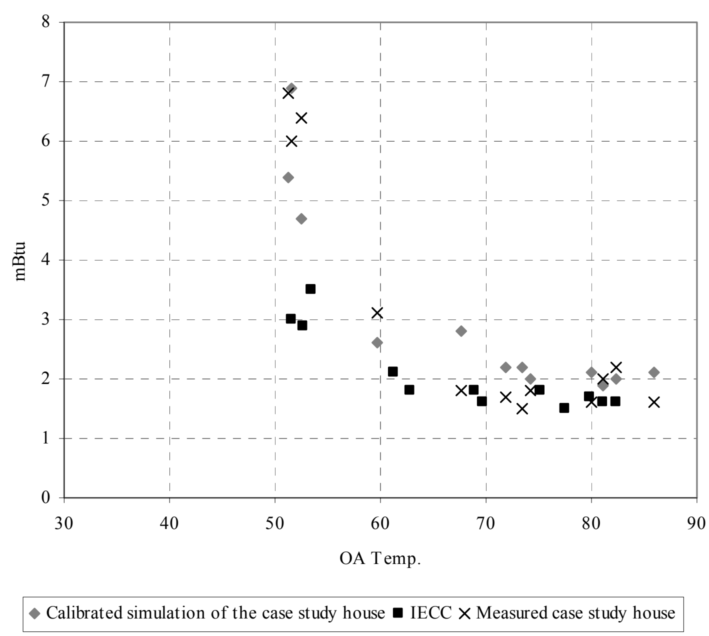


Figure 5.6 Measurement and calibration results of the natural gas

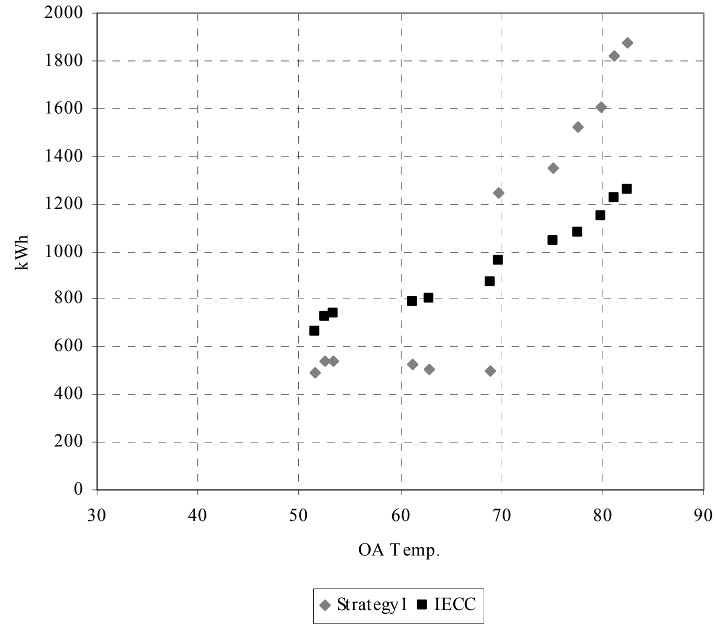


Figure 5.7 Comparison between the IECC and strategy #1 of electricity

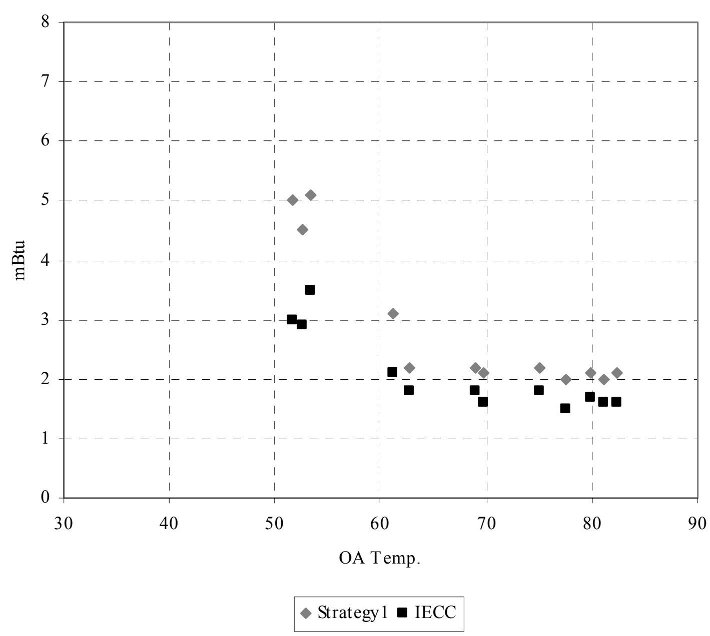


Figure 5.8 Comparison between the IECC and strategy #1 of natural gas

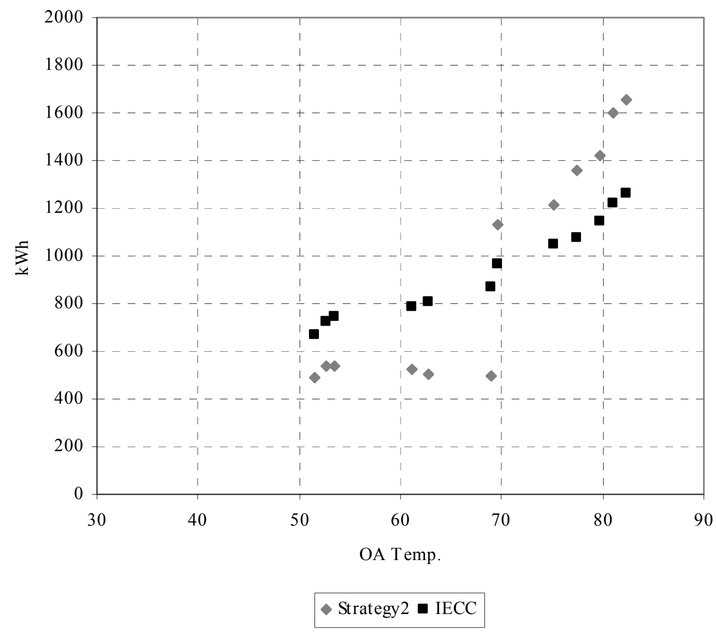


Figure 5.9 Comparison between the IECC and strategy #2 of electricity

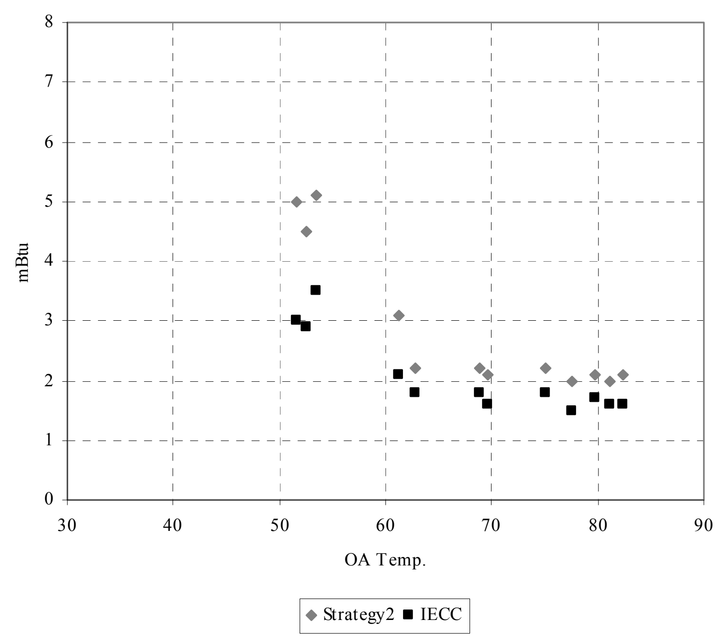


Figure 5.10 Comparison between the IECC and strategy #2 of natural gas

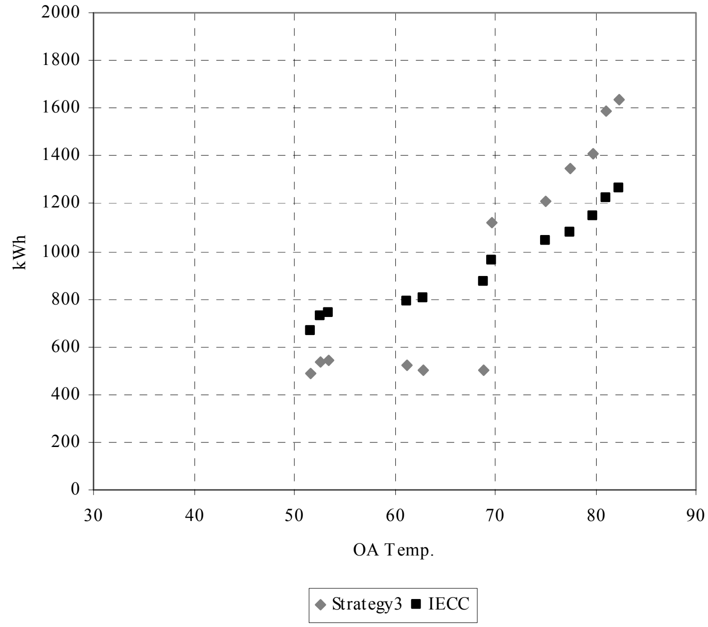


Figure 5.11 Comparison between the IECC and strategy #3 of electricity

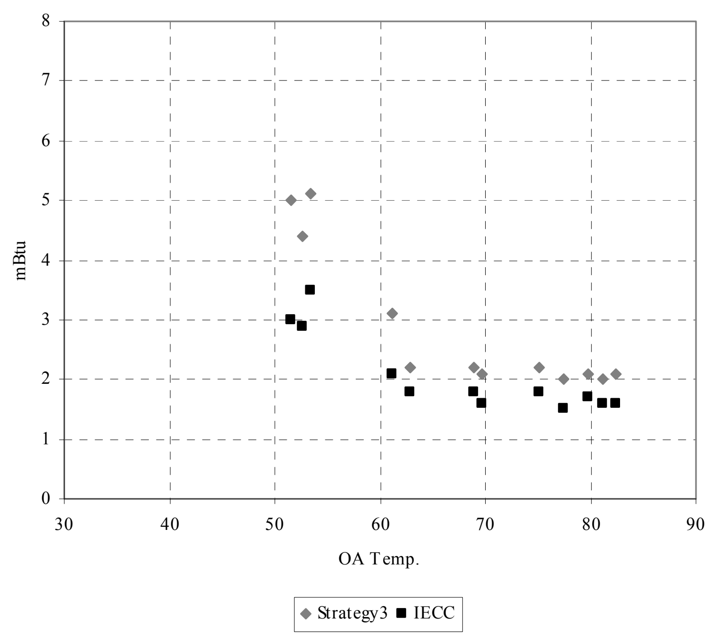


Figure 5.12 Comparison between the IECC and strategy #3 of natural gas

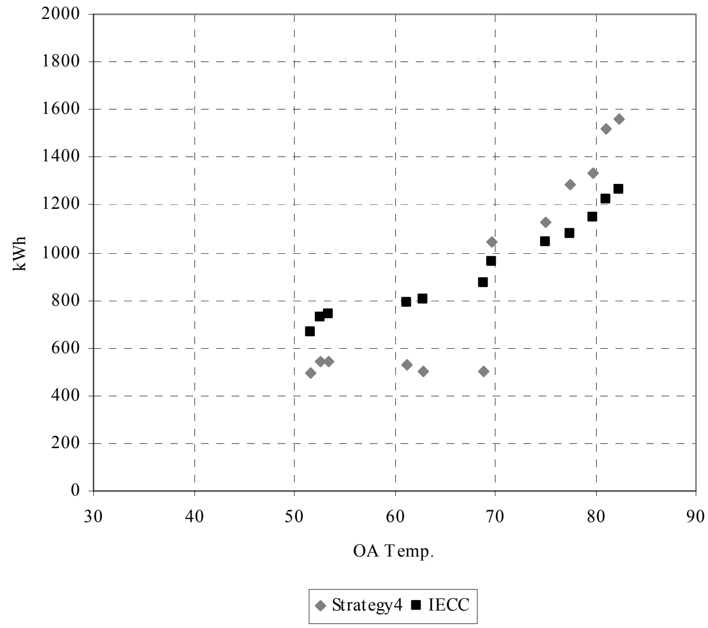


Figure 5.13 Comparison between the IECC and strategy #4 of electricity

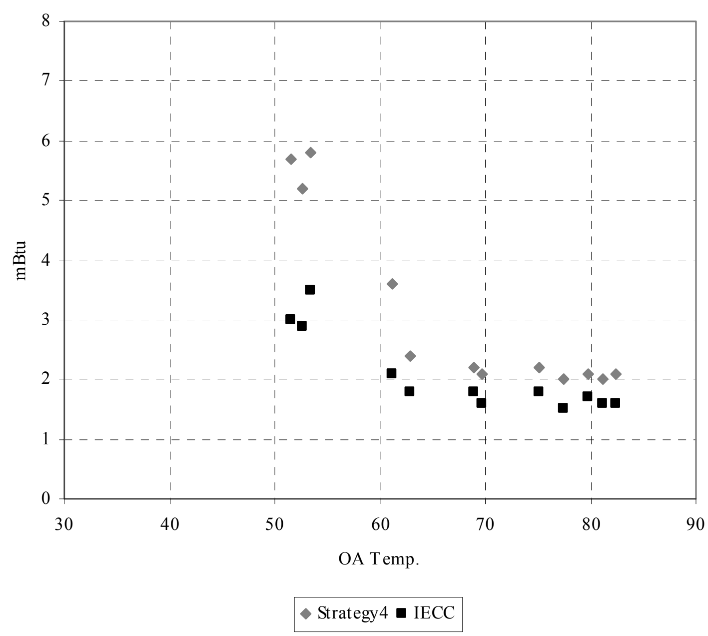


Figure 5.14 Comparison between the IECC and strategy #4 of natural gas

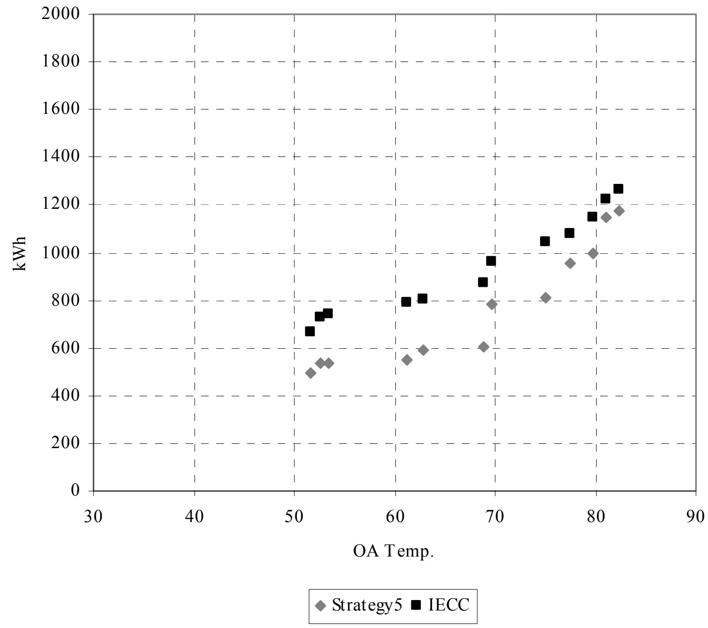


Figure 5.15 Comparison between the IECC and strategy #5 of electricity

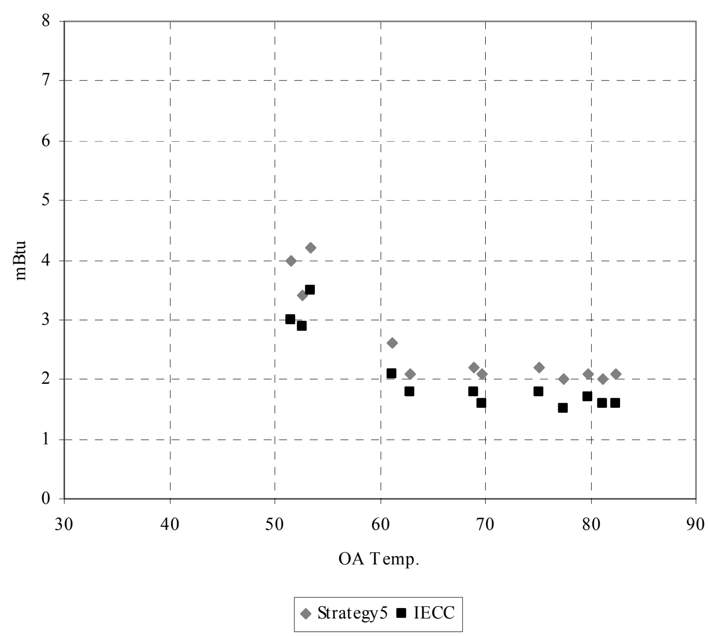


Figure 5.16 Comparison between the IECC and strategy #5 of natural gas

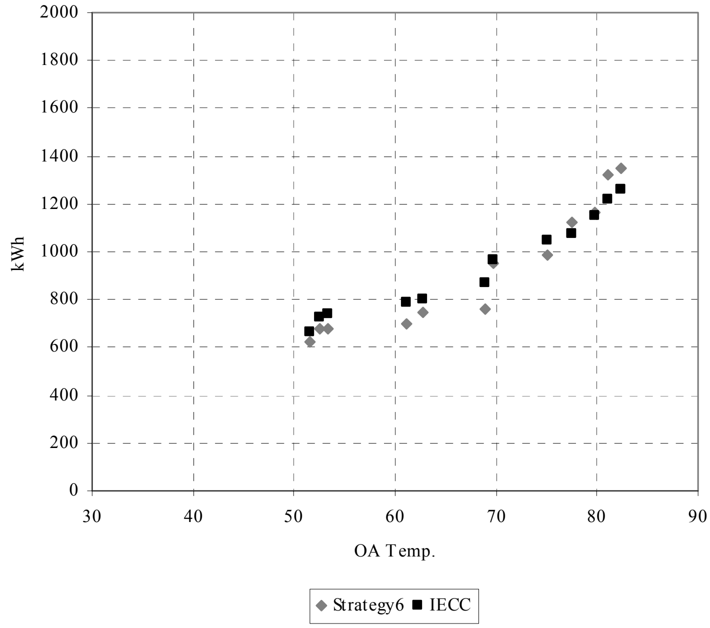


Figure 5.17 Comparison between the IECC and strategy #6 of electricity

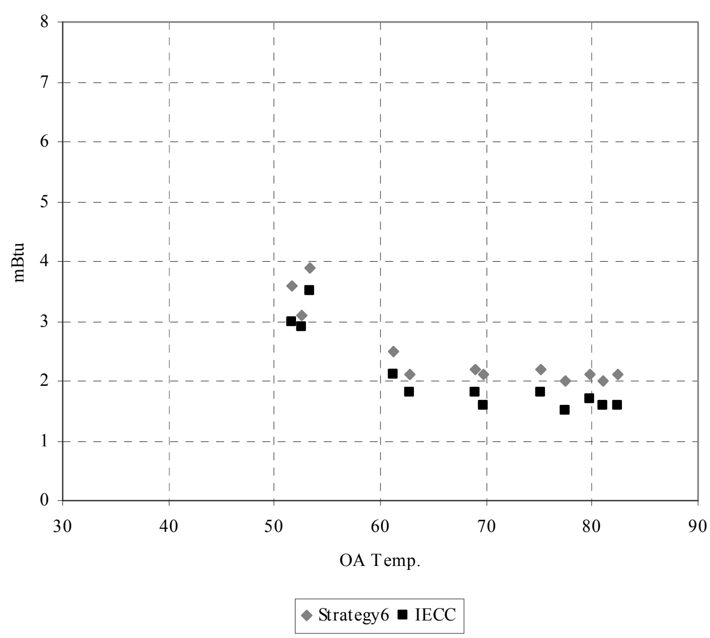


Figure 5.18 Comparison between the IECC and strategy #6 of natural gas

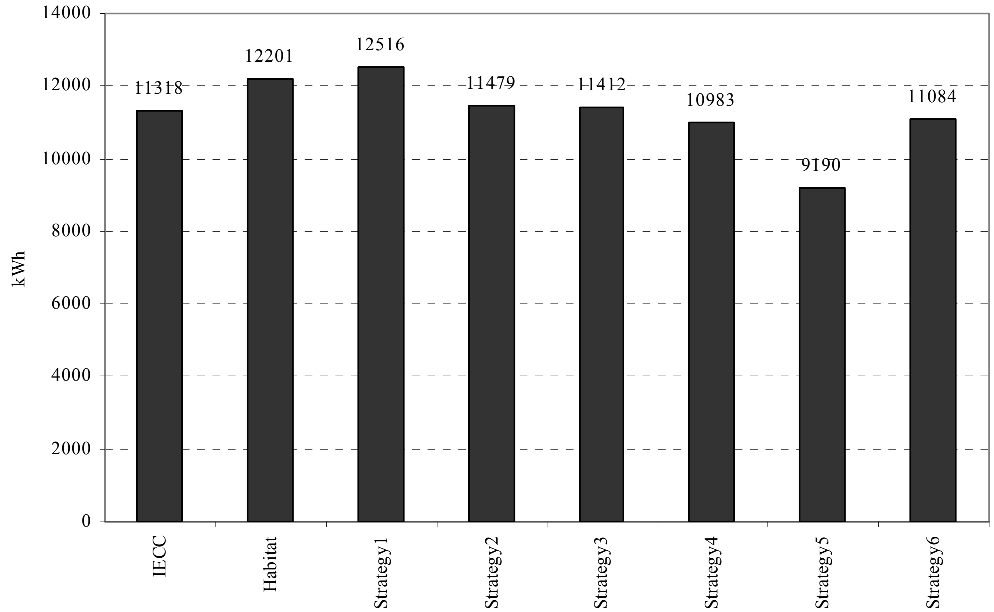


Figure 5.19   One-year electricity use of each simulation

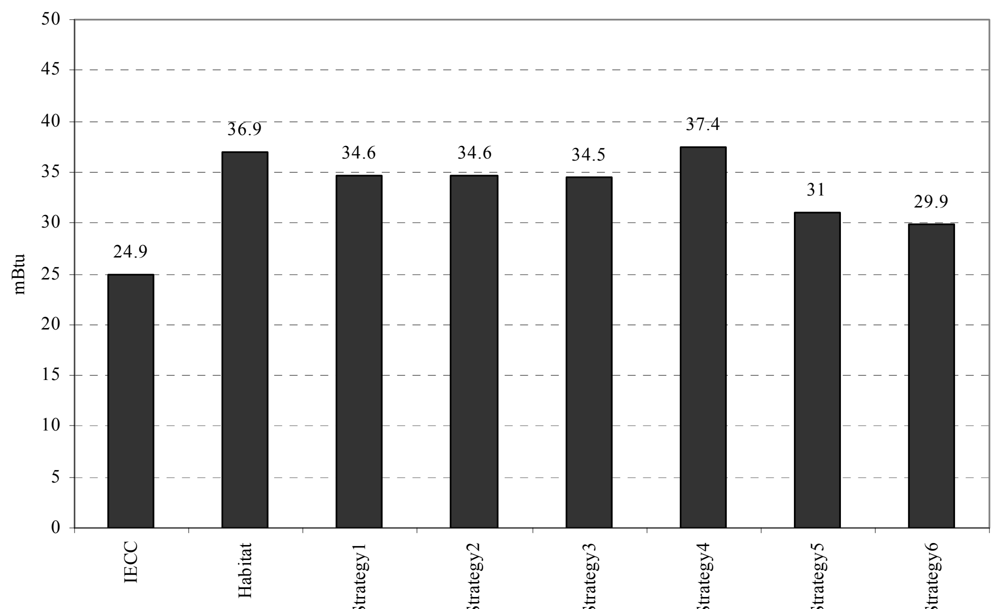


Figure 5.20   One-year natural gas use of each simulation

Table 5.6 shows a summary of the statistics of CV(RMSE) and MBE as adding each strategy to the base-case house. Figures 5.21 through 5.23 show the CV(RMSE) and MBE of electricity use, natural gas and total energy use graphically. From Table 5.6, the results can be seen to show that the base-case house used more electricity by approximately 7.6% (the CV(RMSE) was 37.9%, and MBE was -8.3%), natural gas by 49.06% (the CV(RMSE) was 75.1%, and MBE was -53.5%) and total of (electricity and natural gas) by 28.3% (the CV(RMSE) was 56.5%, and MBE was -30.9%).

After 6 strategies that are compliant with the 2000/2001 IECC were applied to the base-case simulation model, the results showed that base-case model was determined to have a 7.5% CV (RMSE) and a 2.3% MBE for electricity use, a 21.7% CV(RMSE) and -21.94% MBE for natural gas use, and 14.6% CV(RMSE) and -9.84% MBE for total energy use (electricity and natural gas).

From the comparison results, if the base-case house was followed by the 2000/2001 IECC, the energy use of electricity and natural gas use could be reduced by 9.2% for electricity use and 20.0% for natural gas use.

Table 5.6 Each strategy statistics summary

	Electricity			Natural Gas			Average		
	Difference (%)	CV(RMSE) %	MBE %	Difference (%)	CV(RMSE) %	MBE %	Difference (%)	CV(RMSE) %	MBE %
Base Case	7.56	37.89	-8.25	49.06	75.11	-53.52	28.31	56.50	-30.88
Strategy #1	10.33	41.77	-11.27	39.18	50.51	-42.74	24.76	46.14	-27.01
Strategy #2	1.23	30.55	-1.34	39.18	50.51	-42.74	20.20	40.53	-22.04
Strategy #3	0.64	29.87	-0.70	38.79	49.89	-42.31	19.71	39.88	-21.51
Strategy #4	-3.12	26.22	3.41	50.51	69.04	-55.10	23.69	47.63	-25.84
Strategy #5	-18.83	20.69	20.54	24.60	27.50	-26.84	2.89	24.09	-3.15
Strategy #6	-2.08	7.47	2.26	20.11	21.68	-21.94	9.02	14.58	-9.84

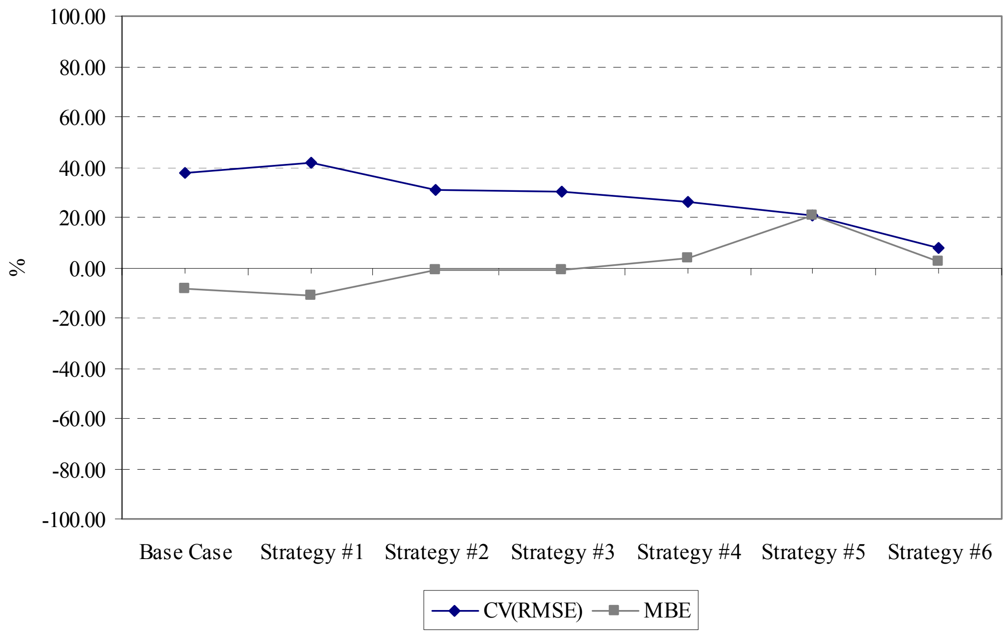


Figure 5.21 Each strategy graphical summary of electiricy use

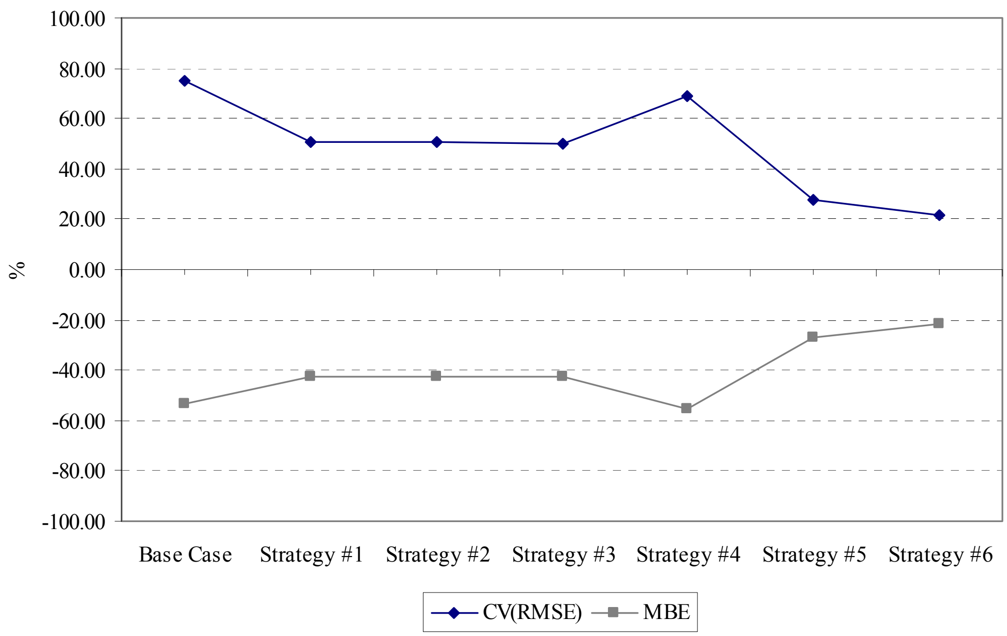


Figure 5.22 Each strategy graphical summary of natural gas use

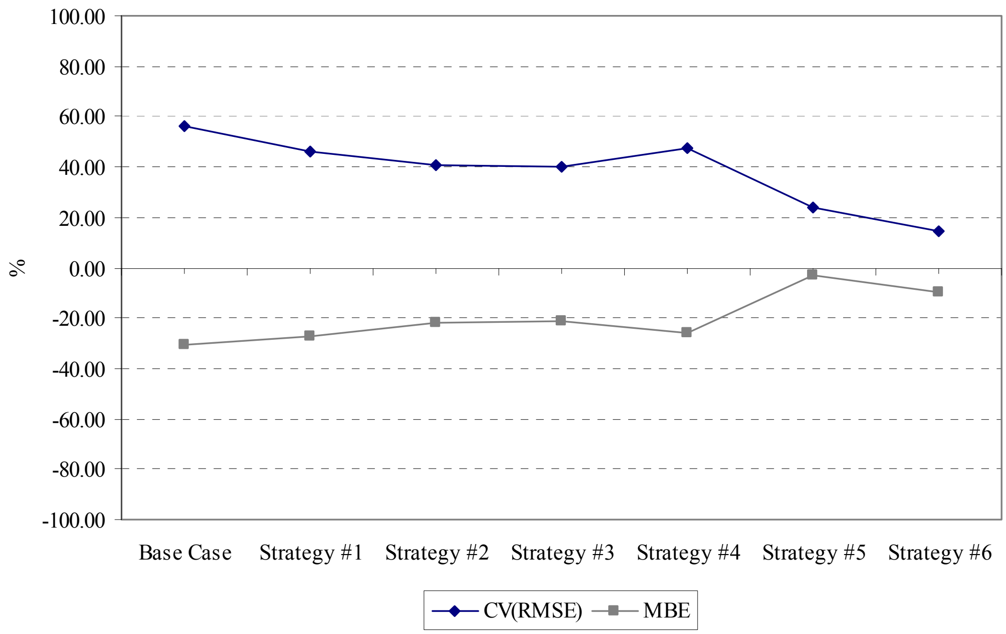


Figure 5.23 Each strategy graphical summary of total energy use

5.2 Data Analysis Tasks for Pre-Calibration of the Case-Study House

Data analysis tasks required to improve the quality of the final calibration were: 1) a investigation of a conditions space and an unconditioned space (attic) temperature patterns, and annual energy consumptions using the whole year measured data, 2) a characterization of the thermostat setting of the case-study house for a two-week cooling and two-week heating period, and 3) a investigation of the duct heat loss to the unconditioned space using clear days. The two-week calibration period of cooling (August 1 to August 14, 2004) and heating (December 18 to December 31, 2004) period were shown in Figures 5.24 and 5.25.

5.2.1 Measured Data for the Whole Year

The case-study house consists of a conditioned space, an unconditioned space (attic), and a duct system located in the unconditioned space. Thus, measurements of thermal conditions and energy consumption of the case-study house were performed for the purpose of investigating the duct heat loss / gain to the unconditioned space and the pattern of energy use.

Figure 5.24 shows the measured attic, indoor and outdoor temperature as well as heating and cooling energy use for the period of January 1 to December 31, 2004. The attic temperature covers a wider range than that of the outdoor temperature, while the indoor temperature (conditioned space) is in a narrow range between 70 ºF and 80 ºF. It can be clearly seen that the cooling energy use increases during the summer period due to the air conditioner load. Also, the heating energy use increases during the winter period due to the use of the gas furnace. Summertime gas use is considerable due to domestic water heating, cooking and five pilot lights (furnace, DHW and stove-3).

Figure 5.25 shows the temperature characteristics of the attic, supply, duct (close to diffuser) temperature, and the temperature difference (diffuser temperature – supply temperature) to investigate the duct heat / gain in the attic space. The detail measurement methods are explained in the next Section 5.1.5. In this plot, the negative value of the temperature difference between the duct (close to diffuser) and the supply temperature indicates that there is the heat loss to the attic space because the attic temperature is lower than the supply temperature. On the other hand, the positive value of temperature difference denotes that there is the heat gain from the attic space because the attic temperature is higher than the supply temperature.

Therefore, for the heating season (January, February, November and December), the negative values were used in the analysis. The positive values are used for the cooling season from May to October.

5.2.2 Temperature Profiles of the Conditioned Zone and Unconditioned Zone for the Summer Period

To characterize the thermostat settings of the conditioned space (i.e., the living space of the case-study house) and investigate the temperature pattern of the unconditioned space (i.e., the attic space of the case-study house), an examination of the conditioned and unconditioned space temperatures was performed. This examination investigates the minimum, maximum values and the range of temperatures for the study period.

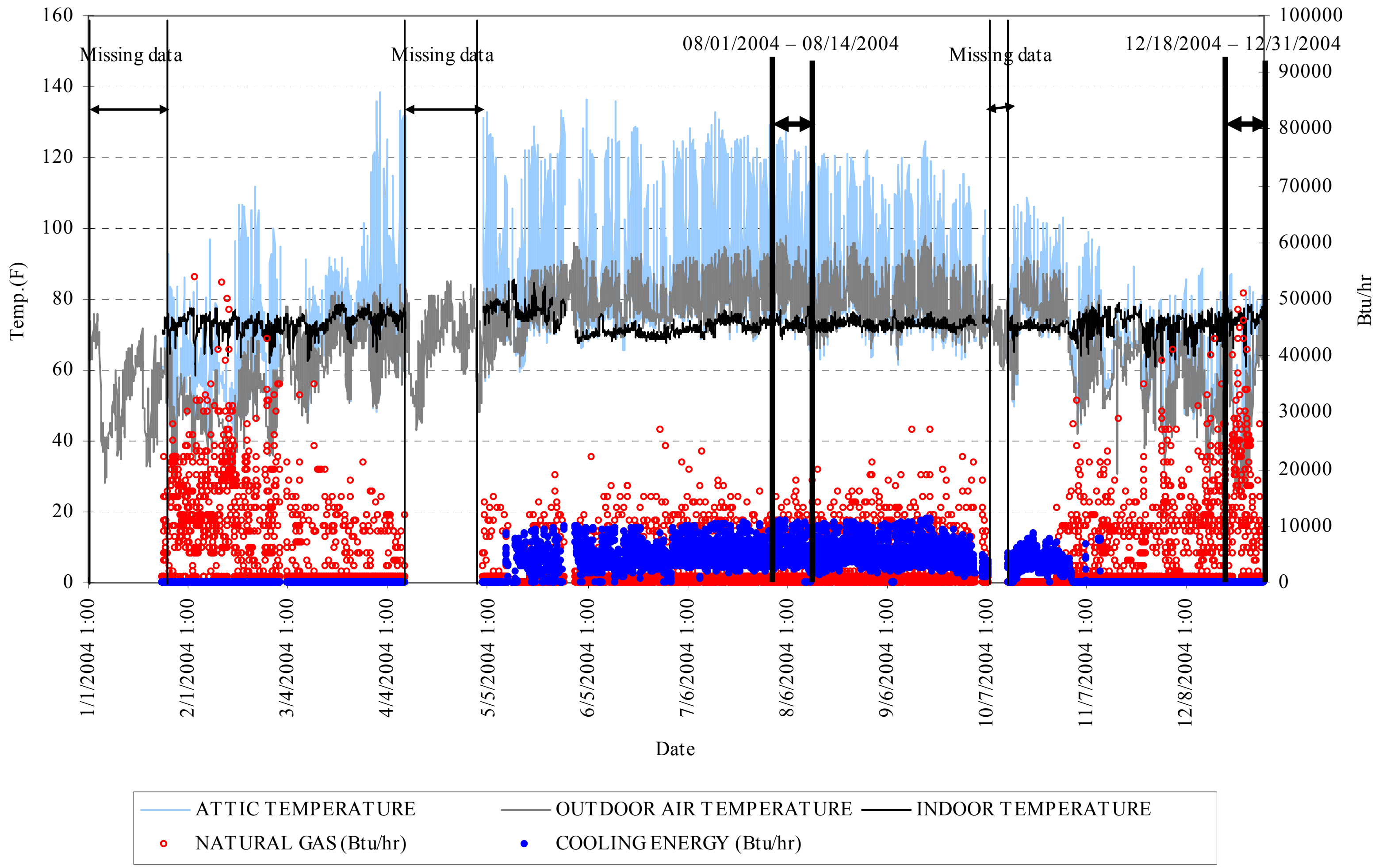


Figure 5.24 Measured attic, indoor, outdoor temperature, and heating and cooling energy

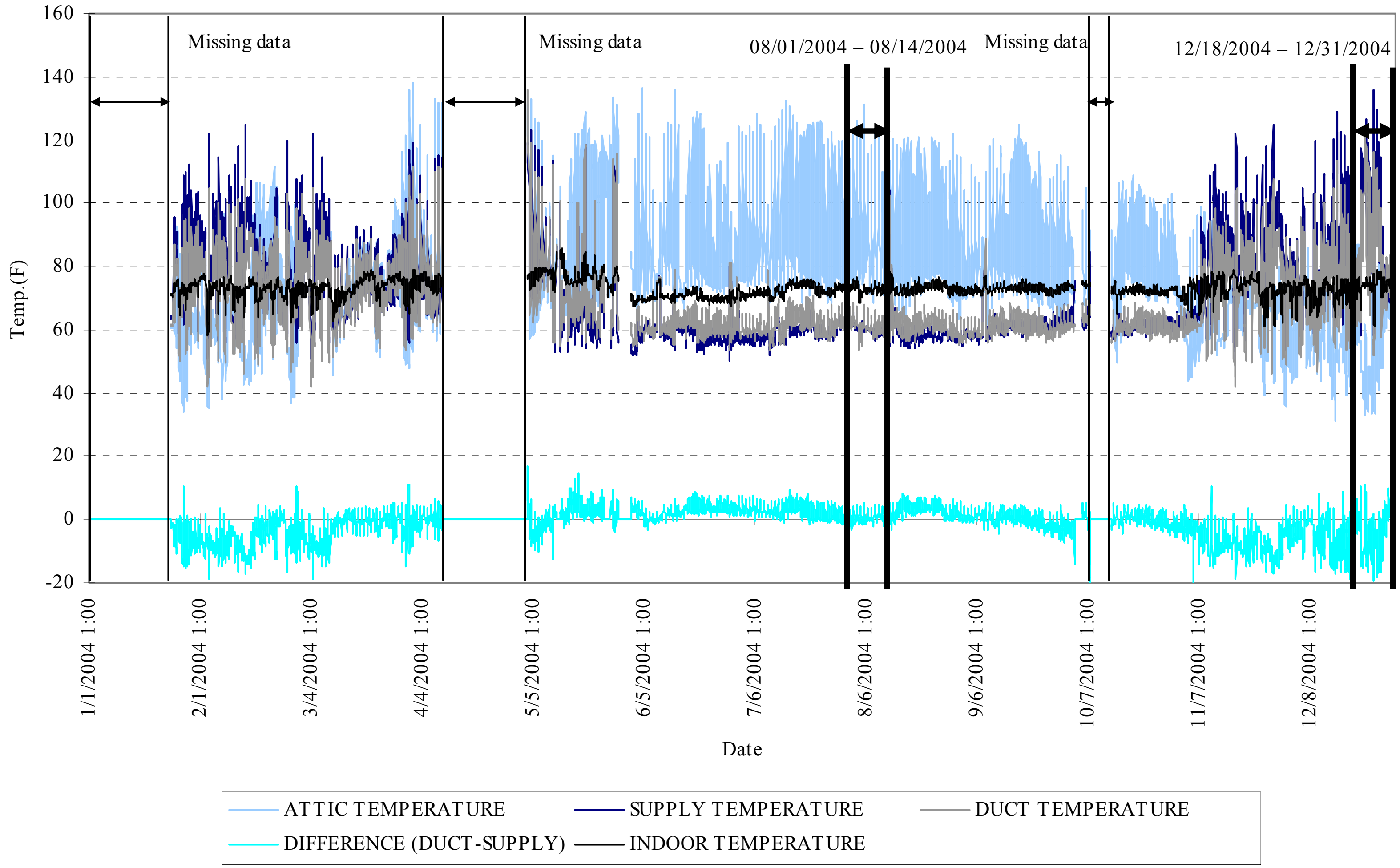


Figure 5.25 Measured attic, supply and duct temperature, and difference between duct and supply temperature

Figures 5.26 and 5.27 illustrate the outdoor environmental conditions and the comparison of the conditioned space and outdoor temperatures during the period August 1 and August 14, 2004. An examination of the data for this cooling period shows that the outdoor temperature range is 33ºF (from 65ºF to 98 ºF). The maximum indoor temperature is 79ºF and the minimum indoor temperature is 70ºF. The average temperature during this period is 74ºF. The maximum hourly solar radiation measurement for the period was 995 W/m^2. For ten days in the period, the solar radiation measurements were in excess of 800 W/m^2. Over the period, the wind measurements varied between 0 to 21mph. The ground temperature for the period fluctuated between 73ºF and 79ºF. Figure 5.28 presents a 24-hour profile of the indoor temperature for the two-week period. Using the statistical procedures developed by Abushakra et al. (2001), the maximum, minimum, 90^{th}, 75^{th}, 50^{th}, 25^{th}, and 10^{th} percentiles of the temperatures were developed for this period. Using the 50^{th} percentile to evaluate the temperature, the lowest indoor temperature was 73ºF at the 7:00 a.m. and the highest values were 74ºF at 4:00 p.m. The average temperature (71.4ºF) measured from the case-study house for one year was used on LOADS part of DOE-2 to calculate the HVAC size and the average temperature (74.3ºF) measured from the case-study house for two weeks provides a characterization of the thermostat settings for the house, which was used for the SYSTEMS part on the DOE-2 input file.

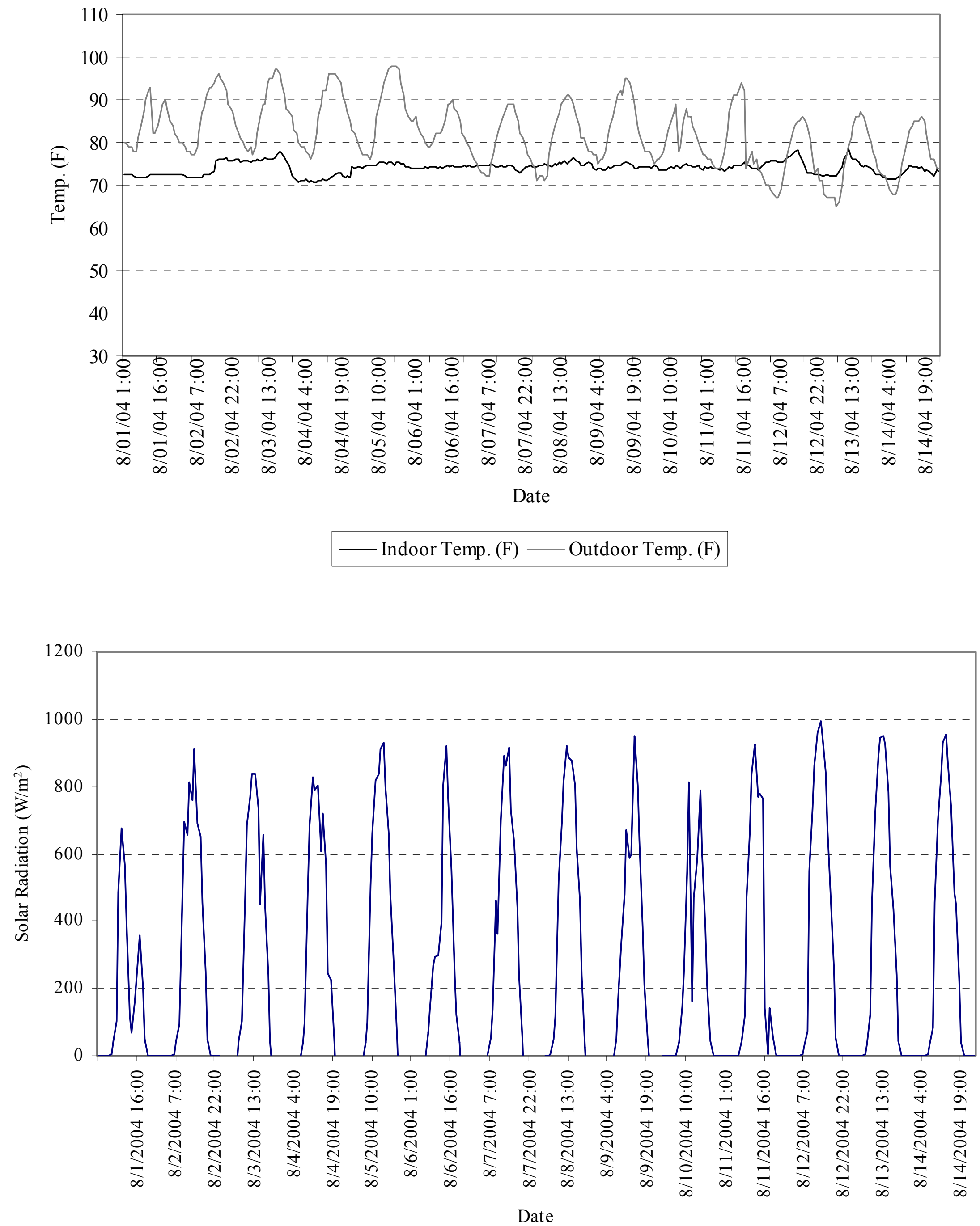
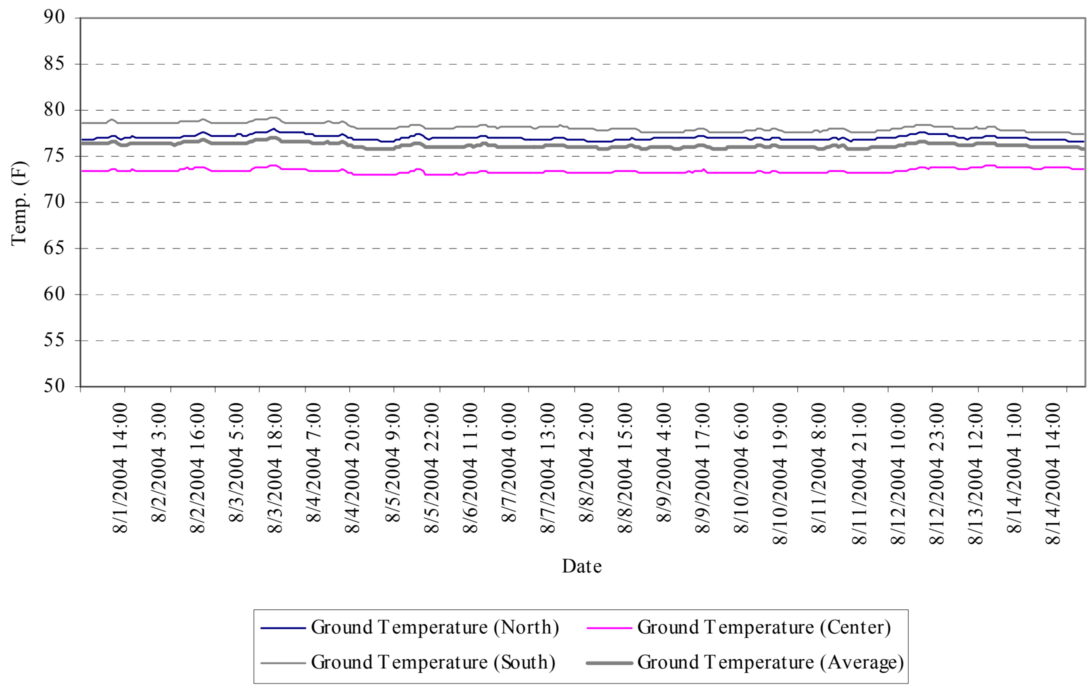


Figure 5.26 The indoor, outdoor temperature and solar radiation for the period August 1 to August 14, 2004



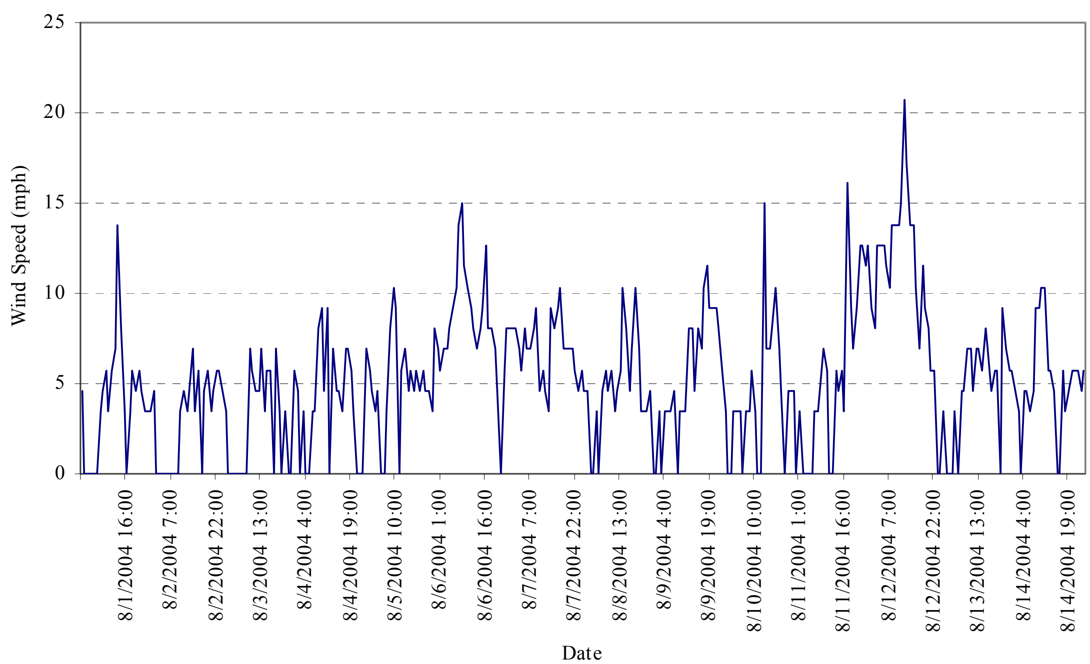


Figure 5.27 The ground temperature and wind speed for the period August 1 to August 14, 2004

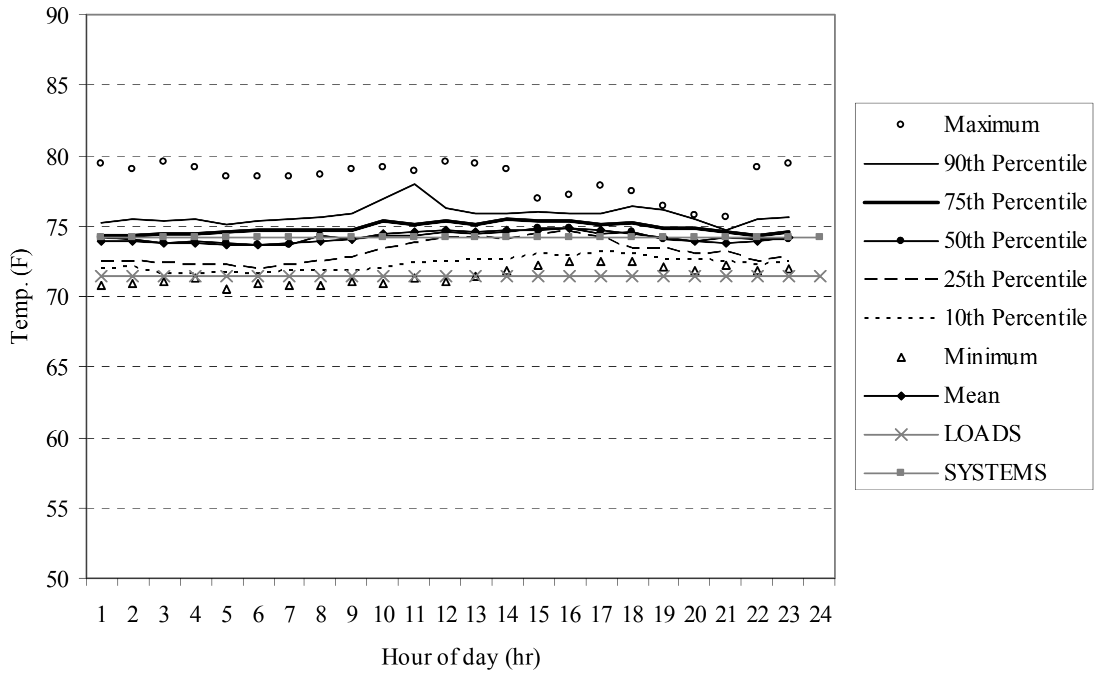


Figure 5.28 Indoor temperature profile for the period August 1 to August 14, 2004

Since the duct system is located in the attic space at the case-study house, the attic temperature for the same period of the conditioned space was also analyzed to investigate the temperature pattern. Figure 5.29 illustrates the attic and outdoor temperature measurements. The maximum attic temperature during this period was 131 ºF and the minimum value was 63 ºF, a range of 68ºF. The maximum temperature difference between attic space and outdoor was 34 ºF at 2:00 p.m. and the minimum temperature difference is -5ºF at 7:00 a.m.

This high attic temperature can cause heat gain from the attic space to the duct system because the duct system is located in the attic space. Figure 5.30 shows the attic temperature profile for the period. By examining the 50th percentile, it was found that the lowest mean value was 72ºF at 6:00 a.m. and the highest value was 117 ºF at 3:00 p.m.

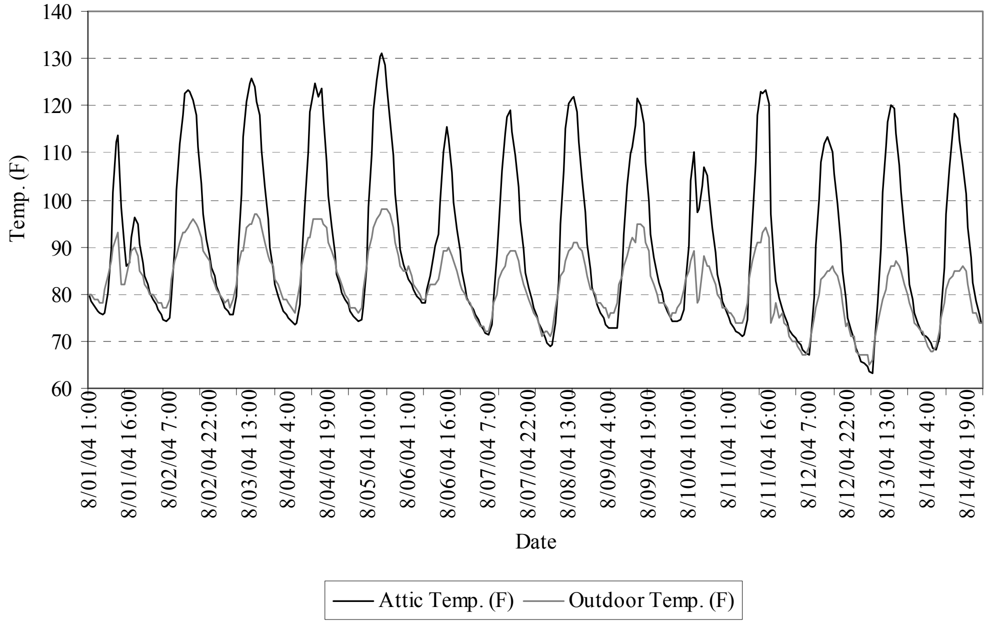


Figure 5.29 The attic and outdoor temperature for the period August 1 to August 14, 2004

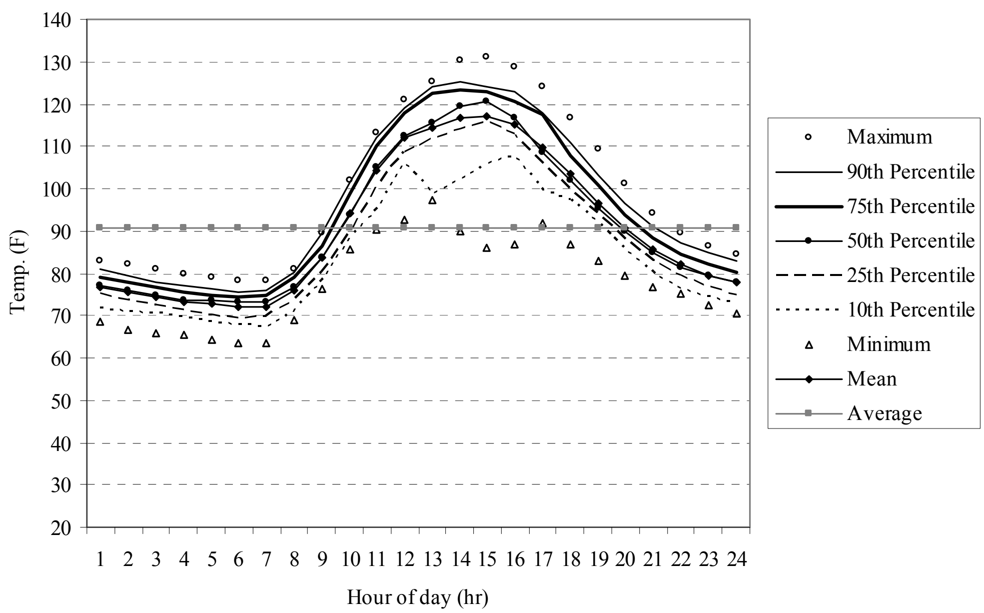


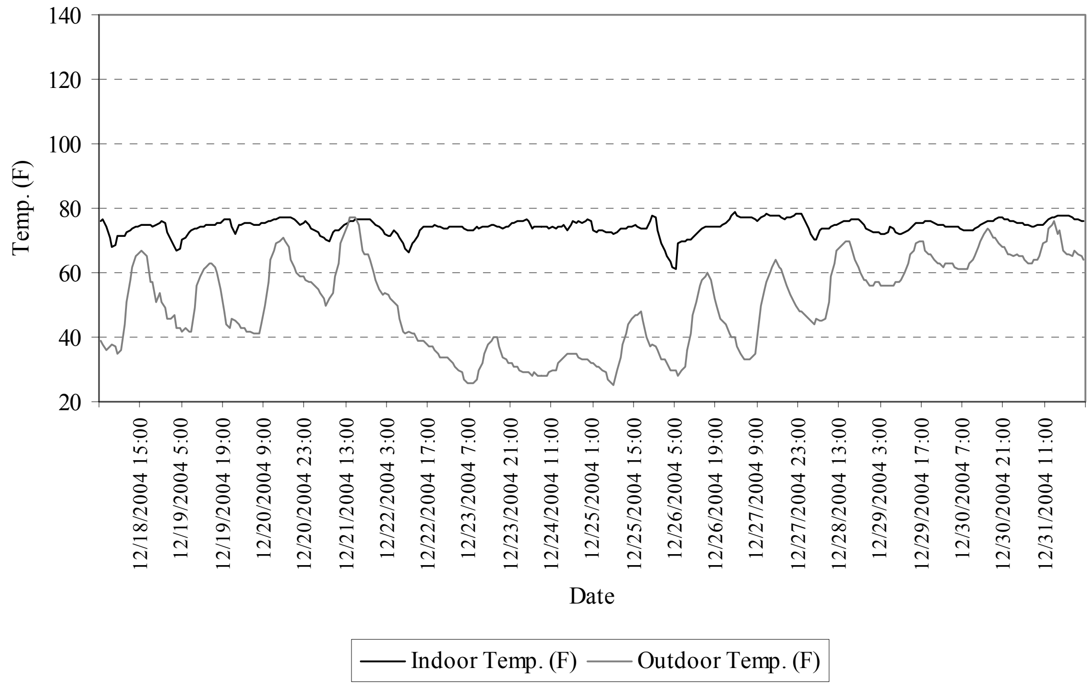
Figure 5.30 Attic temperature profile for the period August 1 to August 14, 2004

5.2.3 Temperature Profiles of the Conditioned Zone and Unconditioned Zone for the Winter Period

An examination of the winter conditions was made for the two-week calibration period. Figures 5.31 and 5.32 illustrate the environmental conditions for the two-week winter calibration period December 18 to December 31, 2004. The maximum outdoor temperature measurements during this period was 77.2ºF and the minimum outdoor temperature was 25.3ºF. This represents a temperature range of 51.9ºF and an average outdoor temperature of 50.3ºF. The maximum hourly solar radiation measurement for the period was 675 W/m^2. For nine days in the period, the solar radiation measurements were in excess of 600 W/m^2. Over the period, the wind measurements varied between 0 to 20.7 mph. The ground temperature for the period fluctuated between 65.4 ºF and 74.4 ºF.

Figure 5.31 illustrates the comparison of the indoor and outdoor temperatures for the period December 18 to December 31, 2004. The indoor temperature shows a larger amount of fluctuation in range than during the summer period. The maximum indoor temperature was 78.7 ºF and the minimum indoor temperature was 61.0ºF. This represented a range of 17.7ºF and an average of 74.3ºF.

The profile of the indoor temperature during this two-week period is illustrated in Figure 5.33. An examination of the 50th percentile for the period shows that the maximum value was 76.1 ºF at 7:00 p.m. and the minimum value was 72.4 ºF at 4:00 a.m. The one-year measured average temperature (71.4ºF) from the case-study house was used on LOADS part of DOE-2 as the summer period. The average temperature measured from the case-study house for two weeks provides a characterization of the thermostat settings for the house, which was used for the SYSTEMS on the DOE-2 input file.



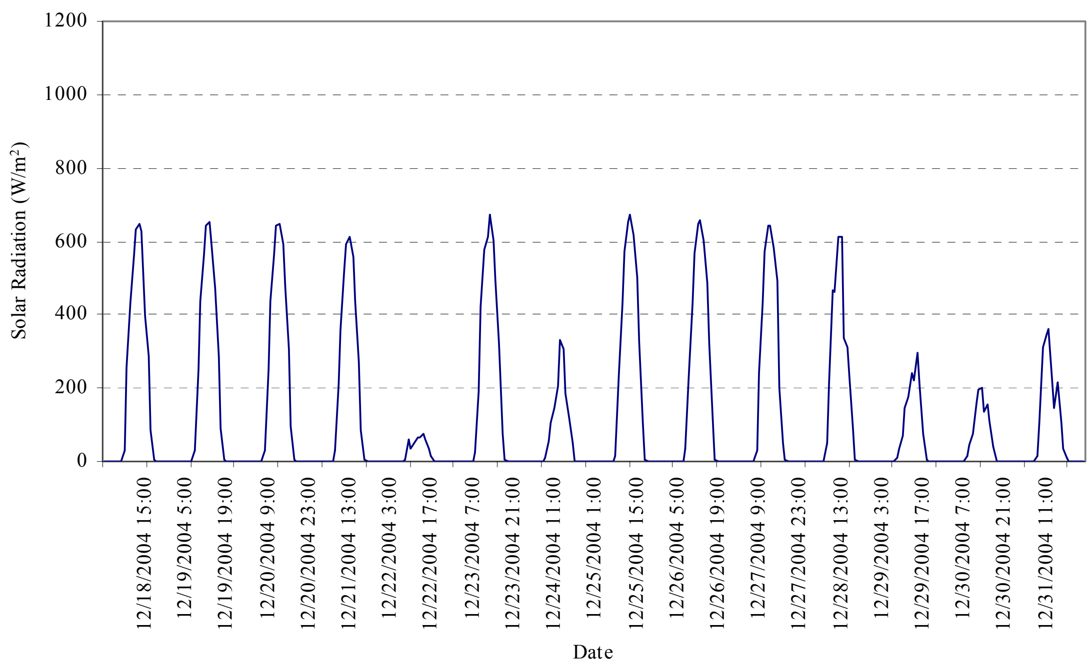
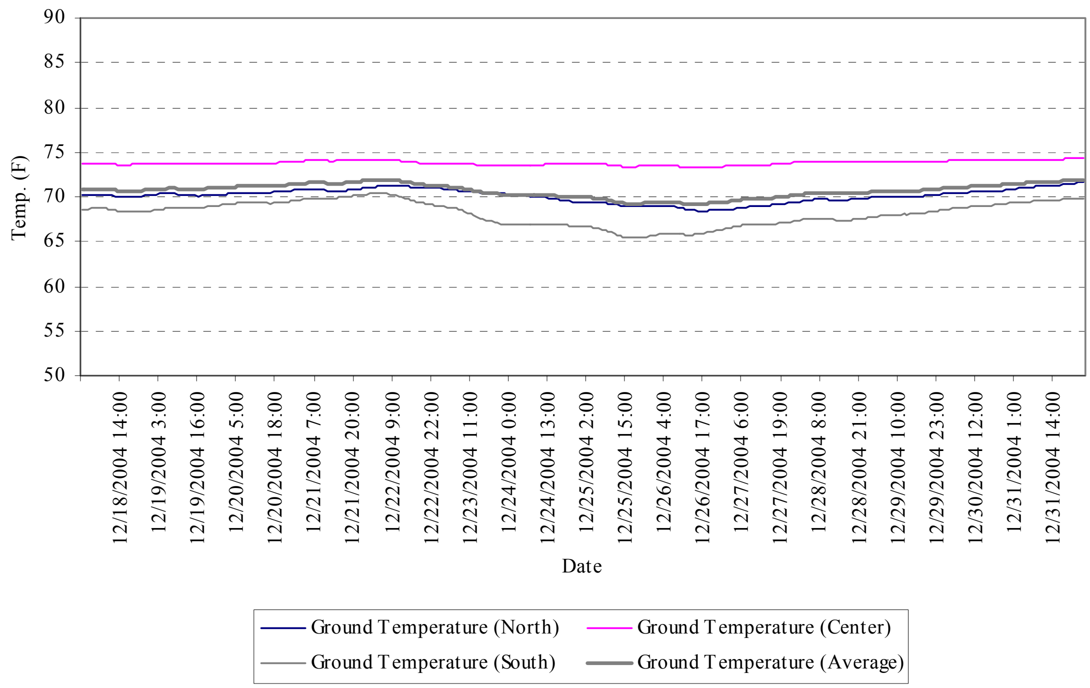


Figure 5.31 The indoor, outdoor temperature and solar radiation for the period December 18 to December 31, 2004



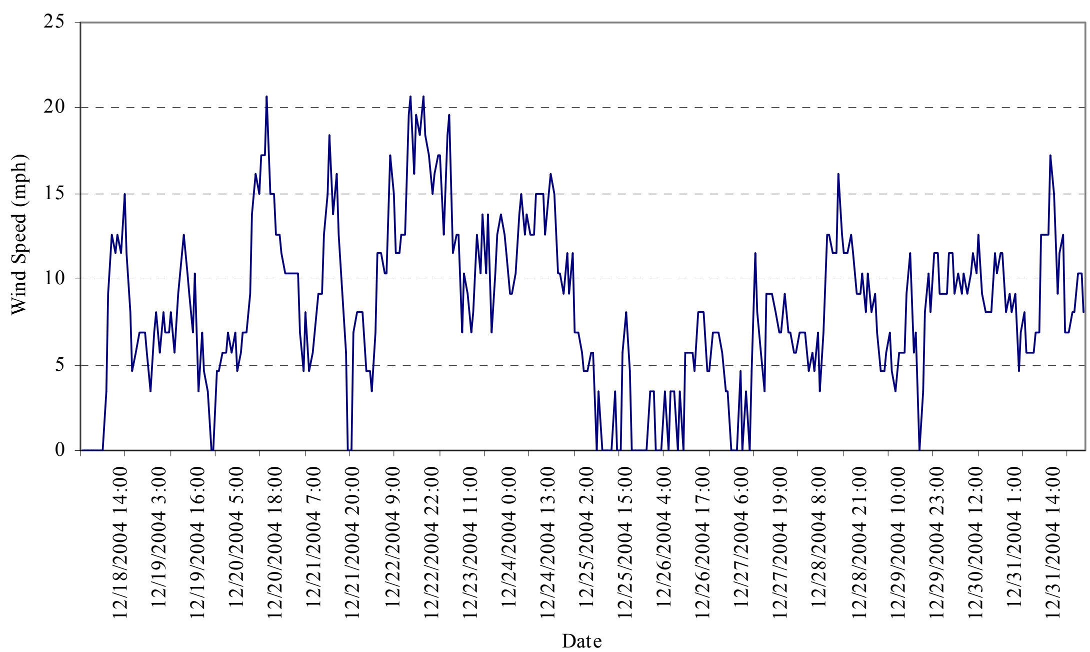


Figure 5.32 The ground temperature and wind speed for the period December 18 to December 31, 2004

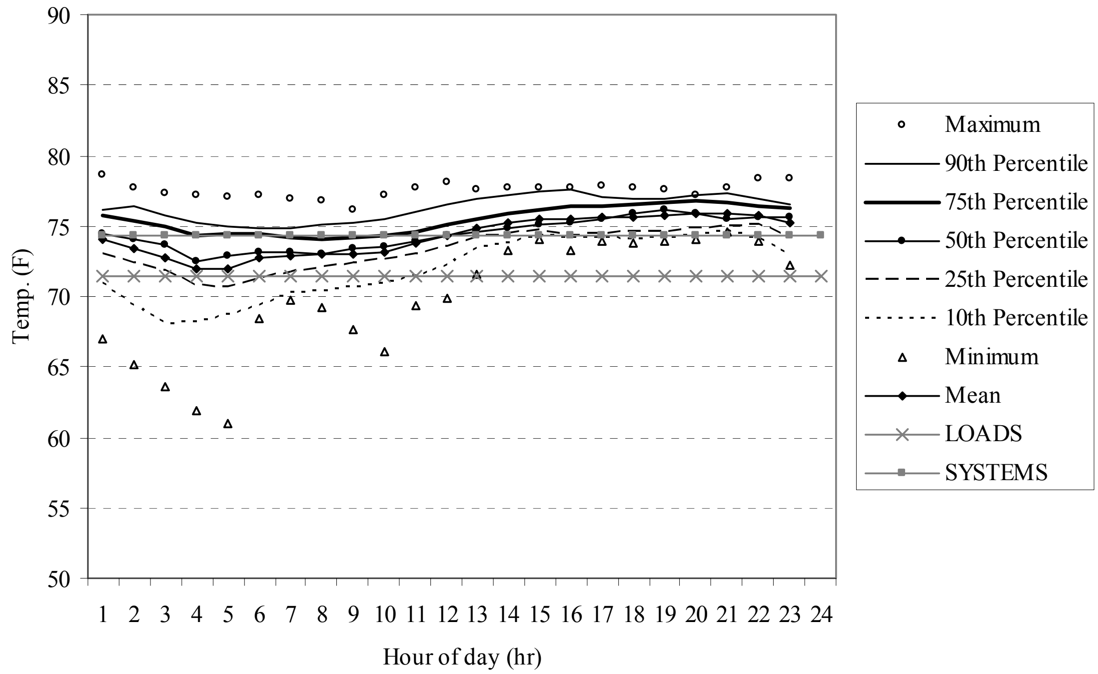


Figure 5.33 Indoor temperature profile for the period December 18 to December 31, 2004

The case-study house has the duct system in the attic space. The attic temperature for the same period of the conditioned space for the winter period was also analyzed to investigate the temperature pattern. Figure 5.34 illustrates the attic and outdoor temperature measurements. The maximum attic temperature during this period was 87ºF and the minimum value was 33ºF, a range of 54ºF. The maximum temperature difference between attic space and outdoor was 30ºF at 2:00 p.m. and the minimum temperature difference is -3ºF at 9:00 a.m. This low attic temperature can cause heat loss from the duct system to the attic space since the duct system is located in the attic space. Figure 5.35 shows the attic temperature profile for the period. Using the 50th percentile, it was found that the lowest value was 44ºF at 7:00 a.m. and the highest value was 80ºF at 2:00 p.m.

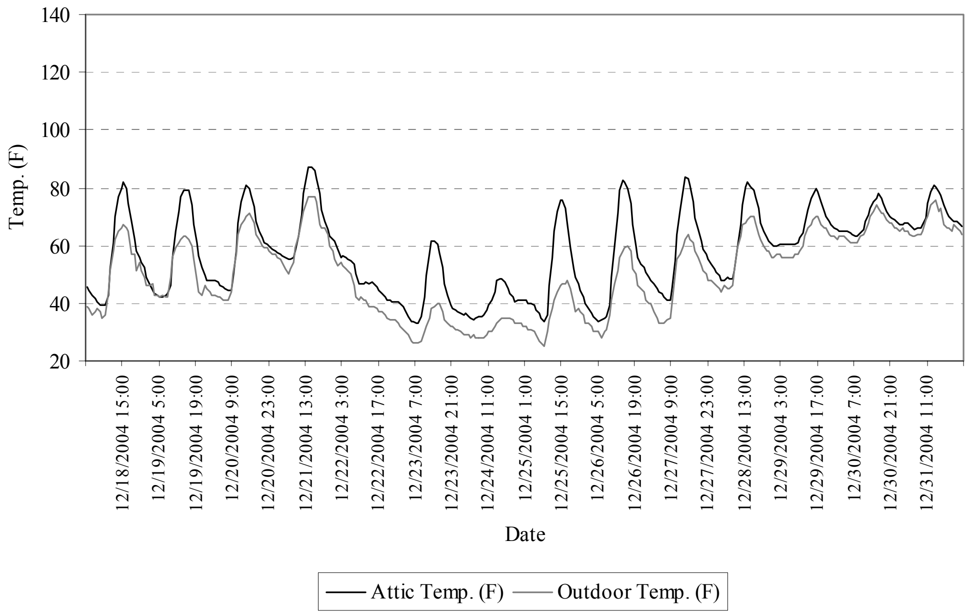


Figure 5.34 The attic and outdoor temperature for the period December 18 to December 31, 2004

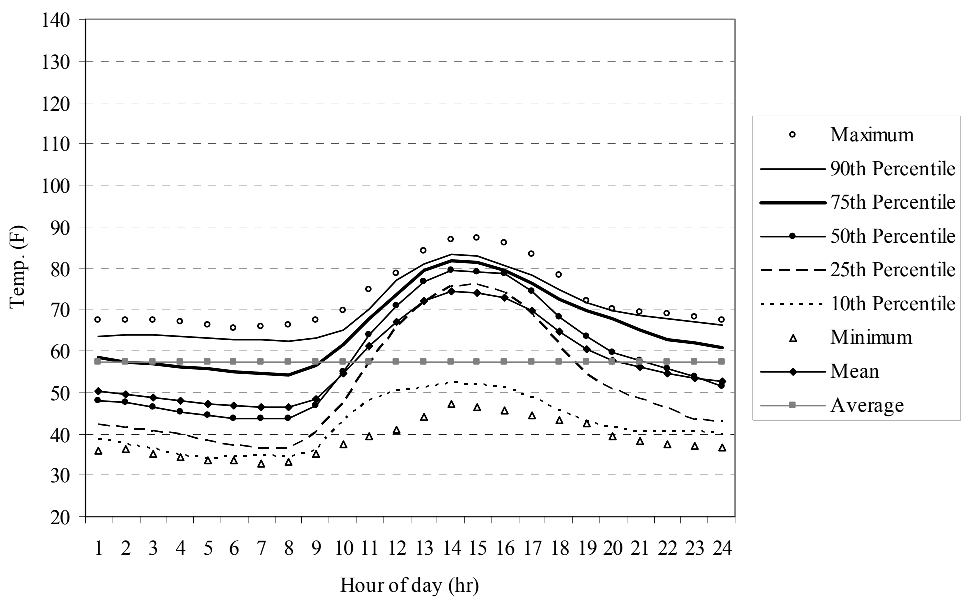


Figure 5.35 Attic temperature profile for the period December 18 to December 31, 2004

5.2.4 Measured Duct Heat Losses

In order to measure the duct loss in the attic space in detail, three measured temperatures from the return, supply and end of duct (diffuser) were used. Several clear days (Figure 5.28) were selected to investigate the duct heat gain from the attic space more clearly. Figure 5.36 shows the location of sensor. The area of supply duct is 170 ft^2, return duct is 60 ft^2, and the insulation level of the supply and return side is R-6.

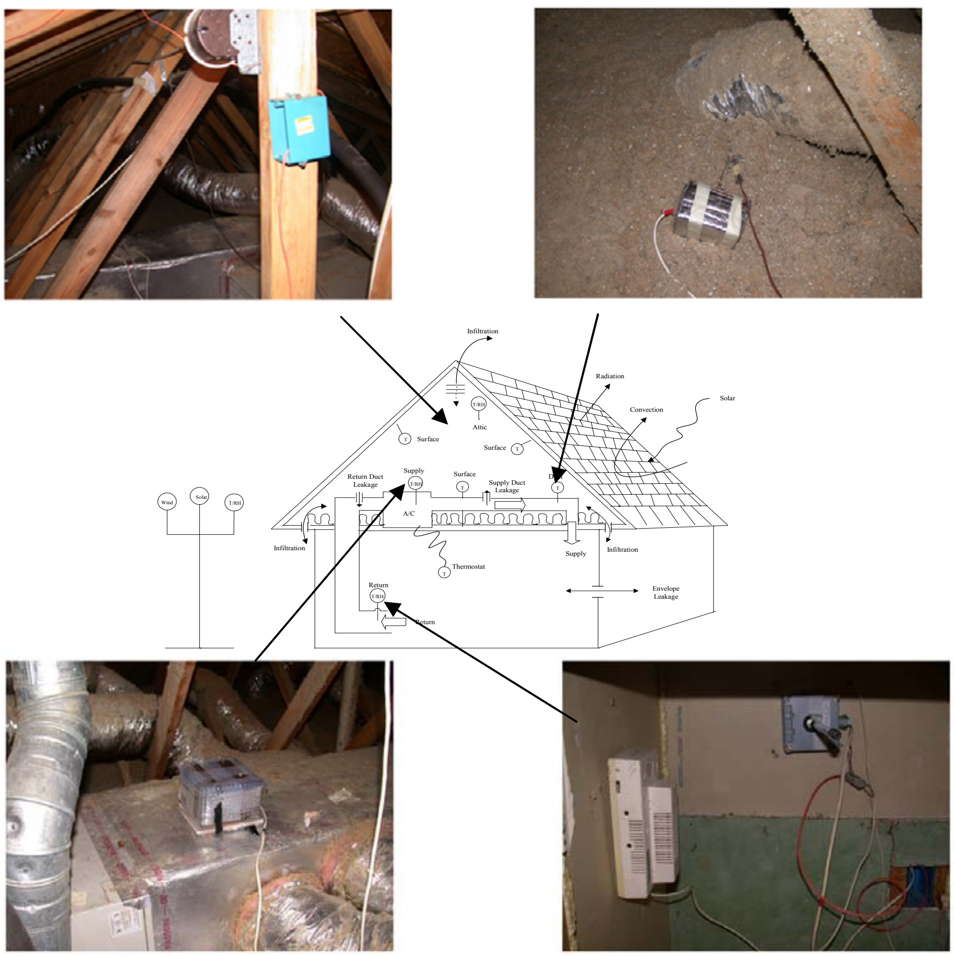


Figure 5.36 The location of sensor on case study house

Figure 5.37 illustrates the measured solar radiation, attic and OA temperature on clear days, and Figure 5.38 shows the air conditioner use of the same clear days. The maximum solar radiation measurement for several clear days was 975 W/m^2. For clear days, the solar radiation measurements were in excess of 900 W/m^2. The maximum hourly outdoor temperature for the same period was 99.2ºF, and the minimum measured outdoor temperature was 52.4ºF, representing a range of 46.8ºF with an average outdoor temperature of 75.6ºF. The maximum attic temperature was 132.9ºF. The minimum attic temperature was 62.9ºF. This represents a temperature range of 70ºF, and average attic temperature on clear days of 91.5ºF. During this period, the maximum attic temperature and outdoor temperature was recorded on July 14. It corresponds to the day when the air conditioner showed the maximum electricity use for the cooling.

An examination of the data for the measured air conditioner electricity use for the same days showed that the maximum air conditioner electricity use was 3.1 kWh, occurring at 3:00 p.m. The average air conditioner during this period was 1.6 kW.

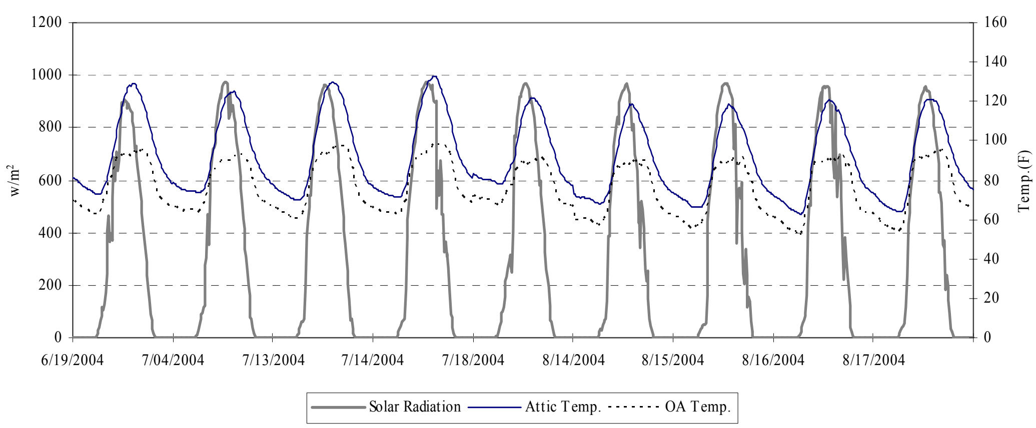


Figure 5.37 Measured solar radiation, attic and OA temperature on clear days

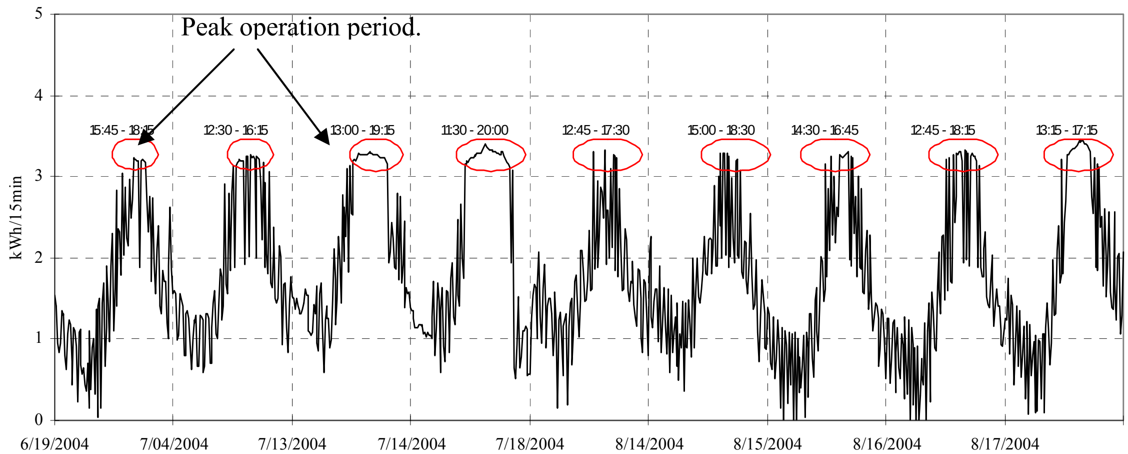
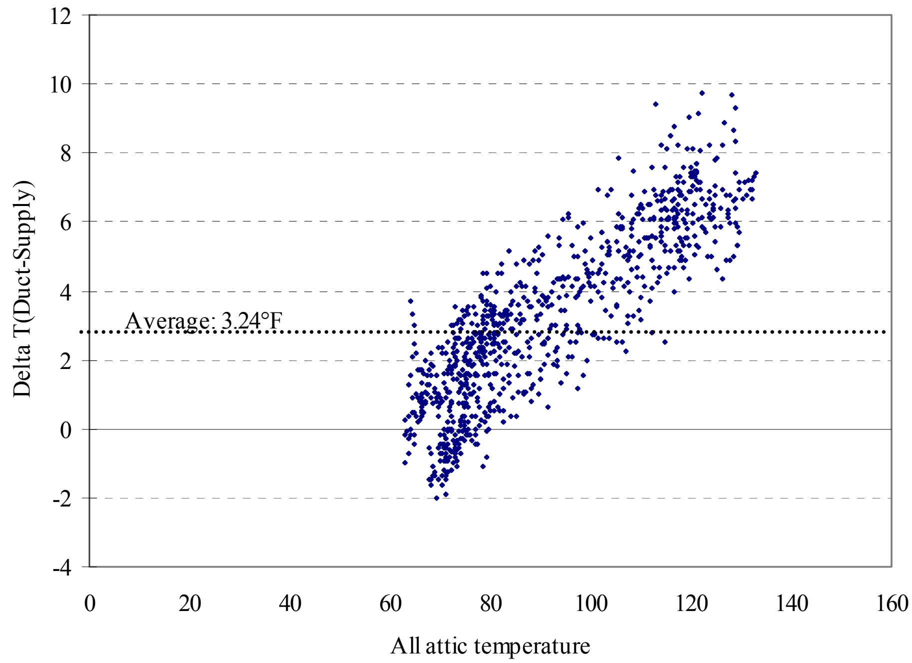


Figure 5.38 Measured AC and AC blower electricity (AC + AC blower) use

Figure 5.39 illustrates the relationship between the attic temperature and Δt (the duct temperature – the supply temperature). The positive value of Δt (the duct temperature – the supply temperature) represents heat gain from the attic space to the duct system, while the negative value indicates heat loss to the attic space. Figure 5.39 shows that the maximum Δt (the duct temperature – the supply temperature) was 9.8 ºF and the average Δt was 3.2 ºF at the selected days. For the peak operation period from selected days, the maximum Δt was 9.1 ºF and the average Δt was 5.5 ºF. According to the average Δt, the duct heat gain is more serious at the peak operation period from selected days than other periods from selected days relatively. The pattern of the plots also shows the linear relationship between attic temperature and Δt (duct temperature – supply temperature) as the attic temperature reaches high.

Therefore, the unconditioned space with duct system such as attic space plays a very significant role for duct heat loss or gain and should be recognized important in terms of thermal properties of the attic space or the duct insulation levels.



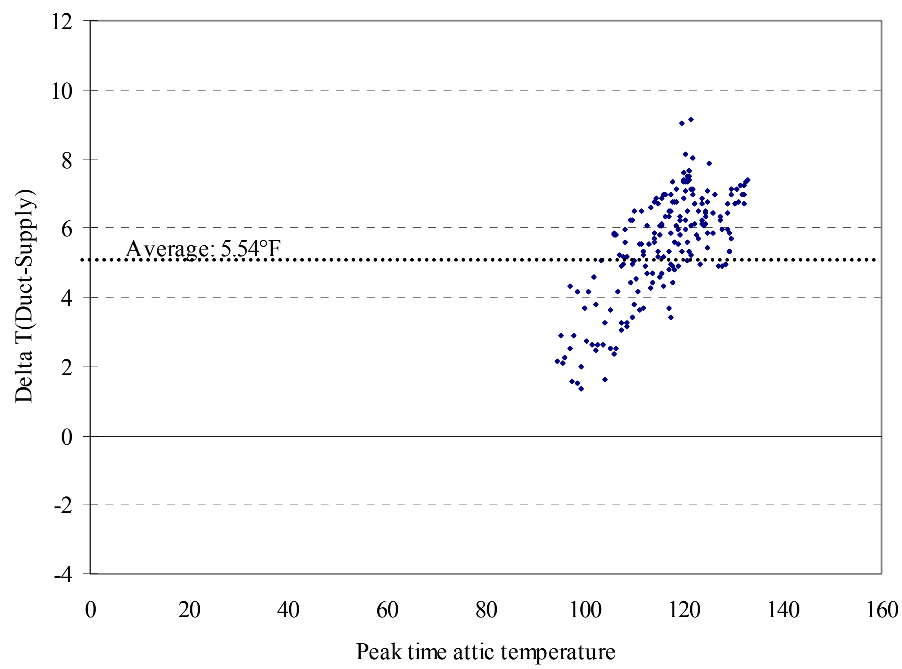


Figure 5.39 Plots of measured attic temp. vs. the difference between duct and supply temperatures

5.3 Base-Case Model Calibration

In order to develop a calibrated DOE-2 simulation of the case-study house, a series of simulations were used to assess the improved accuracy. The calibration process included the calibration of the attic temperature, the zone temperature, the electricity use and the natural gas use. The calibration process for the attic and zone temperatures were performed using hourly measured and simulated data. In this simulation, the input model was divided into two adjacent zones, a living space and an attic space. In the base-case model calibration, an accurate attic temperature is critical since the attic space is the direct environmental condition for the duct system. Therefore, the hourly attic and indoor temperatures were calculated and reported by using the DOE-2 hourly report capability. Table 5.7 shows the attic temperature calibration process. Calibration process started from quick mode which used only U-value of building envelopes. Then layered materials, which were explained at Chapter 4.2.3.2, were added to base-case model. Finally, several air change rates in the attic space were applied to achieve the accurate attic temperature.

Table 5.7 Attic temperature calibration process

Run No.	Summer Period	Winter Period
1	Quick mode, Air-change = 0	Quick mode, Air-change = 0
2	Thermal mass mode, Air-change = 0, Infiltration Schedule = 1	Thermal mass mode, Air-change = 0, Infiltration Schedule = 1
3	Thermal mass mode, Air-change = 5, Infiltration Schedule = 1	Thermal mass mode, Air-change = 5, Infiltration Schedule = 1
4	Thermal mass mode, Air-change = 10, Infiltration Schedule = 1	Thermal mass mode, Air-change = 10, Infiltration Schedule = 1
5	Thermal mass mode, Air-change = 15, Infiltration Schedule = 1	Thermal mass mode, Air-change = 15, Infiltration Schedule = 1
6	Thermal mass mode, Air-change = 20, Infiltration Schedule = 1	Thermal mass mode, Air-change = 20, Infiltration Schedule = 1
7	Thermal mass mode, Air-change = 25, Infiltration Schedule = 1	Thermal mass mode, Air-change = 25, Infiltration Schedule = 1
8	Thermal mass mode, Air-change = 30, Infiltration Schedule = 1	Thermal mass mode, Air-change = 30, Infiltration Schedule = 1
9	Thermal mass mode, Air-change = 25, Infiltration Schedule = (1,7) (1) (8,20) (0.20) (21,24) (1)	Thermal mass mode, Air-change = 25, Infiltration Schedule = (1,7) (0.2) (8,17) (0.40) (18,24) (0.2)

5.3.1 Attic and Indoor Temperature Calibration

The calibrations for attic and indoor temperature were performed using the developed initial simulation input file of the case-study house. Attic temperature calibration was especially crucial because the well-calibrated attic temperature was the direct environmental conditions to the duct model in the attic space.

The hourly attic temperature comparisons shown in Figure 5.40 demonstrate that there were wide differences between the uncalibrated simulated and the measured attic temperatures. The uncalibrated, simulated attic temperatures from Figure 5.40, which used overall U-value of the attic space and pre-calculated ASHRAE weighting factors showed constant patterns compared to the measured attic temperatures.

Figure 5.41 shows the uncalibrated simulation (run #1) and measured results of the indoor temperature for the period August 1 to August 14, 2004

The calibration results of the attic temperature and indoor temperature for the period of August 1 to August 14, 2004 (summer season) are illustrated in the Figures 5.41 to 5.43. Figure 5.44 includes the Coefficient of Variation for the Root Mean Squared Error (CV(RMSE)) and the Mean Biased Error (MBE).

For the first simulation of the attic temperatures, the Coefficient of Variation for the Root Mean Squared Error (CV(RMSE)) was 14.5 %, and the Mean Biased Error (MBE) was 6.9 %. For the living space, CV(RMSE) was 2.5 %, and the MBE -1.3 %. In run #2, actual layered materials with DOE-2's custom weighting factors were added to the base-case model, called the "thermal mass mode", with the same infiltration rate as the quick mode model. This caused the CV(RMSE) and MBE for the attic temperature to be reduced from 14.5 % to 8.0 % and 6.9 % to 2.0 %.

These results showed that using layered materials with DOE-2's custom weighting factors predicted more accurately than using overall U-value and pre-calculated ASHRAE weighting factors.

For the conditioned space, in general, the model predicted the indoor temperatures fairly well since the indoor temperature were usually constant over the year. From run #3 and run #7, it was found that an infiltration schedule of 25 ACH for the nighttime (from 9:00 p.m. to 7:00 a.m.) and 5 ACH for the daytime (from 8:00 a.m. to 8:00 p.m.) yielded the best results. Therefore, a modified infiltration schedule was used on run #9, as shown in Figures 5.42 and 5.43 that the simulated temperatures were significantly closer to the actual data than the results of run #1 (Figure 5.40). In terms of statistical analysis, the CV(RMSE) has decreased from 14.5 % to 5.9 %, and MBE also has decreased from 6.9 % to 0.1 %.

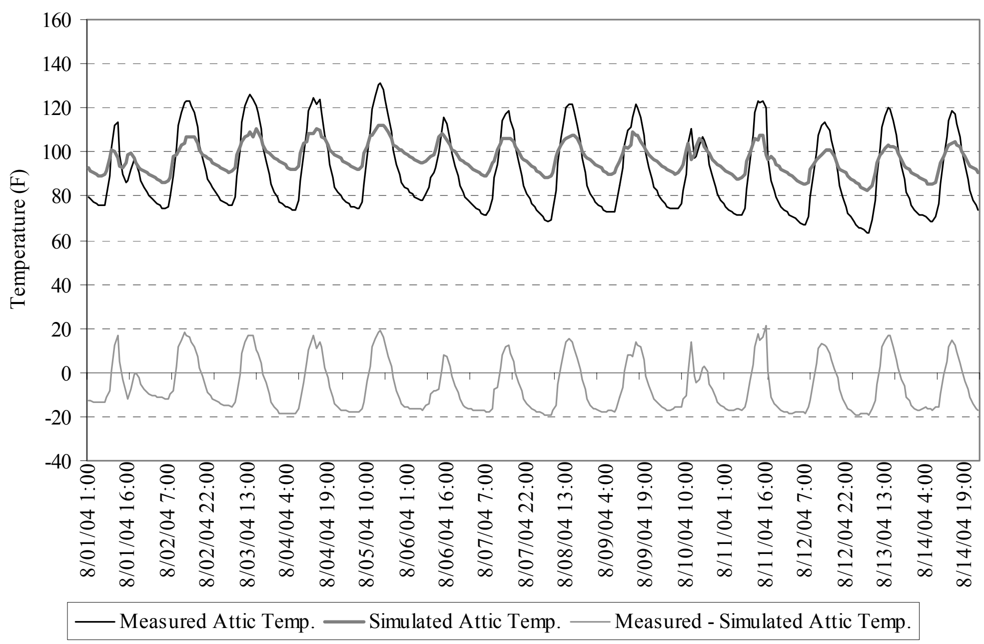


Figure 5.40 The uncalibrated simulation (run #1) and measured results of the attic temperature for the period August 1 to August 14, 2004

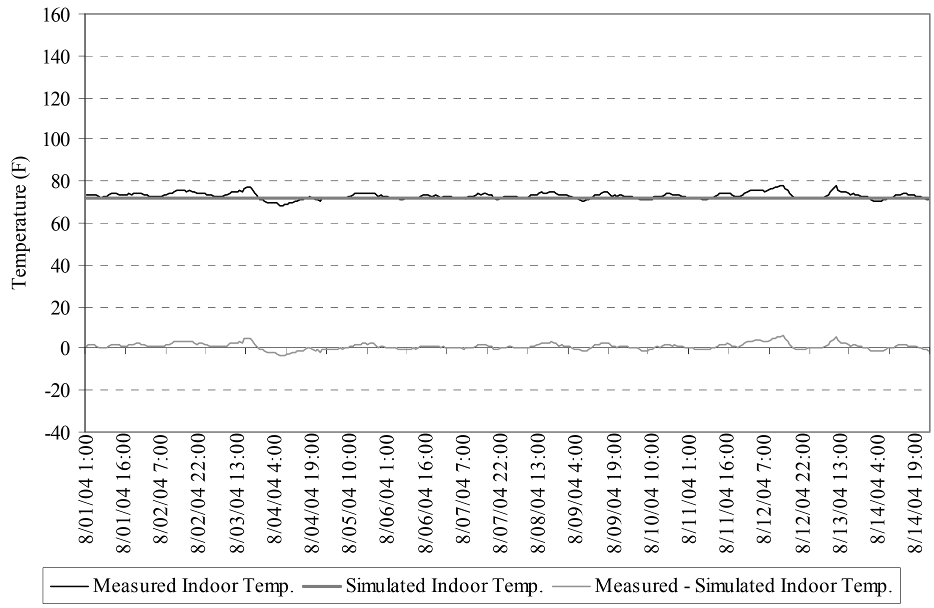


Figure 5.41 The uncalibrated simulation (run #1) and measured results of the indoor temperature for the period August 1 to August 14, 2004

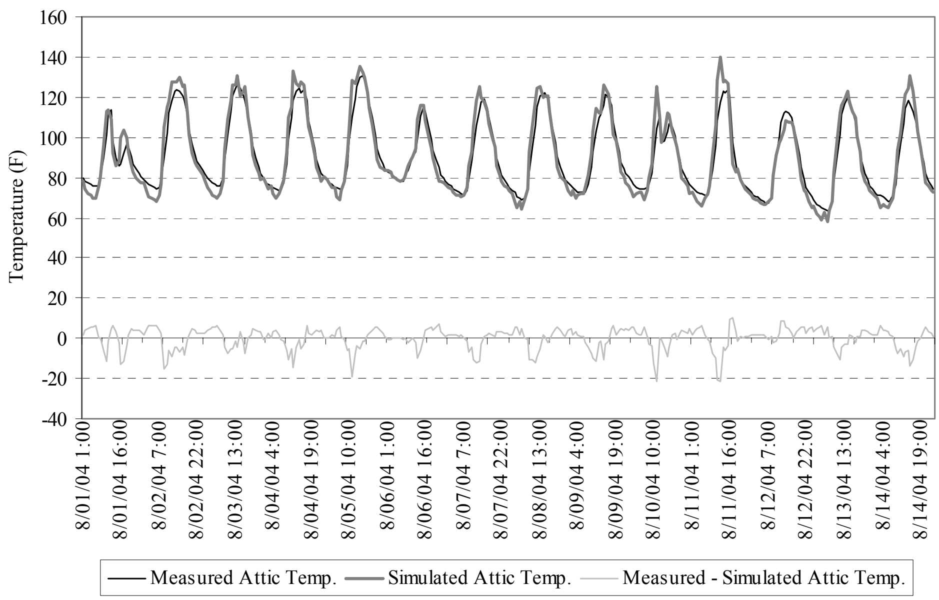


Figure 5.42 The calibrated simulation (run #9) and measured results of the attic temperature for the period August 1 to August 14, 2004

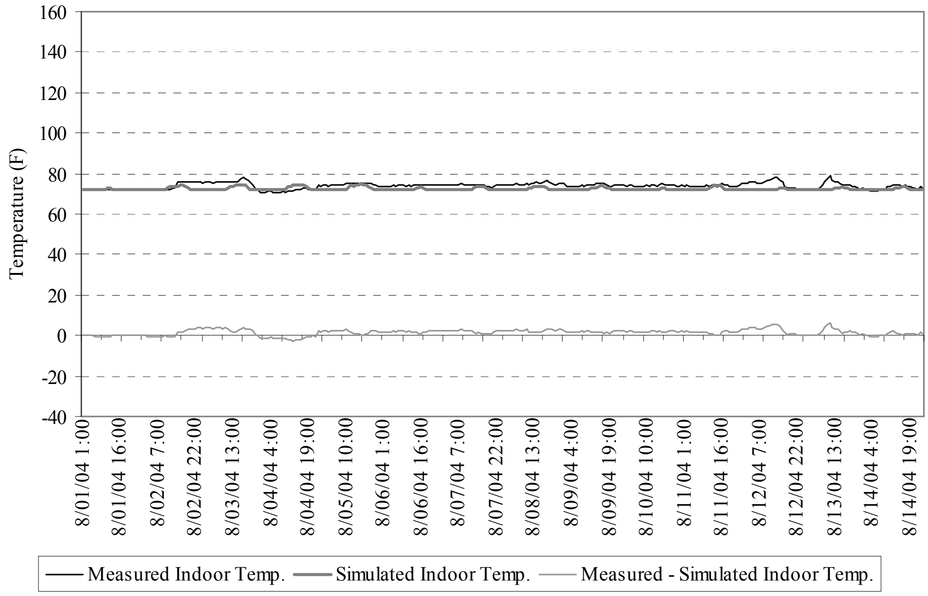


Figure 5.43 The calibrated simulation (run #9) and measured results of the indoor temperature for the period August 1 to August 14, 2004

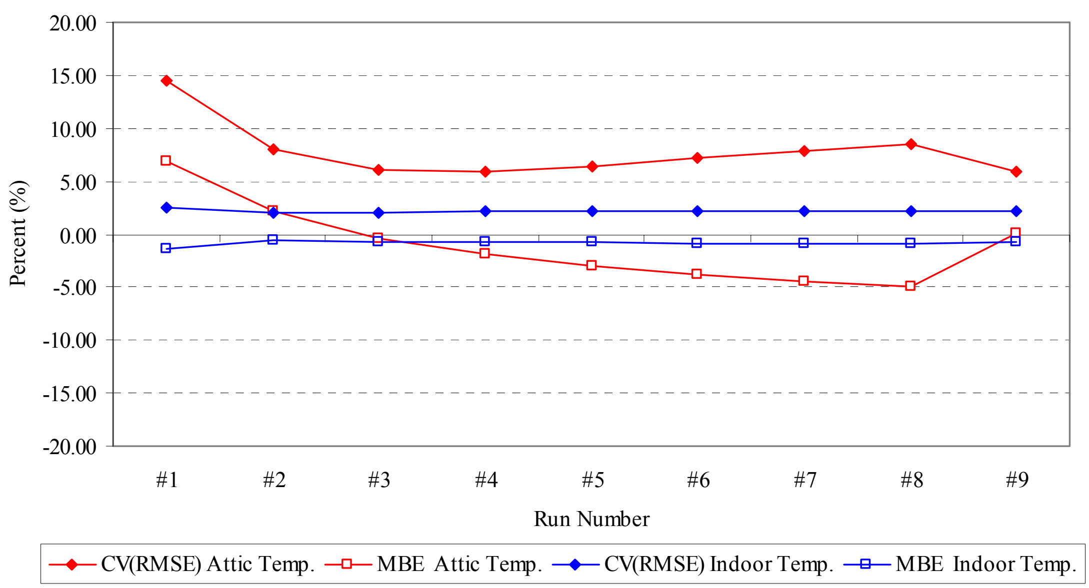


Figure 5.44 CV(RMSE) and MBE of attic and indoor temperature calibration

The calibration results of the simulation of the attic temperature and indoor temperature for the period December 18 to December 31, 2004 (winter season) are also performed using the similar procedure in the calibration of the summer period.

From Figures 5.45 and 5.46, the uncalibrated attic and indoor temperatures which were performed using the quick mode, showed constant patterns as the summer period simulation. For the first simulation of the attic temperatures for the winter period, the Coefficient of Variation for the Root Mean Squared Error (CV(RMSE)) was 14.1 %, and the Mean Biased Error (MBE) was -1.7 %. For the living space, CV(RMSE) was 3.3 %, and the MBE was -0.4 %. In run #2, actual layered materials were modeled. The CV(RMSE) for attic temperature decreased to 13.71 % for CV(RMSE), but MBE increased to -4.7 %. Although the MBE of the attic temperatures of run #2 increased, the pattern of the attic temperatures were close to the measured attic temperatures. The reason for the MBE increase is that the measured attic temperature for winter period did not fluctuate as did for the summer period.

From run #3 and run #4, it was found that an ACH of 5 for the nighttime (from 6:00 p.m. to 7:00 a.m.) and ACH of 10 for the daytime (from 8:00 a.m. to 5:00 p.m.) yielded the best results. Therefore, the modified infiltration schedule was used on run #9. Figures 5.47 and 5.48 show that the simulated temperatures were closer to the actual data than the results of run #1 (Figures 5.45 and 5.46). In terms of statistical analysis, the CV(RMSE) has decreased from 14.1 % to 10.1 %, but MBE has increased from -1.7 % to 6.5 %, which were considered statistically acceptable (Figure 5.49).

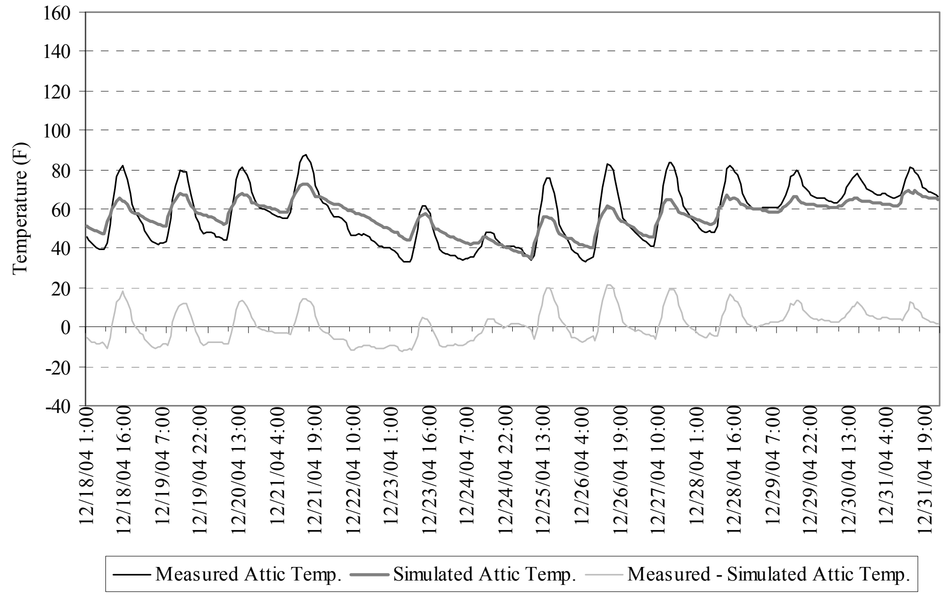


Figure 5.45 The uncalibrated simulation (run #1) and measured results of the attic temperature for the period December 18 to December 31, 2004

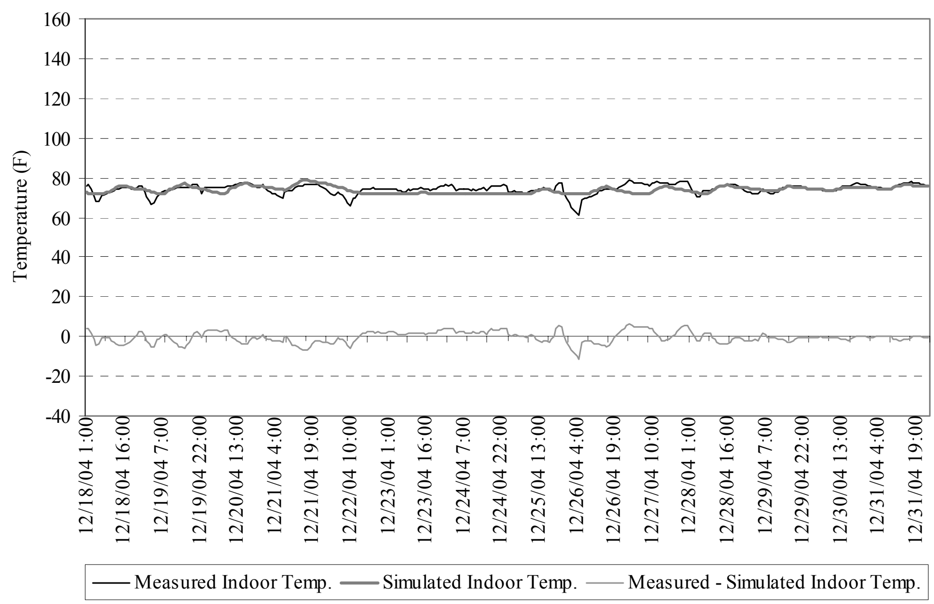


Figure 5.46 The uncalibrated simulation (run #1) and measured results of the indoor temperature for the period December 18 to December 31, 2004

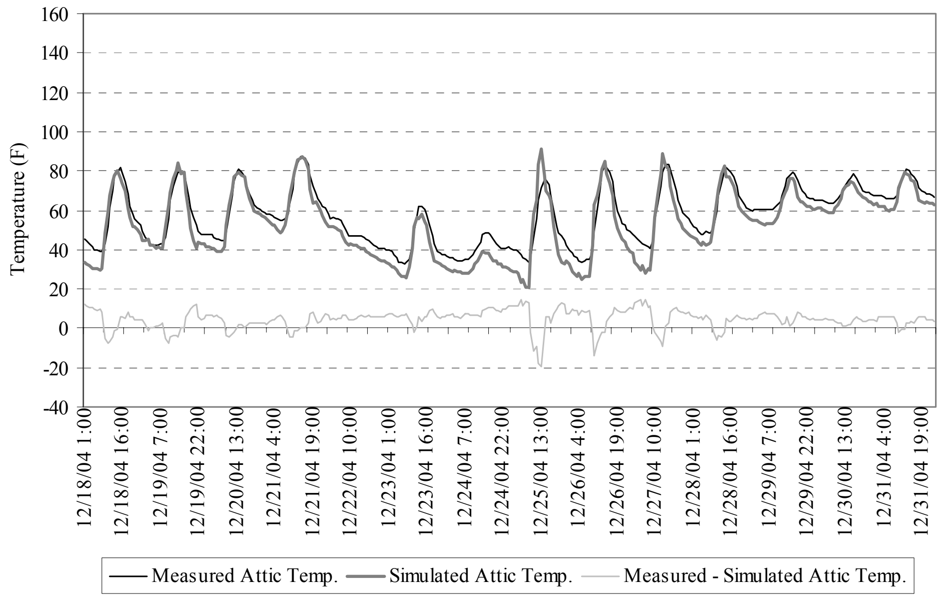


Figure 5.47 The calibrated simulation (run #9) and measured results of the attic temperature for the period December 18 to December 31, 2004

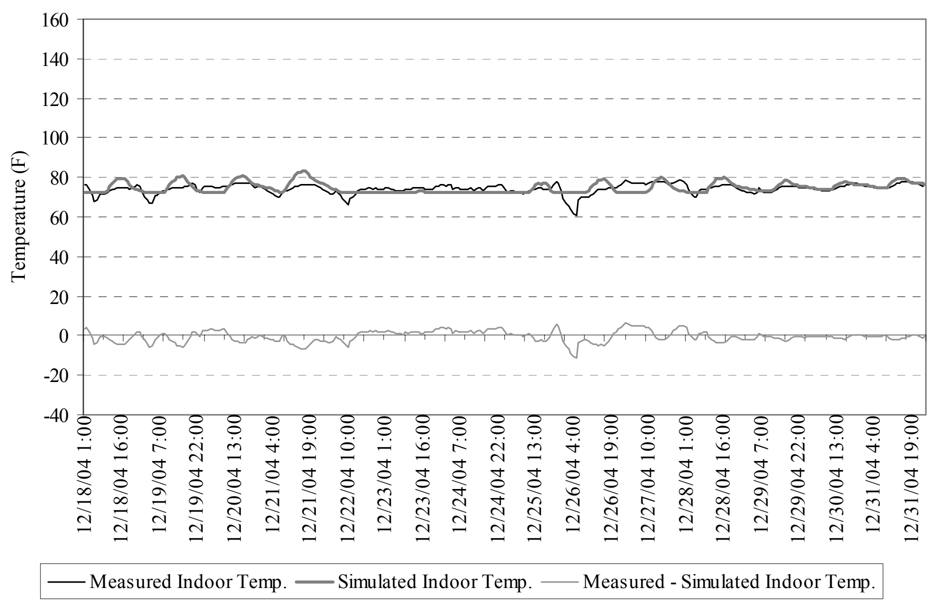


Figure 5.48 The calibrated simulation (run #9) and measured results of the indoor temperature for the period December 18 to December 31, 2004

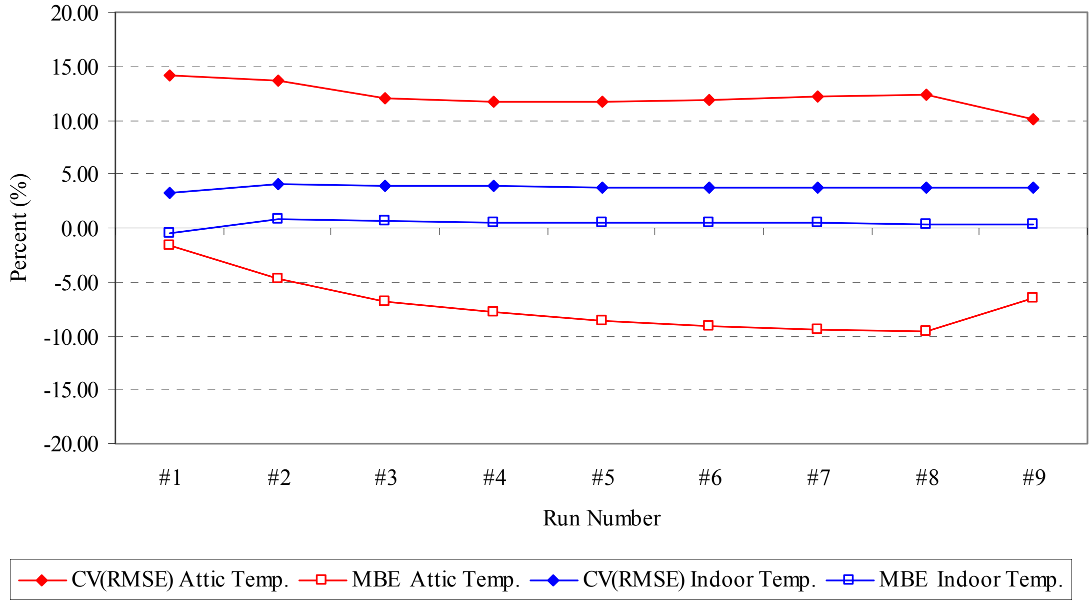


Figure 5.49 CV(RMSE) and MBE of attic and indoor temperature calibration

5.4 Analysis of the Results

In order to apply new simulation methodologies such as duct model, new system / domestic hot water heater performance curves and new underground surface simulation method, the DOE-2.1e (version 119) building simulation program was used. This chapter discusses the results of new simulation methodologies using the base-case house simulation model.

5.4.1 Duct Model

Once the calibration of the attic temperature and the indoor temperature were completed, duct model using the ASHRAE 152-2004 (Chapter 4.2.3.3) was incorporated into the calibrated DOE-2 model. As mentioned before, the exact simulation of the attic temperatures was critical, since attic temperature was the direct environmental condition of the duct systems.

Figure 5.50 illustrates temperatures, and cooling and heating energy over the entire year before duct model is incorporated into the temperature calibrated simulation models. The results show that the measured maximum cooling energy was 3.26 kW (11110.70 Btu/hr), but the simulated maximum cooling energy was 1.97 kW (6729.75 Btu/hr), since heat gains to duct system from attic space were not considered at this simulation. On average, the measured cooling energy use was 0.72 kW for one-year, but the simulated cooling energy use was 0.46 kW, which was lower than the measured cooling energy use. From two-week data from August 1 to August 14, 2004 (Figure 5.51), the results show the range of 0.44 kW to 3.20 kW for the measured results and 0.33 kW to 2.48 kW for the simulation results in the cooling energy use, which indicate that there is major difference between the measured and simulated cooling energy use (i.e., the simulated cooling energy had less energy consumption than the measured cooling energy.).

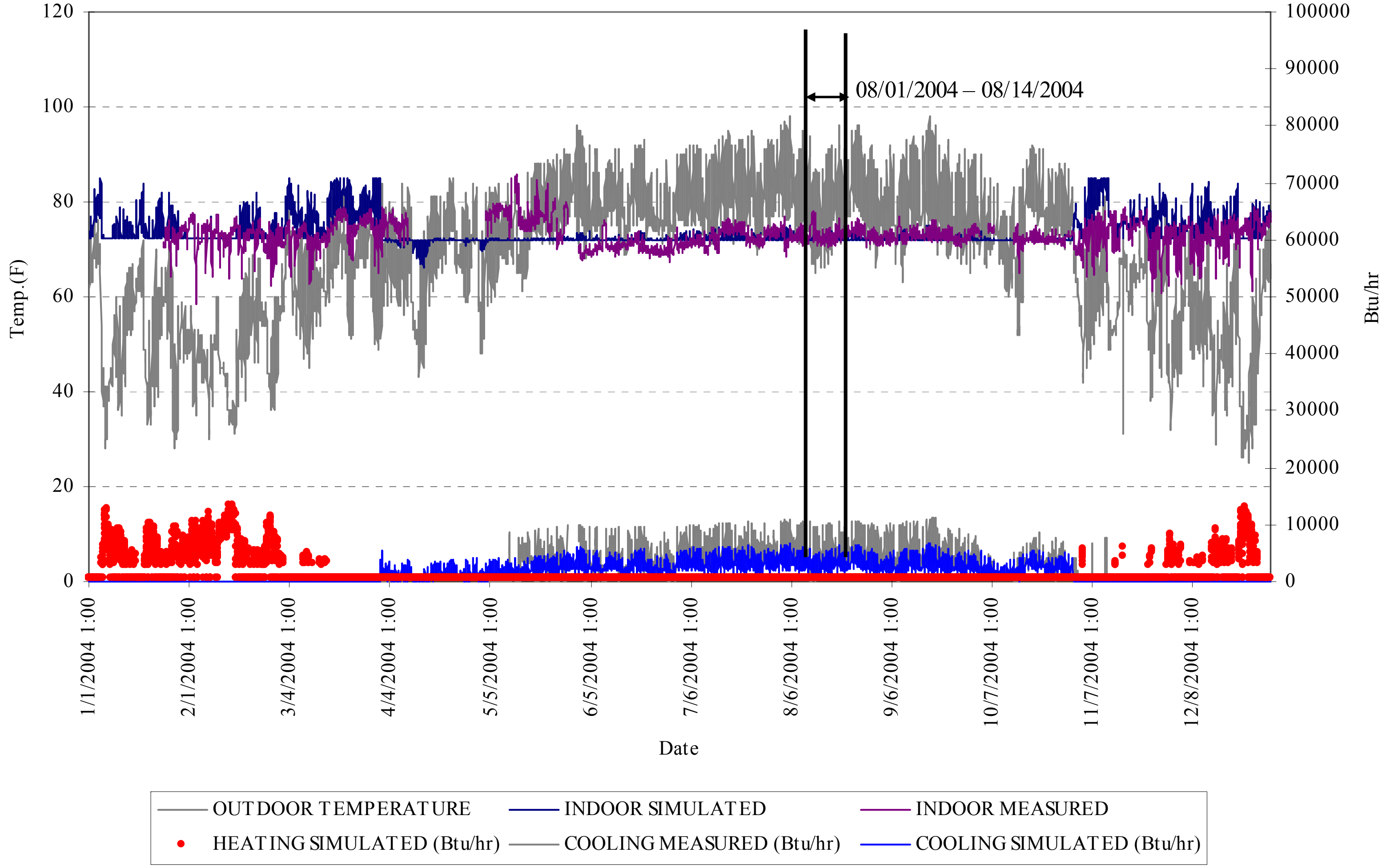
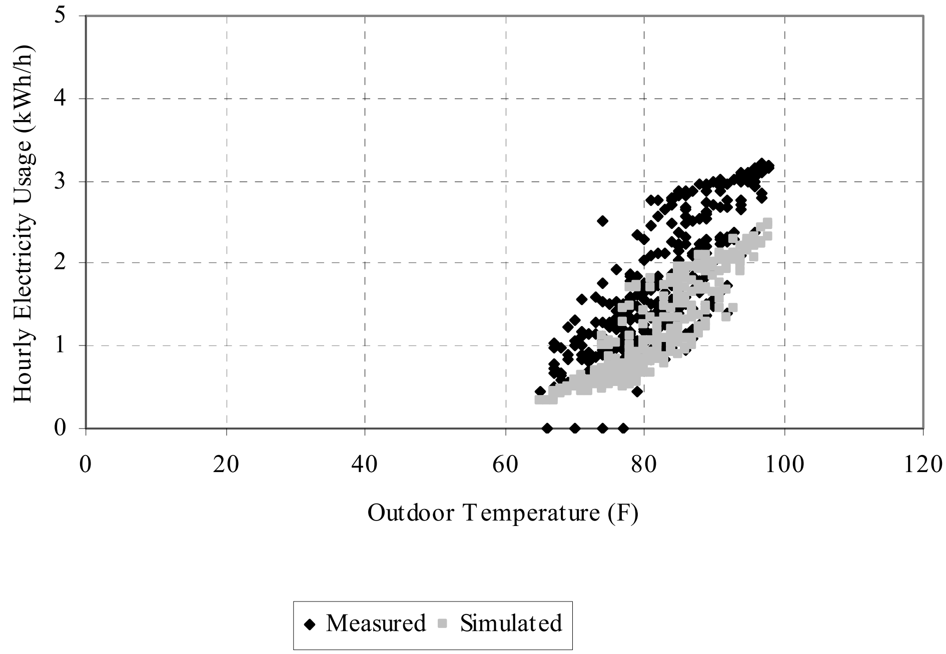


Figure 5.50 Temperature and cooling energy plots without duct model for the whole year



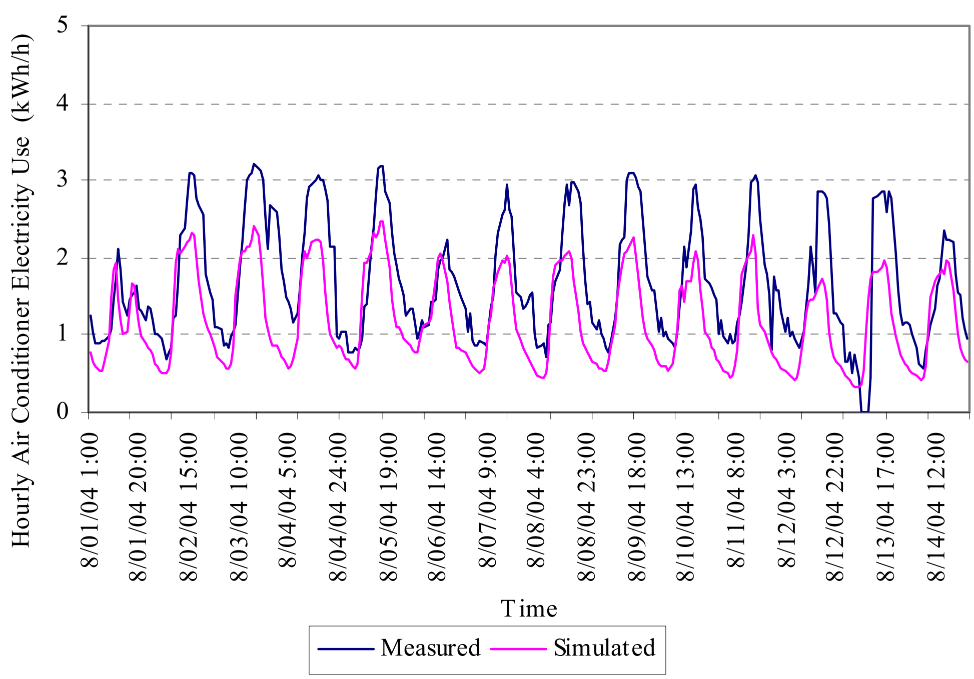


Figure 5.51 Cooling energy plots without duct model for two weeks (08/01/2004 – 08/14/2004)

In terms of statistic analyses, the Coefficient of Variation for the Root Mean Squared Error (CV (RMSE)) was 40.24 %, and the Normalized Mean Biased Error (MBE) was -29.10 % which were statistically inappropriate.

Figures 5.52 and 5.53 present results after duct model was incorporated to the DOE-2 simulation model. From a one-year plot (Figure 5.52), it was found that simulated cooling energy use increased compared to a one-year plot (Figure 5.50) which the duct model was not applied to the DOE-2 simulation model.

On average, the simulated average cooling energy increased from 0.46 kW to 0.66 kW after the duct model was added to DOE-2 model. As shown in Figure 5.53, the range of simulated cooling energy was 0.38 kW to 3.44 kW after the duct model was incorporated into DOE-2 input, while the range of simulated cooling energy was 0.33 kW to 2.48 kW before incorporating the duct model into DOE-2 input.

From this plot, the amounts of cooling energy use were closer to the measured cooling energy use than the simulation results before duct model was applied to the DOE-2 simulation model. Furthermore, the Coefficient of Variation for the Root Mean Squared Error (CV (RMSE)) was reduced from 40.24% to 25.4 %, and the Normalized Mean Biased Error (MBE) was reduced from -29.10% to -8.25 %.

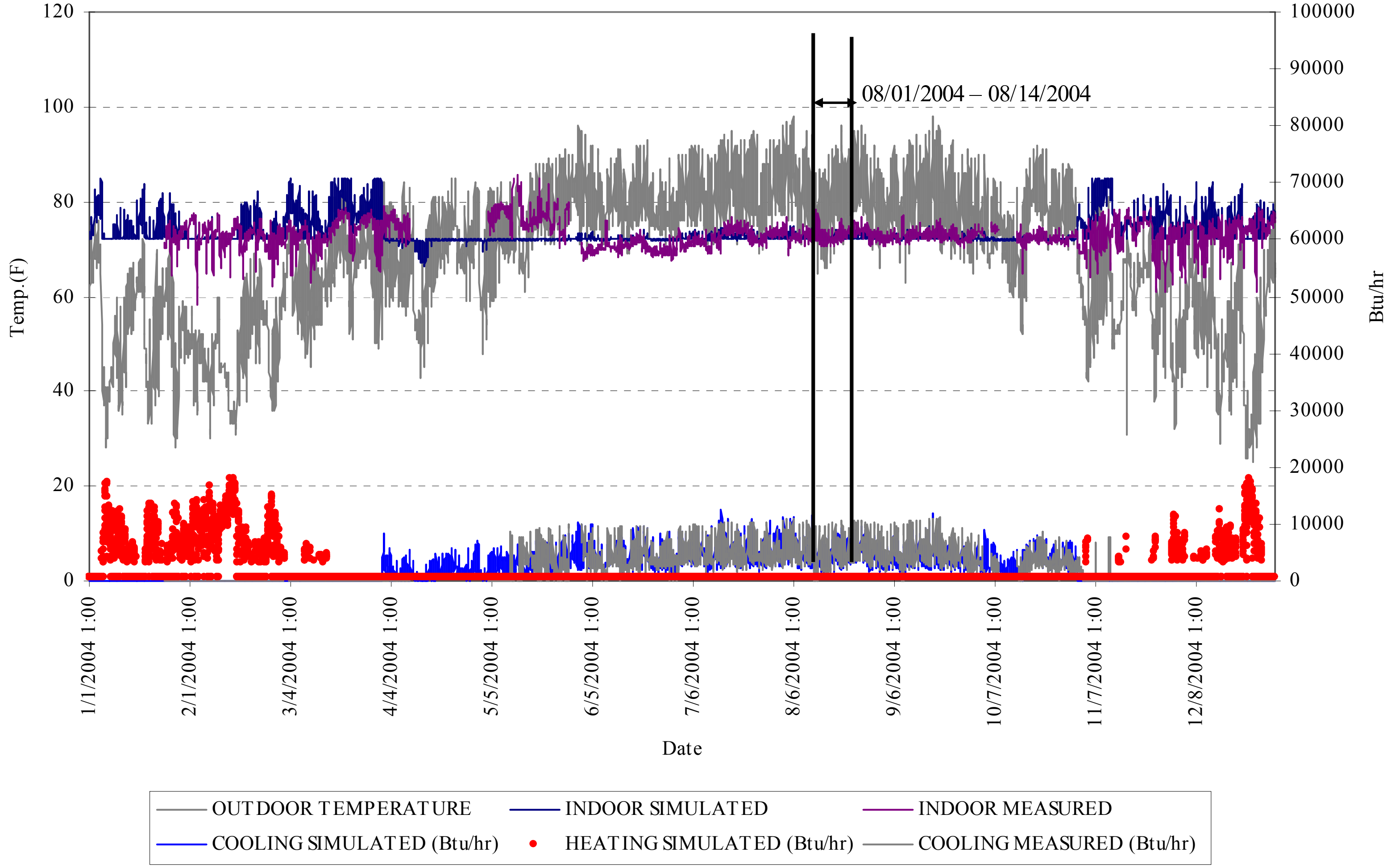
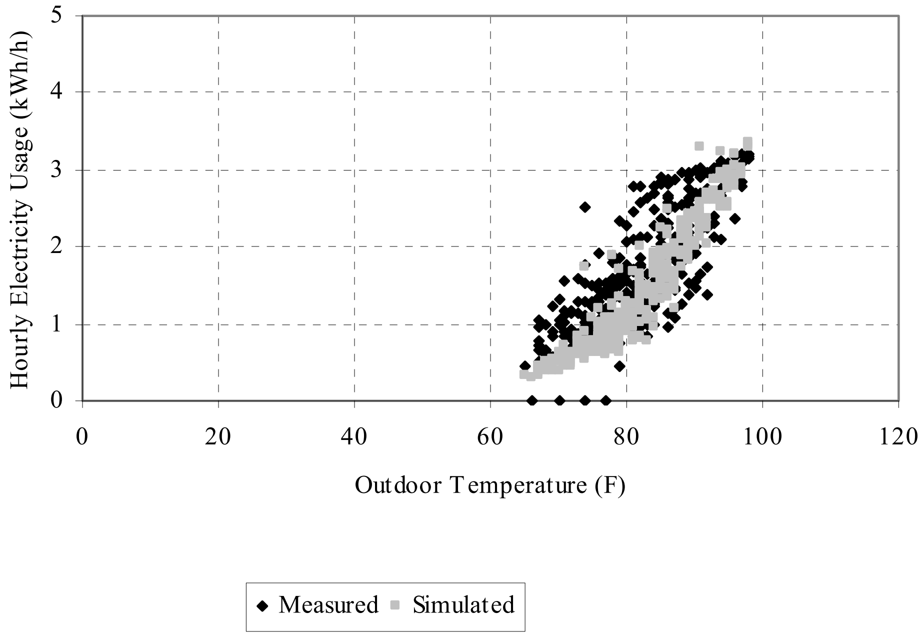


Figure 5.52 Temperature and cooling energy plots with duct model for whole year



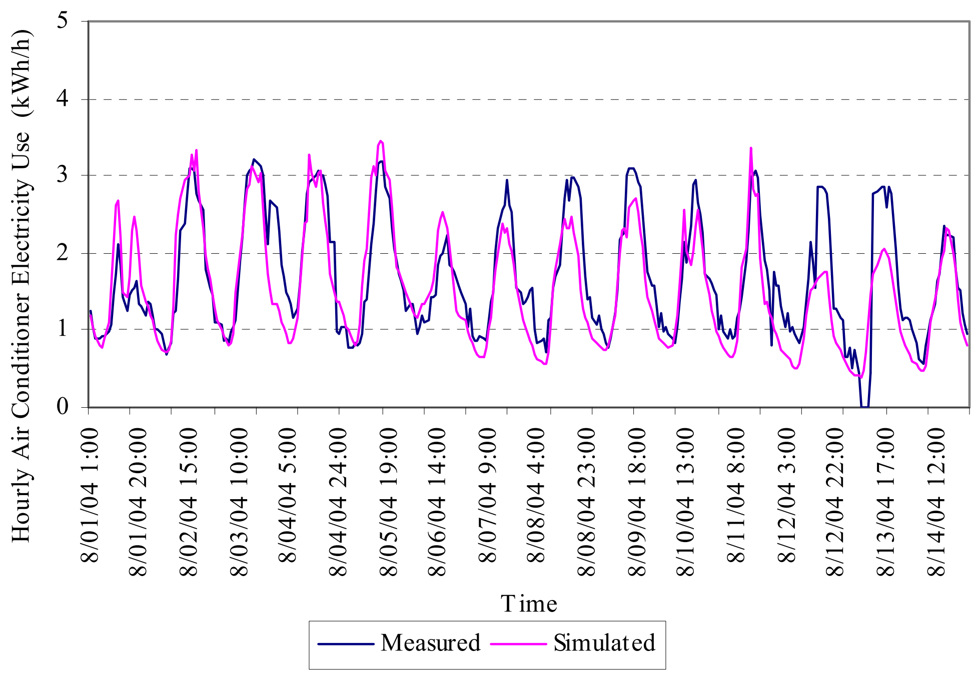


Figure 5.53 Cooling energy plots with duct model for two weeks (08/01/2004 – 08/14/2004)

5.4.2 Application of New A/C Curves

As mentioned in the literature review, Henderson et al. (2000) developed several new, improved part load performance curves for air conditioners in the RESYS (residential air conditioning system) system in DOE-2. According to LBNL (2000), a new AC performance curve was added for DOE-2.1e version 107 that includes Henderson el al.'s different curves to replace the old DOE-2 performance curves. For an additional test, the old AC performance curve (old SDL-C17) was also tested to compare with the new curve (new SDL-C17).

In this chapter, the five AC performance curves, which were introduced at Chapter 4.2.3.4 were simulated to investigate whether there are improvements in the accuracy of the simulation results. Figures 5.54 to 5.58 show two-week plots of the measured data and the calibrated simulation results according to the different types of curves. The maximum measured data for the A/C plus fan was 3.2 kW and the result using the new default curve (new SDL-C17) had the closest maximum values (3.4 kW) compared with the measured data. The poor A/C curve reached to the highest maximum value of 3.7 kW, and the new default A/C curve (new SDL-C17) resulted in the smallest maximum value of 3.4 kW, which is the closest to the measured data. The average electricity consumption of the new default curve (new SDL-C17) was 1.55 kW for the period and the old default curve (old SDL-C17) was 1.79 kW. This indicates that the current A/C system was considered more efficient.

In terms of statistical analysis, the range of the CV (RMSE) was between 24.7 % and 25.4 %, which had little difference among the different curves. In the case of the MBE, the range was between -8.3 % and -0.79 %, and the typical A/C curve from Henerson et al. (2000) had the lowest value (-0.79 %). From the measured data, there were periods of time when the air conditioner electric consumptions dropped to "0" for no apparent reason. In this period, the resident seemed to have shut off the A/C manually, and data from this period made the CV

(RMSE) and the MBE worse, because the schedule of DOE-2 simulation was set to turn on A/C and it calculated the air conditioner electric consumption.

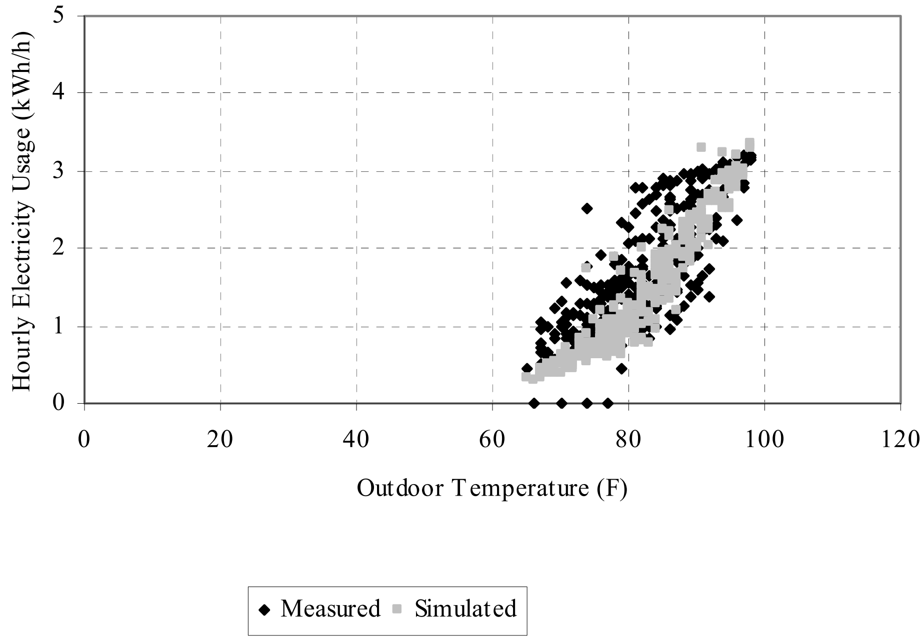
For the base-case house simulation, the typical A/C curve from Henderson et al. (2000) was used because the pattern and the maximum electricity consumption were the most close to the measured consumption and the CV (RMSE) and MBE showed the best results.

5.4.3 Domestic Hot Water Method of National Renewable Energy Laboratory (NREL)

From Figure 5.2, an average base-line gas energy use of 58.2 kBtu/day was observed during the summer months in the case-study house. This gas use represented gas used by the DHW and pilot lights. In the case-study house, pilot lights were found in three locations including the gas-furnace, the DHW heater and the cooking equipment. Table 5.8 shows the possible DHW energy use according to the numbers of pilot lights. The DHW energy use (Btu/year) was calculated by subtracting use of the pilot lights from the base line use of the natural gas. If the gas use of the pilot light is 600 Btu/hr, then the DHW energy use was 15,987,000 which was calculated as 21,243,000 Btu/year - (600 Btu/hr * 8,760 hr/year).

Table 5.8 DHW energy use according to the use of the pilot lights

Pilot light	DHW energy use (Btu/year)
No pilot light	21,243,000
300 Btu/hr	18,615,000
600 Btu/hr	15,987,000
900 Btu/hr	13,359,000



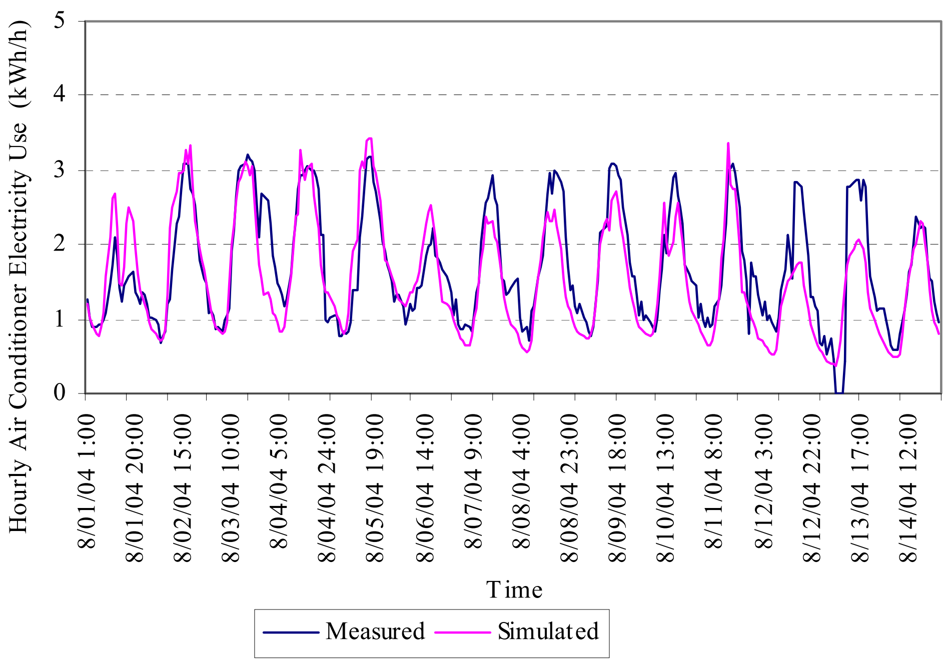
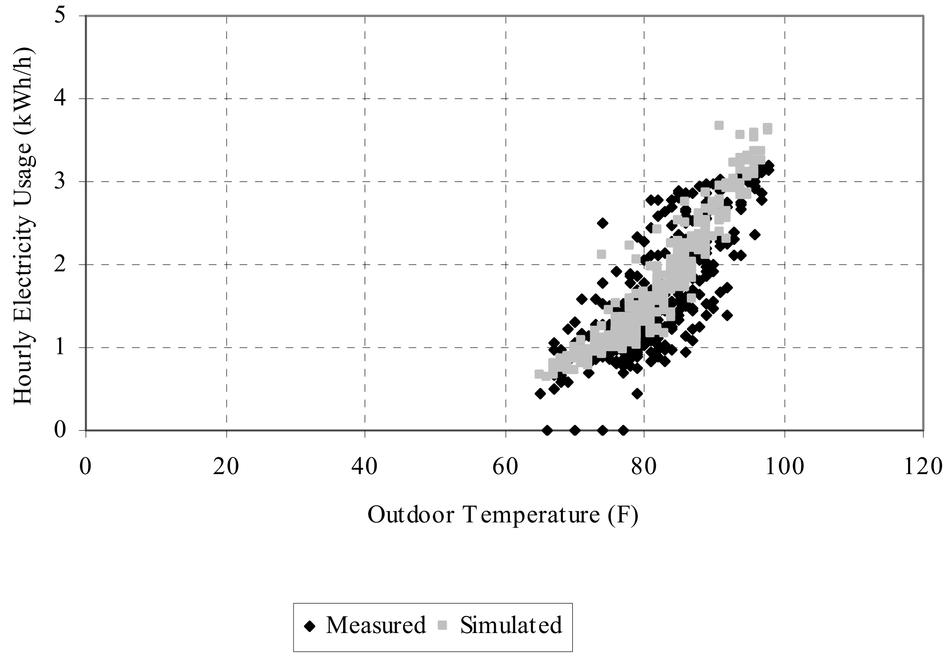


Figure 5.54 Cooling energy with default A/C curve (new SDL-C17)



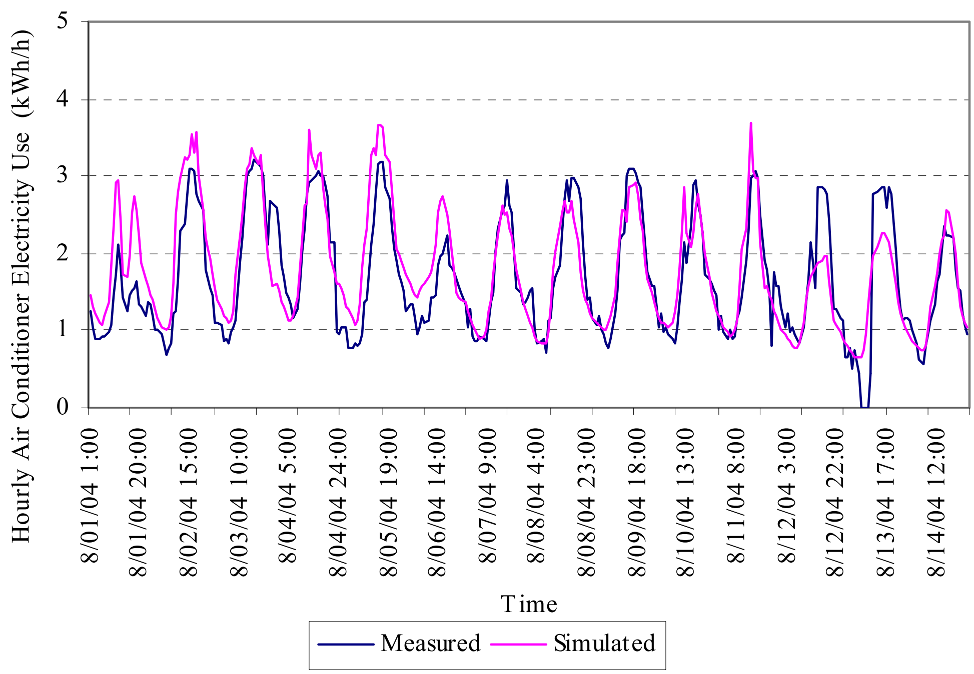
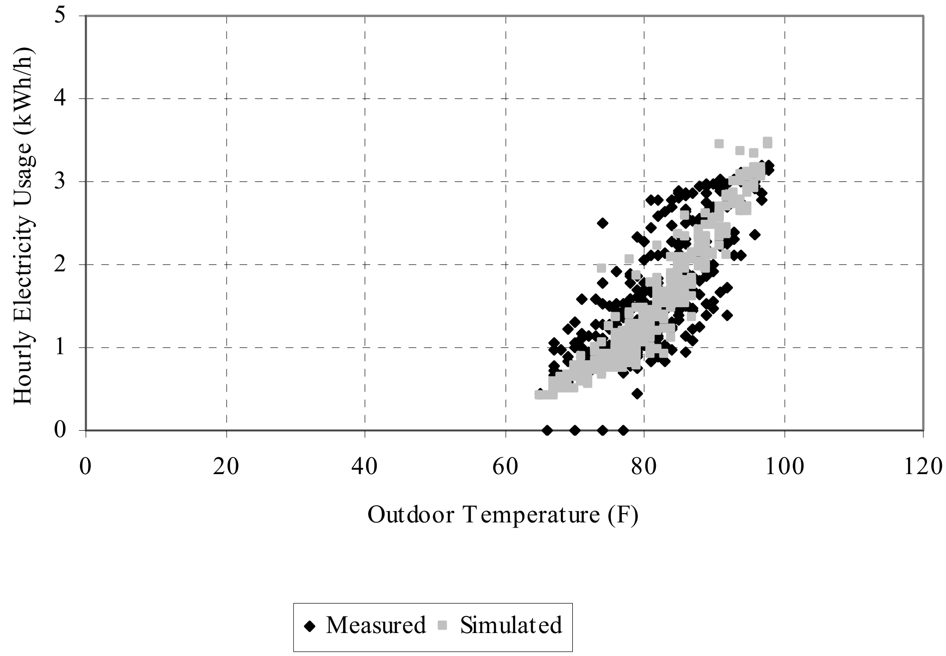


Figure 5.55 Cooling energy with old DOE-2.1e A/C curve (old SDL-C17)



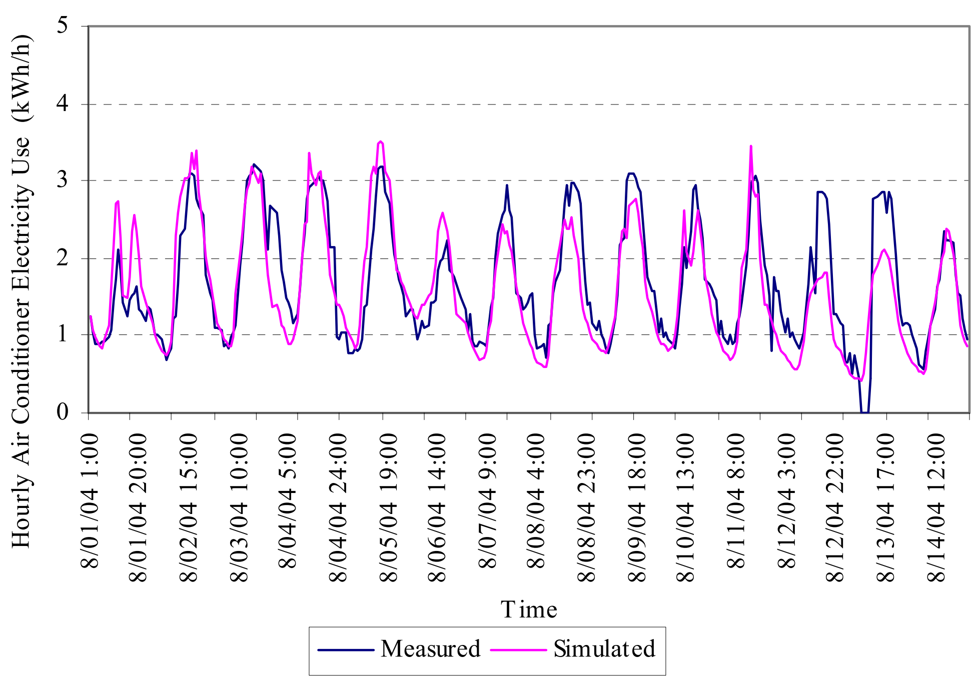


Figure 5.56 Cooling energy with good A/C curve from Henderson et al. (2000)

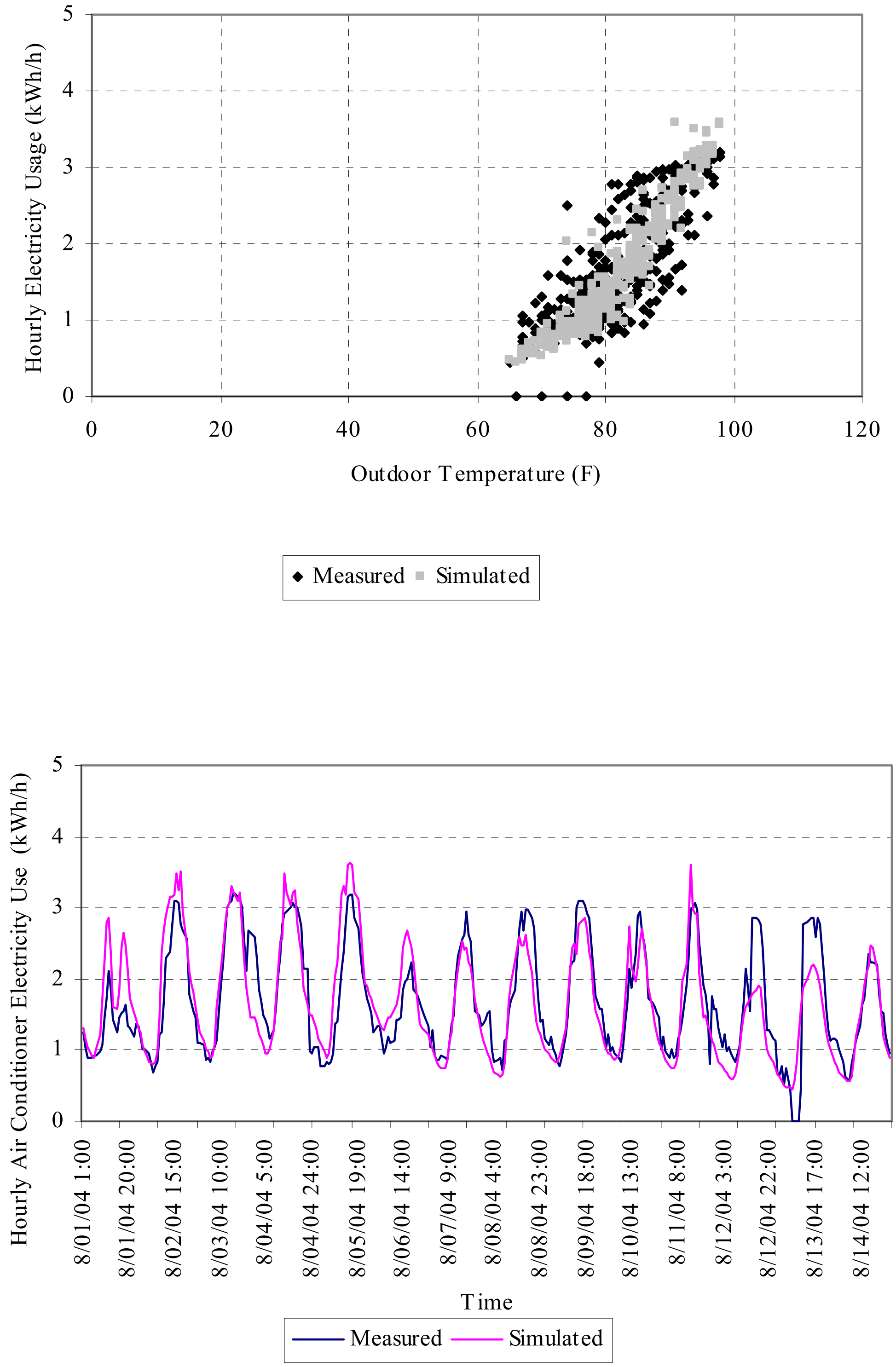
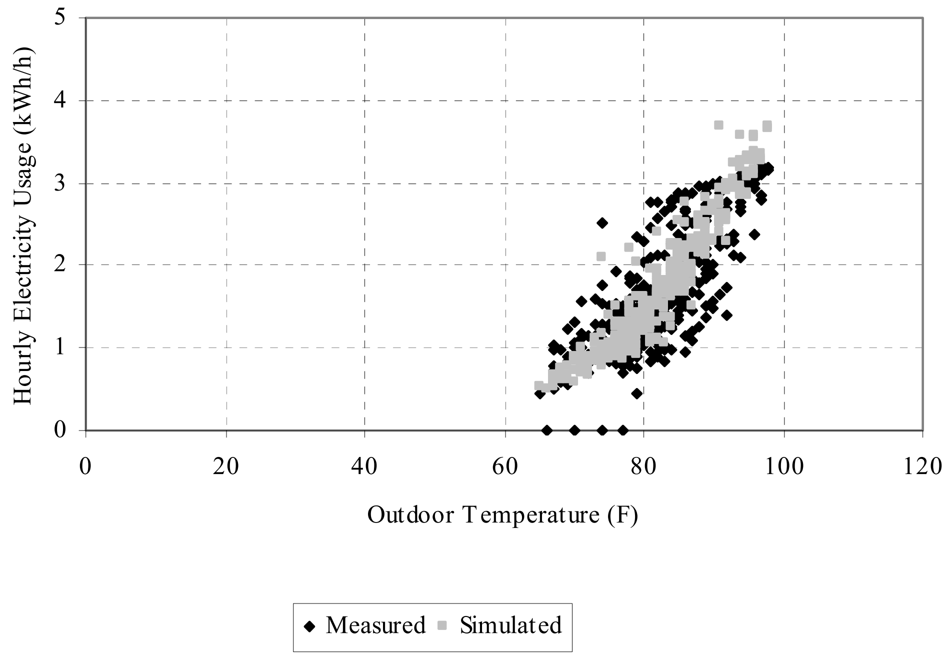


Figure 5.57 Cooling energy with typical A/C curve from Henderson et al. (2000)



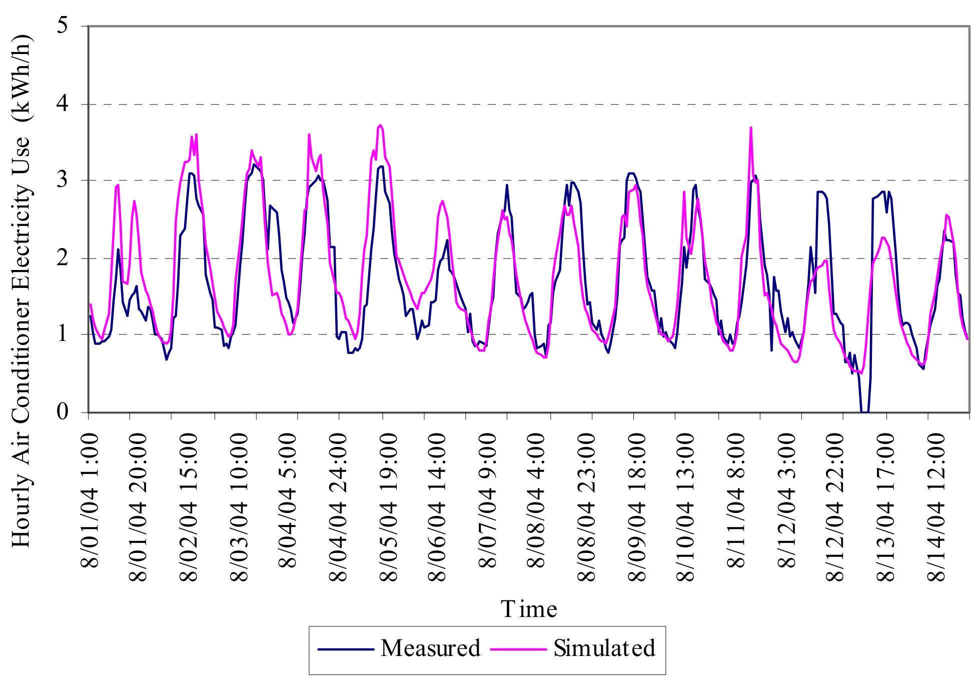


Figure 5.58   Cooling energy with poor A/C curve from Henderson et al. (2000)

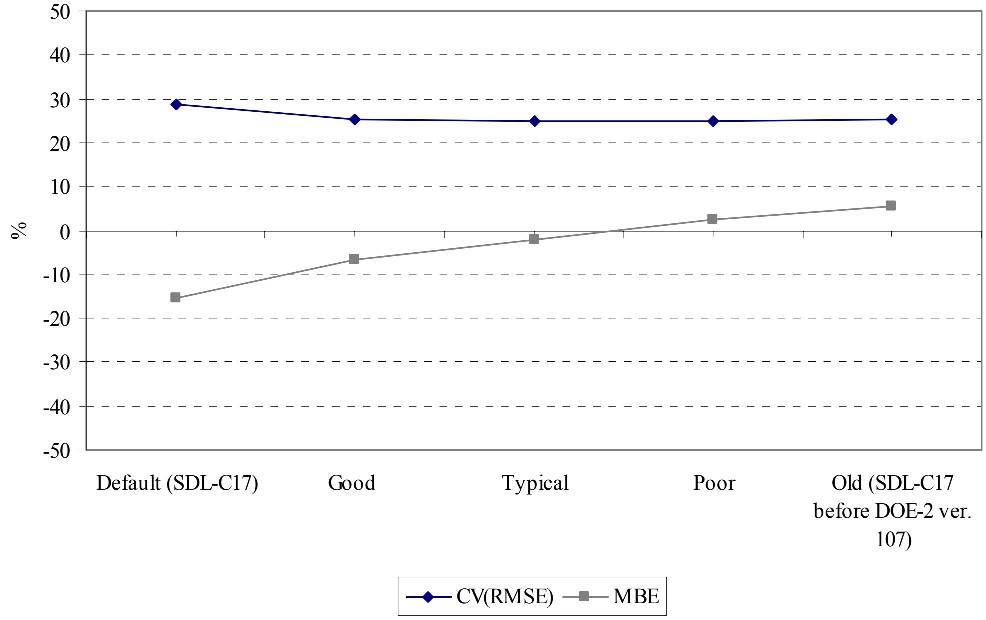


Figure 5.59 CV (RMSE) and MBE according to the different A/C curves

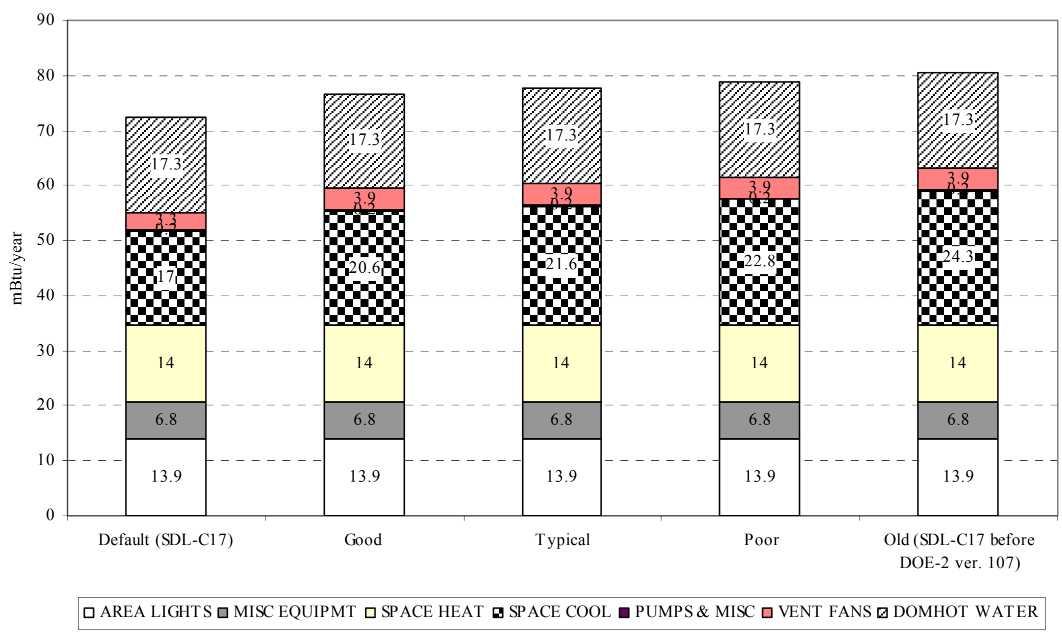


Figure 5.60 BEPS results according to the different A/C curves

The DHW energy use calculated with ASHRAE 90.2-2001, 8.9.2 was previously discussed in Chapter 4.2.3.5. In addition, the DOE-2 simulation results using the NREL method and the DOE-2 default were also discussed in Chapter 4.2.3.5. Table 5.9 shows the comparison results of each calculation method of the DHW energy use according to the different analysis of pilot lights.

Table 5.9 Comparison of DHW energy use (Btu/year)

Pilot light use	DHW use	ASHRAE 90.2-2001, 8.9.2	DOE-2 (NREL)	DOE-2 default
No pilot light	21,243,000	19,439,000	17,300,000	26,500,000
300 Btu/hr	18,612,000			
600 Btu/hr	15,984,000			
900 Btu/hr	13,356,000			

Figures 5.61 to 5.63 show the difference between the measured data and simulation results using the NREL method and the DOE-2 methods. The maximum difference between simulation result using the NREL method and the measured data was 29.5% when the pilot light use was 900 Btu/hr. The other differences were -7.1% for a 300 Btu/hr pilot light use and 8.2% for a 600 Btu/hr pilot light use.

The maximum difference between the ASHRAE 90.2-2001 value and the measured data was 45.6% when the pilot light use was 900 Btu/hr, and 4.5 % and 21.6% when the pilot light use was 300 Btu/hr and 600 Btu/hr, respectively. On the other hand, the previous DOE-2 DHW calculation method with a tank loss of 3% shows quite a large difference between the measured data and the NREL method. When the pilot light used 300 Btu/hr, 600 Btu/hr and 900 Btu/hr, the difference was 42.4%, 65.8% and 98.4%, which were more than three times as large as the NREL method. Furthermore, the comparison using the ASHRAE 90.2-2001 also shows twice as much of difference between the NREL method and the measured data.

This analysis indicates that the previous DOE-2 method with the tank loss over-estimated the DHW energy use. From the simulation results, the calculation using the NREL method was the most reasonable because the results from this method was the closest to the results of both the measured data and the ASHRAE 90.2-2001 calculations.

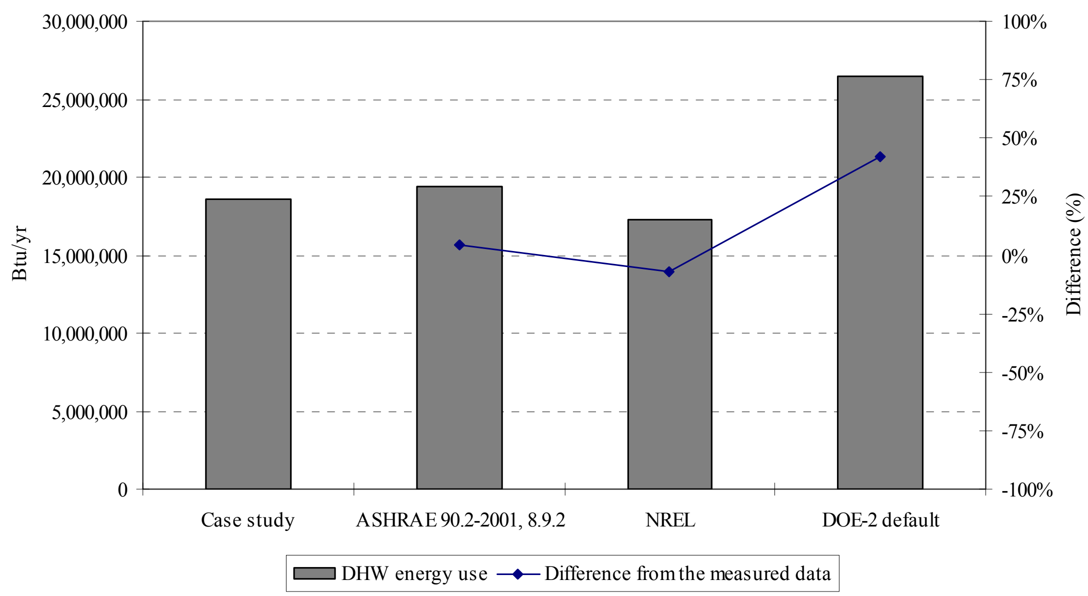


Figure 5.61 Comparison of DHW energy use (pilot light = 300 Btu/hr)

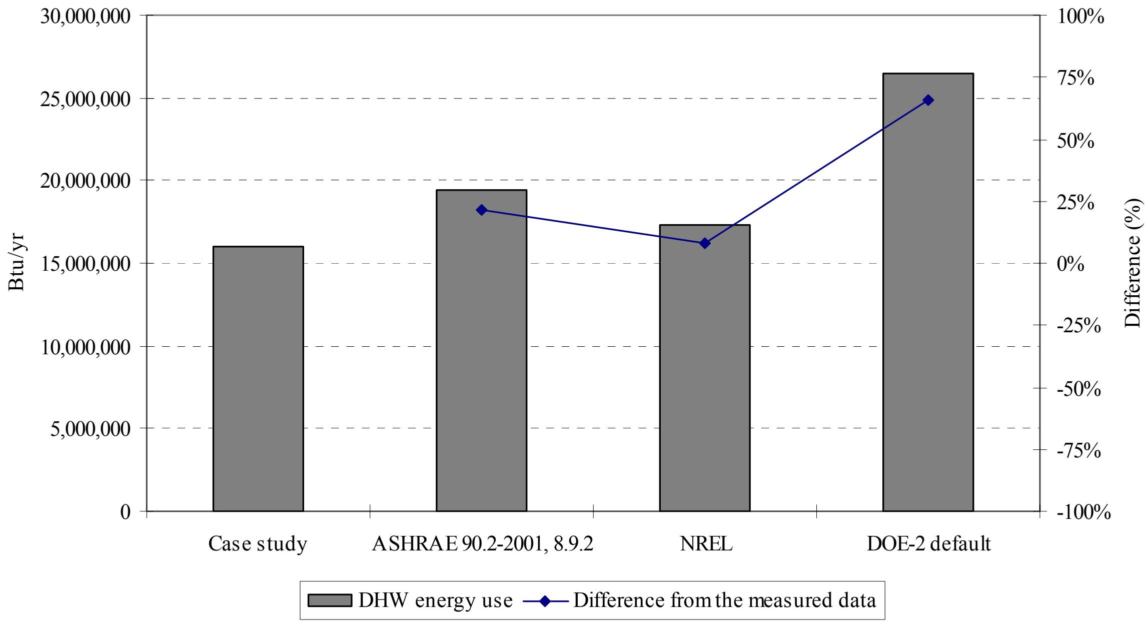


Figure 5.62 Comparison of DHW energy use (pilot light = 600 Btu/hr)

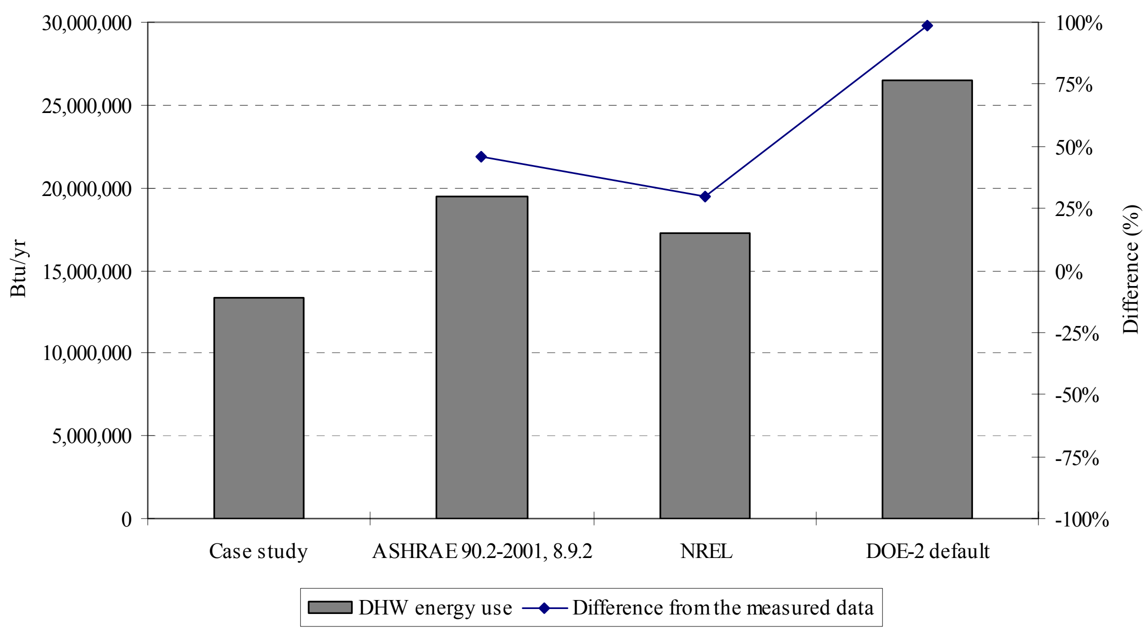


Figure 5.63 Comparison of DHW energy use (pilot light = 900 Btu/hr)

5.4.4 New Heat Flow Method for Underground Surface

In order to investigate a more accurate method to calculate the underground surface heat transfer, several simulations were performed using the DOE-2 program. Detailed methods of the base-case model and the DOE-2 simulation commands were previously discussed in Chapter 4.2.3.6. Since the base-case house has three ground temperature sensors which are located at north, center and south side of the house under the slab of the house, these three measured temperatures were converted to monthly average temperatures and incorporated into DOE-2 simulation using the GROUND-T DOE-2 keyword. Before converting three measured temperatures to the monthly average temperatures, the data verification process of the measured ground temperatures was performed.

As shown in Figures 5.64 and 5.65, the ground temperatures for the summer period fluctuated more than those for the winter period because hot solar radiation for the summer season affected the ground temperatures. Hourly ground temperature plots (Figure 5.66) for August showed obviously that the ground temperatures for the summer period had more fluctuated pattern than those for the winter period for December. In order to investigate the impacts due to the temperature increases because of the temperature fluctuations, two calculations were performed and compared including: 1) the monthly average temperatures before removing the fluctuated peak temperatures (Figure 5.66), and 2) the monthly average temperature after removing the fluctuated peak temperatures (Figure 5.67).

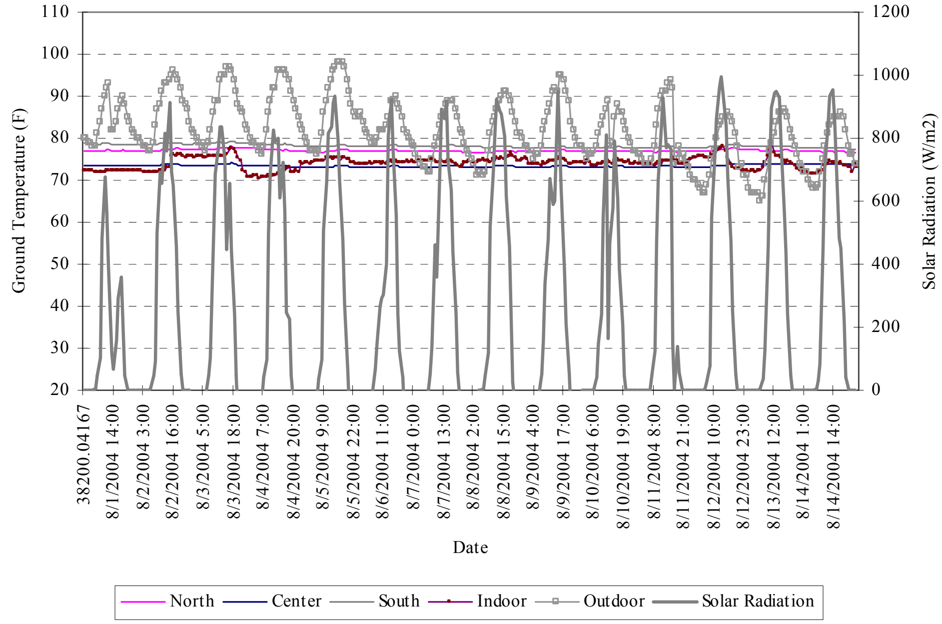


Figure 5.64 Three ground temperatures versus solar radiation for summer period

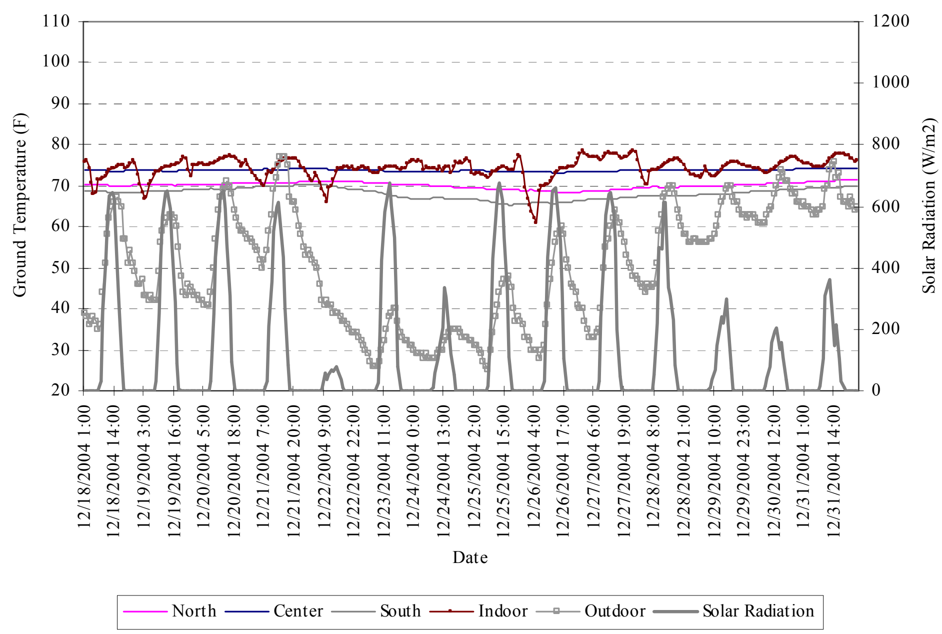
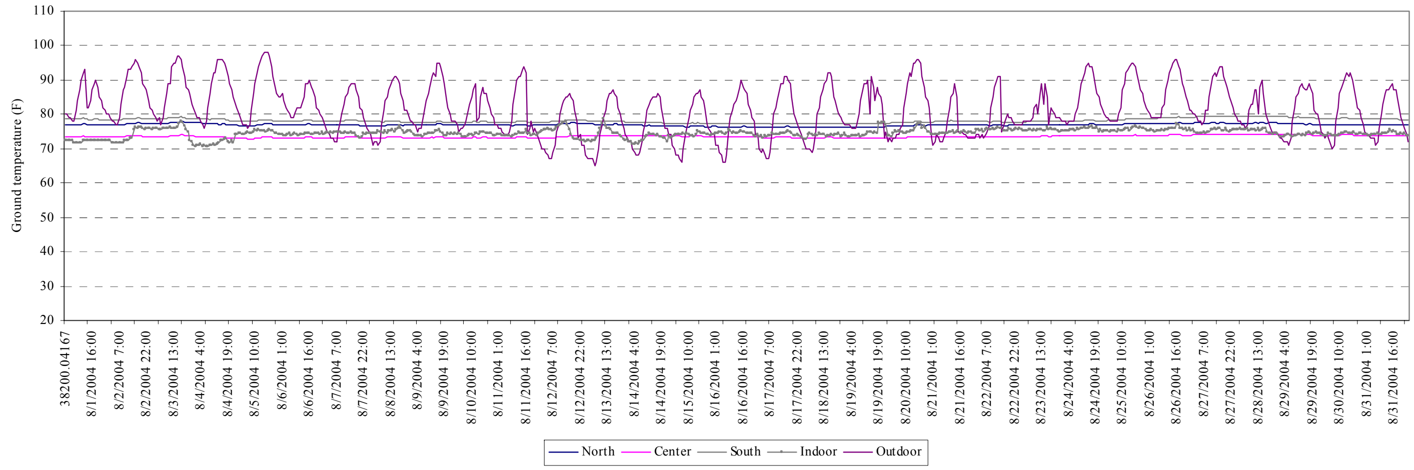


Figure 5.65 Three ground temperatures versus solar radiation for winter period



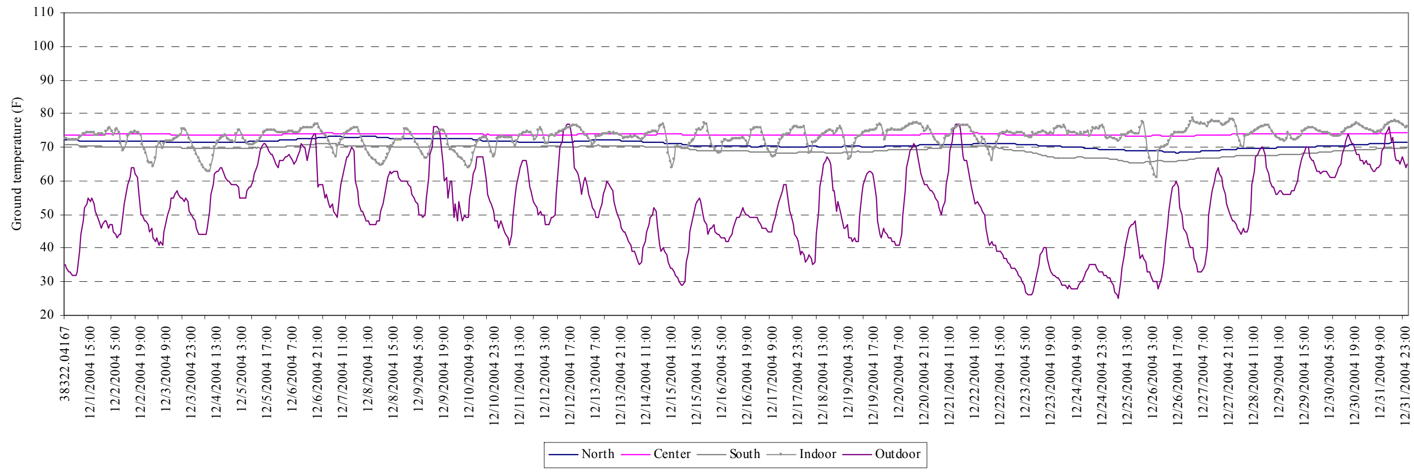


Figure 5.66   Monthly ground temperature plots for summer period (August, left) and winter period (December, right)

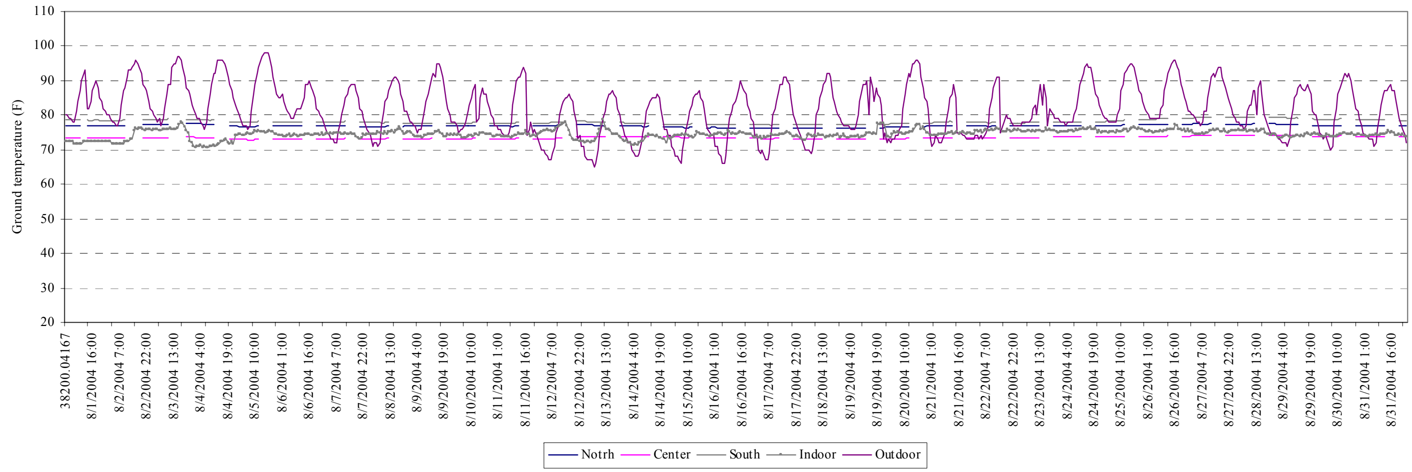


Figure 5.67 Hourly ground temperature plot for summer period (August) after removing the fluctuated peak temperatures.

Table 5.10 showed the average temperatures of August from the calculations of three ground temperatures before and after removing the fluctuated peak temperatures. From this table, it was found that both calculated average temperatures were very similar and the temperature differences between two cases were in the range of 0.02 ºF to 0.05 ºF. Therefore, the monthly average temperatures before removing temperatures were used.

Table 5.10 Monthly average ground temperatures for August before and after removing fluctuated temperature (°F)

Location	Before removing fluctuated temperatures (°F)	After removing fluctuated temperature (°F)
North	76.93	76.91
Center	73.51	73.47
South	78.15	78.10

Figure 5.68 presents the measured monthly ground temperatures (north, center, south and average of north, center and south side), return temperature and TRY ground temperature. From this plot, it was found that the center ground temperature showed lower for June, July, August and September for space cooling and higher temperature for January, February, November and December for space heating. Furthermore, the center ground temperature showed the similar pattern with the return temperature in the conditioned space.

In addition, for the summer period, the solar heat gain seemed to make the south side ground temperatures higher than the north side ground temperatures. However, for the winter period, the north side ground temperatures was slightly higher than the south side ground temperature, because the heating air from the HVAC system affected the north side ground temperature under the living room, which was close to the main entrance, while the heating air hardly reached to spot above the south side ground temperature sensor which was located under the closet between the bedrooms on the south side.

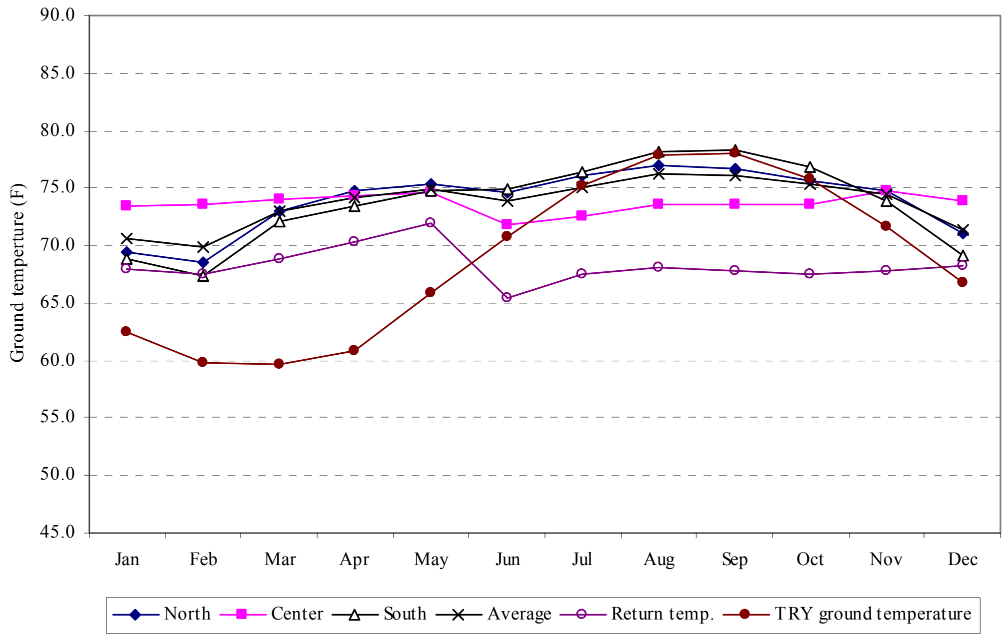


Figure 5.68 Measured ground temperatures

Simulations for underground surface included several methods: 1) with U-EFFECTIVE, with the ground temperature from a packed TRY weather tape with weather data corresponding to the measured energy use, 2) without U-EFFECTIVE, with the ground temperature from the packed TRY weather tape, 3) with U-EFFECTIVE, with the ground temperature from the measured north ground temperature, 4) with U-EFFECTIVE, with the ground temperature from the measured center ground temperature, 5) with U-EFFECTIVE, with the ground temperature from the measured south ground temperature, and 6) with U-EFFECTIVE, with the ground temperature from the measured average ground temperature (i.e., the average of north, south and center). Table 5.11 presents the simulation conditions with and without U-EFFECTIVE, and the run numbers which appear on Figures 5.69 to 5.74.

The comparison of the simulated monthly energy use from the six simulations and the measured data from the case-study house was performed to find the most accurate method. Figures 5.69 to 5.71 showed the results of monthly natural gas use from the six simulations and from the case-study site data. Figures 5.72 to 5.74 show the results of the monthly electricity use. Data presented in the figures were in the unit of energy use per month.

Table 5.11 Simulation conditions of underground heat transfer

Run No.	Description
1.	Measured data from the case-study house.
2.	Simulation with U-EFFECTIVE, with TRY ground temperature.
3.	Simulation without U- EFFECTIVE, with TRY ground temperature.
4.	Simulation with U- EFFECTIVE, with measured north ground temperature.
5.	Simulation with U- EFFECTIVE, with measured center ground temperature.
6.	Simulation with U- EFFECTIVE, with measured south ground temperature.
7.	Simulation with U- EFFECTIVE, with measured average ground temperature.

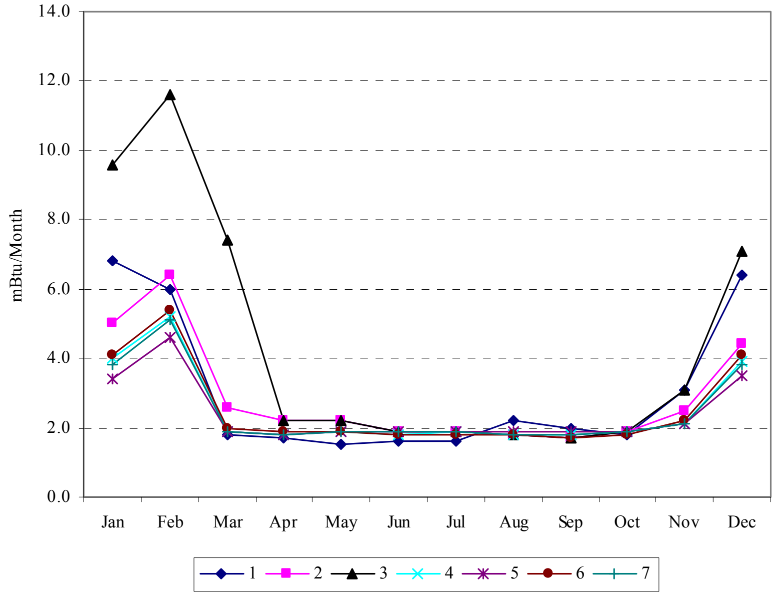


Figure 5.69 Monthly natural gas use from the measured data of the case-study house and DOE-2 simulations

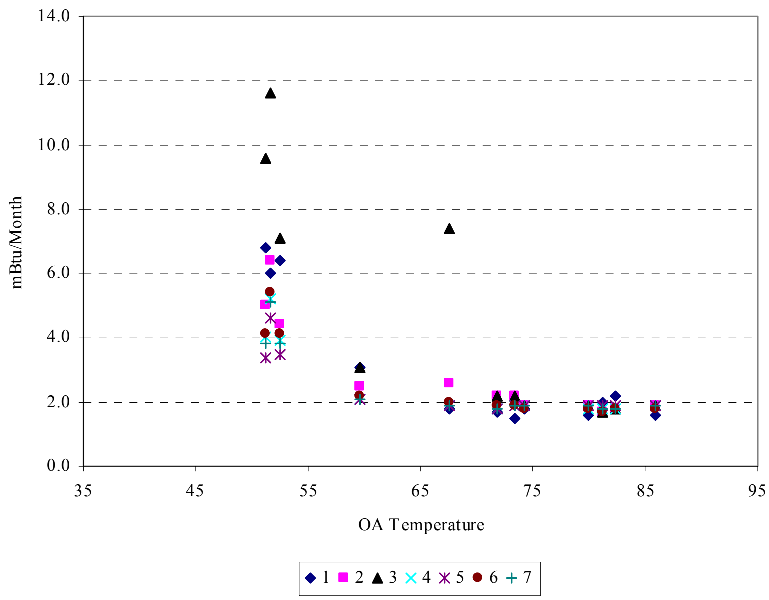


Figure 5.70 Monthly natural gas use from the measured data of the case-study house and DOE-2 simulations vs. average monthly outdoor temperature

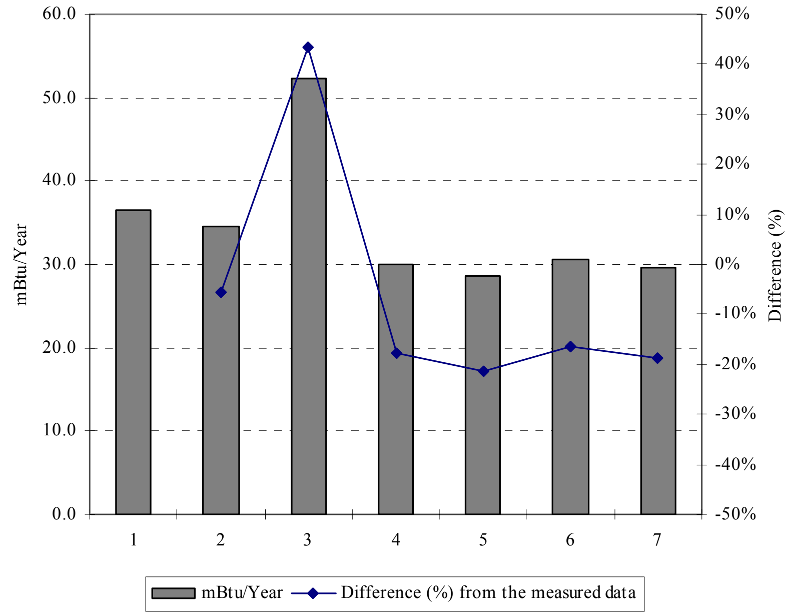


Figure 5.71 Total natural gas use and the difference from the measured data

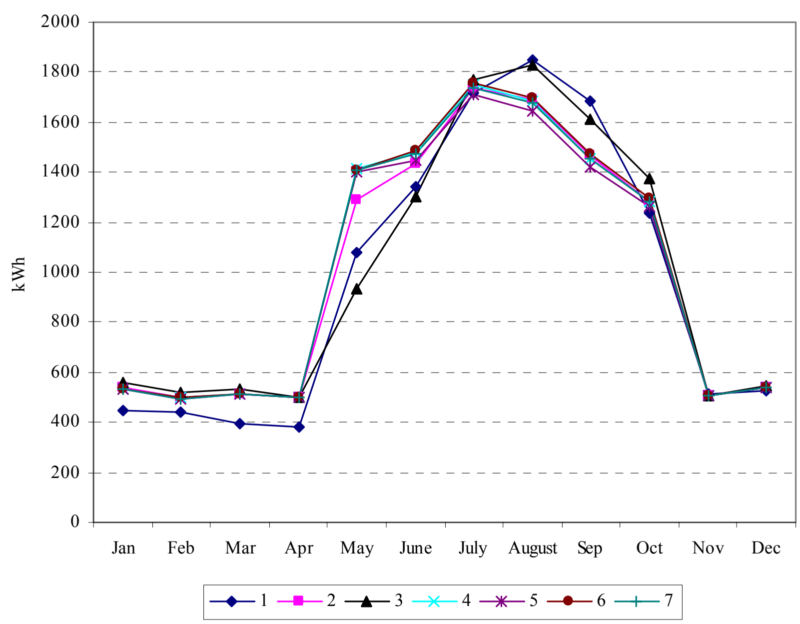


Figure 5.72 Monthly electricity use from the measured data of the case-study house and DOE-2 simulations

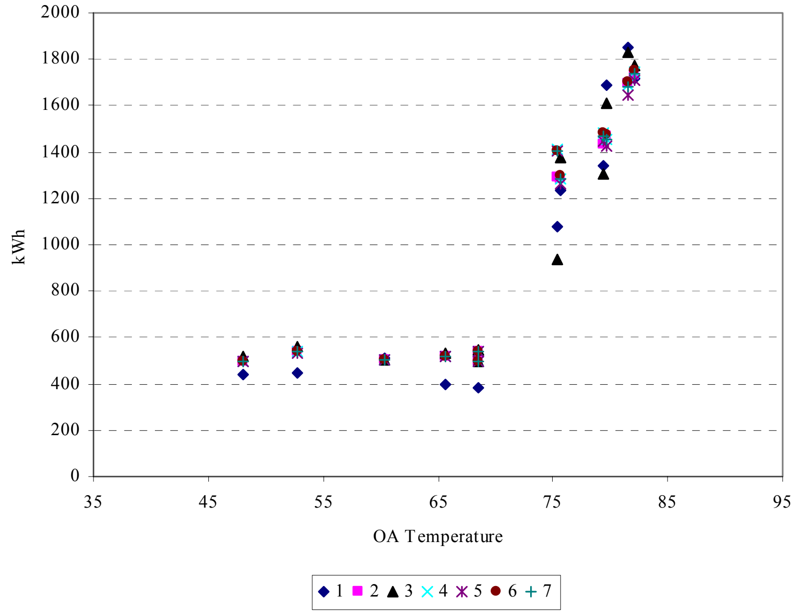


Figure 5.73 Monthly electricity use from the measured data of the case-study house and DOE-2 simulations vs. average monthly outdoor temperature

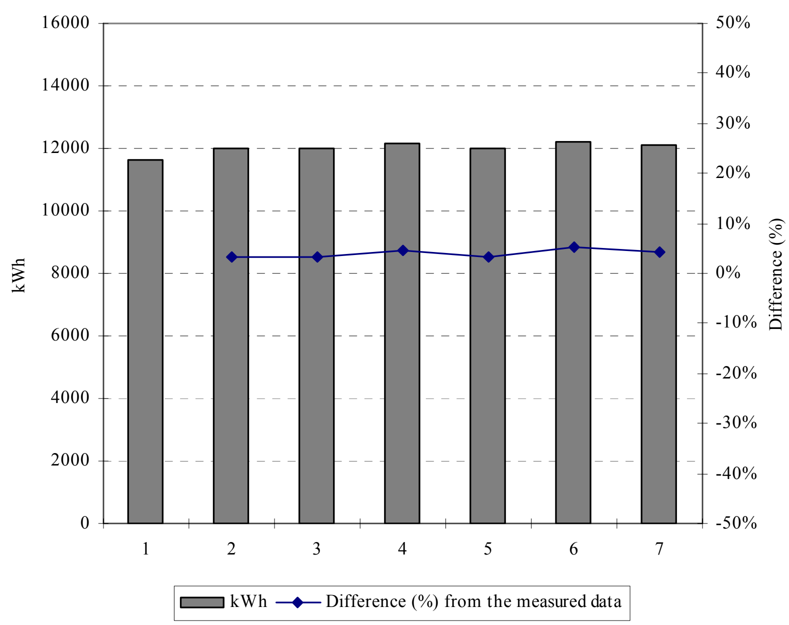


Figure 5.74 Total electricity use and the difference from the measured data

As seen from the figures above, there were significant changes between simulating the model using the U-EFFECTIVE versus the simulations without U-EFFECTIVE. Results show that monthly gas use from simulation with U-EFFECTIVE and TRY ground temperatures (run no. 2) was close to the measured data, and obviously lower than the gas uses using the previous method without U-EFFECTIVE, although there was not a significant difference of electricity uses according to each simulation method. The simulation with U-EFFECTIVE and ground temperature from TRY weather file shows the least difference (-5.5%) from the measured gas use from the case-study house, and simulation result using the previous method without U-EFFECTIVE shows the largest difference (43.6%). In the case of the electricity use, the simulation with U-EFFECTIVE and ground temperature from TRY weather file and simulation with the previous method show the least difference (3.3 %). However, none of simulation methods made a significant difference toward improving the simulation results of the electricity use of the case-study house.

In terms of statistical analysis (from Figures 5.75 to 5.77), for the natural gas uses (Figure 5.75), the CV (RMSE) was 30.68% and the MBE was -5.98% for run no. 2, which was simulation with U-EFFECTIVE and TRY ground temperatures. This run showed the closest to the measured data. In run no. 3 which was simulation without U-EFFECTIVE, the CV (RMSE) was 84.25% and the MBE was 47.52%, which showed the largest CV (RMSE) and MBE.

For the electricity uses (Figure 5.76), there was no significant improvement, but statistically accepted for all runs. The CV (RMSE) was in the range of 10.0 % and 16.1% and the MBE was in the range of 3.47 % and 5.57 %.

For the total energy use (Figure 5.77), the run no. 2, which was simulation with U-EFFECTIVE and TRY ground temperatures showed the least CV (RMSE) and MBE as the natural gas uses. The CV (RMSE) was 17.54% and the MBE was -0.97. In the run no. 3, which was simulation without U-EFFECTIVE, the results showed the largest CV (RMSE) and the MBE, which was 43.54% and 24.65%, respectively. In addition, although the simulations with U-EFFECTIVE and the measured temperatures (from run no. 4 to run no. 7) showed the more reasonable results than the simulation results without U-EFFECTIVE, the simulation with the U-EFFECTIVE and TRY ground temperatures showed the best results.

These results do suggest that the use of U-EFFECTIVE in defining the underground surface heat transfer makes a significant difference in improving the accuracy of the simulation of the case-study house.

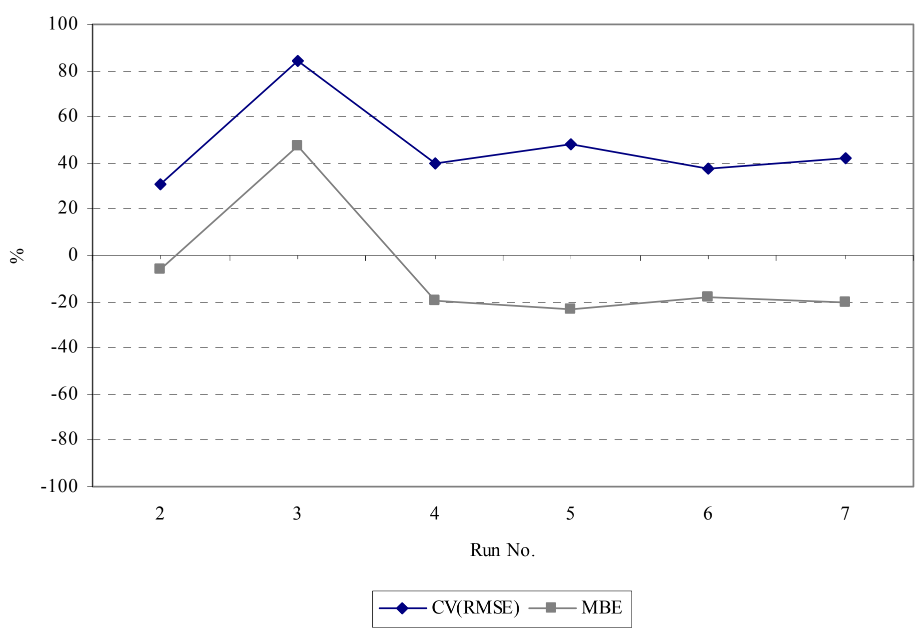


Figure 5.75 CV (RMSE) and MBE of natural gas uses

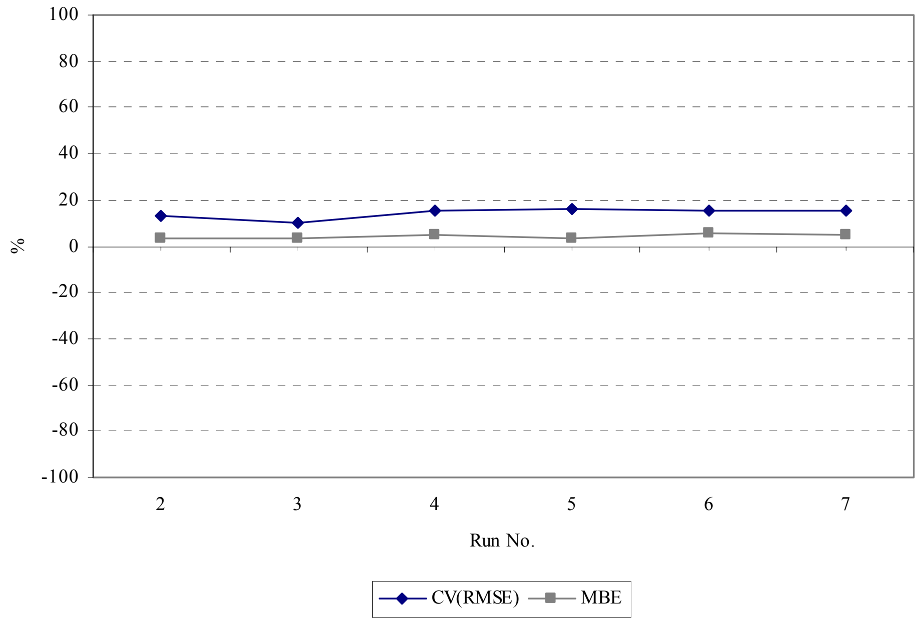


Figure 5.76 CV (RMSE) and MBE of electricity uses

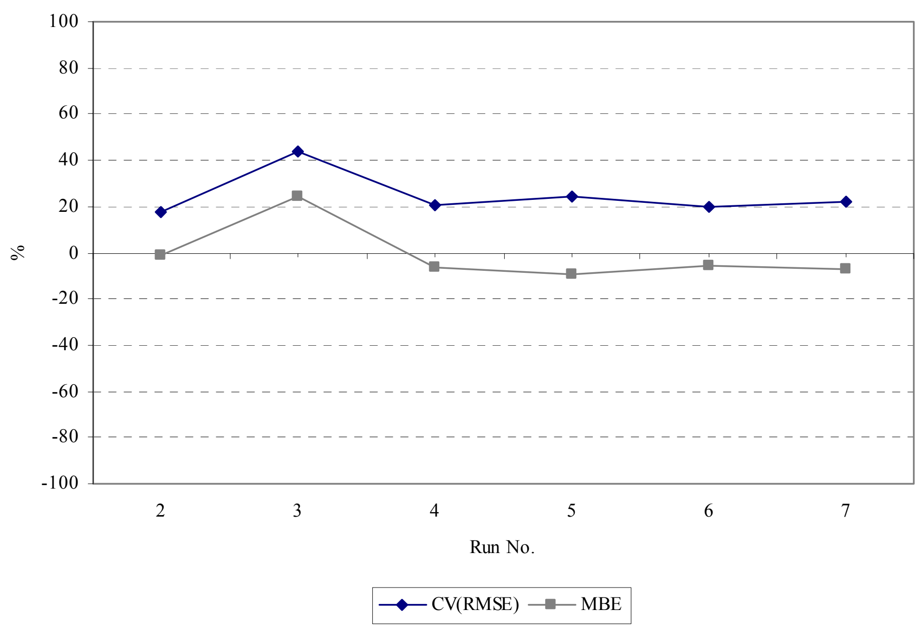


Figure 5.77 CV (RMSE) and MBE of total energy uses

5.5 Summary

This chapter has presented the results of the simulation of the case-study house including the calibration of the base-case model against the measured data. This chapter also showed how new improved simulation methods such as a duct model, improved system performance curves, an improved domestic hot water model, and an improved underground heat transfer model were utilized and incorporated into the base-case simulation model to improve the case-study simulation model. In order to verify the results from the simulation, the statistical method of the CV (RMSE) and the MBE were used to compare the results with the measured data from the case-study house.

CHAPTER VI

RESULTS OF THE SIMULATION OF THE IECC-COMPLIANT HOUSE

6.1 Analysis of Results

As discussed in Section 4.3.6.6, simulations were performed for seven construction wall types (Table 6.1): 1) a quick mode wall that uses U-values instead of the layered materials, 2) a 2x4, wood-framed wall with studs 16” O.C. with insulation between the studs, 3) a 3” facia brick wall with 2x4 wood-framed with studs 16” O.C. with insulation between the studs, 4) an 8” concrete block wall with perlite fill in the cells of the block and insulation between the block and the interior gypsum board, 5) an 8” concrete block wall with perlite and concrete fill in the cells of the block and insulation between the block and the interior gypsum board, 6) an 8” concrete block wall with perlite fill in the cells of the block and insulation outside the block, covered by stucco, and 7) an 8” concrete block with perlite and concrete fill in the cells of the block and insulation outside the block, covered by stucco. The primary purpose of this exercise was to investigate the thermal mass effect according to the 2000/2001 IECC.

Table 6.1 Different construction types for each simulation

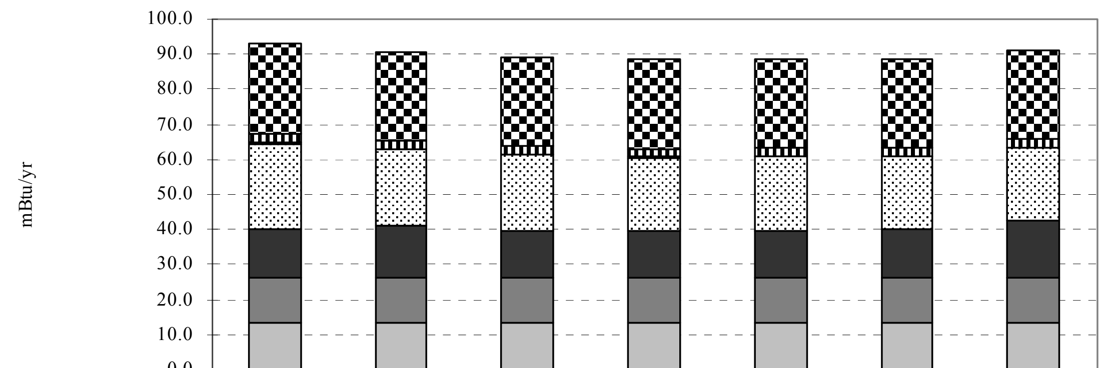
No	R-value hr-ft^2-°F/Btu	Uw Btu/ hr-ft^2-°F	Heat Capacity Btu/ft^2-°F	Insulation	DOE-2 calc. method	Description
1	13.0	0.076	N/A	N/A	Quick	Quick construction mode
2	13.0	0.077	4.39	Center	CWFs	Asbestos-vinyl tile + Plywood + Insulation + Stud + Gypsum board
3	11.0	0.091	8.05	Inside	CWFs	3" Face Brick + Plywood + Insulation + Gypsum board
4	11.1	0.090	7.94	Inside	CWFs	8" Block with perlite filled + Insulation + Gypsum board
5	11.1	0.090	10.77	Inside	CWFs	8" Block with perlite and concrete filled + Insulation + Gypsum board
6	7.8	0.129	10.87	Outside	CWFs	Stucco + Insulation + 8" Block with perlite filled + Stud + Air + Gypsum board
7	7.7	0.130	13.68	Outside	CWFs	Stucco + Insulation + 8" Block with perlite and concrete filled + Stud + Air + Gypsum board

6.2 Thermal Mass Analysis

Figure 6.1 shows the annual energy consumption from the simulations using DOE-2's Building Energy Performance Summary (BEPS) report. The number on the figure corresponds to the number on Table 6.1 for all the construction types. Figure 6.2 shows the difference between the quick construction mode (#1) and the delayed construction mode (from #2 to #7), and Figure 6.3 shows the difference between without high thermal mass wall which is less than 6 Btu/ft^2-°F of heat-capacity and with high thermal mass wall which is more than 6 Btu/ft^2-°F of heat-capacity from the delayed construction mode.

In order to compare the thermal mass effect, the typical wood frame wall (#2) which has the same U-value with the quick construction mode (#1) was created. The detail calculation method of the U-value was presented at the Chapter 4.3.6.6.2. From the simulation results (#1 and #2) (Figure 6.2), it was observed that the quick construction mode shows more annual energy consumptions from 92.9 mBtu to 90.7 mBtu, which is a 2.4% difference even though the models had the same U-value in the walls. This shows that the quick mode construction mode over-states the annual energy use. The reason for this is complex. However, one of the primary observed reasons is that the quick (i.e., ASHRAE pre-calculated weighting factors) method requires additional heating and cooling to maintain thermostat settings.

In terms of the total annual energy use, the #4 wall type (an 8" concrete block wall with perlite fill in the cells of the block and insulation (R-5.21) between the block and the interior gypsum board) was the most efficient wall type, even though the R-value of the #4 wall type was less that the of the typical wood frame wall (#2). It was also found that the high thermal mass wall type #7 with external insulation (R-3.33) had the most annual energy consumption, slightly higher than the typical wood frame wall.



	1(92.9)	2 (90.7)	3 (89.3)	4 (88.4)	5 (88.8)	6 (88.8)	7 (91.1)
DOMHOT WATER	25.5	25.5	25.5	25.5	25.5	25.5	25.5
VENT FANS	2.6	2.3	2.3	2.2	2.2	2.2	2.2
PUMPS &MISC	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SPACE COOL	24.7	21.8	21.5	21.1	21.2	20.9	20.8
SPACE HEAT	13.5	14.5	13.4	13.0	13.3	13.6	16.0
MISC EQUIPMT	13.2	13.2	13.2	13.2	13.2	13.2	13.2
AREA LIGHTS	13.2	13.2	13.2	13.2	13.2	13.2	13.2

AREA LIGHTS ■ MISC EQUIPMT ■ SPACE HEAT ■ SPACE COOL ■ PUMPS & MISC ■ VENT FANS ■ DOMHOT WATER

Figure 6.1 Total energy use

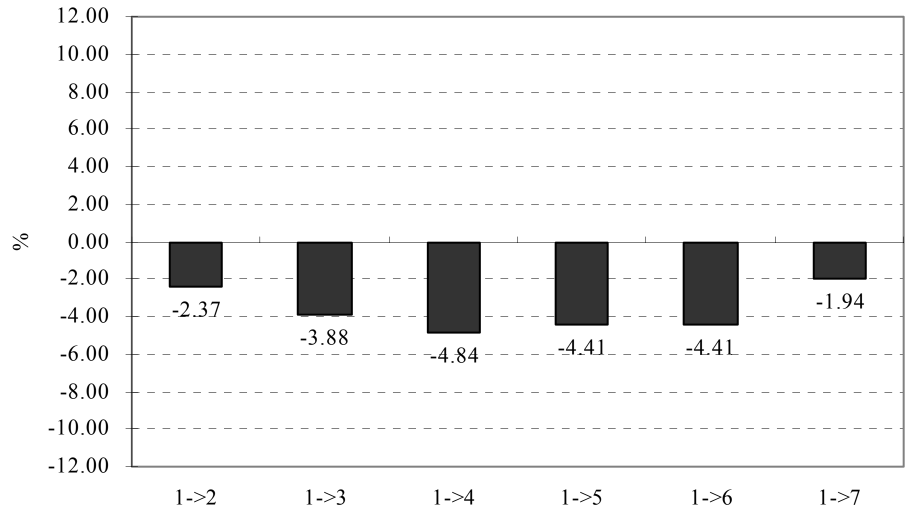


Figure 6.2 Annual energy consumption difference between quick mode and thermal mass modes

Figures 6.3 to 6.5 show the percent difference in annual energy consumption, cooling energy consumption, and heating energy consumption in simulations without high thermal mass wall (#2) and simulations with high thermal mass wall (#3 to #7). In addition, the different insulation levels were applied to high thermal mass walls according to the location of the insulation (exterior and interior) as explained at the Chapter 4.3.6.6, since the 2000/2001 IECC (Table 502.2.1.1.2(1) and 502.2.1.1.2(2)) provides for different requirements. From Figures 6.3 to 6.5, the following observations were made:

1) In Figure 6.3, it was found that the high thermal mass wall type #4 with the interior insulation (R-5.21) had the least annual energy consumptions of 88.4 mBtu/yr, which decreased by 2.5% from the typical wood frame wall (90.7 mBtu/yr). Both wall types were simulated with DOE-2's Custom Weighting Factors (CWFs), and layered walls and Winkelmann's (1998) floor model for a slab-on-grade. The high thermal mass wall type #7 with exterior insulation (R-3.33) had almost

similar annual energy consumption (91.1 mBtu/yr) as the typical wood frame of with R-13 (90.7 mBtu/yr). This implies that the a appropriate combination of heat capacity and correctly-placed R-value is important because a lower R-value can have the same annual energy use as a larger R-value if there is proper heat-capacity of the building materials and if the insulation is properly placed.

2) It was found that from Figure 6.4 that the high thermal mass wall type #7 was the most efficient in terms of the cooling energy savings. This wall type has the largest heat capacity and the smallest R-value of the other high thermal mass wall types. This shows that the heat capacity of the building materials can play a significant role in reducing the cooling energy consumption.

3) From Figure 6.5, it was found that the high thermal mass wall type #4 was the most efficient in terms of the heating energy savings. This wall type has the highest R-value and the smallest heat capacity among other high thermal mass wall type. This implies that a high R-value with low heat capacity of the building materials can be crucial to reducing the heating energy consumption.

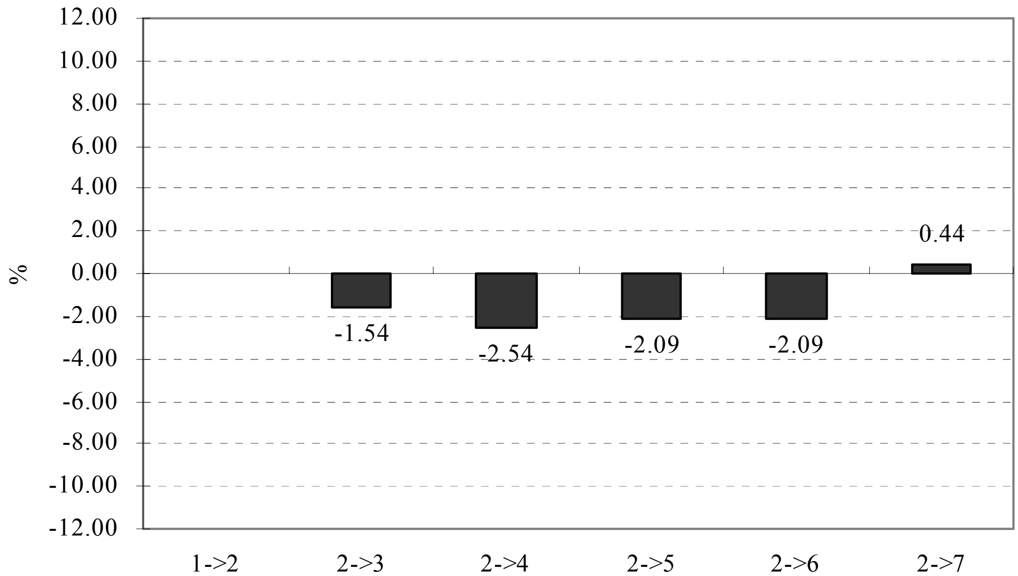


Figure 6.3 Annual energy consumption difference between thermal mass modes

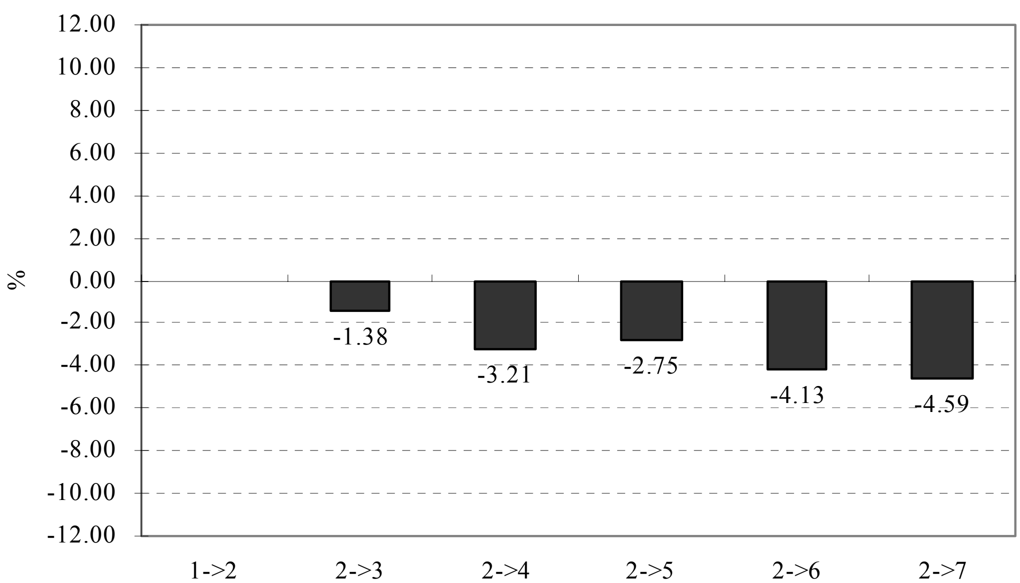


Figure 6.4 Cooling energy consumption difference between thermal mass modes

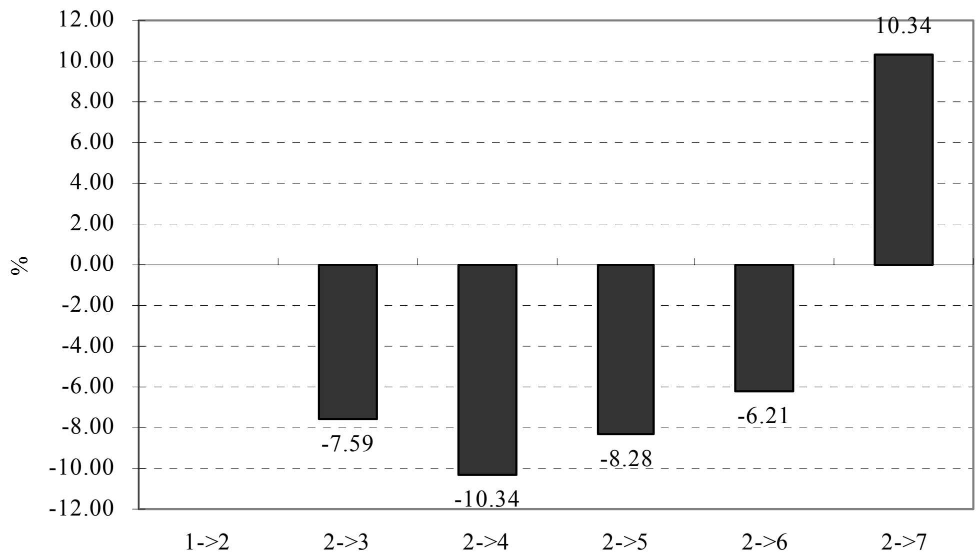
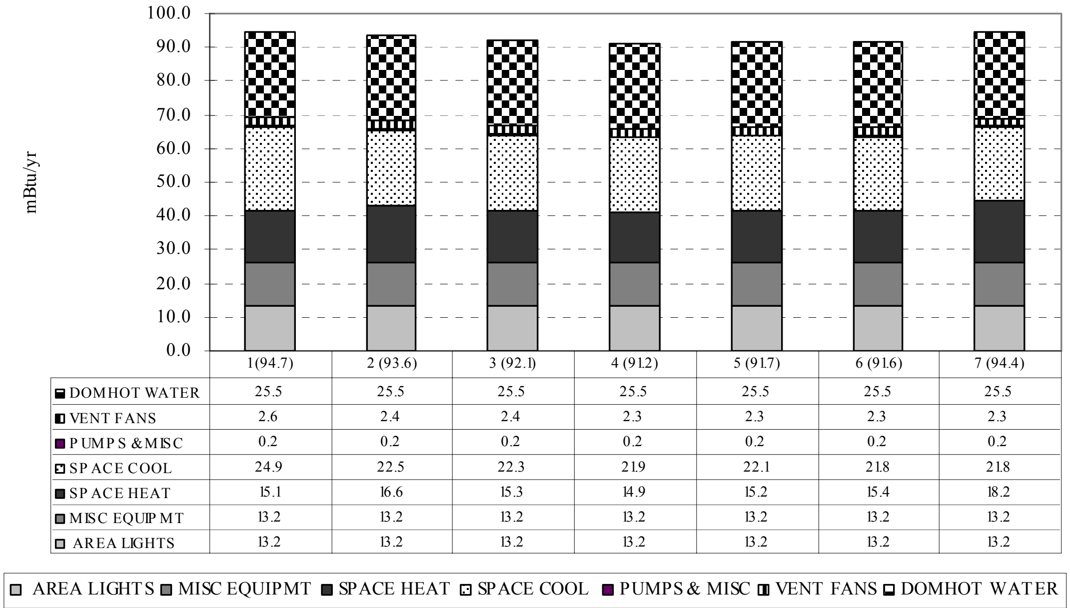


Figure 6.5 Heating energy consumption difference between thermal mass modes

Since the IECC defines the thermostat setback (6 hours setup and setback to 63°F from 68°F winter set-point temperature for heating and 83°F from 78°F summer set-point temperature for cooling), simulations for thermal mass effect analyses were performed using thermostat setback. In order to investigate the effects of thermostat setback, simulations without thermostat setback were performed.

From the simulation results of #1 and #2, which have the same U-value (Figures 6.6 and 6.7), it was found that the quick construction mode (#1) shows more annual energy consumptions from 94.7 mBtu to 93.6 mBtu, which is a 1.2% difference. In terms of the total annual energy use, the #4 wall type (an 8” concrete block wall with perlite fill in the cells of the block and insulation (R-5.21) between the block and the interior gypsum board) was the most efficient wall type, and the #7 wall type with exterior insulation showed the most annual energy consumption as the simulation results with thermostat setback.



	1(94.7)	2 (93.6)	3 (92.1)	4 (91.2)	5 (91.7)	6 (91.6)	7 (94.4)
DOMHOT WATER	25.5	25.5	25.5	25.5	25.5	25.5	25.5
VENT FANS	2.6	2.4	2.4	2.3	2.3	2.3	2.3
PUMPS &MISC	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SPACE COOL	24.9	22.5	22.3	21.9	22.1	21.8	21.8
SPACE HEAT	15.1	16.6	15.3	14.9	15.2	15.4	18.2
MISC EQUIPMT	13.2	13.2	13.2	13.2	13.2	13.2	13.2
AREA LIGHTS	13.2	13.2	13.2	13.2	13.2	13.2	13.2

Figure 6.6 Total energy use without thermostat setback

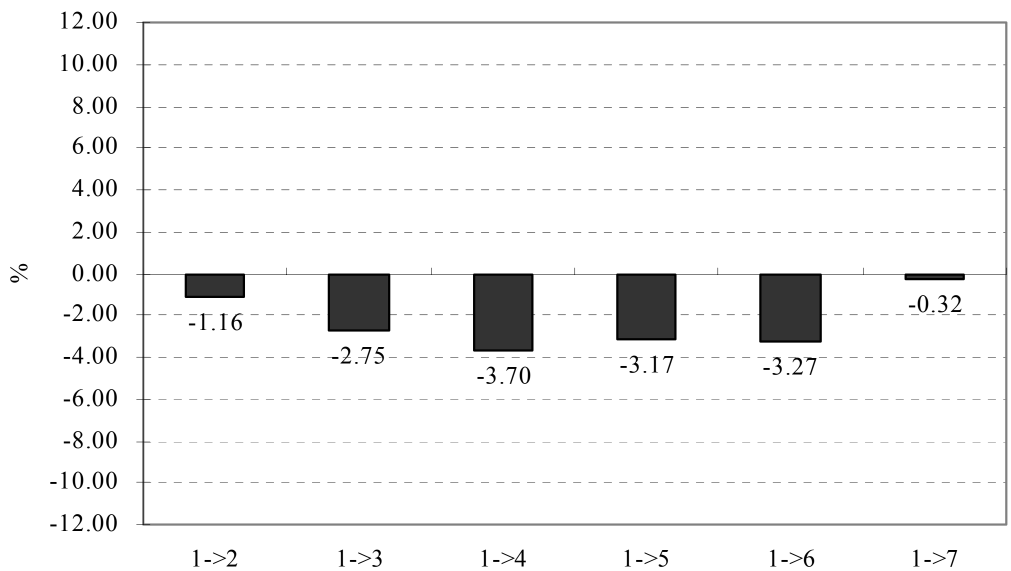


Figure 6.7 Annual energy consumption difference between quick mode and thermal mass modes without the thermostat setback

When comparing the annual energy consumption between simulation with and without thermostat setback, simulation without thermostat setback showed more energy consumptions in the range of 1.94% (quick construction mode) and 3.62% (#7 wall type).

From the results of total energy difference (Figure 6.8), it was found that the thermostat setback affected the thermal mass walls (from #2 to #7) more than the massless wall type (quick construction mode, #1). It was also found that the highest thermal mass wall (#7, 13.68 Btu/ft^2-°F) showed the most difference of 3.62% among the thermal mass walls from #2 to #7 wall types.

The results implied that the thermostat setback plays a significant role for the high thermal mass walls because the high heat capacity of thermal mass wall could maintain the indoor condition constantly during the thermostat setback.

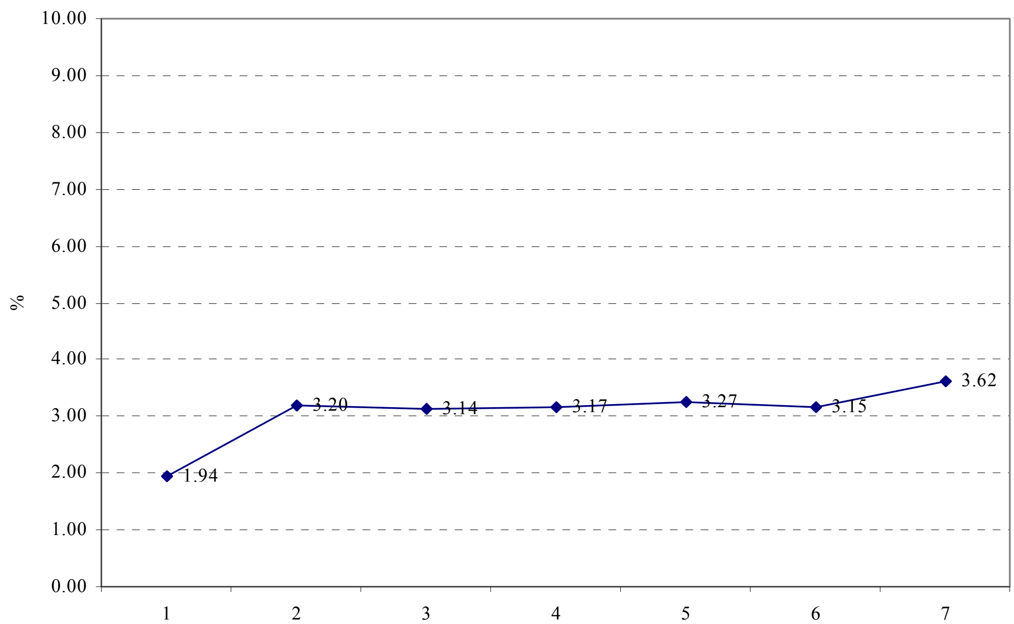


Figure 6.8 Total energy difference between with thermostat setback and without thermostat setback

From the case-study house simulation using the Habitat for Humanity house described in Chapter 5.2, it was found that the delayed construction mode calculated the energy consumptions more accurately than the quick mode construction mode. Nevertheless, the current 2000/2001 IECC defines the wall and roof constructions using only R-value and the fixed floor weight, which makes it impossible to simulate a code-compliant house and properly evaluate the thermal mass effects with the DOE-2 program. Therefore, the new version of the IECC needs to consider the prescriptive table in terms of the delayed construction mode.

6.3 Window Input Mode Analysis

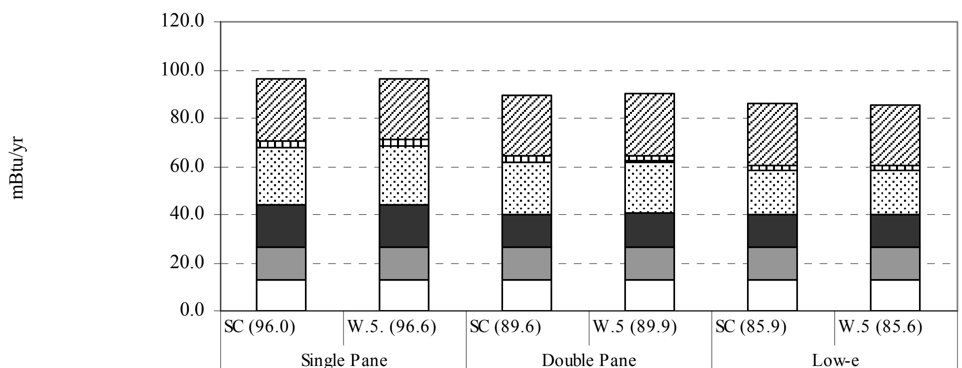
In order to investigate the window input mode analysis of the SC method and the Window-5 method, the results were obtained from DOE-2's BEPS (Building Energy Performance Summary) reports. The simulation of the window input mode analysis was also performed using two different construction modes (i.e., the quick construction mode and the thermal mass construction mode). Then, the percentage savings were calculated by changing from lower performance window to higher performance windows: 1) from the single pane clear to the double pane clear, 2) the single pane clear to the double pane low-e glass, and 3) the double pane clear to the double pane low-e glass. Finally, results are presented as total BEPS energy use as well as a difference in percentage savings for the SC and the Window-5 for both quick and thermal mass construction methods of input. Figures 6.9 to 6.11 present the complete results obtained from the BEPS report according to the different window types using the quick construction mode and the thermal mass construction mode. The results presented in Figures 6.9 to 6.11 for overall energy consumption, space heating and cooling are described in Tables 6.2 and 6.3 in detail to compare the SC, Window-5, quick construction mode and thermal mass construction mode.

It was found that there was little difference, which was less than 1% difference when comparing the Window-5 and the SC method for all glazing for either the quick construction mode or the thermal mass construction mode because there was compensating changes in heating and cooling loads. Figures 6.10 to 6.12 indicate the percentage difference of compensating change in the heating and cooling loads.

From Figures 6.9 to 6.12 and Tables 6.2 to 6.3, it was found that when the quick construction mode of the single pane clear glass is changed to the double pane clear glass using the SC method, the annual energy use decreases from 96.0 mBtu to 89.6 mBtu, a difference of 6.4 mBtu, or a 6.67 % decrease in total consumption. When using the Window-5 method with the quick construction method to simulate the single pane clear glass to compare the double pane clear glass, the annual energy use decreases from 96.6 mBtu to 89.9 mBtu, a difference of 6.7 mBtu, which is a 6.94% decrease. This indicates that the use of the SC method which is combined with the quick construction mode understates the total savings by 4.04% when compared to the Window-5 method using the quick construction mode. From this result, a difference of 0.27 % is observed in the savings.

In the case of options from the single pane clear glass to the double pane low-e glass in the quick construction mode using the SC method, the annual energy use decreases from 96.0 mBtu to 85.9 mBtu, a difference of 10.1 mBtu, which is a 10.52 % decrease. When using the Window-5 method, changing from the single pane clear glass to the double pane low-e glass decreased the annual energy use from 96.0 mBtu to 85.9 mBtu, a decrease of 10.1 mBtu, which is a 10.52% decrease. The comparison of the SC method and the Window-5 method results for the quick construction mode shows that a difference of 0.87 % is observed in the savings, which represents 8.23% of the SC savings.

For the results for the double pane clear glass compared to the double pane low-e glass in the quick construction mode, the annual energy use decreases from 89.6 mBtu to 85.9 mBtu, a difference of 3.7 mBtu, which is 4.13 % decrease. When using the Window-5 method with the same window change option, the result decreases from 89.9 mBtu to 85.6 mBtu, a difference of 4.3 mBtu, which is a 4.78 % decrease. When comparing the results from the SC and the Window-5 methods, savings increased by 0.65%, which represents a change in savings of 15.83 %.



	SC (96.0)	W.5. (96.6)	SC (89.6)	W.5 (89.9)	SC (85.9)	W.5 (85.6)
DOMHOT WATER	25.5	25.5	25.5	25.5	25.5	25.5
VENT FANS	2.6	2.7	2.3	2.3	2.0	1.9
PUMPS & MISC	0.2	0.2	0.2	0.2	0.2	0.2
SPACE COOL	23.3	24.2	21.5	21.4	18.5	17.9
SPACE HEAT	18.0	17.6	13.7	14.1	13.3	13.7
MISC EQUIPMT	13.2	13.2	13.2	13.2	13.2	13.2
AREA LIGHTS	13.2	13.2	13.2	13.2	13.2	13.2

AREA LIGHTS · MISC EQUIPMT · SPACE HEAT · SPACE COOL · PUMPS & MISC · VENT FANS · DOMHOT WATER

Figure 6.9 Annual building energy performance report using the quick mode

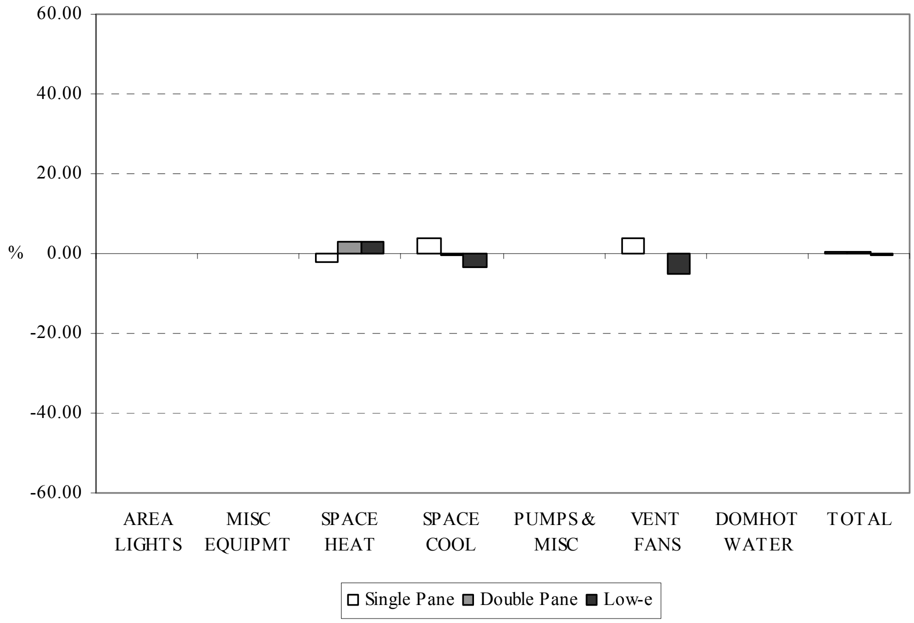
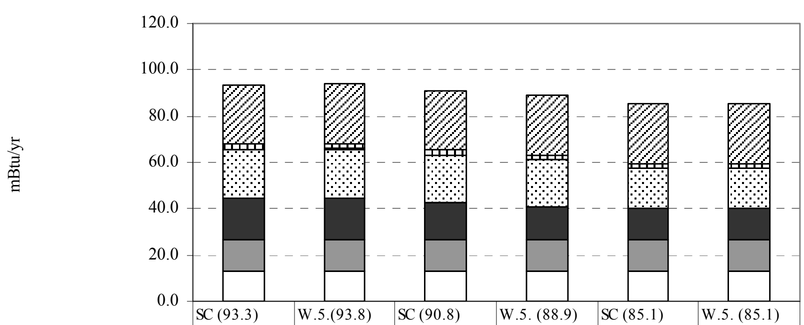


Figure 6.10   Percentage difference between SC and W-5 using the quick mode



	Single Pane		Double Pane		Low-e	
	SC (93.3)	W.5.(93.8)	SC (90.8)	W.5. (88.9)	SC (85.1)	W.5. (85.1)
DOMHOT WATER	25.5	25.5	25.5	25.5	25.5	25.5
VENT FANS	2.2	2.3	2.2	2.1	1.9	1.8
PUMPS & MISC	0.2	0.2	0.2	0.2	0.2	0.2
SPACE COOL	20.6	21.4	20.4	20.1	17.6	17.4
SPACE HEAT	18.4	18.0	16.1	14.6	13.5	13.8
MISC EQUIPMT	13.2	13.2	13.2	13.2	13.2	13.2
AREA LIGHTS	13.2	13.2	13.2	13.2	13.2	13.2

AREA LIGHTS MISC EQUIPMT SPACE HEAT SPACE COOL
PUMPS & MISC VENT FANS DOMHOT WATER

Figure 6.11   Annual building energy performance report using the thermal mass mode

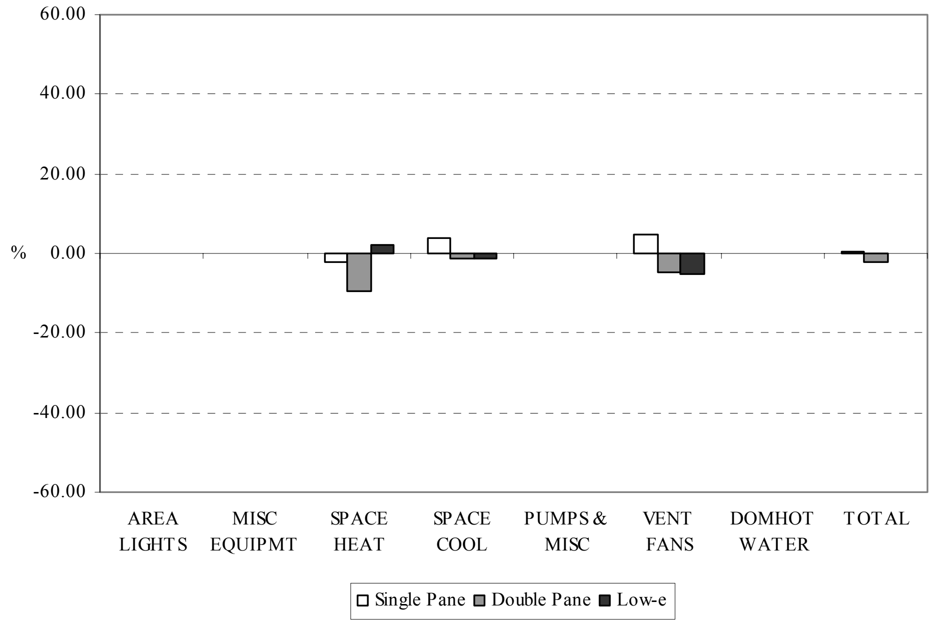


Figure 6.12   Percentage difference between SC and W-5 using the thermal mass mode

Table 6.2 Difference in energy consumption

			SC	Window-5	Difference
			Savings (mBtu/yr)	Savings (mBtu/yr)	SC-W5 (mBtu/yr)
Quick mode	From SP to DP	Annual BEPS	-6.4	-6.7	0.3
		Annual Heating	-4.3	-3.5	-0.8
		Annual Cooling	-1.8	-2.8	1.0
	From SP to Low-e	Annual BEPS	-10.1	-11.0	0.9
		Annual Heating	-4.7	-3.9	-0.8
		Annual Cooling	-4.8	-6.3	1.5
	From DP to Low-e	Annual BEPS	-3.7	-4.3	0.6
		Annual Heating	-0.4	-0.4	0.0
		Annual Cooling	-3.0	-3.5	0.5
Thermal Mass Mode	From SP to DP	Annual BEPS	-2.5	-4.9	2.4
		Annual Heating	-2.3	-3.4	1.1
		Annual Cooling	-0.2	-1.3	1.1
	From SP to Low-e	Annual BEPS	-8.2	-8.7	0.5
		Annual Heating	-4.9	-4.2	-0.7
		Annual Cooling	-3.0	-4.0	1.0
	From DP to Low-e	Annual BEPS	-5.7	-3.8	-1.9
		Annual Heating	-2.6	-0.8	-1.8
		Annual Cooling	-2.8	-2.7	-0.1

Table 6.3 Percentage difference in energy consumption

			SC	Window-5	Difference	% Difference
			% Savings	% Savings	SC-W5	((SC-W5)/SC)*100
Quick mode	From SP to DP	Annual BEPS	-6.67	-6.94	0.27	-4.04
		Annual Heating	-23.89	-19.89	-4.00	16.75
		Annual Cooling	-7.73	-11.57	3.84	-49.77
	From SP to Low-e	Annual BEPS	-10.52	-11.39	0.87	-8.23
		Annual Heating	-26.11	-22.16	-3.95	15.14
		Annual Cooling	-20.60	-26.03	5.43	-26.37
	From DP to Low-e	Annual BEPS	-4.13	-4.78	0.65	-15.83
		Annual Heating	-2.92	-2.84	-0.08	2.84
		Annual Cooling	-13.95	-16.36	2.40	-17.21
Thermal Mass Mode	From SP to DP	Annual BEPS	-2.68	-5.22	2.54	-94.96
		Annual Heating	-12.50	-18.89	6.39	-51.11
		Annual Cooling	-0.97	-6.07	5.10	-525.70
	From SP to Low-e	Annual BEPS	-8.79	-9.28	0.49	-5.53
		Annual Heating	-26.63	-23.33	-3.30	12.38
		Annual Cooling	-14.56	-18.69	4.13	-28.35
	From DP to Low-e	Annual BEPS	-6.28	-4.27	-2.00	31.91
		Annual Heating	-16.15	-5.48	-10.67	66.07
		Annual Cooling	-13.73	-13.43	-0.29	2.13

When using the thermal mass construction mode with the SC method, a change from the single pane clear glass to the double pane clear glass results in annual energy consumption from 93.3 mBtu to 90.8 mBtu, a difference of 2.5 mBtu, which is 2.68 % decrease. When using the Window-5 method with same window change options, the annual energy use decrease from 93.8 mBtu to 88.9 mBtu, a difference of 4.9 mBtu, which is a 5.22 % decrease. When the SC and Window-5 method are compared, a difference of 2.54 % is observed in the total percentage savings.

For the single pane clear glass to the double pane low-e glass option using the SC method with the thermal mass construction mode, the annual energy use decreases from 93.3 mBtu to 85.1 mBtu, a difference of 8.2 mBtu, which is a 8.79 % decrease. When using the Window-5 method from the single pane clear glass to the double pane low-e glass option, the annual energy use decreases from 93.8 mBtu to 85.1 mBtu, a difference of 8.7 mBtu, which is a 9.28% decrease. While comparing the SC and the Window-5 method, a difference of 0.49% is observed in the savings which is a 5.53% increase in the savings when compared to the SC method for the total energy consumption.

Finally, for the option from the double pane clear to the double pane low-e glass with the thermal mass construction mode and the SC method, the annual energy use decreases from 90.8 mBtu to 85.1 mBtu, a difference of 5.7 mBtu, which is 6.28% decrease. When using the Window-5 method with the same option, the annual energy use decrease from 88.9 mBtu to 85.1 mBtu, a difference of 3.8 mBtu, which is 4.27 % decrease. When comparing the results from the SC and the Window-5 method using the thermal mass construction mode, a increase of 2.00% is observed, which is a 31.91% savings in overall energy consumption.

In general, the comparison of the performance of the different glazing types (the single pane clear, the double pane clear and the double pane low-e glass) using the SC or Window-5 method, and the quick construction mode or the thermal mass construction mode showed that the thermal mass construction mode option had lower annual energy use than the quick construction mode. When comparing the percent savings from lower performance glazing to a higher performance glazing while using either the SC or the Window-5 methods, it was observed that the percent savings obtained from the Window-5 method were greater than the percent savings obtained from the SC method for two cases (from single-pane clear to double-pane clear, and from single-pane clear to double-pane low-e). However, in the case of change from double-pane clear to double-pane low-e, the percent savings obtained from the SC method are greater than the percent savings obtained from the Window-5 method. In comparing the percent savings from lower performance glazing to a higher performance glazing based on two construction modes, the savings from the quick construction mode were greater than the percent savings from the thermal mass construction mode except for change from the double-pane clear to double-pane low-e glass.

According to the previous researches by Reilly (1995) and Mukhopadhyay (2005), it was determined that the Window-5 method was more accurate method to calculate the window heat transfer. Hence, it is suggested that the Window-5 method be used in the future code traceable building simulation model to prevent the discrepancy in results from the two different methods (i.e. the SC method and the Window-5 method) even though the same U-value and SHGC of window types were calculated using DOE-2 simulation program. It is also recommended that custom weighting factors (CWFs) be used to properly account for the thermal mass.

6.4 An Energy Efficiency Analysis Using the IECC-Compliant Model

This chapter presents the results of an energy efficiency analysis simulation with different simulation conditions. The simulation conditions of the base-case house were altered individually and in combination with others. For this analysis, different values were assigned to the parameters of the DOE-2 input that represent the characteristics of the building systems and components, as seen in Figures 4.62 to 4.64. The simulations were performed in four different climate zones (climate zones 9, 5, 4 and 2).

In order to investigate the impacts of the annual energy use, the Building Energy Performance Summary (BEPS) of the DOE-2 output was used to determine the values of those parameters that resulted in energy savings, when applied individually and in combination. The annual energy results consisted of four categories: 1) an annual other category which included lighting, equipment, etc., 2) the annual DHW (Domestic Hot Water) energy use, 3) the annual heating use and 4) the annual cooling use. Using DOE-2's BEPS output, the heating, cooling and total energy differences were calculated and plotted against the heating degree days, according to each climate zone.

Simulations were performed using the simulation plans described in Chapter 4. The results are shown as annual energy use plots and energy savings plots, according to the different climate zones. In order to present the results of the simulations, stacked bar charts were used to plot the annual energy use for the different values of the parameters and the climate zones, and line graphs were used to show the percentage differences of the energy savings for changes in the value of the parameters. Detailed results of the simulation runs are presented in Appendix G.

6.4.1 Analysis of the Fenestration Properties

The following plots show the effect of the various fenestration properties. In order to find the savings from the fenestration properties, the annual energy use was plotted using simulation results from the base-case code-compliant simulation, the U-value and the SHGC changes. All other properties remain the same as in the base-case simulation. For the base case, the code-compliant window U-value was 0.45 for climate zone 9, 0.65 for climate zone 5, 0.75 for climate zone 4, and 0.90 for climate zone 2. The SHGC was 0.66 for climate zone 9 and 0.40 for climate zones 5, 4 and 2. From the simulations, the following results were observed:

1) The cooling energy savings obtained from decreasing the SHGC was higher than the savings obtained from decreasing both the SHGC and the U-value for all climate zones, and the cooling energy savings from decreasing the SHGC were higher for windows with lower U-values in all climate zones. In addition, the percentage of cooling savings from climate zones 2 to 9 were higher because climate zone 9 had lower cooling loads and showed small differences. This caused a larger percent of difference than that of climate zone 2 which had large cooling loads.

2) The heating energy savings from decreasing the window U-values were higher than those from decreasing both the SHGC and the U-values for all climate zones. The percentage of heating savings from climate zones 9 to 2 were higher because climate zone 2 had low heating loads, and small differences made a larger percent of difference than that of climate zone 9 (as happened with the cooling energy use).

3) The total energy savings from decreasing the U-value and the SHGC were higher than those obtained from decreasing only the U-value or the SHGC. For these simulations, the windows with the U-value decreased by 20%, and an SHGC decreased by 0.04 showed the largest savings for climate zones 5, 4 and 2 (all of which had less heating degree days). For climate zone 9, the window U-value decrease of 20% showed the largest savings. Therefore, for cold climate zones a less conductive window is desirable, and for hot climate zones, less conductive windows with low SHGCs are desirable.

The following sections contain detailed explanations of the results from the different simulation conditions according to the window types.

6.4.1.1 Base case vs. modified (0.02 decrease in SHGC)

In the case of the 0.02 decrease in SHGC, there was an increase in total energy use compared to the base-case house for climate zones 9 and 5, and a reduction in total energy use for climate zones 4 and 2 (Figures 6.13 and 6.14). For total energy use, there was an increase of 0.19% for climate zone 9, no change for climate zone 4 and reductions of 0.12% for climate zone 4 and 0.35% for climate zone 2. The heating energy use showed increases of 1.40% for climate zone 9, 1.63% for climate zone 5, 2.45% for climate zone 4 and 1.45% for climate zone 2. Cooling energy use showed reductions of 1.54% for climate zone 9, 1.89% for climate zone 5, and 1.79% for climate zones 4 and 2.

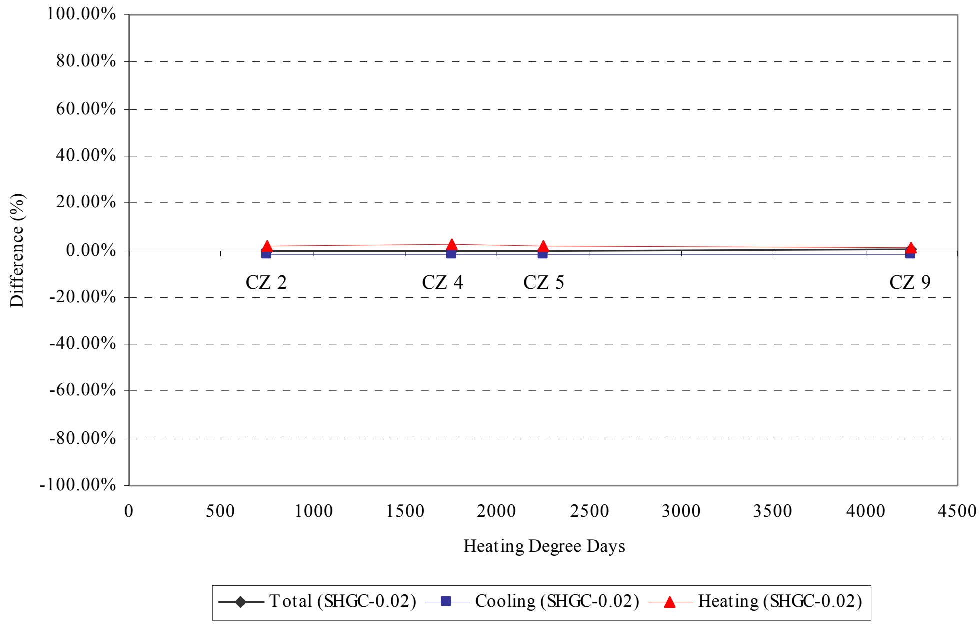


Figure 6.13 Percent difference of annual energy use (base case vs. SHGC-0.02)

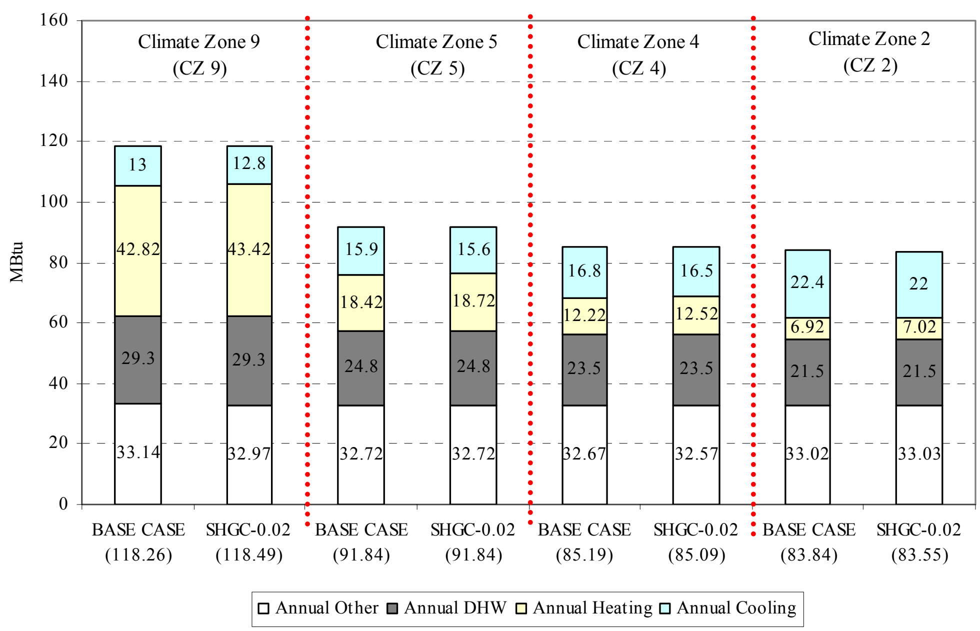


Figure 6.14 Annual energy use (base case vs. SHGC-0.02)

6.4.1.2 Base case vs. modified (0.04 decrease in SHGC)

For the SHGC windows where the SHGC was decreased by 0.04, the results showed the same patterns of heating, cooling and total energy differences as those of the 0.02 decreased SHGC (Figures 6.15 and 6.16). The annual energy use increased by 0.47% for climate zone 9, and decreased by 0.02% for climate zone 5, 0.25% for climate zone 4, and 0.69% for climate zone 2. For heating energy use, there were increases of 2.80% for climate zone 9, 3.80% for climate zone 5, 4.09% for climate zone 4 and 2.89% for climate zone 2. For cooling energy, the simulations showed reductions of 3.85% for climate zone 9, 3.77% for climate zone 5, and 3.57% for climate zones 4 and 2.

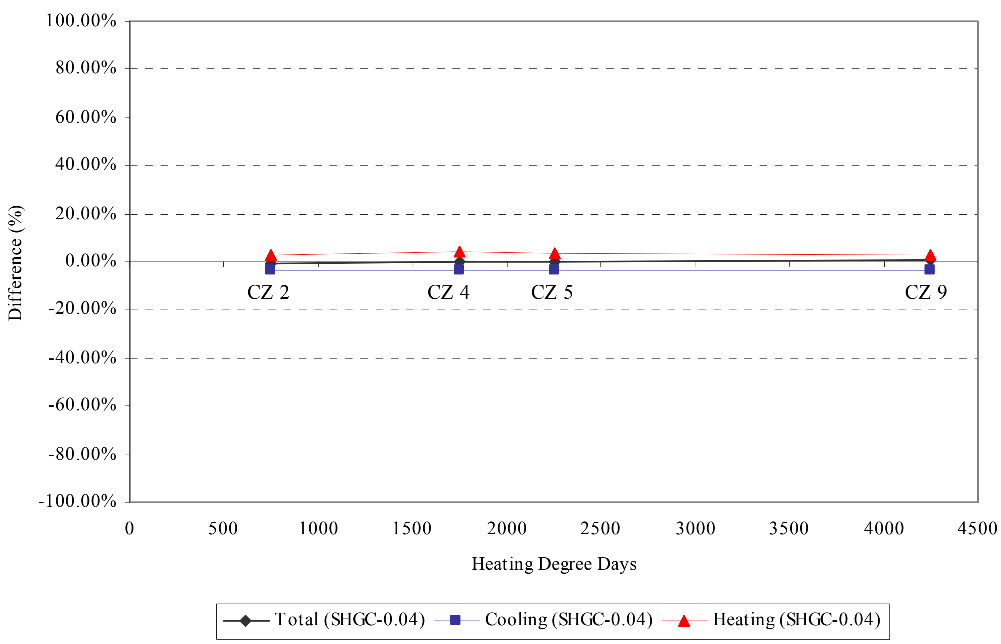


Figure 6.15 Percent difference of annual energy use (base case vs. SHGC-0.04)

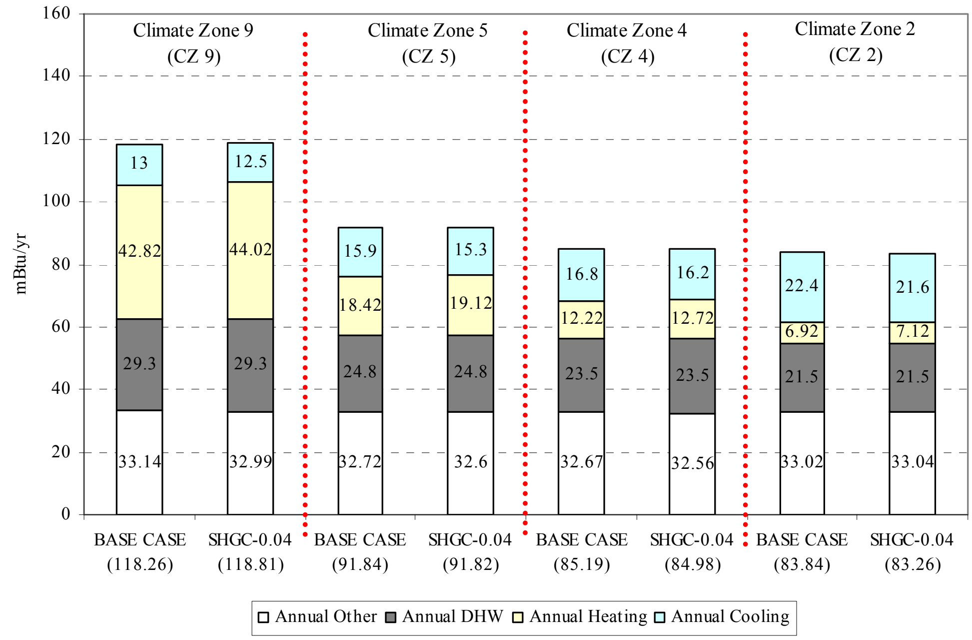


Figure 6.16 Annual energy use (base case vs. SHGC-0.04)

6.4.1.3 Base case vs. modified (5% decrease in U-value)

Simulations with the window where the U-value was decreased by 5% showed a reduction in total energy use and heating energy use, and an increase in cooling energy use, for all climate zones (Figures 6.17 and 6.18). For the total energy use, the simulations showed a reduction of 0.69% compared to the base-case house for climate zone 9, a reduction of 0.58% for climate zone 5, 0.38% for climate zone 4, and 0.19% for climate zone 2, as compared to the base-case house. For heating energy use, each case also showed reductions of 2.10% for climate zone 9, 3.26% for climate zone 5, 3.27% for climate zone 4, and 2.89% for climate zone 2. For cooling energy use, there were increases of 0.77% for climate zone 9, 0.63% for climate zone 5, 0.60% for climate zone 4, and no change for climate zone 2. In these simulations, it seemed that manipulating the U-value decreased the heating energy use, but increased the cooling energy use for all climate zones.

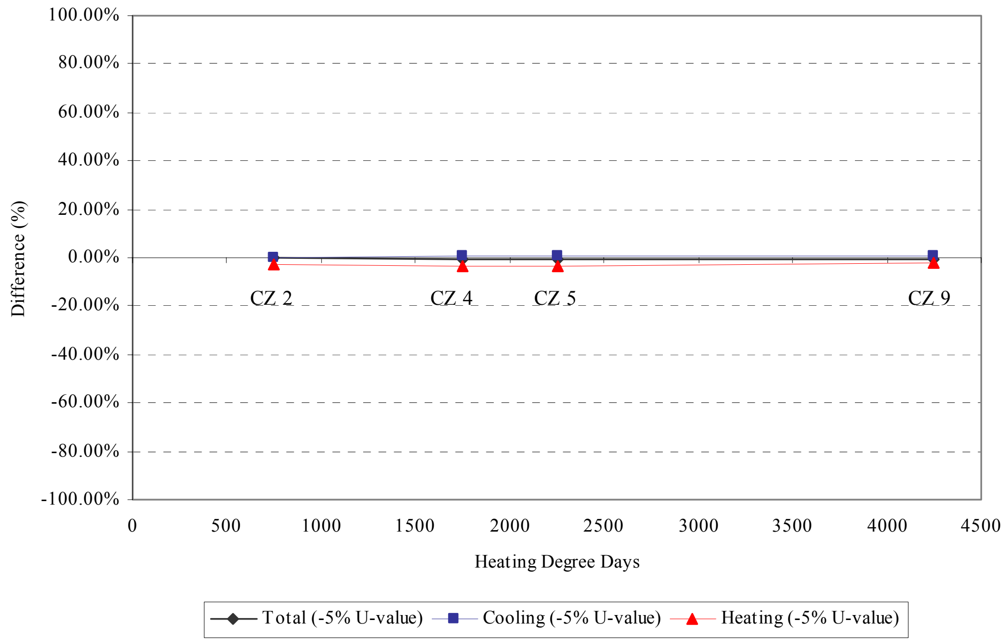


Figure 6.17 Percent difference of annual energy use (base case vs. -5% U-value)

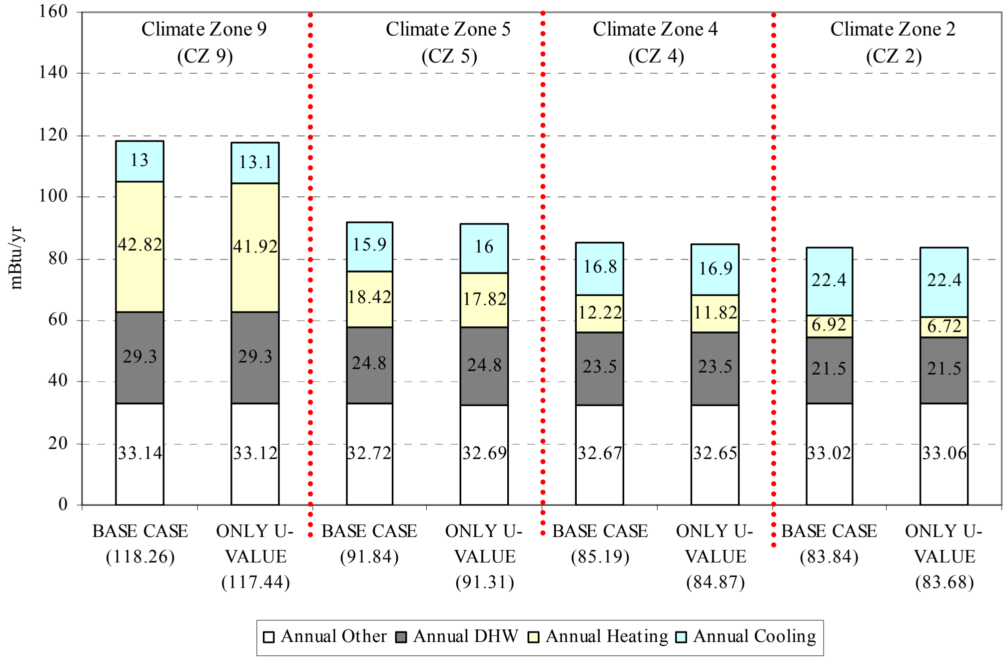


Figure 6.18   Annual energy use (base case vs. -5% U-value)

6.4.1.4 Base case vs. modified (5% decrease in U-value, 0.02 decrease in SHGC)

In simulations where the window's U-value was decreased by 5% and the SHGC decreased by 0.02, the total energy use, heating energy use and cooling energy use showed reductions, as compared to the base-case house for all climate zones (Figures 6.19 and 6.20). For total energy use, there were reductions of 0.51% for climate zone 9, 0.59% for climate zone 5, 0.54% for climate zone 4 and 0.56% for climate zone 2. The heating energy use showed reductions of 0.70% for climate zone 9, 1.63% for climate zone 5, 1.64% for climate zone 4 and 1.45% for climate zone 2. Cooling energy use also showed reductions of 1.54% for climate zone 9, 1.89% for climate zone 5, 1.19% for climate zone 4, and 1.34% for climate zone 2.

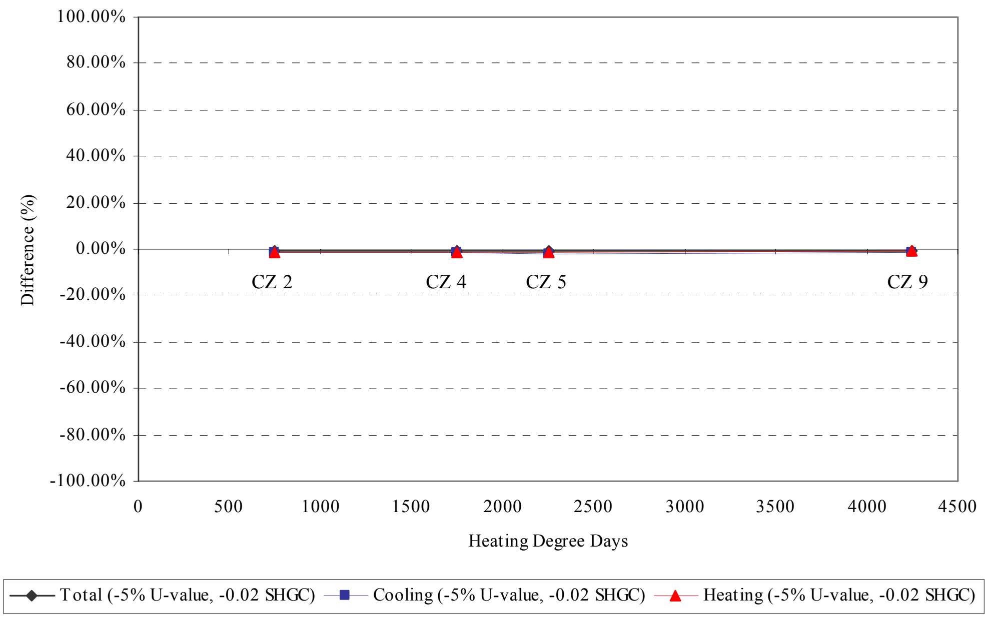


Figure 6.19 Percent difference of annual energy use (base case vs. -5% U-value, SHGC-0.02)

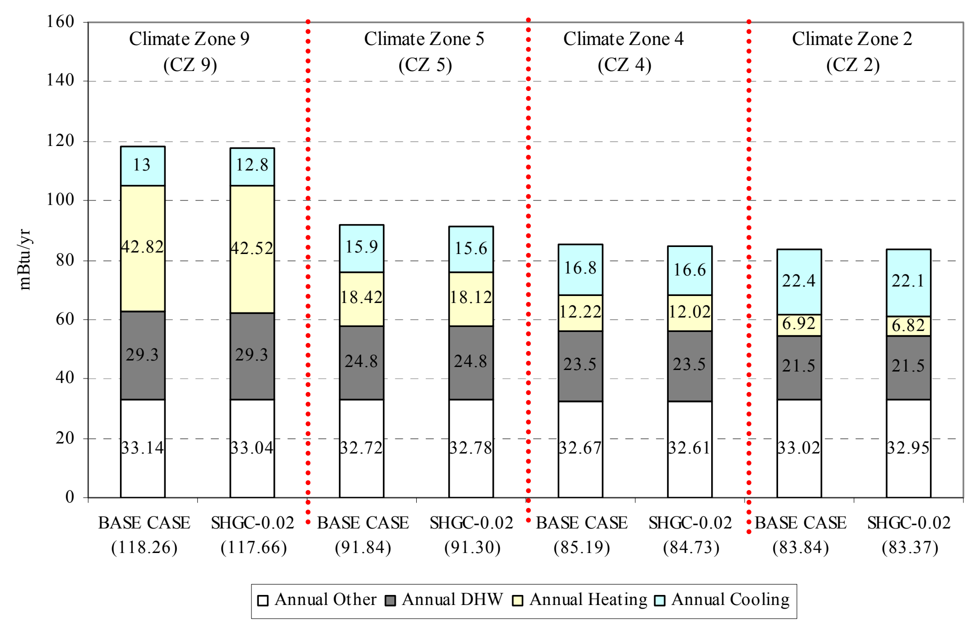


Figure 6.20 Annual energy use (base case vs. -5% U-value, SHGC-0.02)

6.4.1.5 Base case vs. modified (5% decrease in U-value, 0.04 decrease in SHGC)

When a window with a 5% decreased U-value and a 0.04 decreased SHGC was simulated, there were reductions in total energy use and cooling energy use, and an increase in heating energy use (Figures 6.21 and 6.22). The annual energy use decreased by 0.30% for climate zone 9, 0.58% for climate zone 5, 0.67% for climate zone 4, and 0.92% for climate zone 2. For heating energy use, there were increases of 0.47% for climate zone 9, 0.54% for climate zone 5 and no changes for climate zone 4 and 2. For cooling energy, the simulations showed reductions of 3.08% for climate zone 9, 3.77% for climate zone 5, 3.57% for climate zone 4 and 3.13% for climate zone 2.

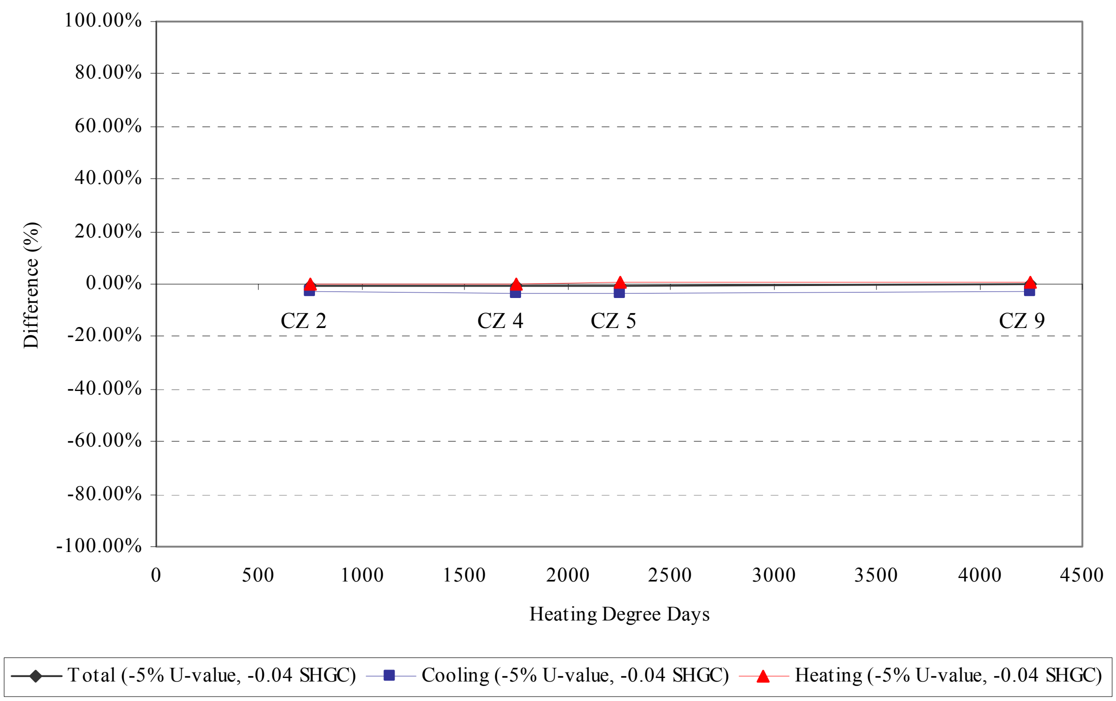


Figure 6.21 Percent difference of annual energy use (base case vs. -5% U-value, SHGC-0.04)

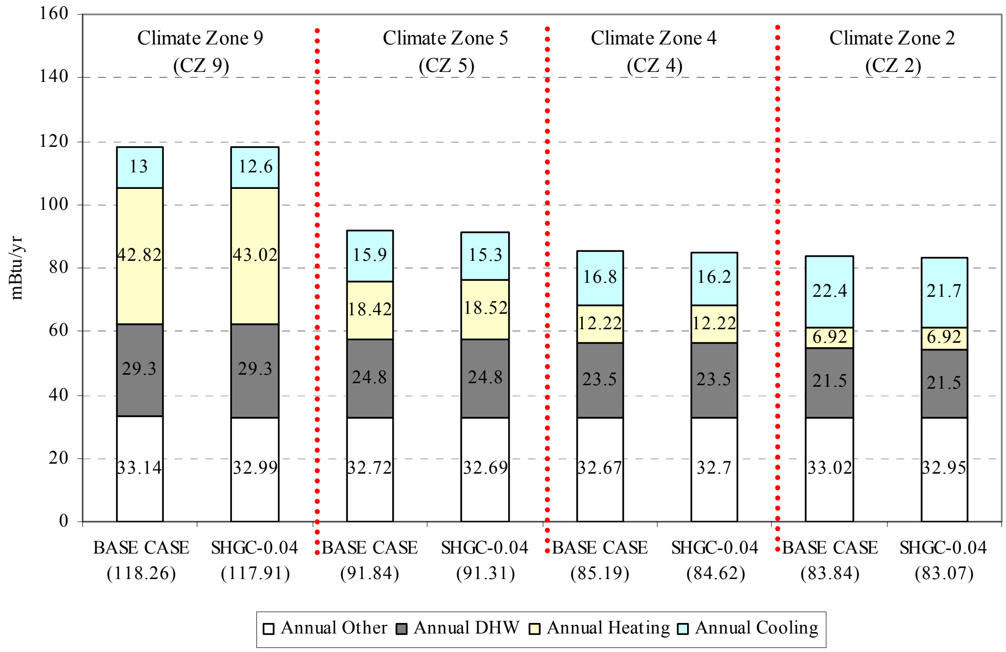


Figure 6.22 Annual energy use (base case vs. -5% U-value, SHGC-0.04)

6.4.1.6 Base case vs. modified (10% decrease in U-value)

A house with a U-value that was decreased by 10% from the base-case house produced reductions in total energy use and heating energy use, and an increase in cooling energy use at the same percentage condition as a house with a U-value that was decreased by 5% (Figures 6.23 and 6.24). For the total energy use, there were reductions of 1.41% for climate zone 9, 1.18% for climate zone 5, 0.85% for climate zone 4, and 0.33% for climate zone 2. Heating energy results also showed reductions of 4.20% for climate zone 9, 6.51% for climate zone 5, 7.36% for climate zone 4 and 5.78% for climate zone 2. However, cooling energy results showed increases of 1.54% for climate zone 9, 0.63% for climate zone 5, 1.19% for climate zone 4 and 0.45% for climate zone 2.

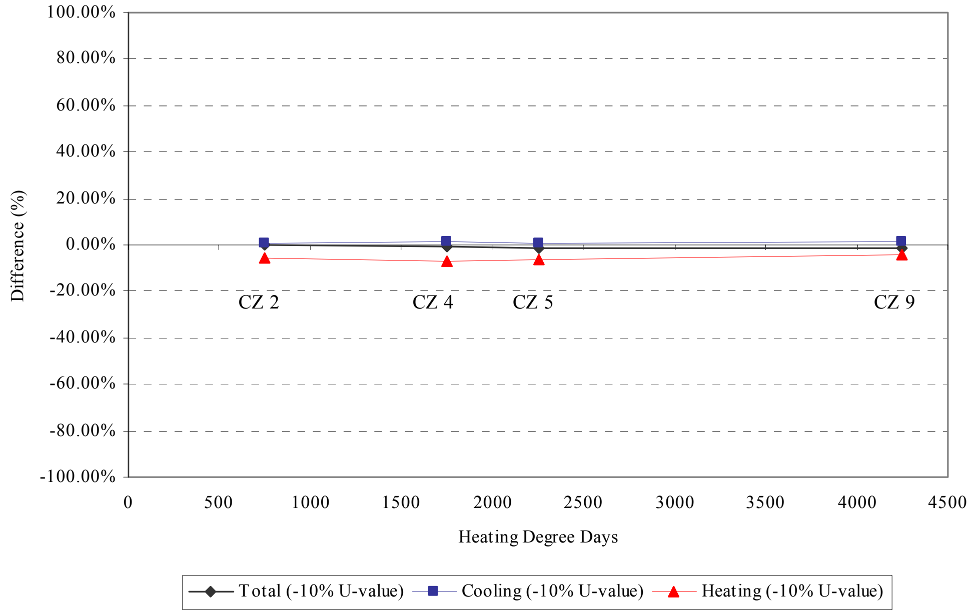


Figure 6.23 Percent difference of annual energy use (base case vs. -10% U-value, same SHGC)

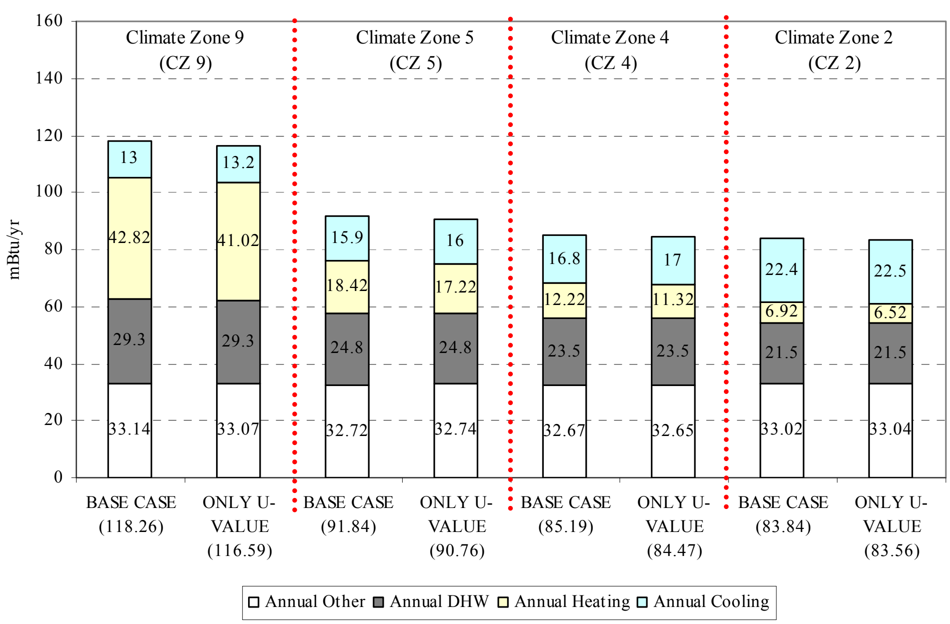


Figure 6.24 Annual energy use (base case vs. -10% U-value, same SHGC)

6.4.1.7 Base case vs. modified (10% decrease in U-value, 0.02 decrease in SHGC)

When a house with a U-value that was decreased by 10% and an SHGC that was decreased by 0.02 was simulated, the results showed decreases compared to the base-case house in total energy use, heating energy use and cooling energy use (Figures 6.25 and 6.26). For the total energy use, there were reductions of 1.26% for climate zone 9, 1.17% for climate zone 5, 1.03% for climate zone 4 and 0.70% for climate zone 2. In the case of the heating energy use, there were reductions of 3.04% for climate zone 9, 4.89% for climate zone 5, 5.73% for climate zone 4 and 4.34% for climate zone 2. In the case of the cooling energy use, there were also reductions of 0.77% for climate zone 9, 1.26% for climate zone 5, 1.19% for climate zone 4 and 1.34% for climate zone 2.

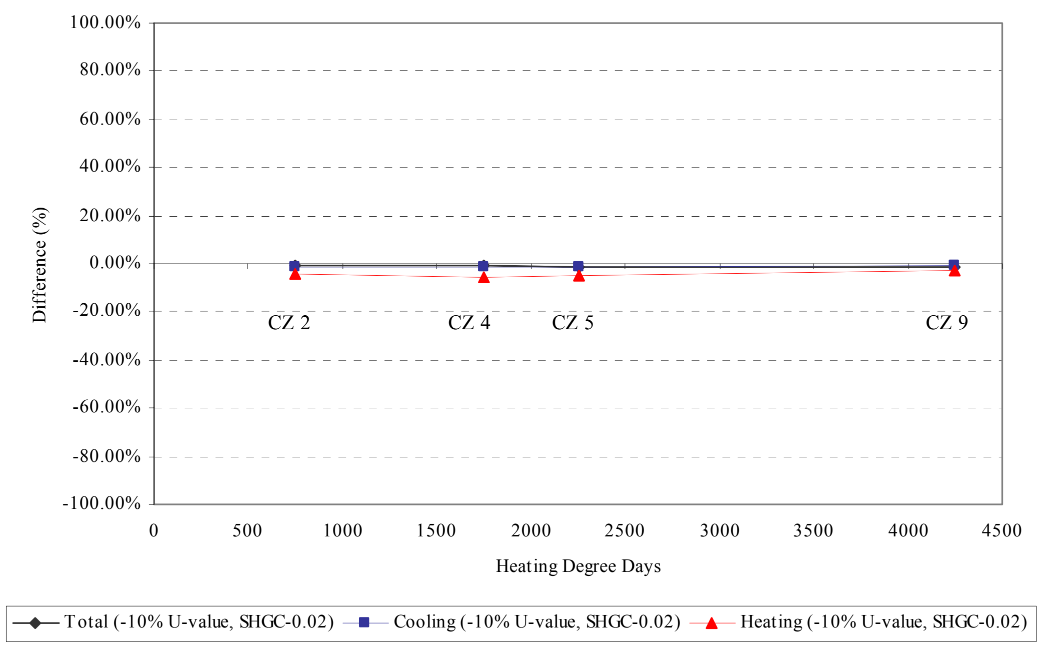


Figure 6.25 Percent difference of annual energy use (base case vs. -10% U-value, SHGC-0.02)

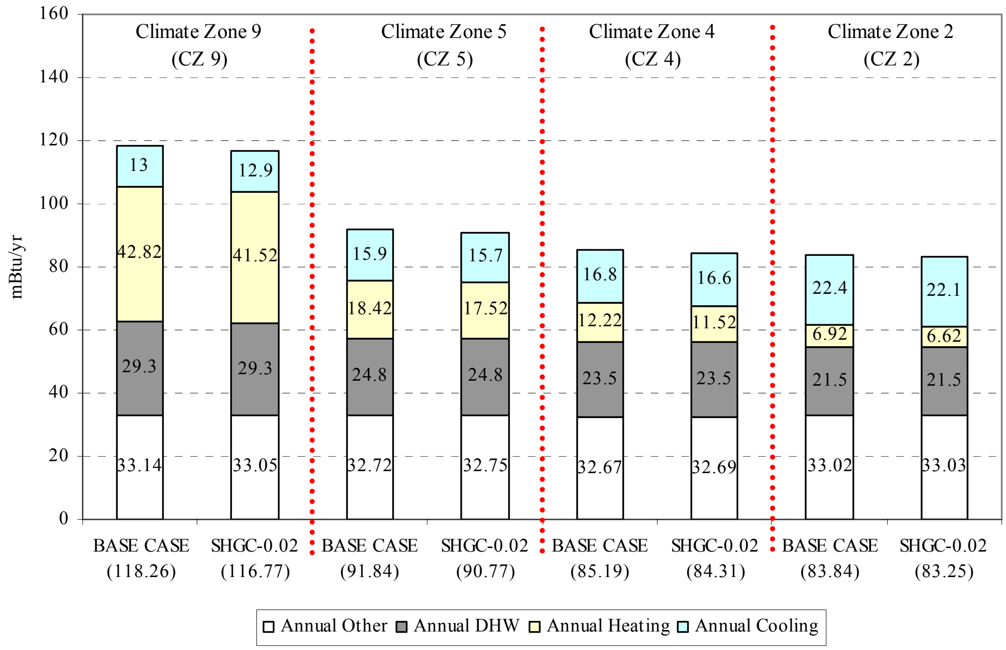


Figure 6.26 Annual energy use (base case vs. -10% U-value, SHGC-0.02)

6.4.1.8 Base case vs. modified (10% decrease in U-value, 0.04 decrease in SHGC)

The results for a house with a U-value that was decreased by 10% and an SHGC that was decreased by 0.04 showed similar reductions in total energy use, heating energy use and cooling energy use as a house with a 10% decreased U-value with 0.02 decreased SHGC (Figures 6.27 and 6.28). For the total energy use, they showed reductions of 1.05% for climate zone 9, 1.22% for climate zone 5, 1.14% for climate zone 4 and 1.12% for climate zone 2. Results of heating energy use produced a 1.87% drop for climate zone 9, a 3.26% drop for climate zone 5, a 3.27% drop for climate zone 4, and a 4.34% drop for climate zone 2. For the cooling energy use, there were also reductions of 3.08% for climate zone 9, 3.14% for climate zone 5, 2.98% for climate zone 4, and 2.68% for climate zone 2.

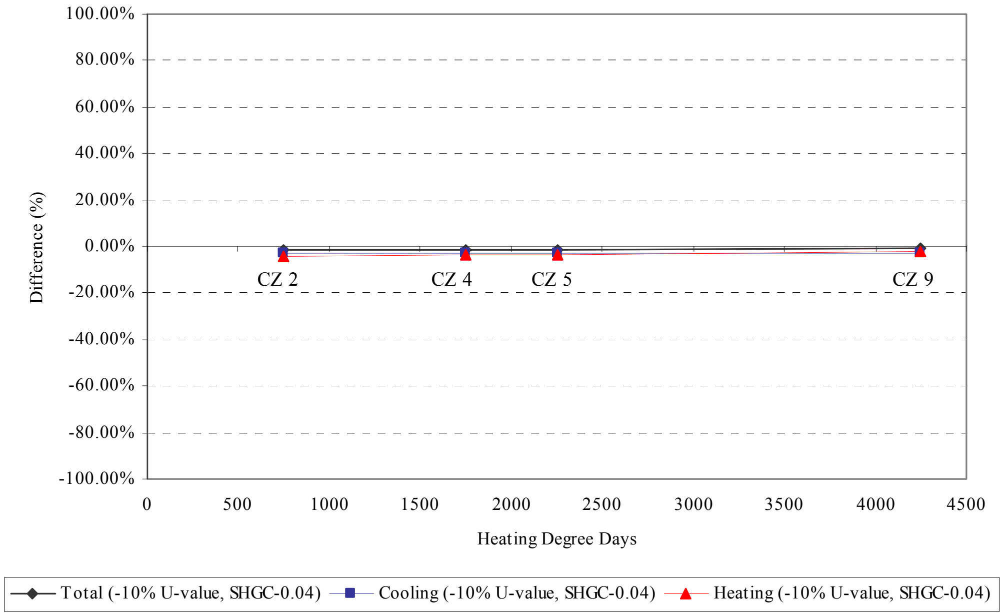


Figure 6.27 Percent difference of annual energy use (base case vs. -10% U-value, SHGC-0.04)

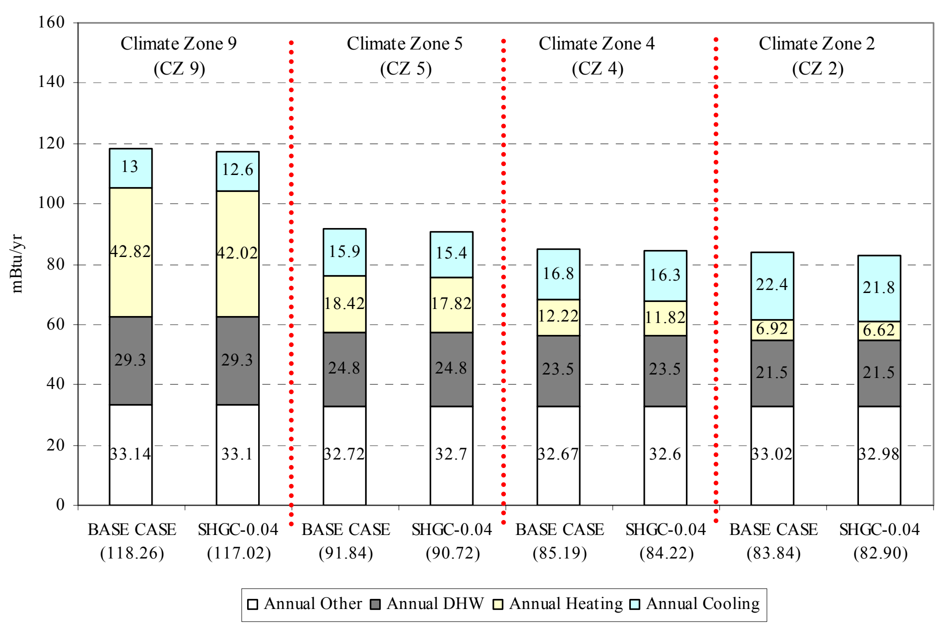


Figure 6.28 Annual energy use (base case vs. -10% U-value, SHGC-0.04)

6.4.1.9 Base case vs. modified (15% decrease in U-value)

When a house with a U-value that was decreased by 15% was simulated, the annual energy use and heating energy use both decreased, while the cooling energy use increased in all climate zones (Figures 6.29 and 6.30). For the total energy use, there were reductions of 2.10% for climate zone 9, 1.69% for climate zone 5, 1.22% for climate zone 4, and 0.50% for climate zone 2. For the heating energy use, there were also reductions of 6.31% for climate zone 9, 9.77% for climate zone 5, 10.64% for climate zone 4 and 10.12% for climate zone 2. For the cooling energy use, there were increases of 2.31% for climate zone 9, 1.26% for climate zone 5, 1.19% for climate zone 5, and 0.89% for climate zone 2.

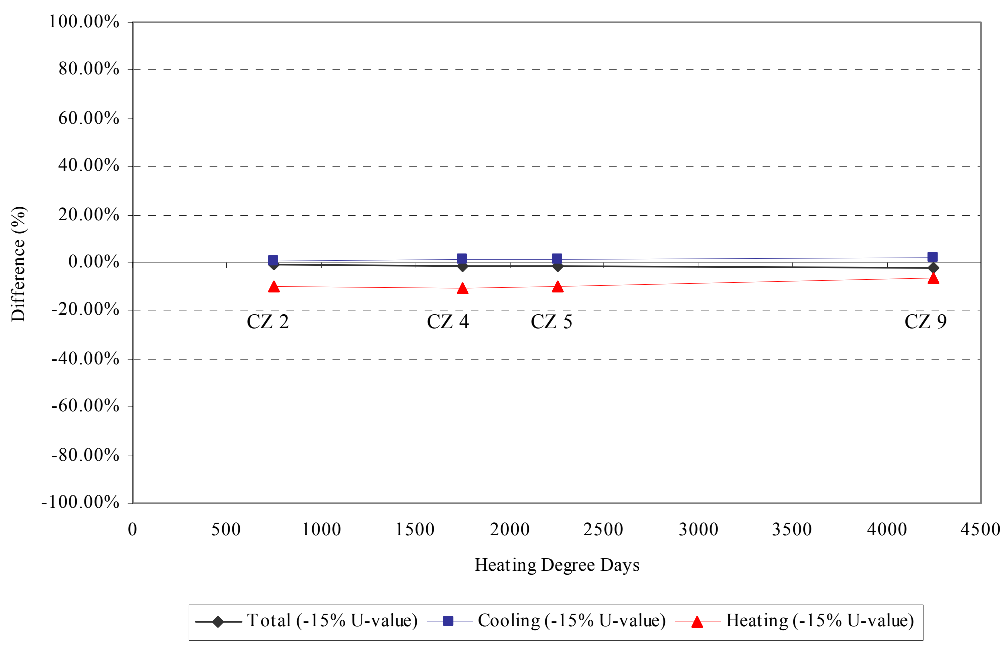


Figure 6.29 Percent difference of annual energy use (base case vs. -15% U-value, same SHGC)

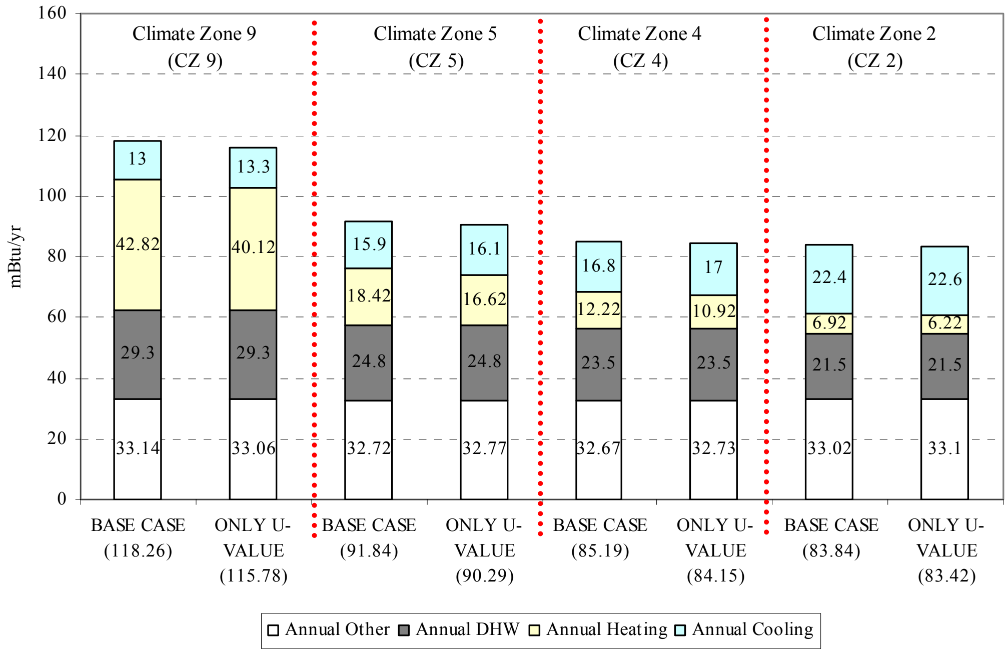


Figure 6.30 Annual energy use (base case vs. -15% U-value, same SHGC)

6.4.1.10 Base case vs. modified (15% decrease in U-value, 0.02 decrease in SHGC)

Using a house with a U-value that was decreased by 15% and an SHGC that was decreased by 0.02, the results produced reductions compared to the base-case house in the total energy use, heating energy use and cooling energy use (Figures 6.31 and 6.32). In the case of the total energy use, they showed reductions of 1.94% for climate zone 9, 1.76% for climate zone 5, 1.43% for climate zone 4, and 0.89% for climate zone 2. In the case of the heating energy use, there were reductions of 5.14% for climate zone 9, 8.14% for climate zone 5, 9.00% for climate zone 4 and 8.67% for climate zone 2. In the case of the cooling energy, there were reductions of 0.63% for climate zone 5, 0.60% for climate zone 4, and 0.89% for climate zone 2, but there was no change for climate zone 9.

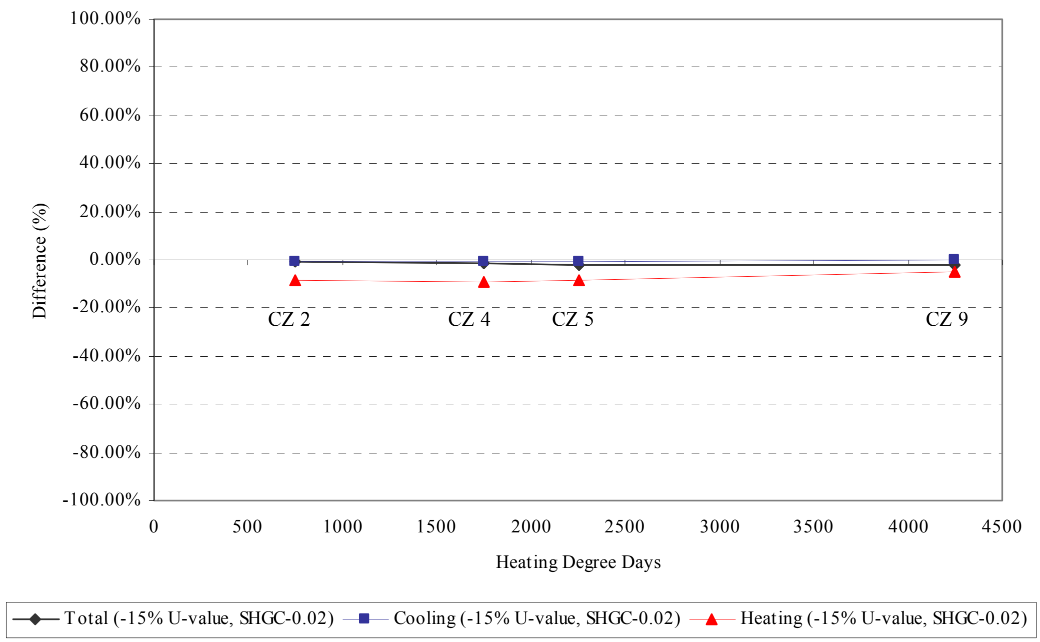


Figure 6.31 Percent difference of annual energy use (base case vs. -15% U-value, SHGC-0.02)

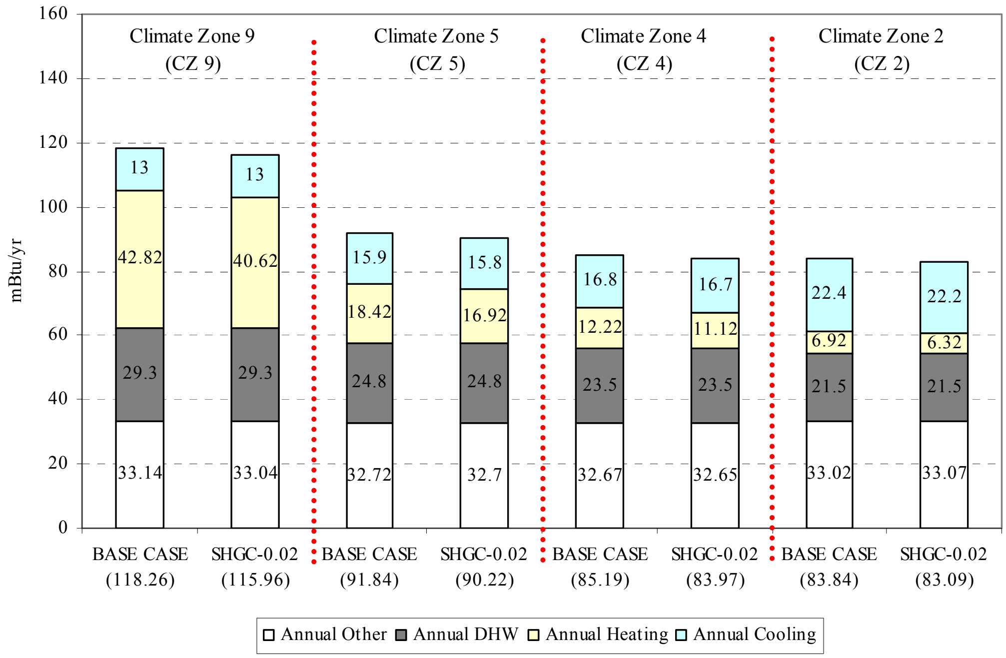


Figure 6.32 Annual energy use (base case vs. -15% U-value, SHGC-0.02)

6.4.1.11 Base case vs. modified (15% decrease in U-value, 0.04 decrease in SHGC)

A house with a U-value that was decreased by 15% and an SHGC that was decreased by 0.04 produced reductions in the total energy use, heating energy use and cooling energy use (Figures 6.33 and 6.34). For the total energy use, there were reductions of 1.79% for climate zone 9, 1.77% for climate zone 5, 1.66% for climate zone 4, and 1.26% for climate zone 2 (as compared to the base-case house). For the heating energy use, there were drops of 3.97% for climate zone 9, 5.97% for climate zone 5, 8.18% for climate zone 4 and 7.23% for climate zone 2. In the case of the cooling energy use, there were also drops of 2.31% for climate zone 9, 2.52% for climate zone 5, 2.38% for climate zone 4, and 2.68% for climate zone 2.

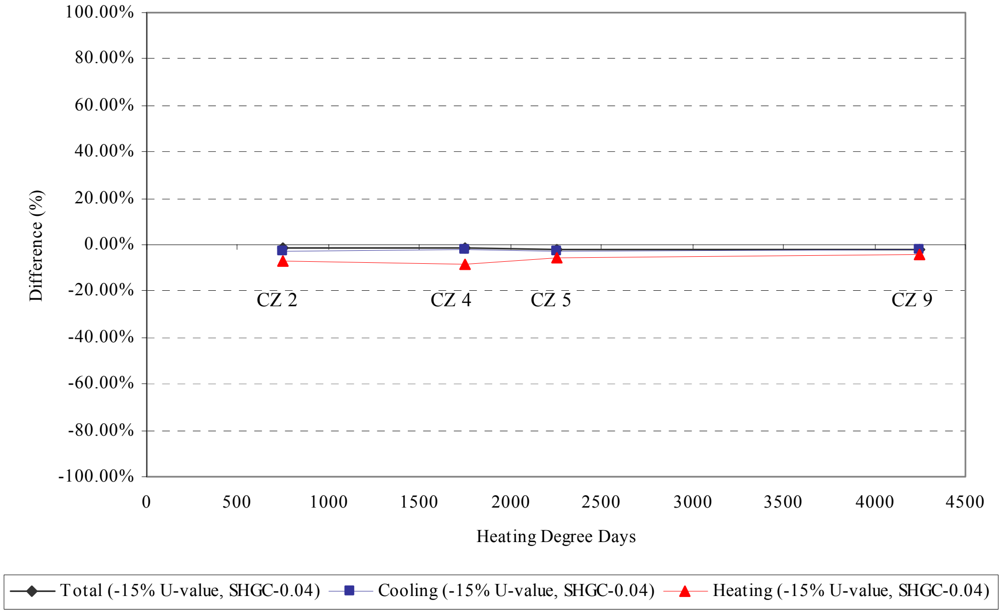


Figure 6.33 Percent difference of annual energy use (base case vs. -15% U-value, SHGC-0.04)

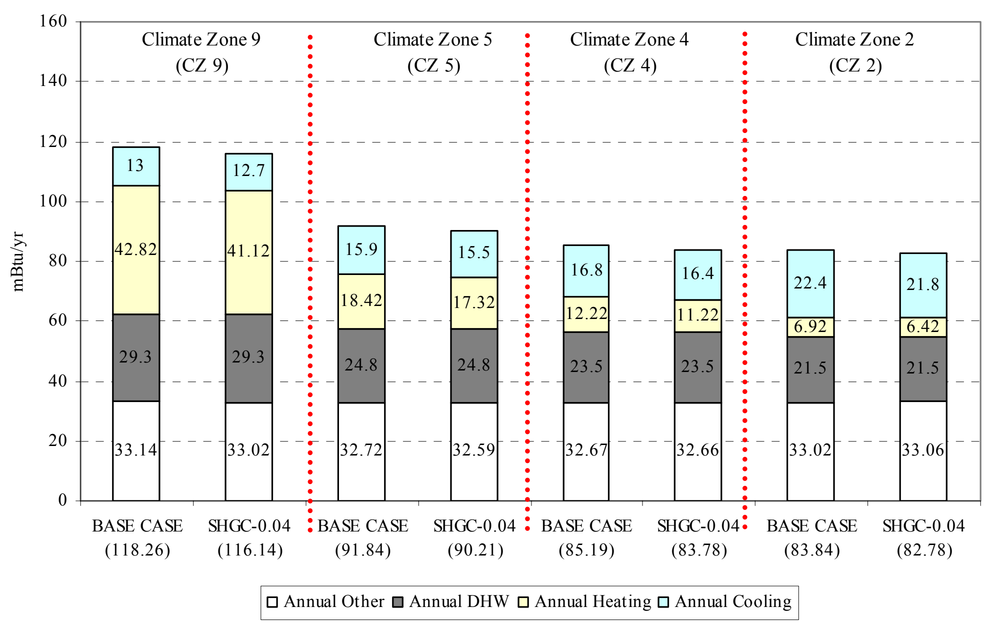


Figure 6.34 Annual energy use (base case vs. -15% U-value, SHGC-0.04)

6.4.1.12 Base case vs. modified (20% decrease in U-value)

In the simulations with a house with a U-value that was decreased by 20%, the heating energy savings were the largest for all climate zones and the total energy savings were the largest for climate zone 9 (Figures 6.35 and 6.36). For the total energy savings, there were reductions of 2.90% for climate zone 9, 2.33% for climate zone 5, 1.76% for climate zone 4 and 0.69% for climate zone 2. For the heating energy savings, 8.64% for climate zone 9, 13.03% for climate zone 5, 15.55% for climate zone 4 and 13.01% for climate zone 2 were all reduced, whereas for cooling energy savings, 2.31% for climate zone 9, 1.89% for climate zone 5, 1.79% for climate zone 4 and 1.34% for climate zone 2 were all increased.

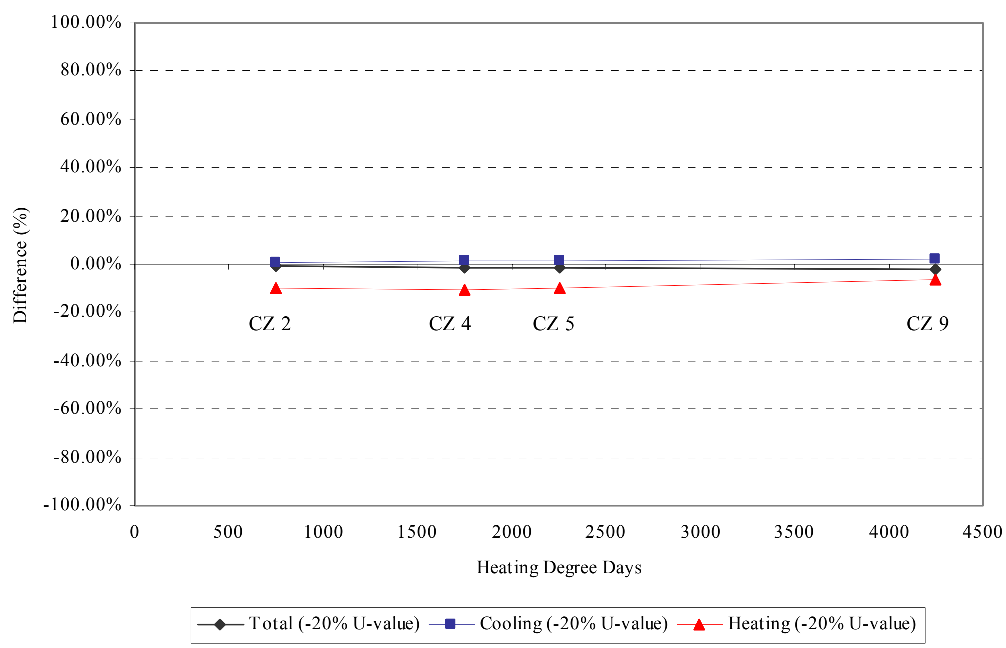


Figure 6.35 Percent difference of annual energy use (base case vs. -20% U-value, same SHGC)

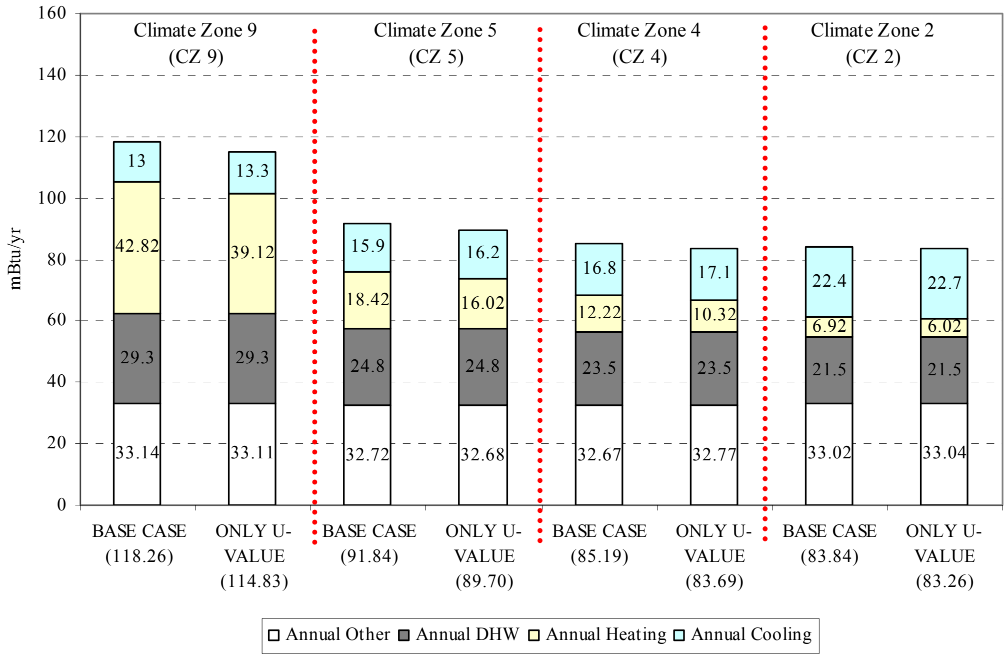


Figure 6.36 Annual energy use (base case vs. -20% U-value, same SHGC)

6.4.1.13 Base case vs. modified (20% decrease in U-value, 0.02 decrease in SHGC)

When a house with a U-value that was decreased by 20% and an SHGC that was decreased by 0.02 was simulated (Figures 6.37 and 6.38), there were reductions of 2.71% for climate zone 9, 2.40% for climate zone 5, 1.90% for climate zone 4 and 1.06% for climate zone 2 for the total energy savings. For the heating energy savings, there were also drops of 7.47% for climate zone 9, 11.40% for climate zone 5, 13.90% for climate zone 4 and 11.56% for climate zone 2, whereas for cooling energy savings, there was an increase of 0.77% for climate zone 9 and a drop of 0.45% for climate zone 2. There were no changes for climate zones 5 and 4.

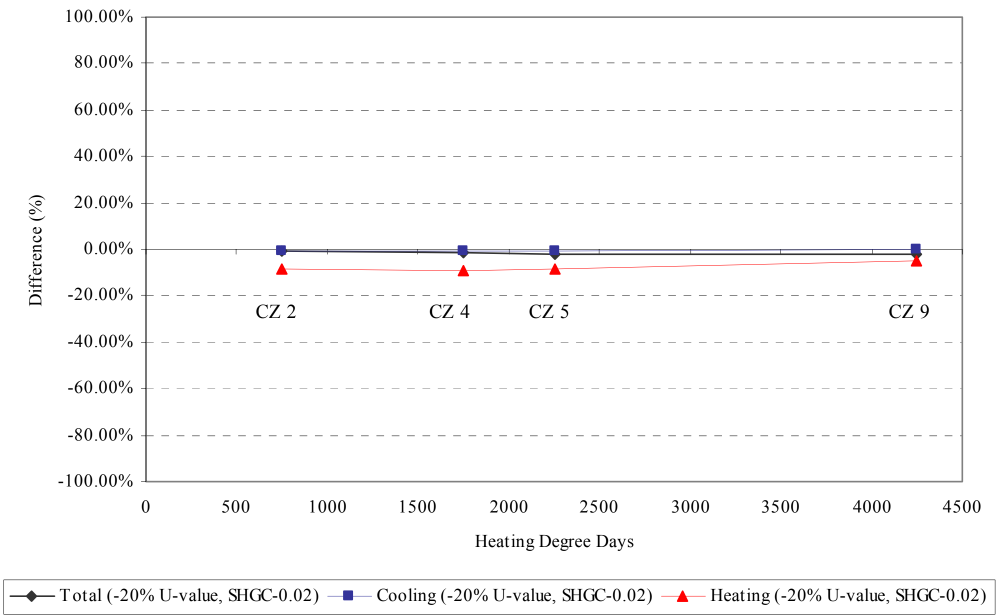


Figure 6.37 Annual energy use and percent difference (base case vs. -20% U-value, SHGC-0.02)

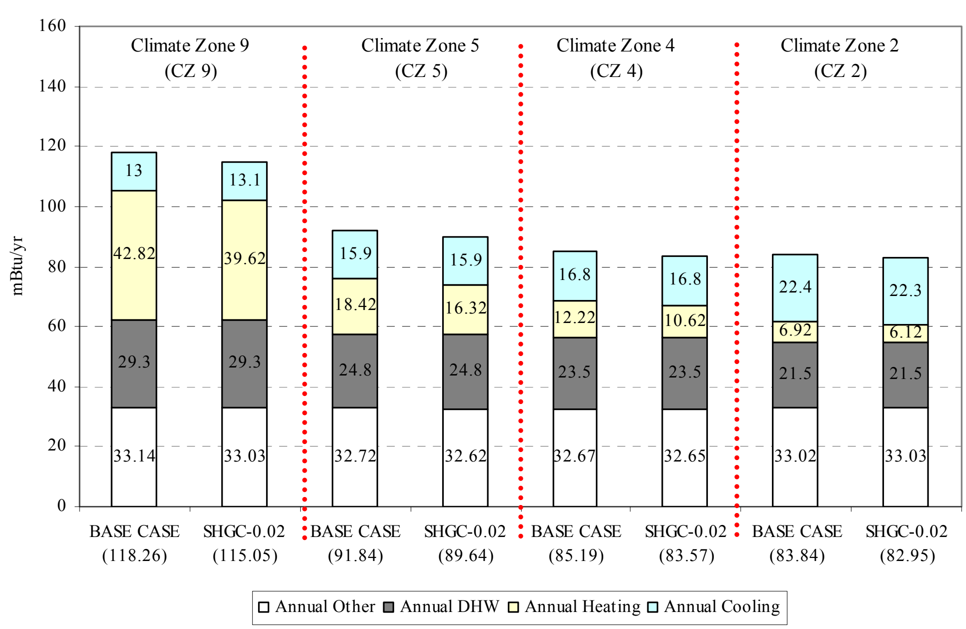


Figure 6.38 Annual energy use (base case vs. -20% U-value, SHGC-0.02)

6.4.1.14 Base case vs. modified (20% decrease in U-value, 0.04 decrease in SHGC)

When a house with a U-value that was decreased by 20% and an SHGC that was decreased by 0.04 was simulated, the total energy use, heating energy use and cooling energy use were all reduced (Figures 6.39 and 6.40). In addition, this window type showed the largest savings of the total energy savings for climate zones 5, 4 and 2. For the total energy savings, there were drops of 2.54% for climate zone 9, 2.45% for climate zone 5, 2.05% for climate zone 4 and 1.41% for climate zone 2, as compared to the base-case house. For the heating energy savings, there were drops of 6.31% for climate zone 9, 9.77% for climate zone 5, 11.46% for climate zone 4 and 10.12% for climate zone 2. For the cooling energy savings, there were also drops of 1.54% for climate zone 9, 2.52% for climate zone 5, 1.79% for climate zone 4 and 2.23% for climate zone 2.

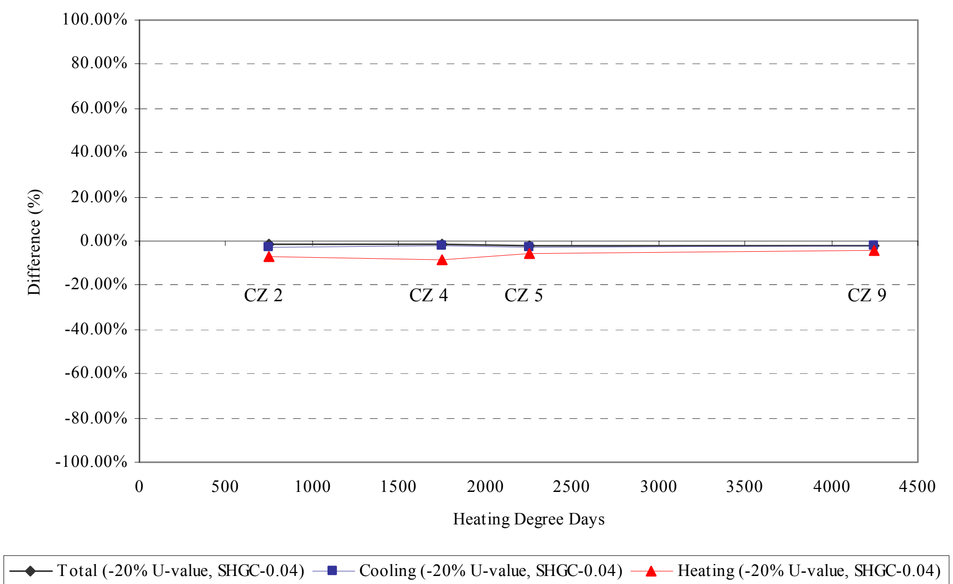


Figure 6.39 Percent difference of annual energy use (base case vs. -20% U-value, SHGC-0.04)

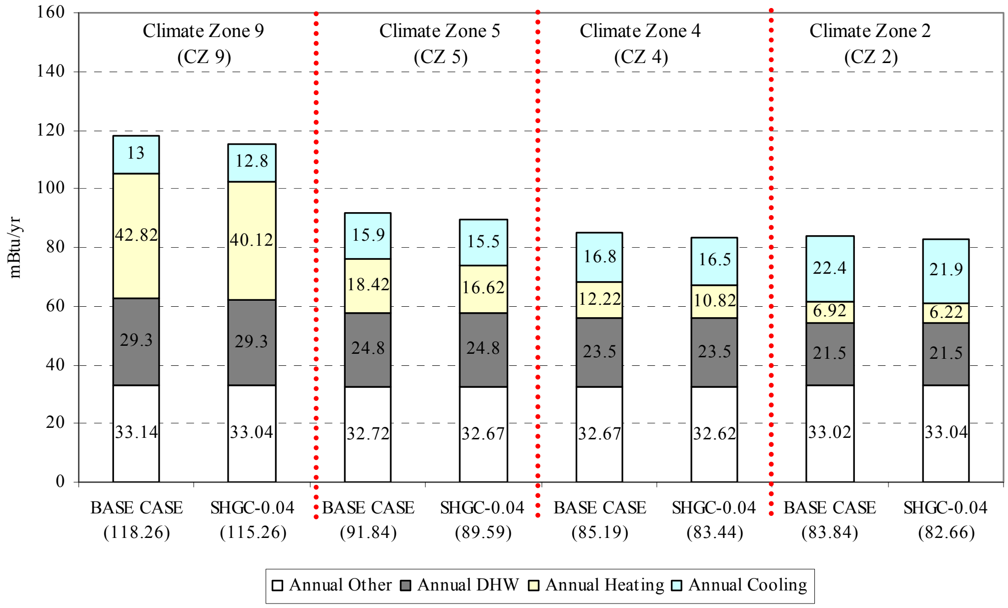


Figure 6.40 Annual energy use (base case vs. -20% U-value, SHGC-0.04)

6.4.2 Analysis of the Duct Properties

The following plots show the annual total energy use, and the heating, cooling and total energy savings achieved by changing the duct properties. In these figures, the percent savings were plotted against the number of heating degree days according to the climate zones.

In order to find the savings achieved from the duct properties, the annual energy use was plotted by changing the R-value for the supply and return side, and the duct leakage rate. The other properties were the same as in the base-case house. For the base-case house, the insulation level for the supply duct was R-8 and the return duct was R-4. Furthermore, since the IECC 2000/2001 does not define the duct leakage rate, the duct leakage rate for the base-case house was set at 0%, and the duct systems were located in the attic space where it was unconditioned. From these simulations, the following traits were observed:

1) The duct leakage rate affected the cooling and heating energy savings more than did different levels of duct insulation.

2) There were more variations in cooling energy in hot climate zones, while more heating energy variations were detected in cold climate zones.

3) Changes for the duct insulation levels from R-8 for the supply side and R-4 for the return side to R-6 for the supply and return sides with the same duct leakage rates produced negative effects for the total, heating and cooling energy levels. Other improvements in duct insulation (from R-8 for the supply and R-4 for the return to R-8 for both the supply and return, R-10 for the supply and return and R-12 for the supply and return) produced significant total, heating and cooling energy savings for ducts located in the attic.

The following are detailed explanations of the results created by the different simulation conditions according to the duct properties.

Simulations were performed by changing duct leakage rates from 5% to 20% in increments of 5%

6.4.2.1 Base case (0% duct leakage rate (DLR), R-8 for supply /R-4 for return) vs. modified (5% duct leakage rate (DLR), R-8 for supply /R-4 for return)

For 5% duct leakage rate (Figure 6.41), there were increases of the total energy consumption of 3.95% for climate zone 9, 3.68% for climate zone 5, 3.89% for climate zone 4 and 4.23% for climate zone 2 compared to the base-case house. For the heating energy use, there were also increases of 8.87% for climate zone 9, 8.14% for climate zone 5, 8.18% for climate zone 4 and 7.23% for climate zone 2. For the cooling energy use, there were increases of 6.92% for climate zone 9, 11.95% for climate zone 5, 13.69% for climate zone 4 and 13.39% for climate zone 2.

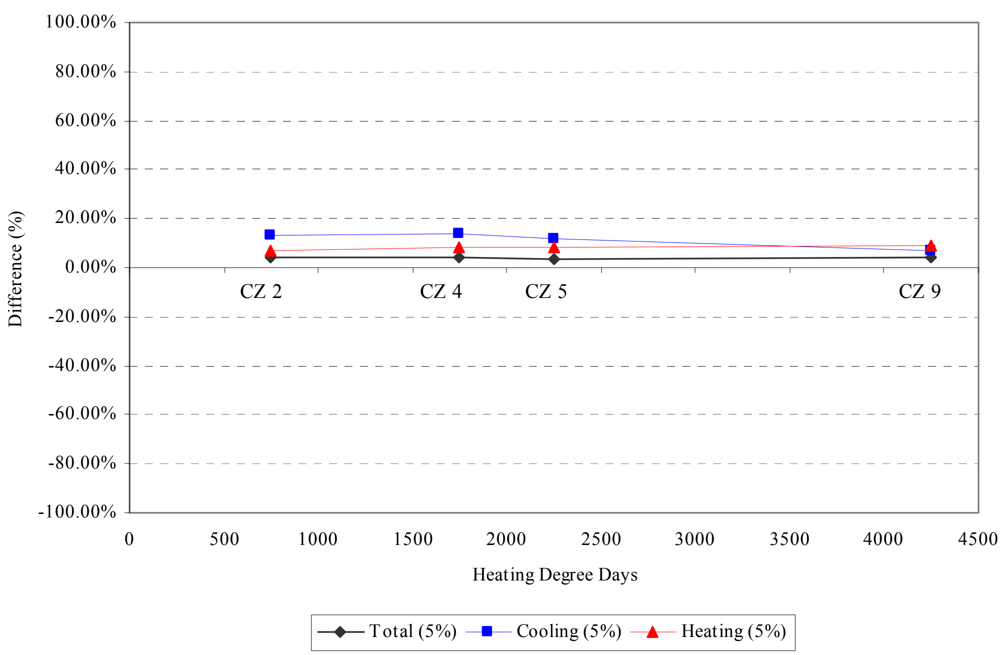


Figure 6.41 Percent difference of annual energy use (base case (0%, SR-8, RR-4) vs. 5% (SR-8, RR-4))

6.4.2.2 Base case (0% duct leakage rate (DLR), R-8 for supply /R-4 for return) vs. modified (10% duct leakage rate (DLR), R-8 for supply /R-4 for return)

When a 10% leakage rate was applied to the base-case house in the simulation (Figure 6.42), there were increases of 8.47% for climate zone 9, 8.07% for climate zone 5, 8.63% for climate zone 4 and 9.45% for climate zone 2 in the total annual energy use. For the annual heating energy use, there were increases of 18.92% for climate zone 9, 17.37% for climate zone 5, 18.00% for climate zone 4 and 15.90% for climate zone 2. For the annual cooling energy use, there were also increases of 15.38% for climate zone 9, 26.42% for climate zone 5 and 30.36% for climate zones 4 and 2.

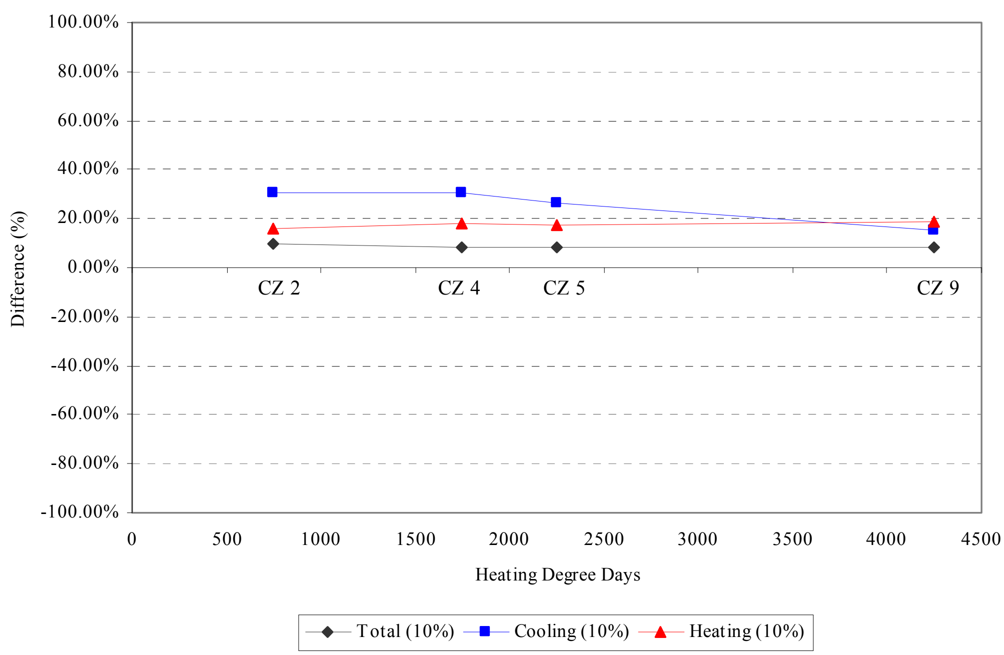


Figure 6.42 Percent difference of annual energy use (base case(0%, SR-8, RR-4) vs. 10% (SR-8, RR-4))

6.4.2.3 Base case (0% duct leakage rate (DLR), R-8 for supply /R-4 for return) vs. modified (15% duct leakage rate (DLR), R-8 for supply /R-4 for return)

In the case of a 15% duct leakage rate (Figure 6.43), there were total energy use increases of 13.70% for climate zone 9, 13.38% for climate zone 5, 14.58% for climate zone 4 and 15.99% for climate zone 2. For the heating energy use, the simulation showed increases of 30.38% for climate zone 9, 28.23% for climate zone 5, 28.64% for climate zone 4 and 24.57% for climate zone 2. For cooling energy use, there were increases of 24.62% for climate zone 9, 44.65% for climate zone 5, 52.98% for climate zone 4 and 51.79% for climate zone 2.

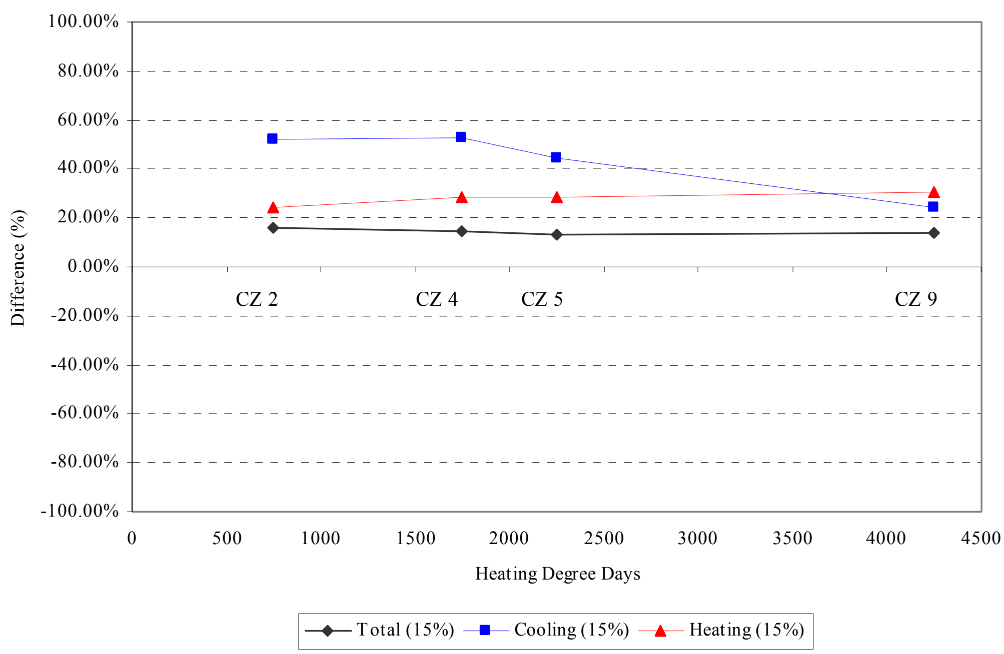


Figure 6.43 Percent difference of annual energy use (base case(0%, SR-8, RR-4) vs. 15% (SR-8, RR-4))

6.4.2.4 Base case (0% duct leakage rate (DLR), R-8 for supply /R-4 for return) vs. modified (20% duct leakage rate (DLR), R-8 for supply /R-4 for return)

Using a 20% duct leakage rate (Figure 6.44), the simulations showed increases of 19.77% for climate zone 9, 20.15% for climate zone 5, 22.41% for climate zone 4 and 24.50% for climate zone 2. For the heating energy use, there were also increases of 43.90% for climate zone 9, 40.72% for climate zone 5, 41.73% for climate zone 4 and 38.13% for climate zone 2, and for the cooling energy use, there were increases of 36.15% for climate zone 9, 69.18% for climate zone 5, 83.33% for climate zone 4 and 80.36% for climate zone 2.

Figure 6.45 shows the annual energy use of SR-8 and RR-4 according to the duct leakage rate

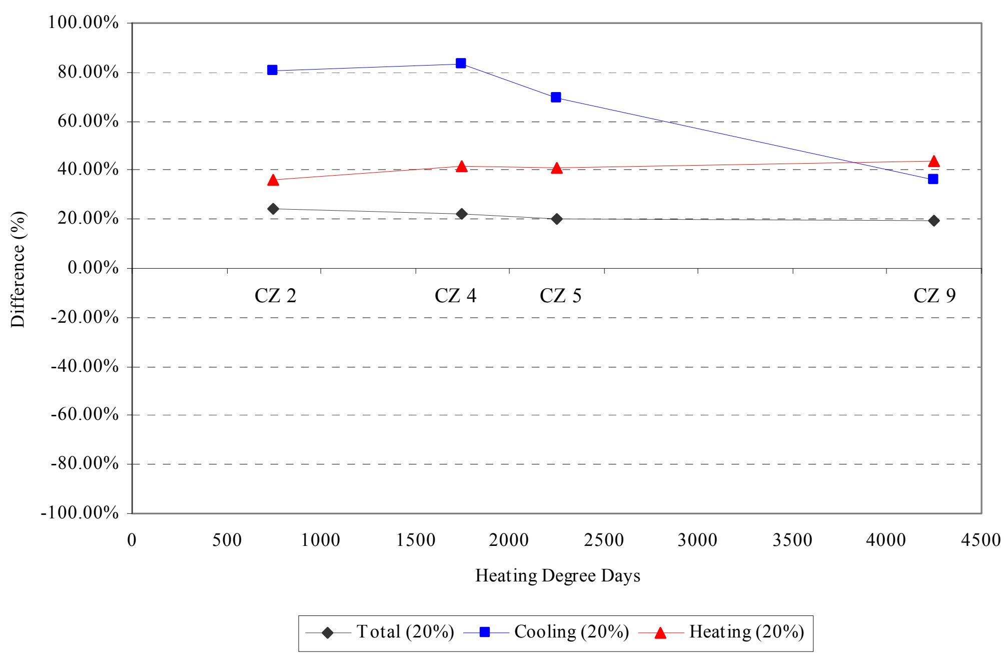


Figure 6.44 Percent difference of annual energy use (base case(0%, SR-8, RR-4) vs. 20% (SR-8, RR-4))

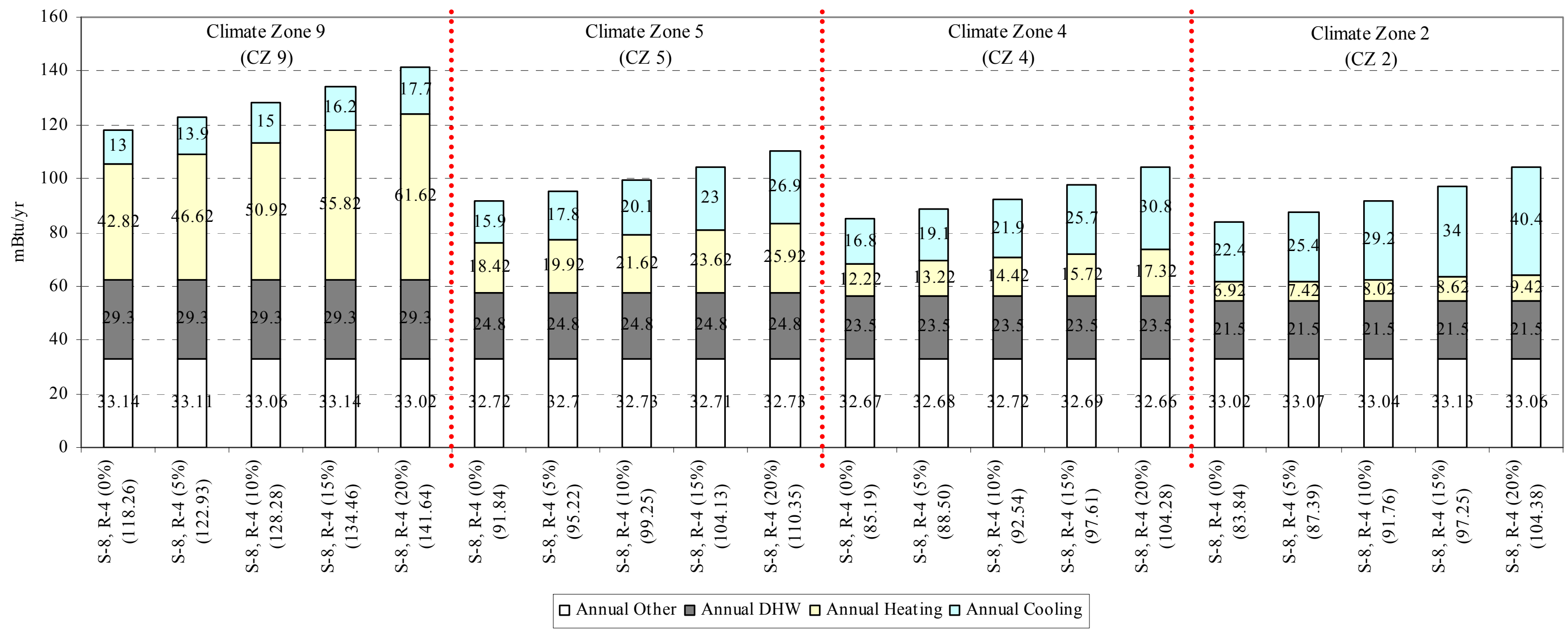


Figure 6.45 Annual energy use of SR-8 and RR-4 according to the duct leakage rate

In order to investigate the impacts of the duct insulation levels, the duct R-value was changed to R-6 for the supply and return side in the base-case house, which had R-8 for supply and R-4 for return in these simulations. Duct leakage rate was also increased from 0% to 20% in increments of 5%.

6.4.2.5 Base case (0% duct leakage rate (DLR), R-8 for supply /R-4 for return) vs. modified (0% duct leakage rate (DLR), R-6 for supply / R-6 for return)

When the R-value of duct was changed to R-6 for the supply and return in the simulations, the total energy use, heating energy use and cooling energy use increased compared to the base-case house (Figure 6.46). For the total energy use, there were increases of 1.16% for climate zone 9, 1.00% for climate zone 5, 1.03% for climate zone 4 and 1.15% for climate zone 2. For the heating energy use, there were increases of 2.10% for climate zone 9, 1.63% for climate zone 5, 1.64% for climate zone 4 and 1.45% for climate zone 2. For the cooling energy use, there were also increases of 4.62% for climate zone 9, 3.77% for climate zone 5, 4.17% for climate zone 4 and 3.57% for climate zone 2.

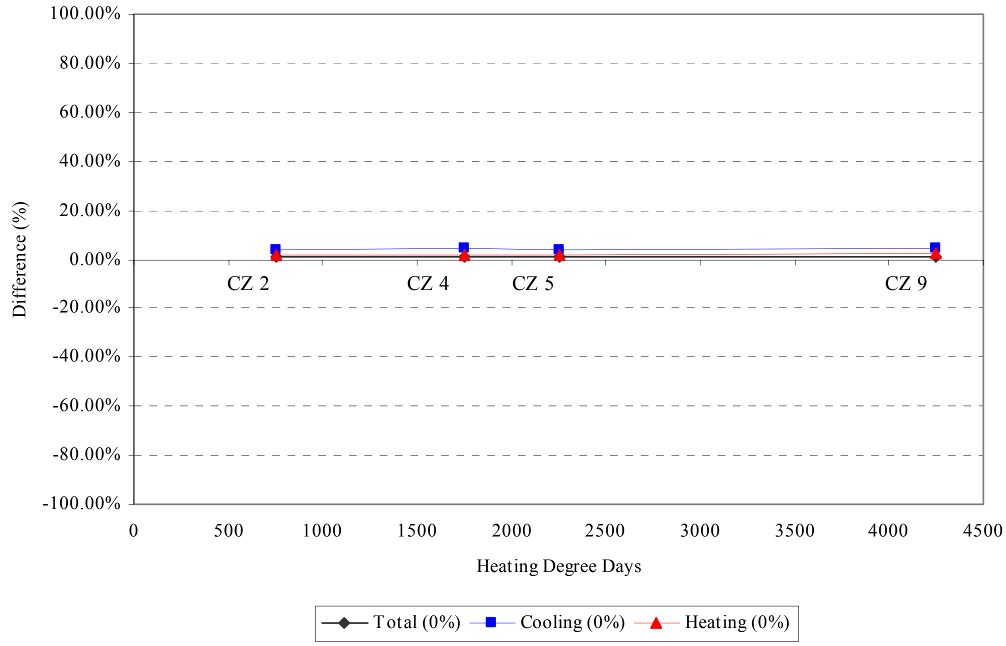


Figure 6.46 Percent difference of annual energy use (base case (0%, SR-8,RR-4) vs. 0% (SR-6,RR-6))

6.4.2.6 Base case (0% DLR, SR-8/RR-4) vs. modified (5% DLR, SR-6/RR-6)

When a duct leakage rate was increased to 5% (Figure 6.47), the total energy use increased by 5.23% for climate zone 9, 4.86% for climate zone 5, 5.12% for climate zone 4 and 5.63% for climate zone 2. The heating energy use increased by 10.98% for climate zone 9, 10.31% for climate zone 5, 10.64% for climate zone 4 and 8.67% for climate zone 2. The cooling energy use also increased by 11.54% for climate zone 9, 16.35% for climate zone 5, 18.45% for climate zone 4 and 18.30% for climate zone 2.

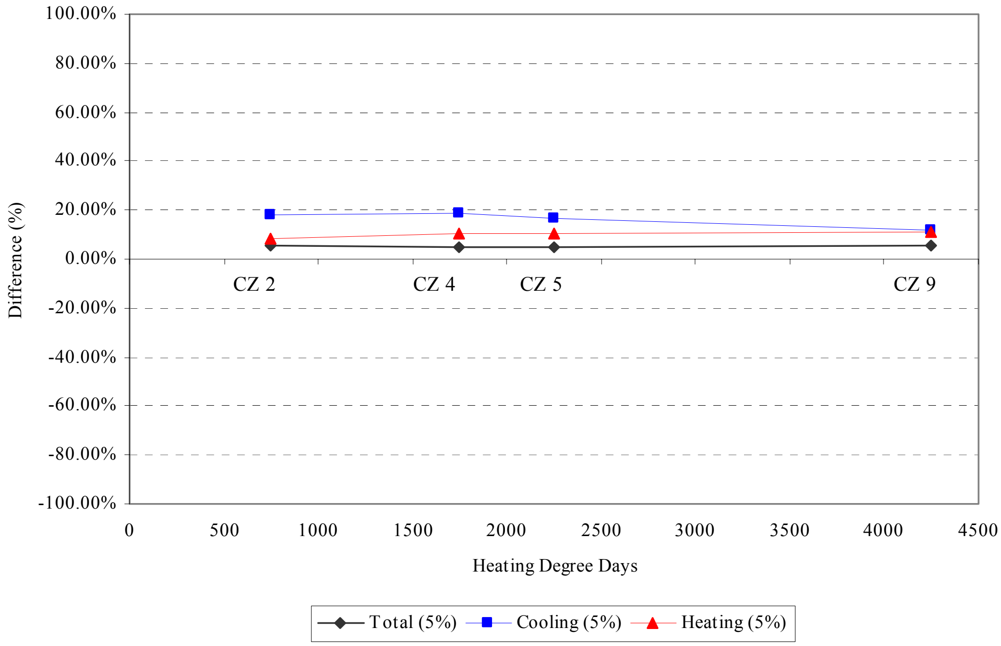


Figure 6.47 Percent difference of annual energy use (base case (0%, SR-8,RR-4) vs. 5% (SR-6,RR-6))

6.4.2.7 Base case (0% DLR, SR-8/RR-4) vs. modified (10% DLR, SR-6/RR-6)

Using a 10% duct leakage rate in the simulation (Figure 6.48), for the total energy use, they showed increases of 9.89% for climate zone 9, 3.47% for climate zone 5, 10.17% for climate zone 4 and 11.19% for climate zone 2. For the heating energy use, there was a 21.25% increase for climate zone 9, a 19.54% increase for climate zone 5, a 19.64% increase for climate zone 4 and a 17.34% increase for climate zone 2. For cooling energy use, there was a 20.00% increase for climate zone 9, a 32.08% increase for climate zone 5, a 36.90% increase for climate zone 4 and a 36.16% increase for climate zone 2.

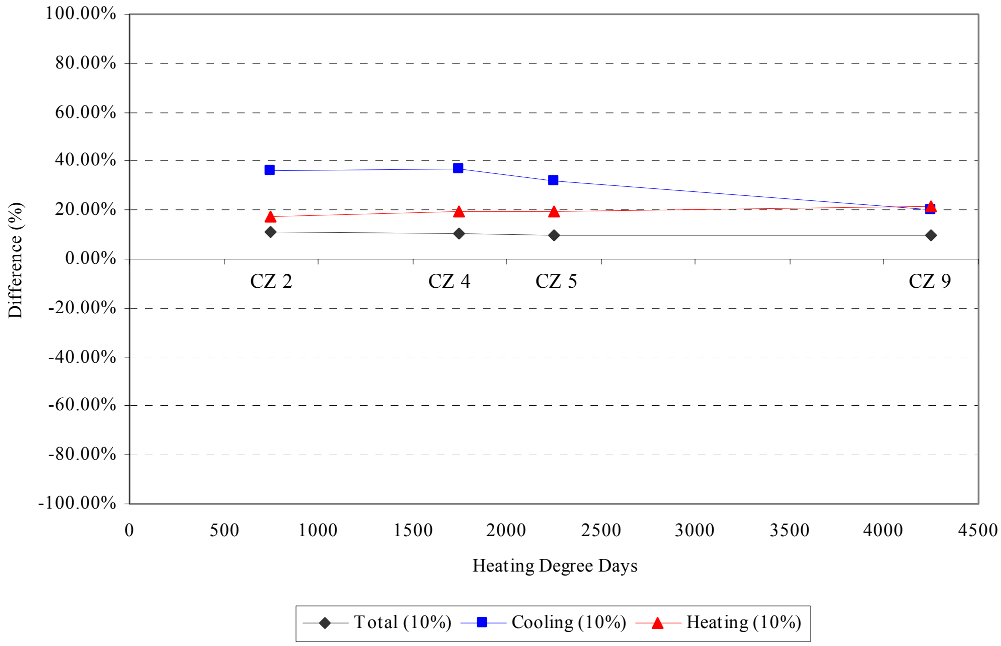


Figure 6.48 Percent difference of annual energy use (base case (0%, SR-8, RR-4) vs. 10% (SR-6,RR-6))

6.4.2.8 Base case (0% DLR, SR-8/RR-4) vs. modified (15% DLR, SR-6/RR-6)

The results of a 15% duct leakage rate (Figure 6.49) showed a 15.30% increase for climate zone 9, a 15.12% increase for climate zone 5, a 16.59% increase for climate zone 4 and a 18.25% increase for climate zone 2 in the total energy use. The results also showed a 33.16% increase for climate zone 9, a 30.40% increase for climate zone 5, a 31.10% increase for climate zone 4 and a 27.46% increase for climate zone 2 for the heating energy use, and a 30.77% increase for climate zone 9, a 52.20% increase for climate zone 5, a 61.31% increase for climate zone 4 and a 59.82% increase for climate zone 2 for the cooling energy use.

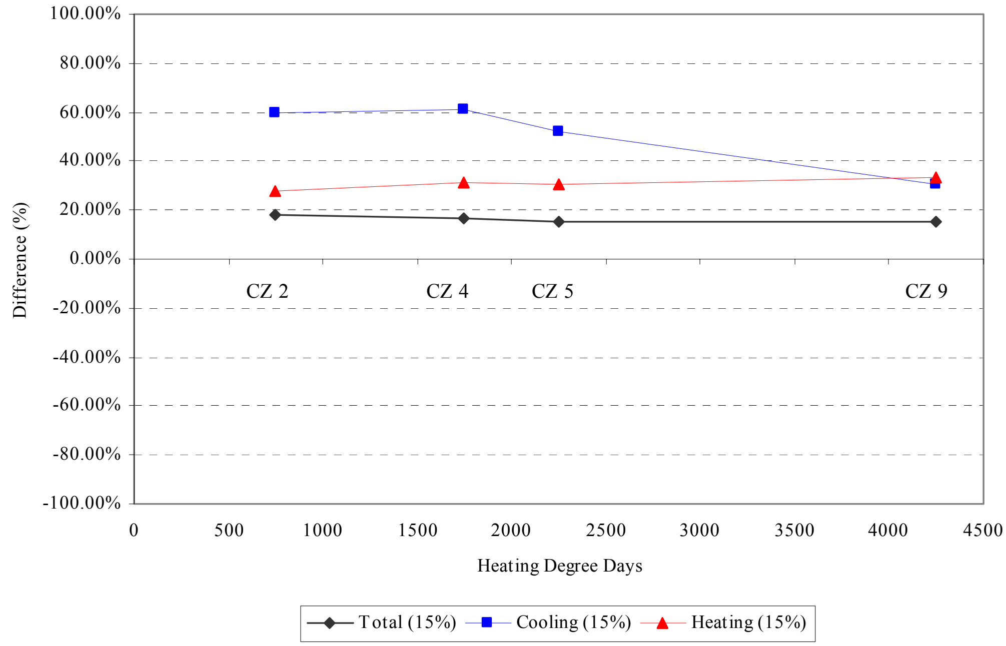


Figure 6.49 Percent difference of annual energy use (base case (0%, SR-8, RR-4) to 15% (SR-6,RR-6))

6.4.2.9 Base case (0% DLR, SR-8/RR-4) vs. modified (20% DLR, SR-6/RR-6)

When a 20% duct leakage rate was applied to the simulations (Figure 6.50), there were increases of 21.58% for climate zone 9, 22.67% for climate zone 5, 25.23% for climate zone 4 and 27.54% for climate zone 2 for the total energy use. For the heating energy use, they showed a 46.94% increase for climate zone 9, a 42.83% increase for climate zone 5, a 44.19% increase for climate zone 4 and a 37.57% increase for climate zone 2. For cooling energy use, they also showed a 42.31% increase for climate zone 9, a 81.18% increase for climate zone 5, a 95.83% increase for climate zone 4 and a 91.07% increase for climate zone 2.

Figure 6.51 shows the annual energy use of SR-6 and RR-6 vs. SR-8 and RR-4 according to the duct leakage rate.

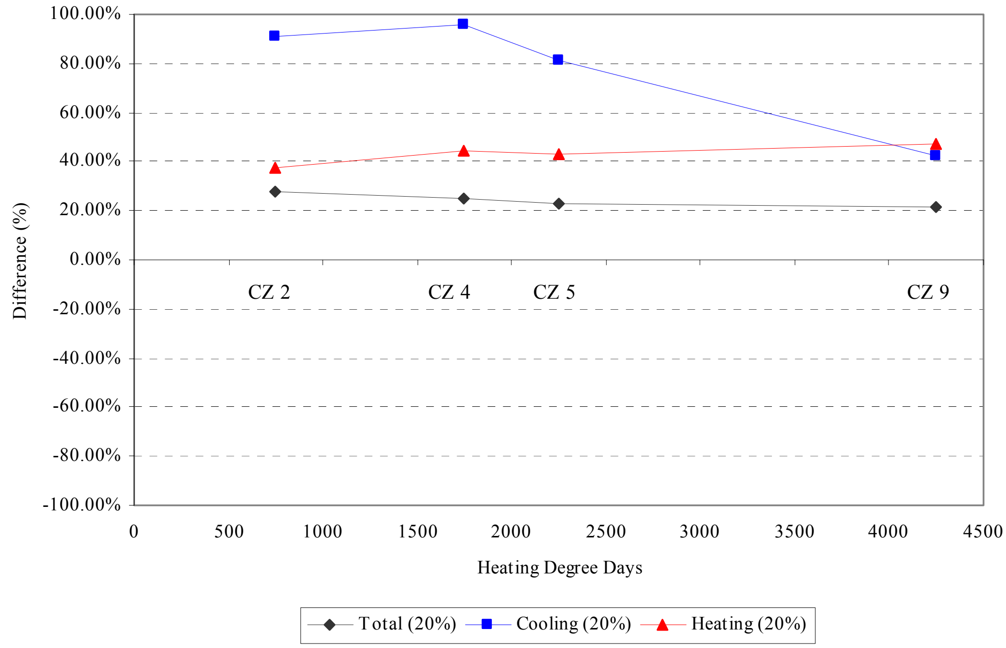


Figure 6.50 Percent difference of annual energy use (base case (0%, SR-8,RR-4) vs. 20% (SR-6,RR-6))

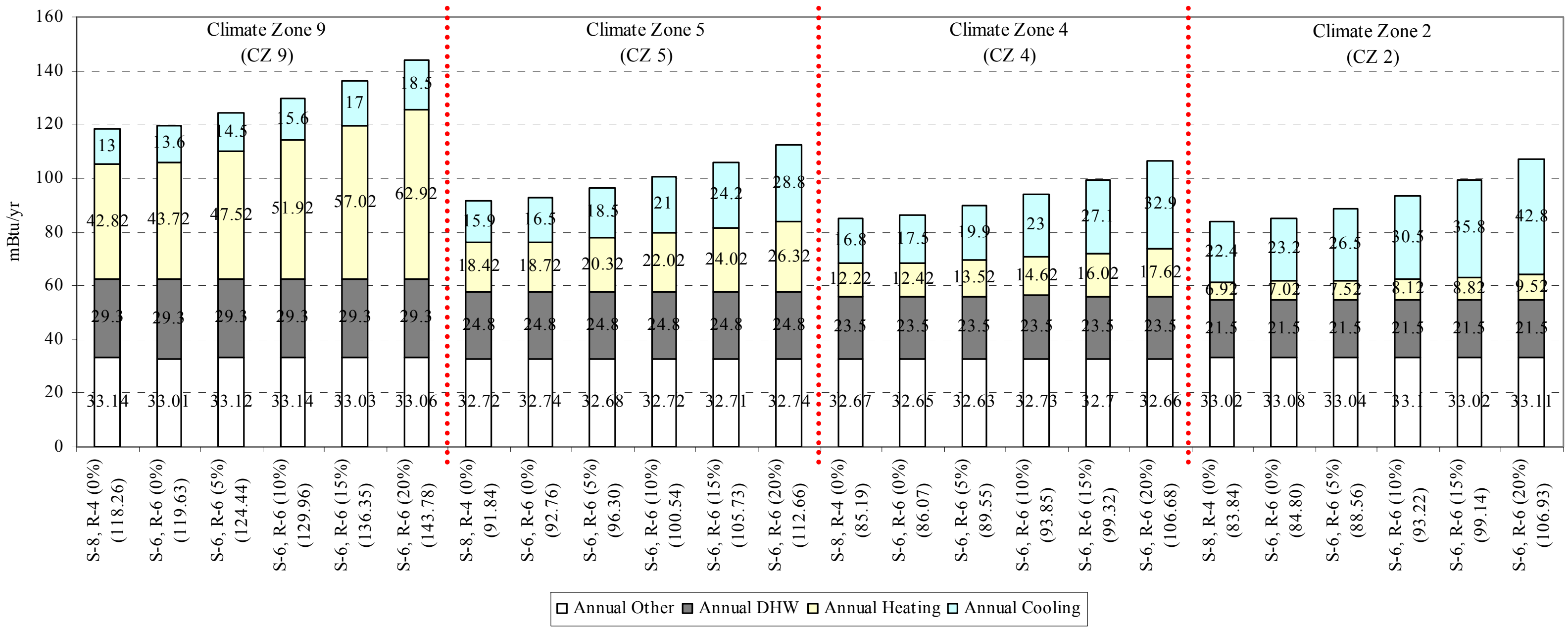


Figure 6.51 Annual energy use of SR-6 and RR-6 vs. SR-8 and RR-4 according to the duct leakage rate

When duct insulation levels were increased to R-8 for the supply and return from the base-case house and the duct leakage rate increased from 0% to 20% in increments of 5%.

6.4.2.10 Base case (0% DLR, SR-8/RR-4) vs. modified (0% DLR, SR-8/RR-8)

The improvement of duct insulation with a 0% duct leakage rate decreased the total energy use, heating energy use and cooling energy use compared to the base-case house, which had R-8 for the supply, R-4 for the return and 0% duct leakage rate (Figure 6.52). For the total energy use, the results showed reductions of 0.18% for climate zone 9, 0.13% for climate zone 5, 0.11% for climate zone 4 and 0.08% for climate zone 2. For the heating energy use, there were also reductions of 0.47% for climate zone 9 and 0.54% for climate zone 5, and there were no changes for climate zones 4 and 2. For the cooling energy use, they showed reductions of 0.63% for climate zone 5, 0.60% for climate zone 4, 0.45% for climate zone 2, and there was no change for climate zone 9.

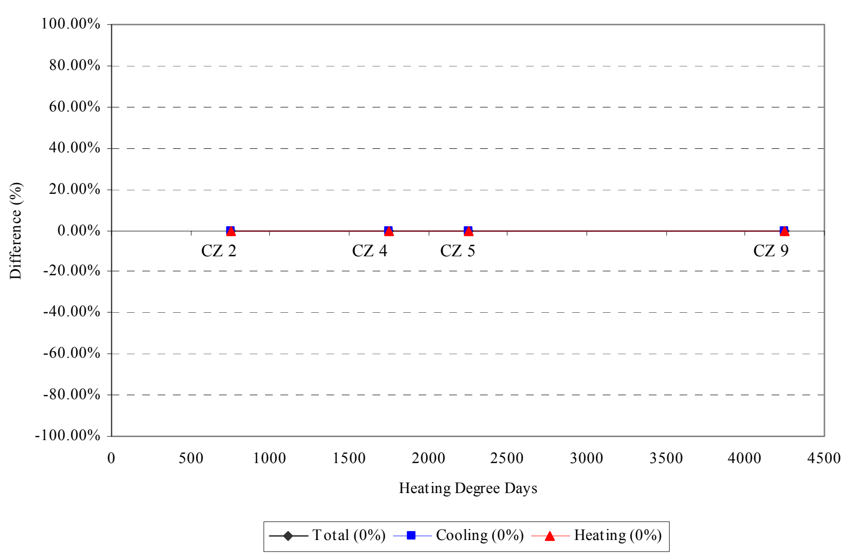


Figure 6.52 Percent difference of annual energy use (base case (0%, SR-8,RR-4) vs. 0% (SR-8, RR-8))

6.4.2.11 Base case (0% DLR, SR-8/RR-4) vs. modified (5% DLR, SR-8/RR-8)

When increasing the duct leakage rate to 5% in the simulations (Figure 6.53), the total energy use, heating energy use and cooling energy use showed increases. Total energy use increased by 3.75% for climate zone 9, 3.54% for climate zone 5, 3.76% for climate zone 4 and 4.14% for climate zone 2. Heating energy use increased by 8.41% for climate zone 9, 8.14% for climate zone 5, 8.18% for climate zone 4 and 7.23% for climate zone 2. Cooling energy use increased by 6.92% for climate zone 9, 11.32% for climate zone 5, 13.10% for climate zone 4 and 12.95% for climate zone 2.

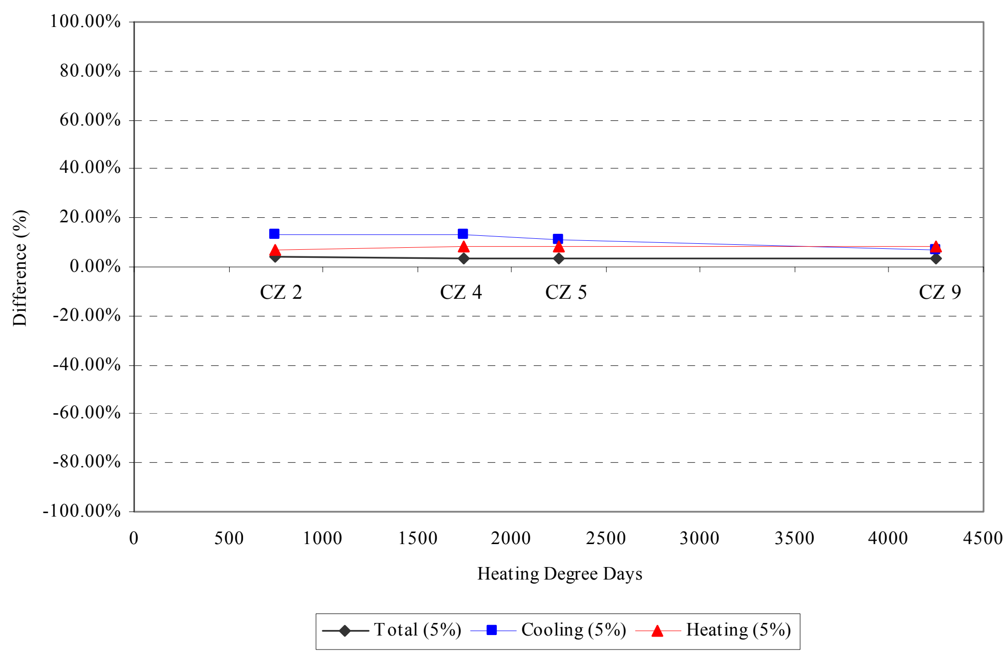


Figure 6.53 Percent difference of annual energy use (base case (0%, SR-8,RR-4) vs. 5% (SR-8, RR-8))

6.4.2.12 Base case (0% DLR, SR-8/RR-4) vs. modified (10% DLR, SR-8/RR-8)

When a 10% duct leakage rate was used in the simulations (Figure 6.54), there were increases of 8.26% for climate zone 9, 7.91% for climate zone 5, 8.49% for climate zone 4 and 9.33% for climate zone 2 for the total energy use. For the heating energy use, they showed a 18.45% increase for climate zone 9, a 17.37% increase for climate zone 5, a 17.18% increase for climate zone 4 and a 15.90% increase for climate zone 2, and for cooling energy use, they also showed a 15.38% increase for climate zone 9, a 25.79% increase for climate zone 5, a 30.36% increase for climate zone 4 and a 29.91% increase for climate zone 2.

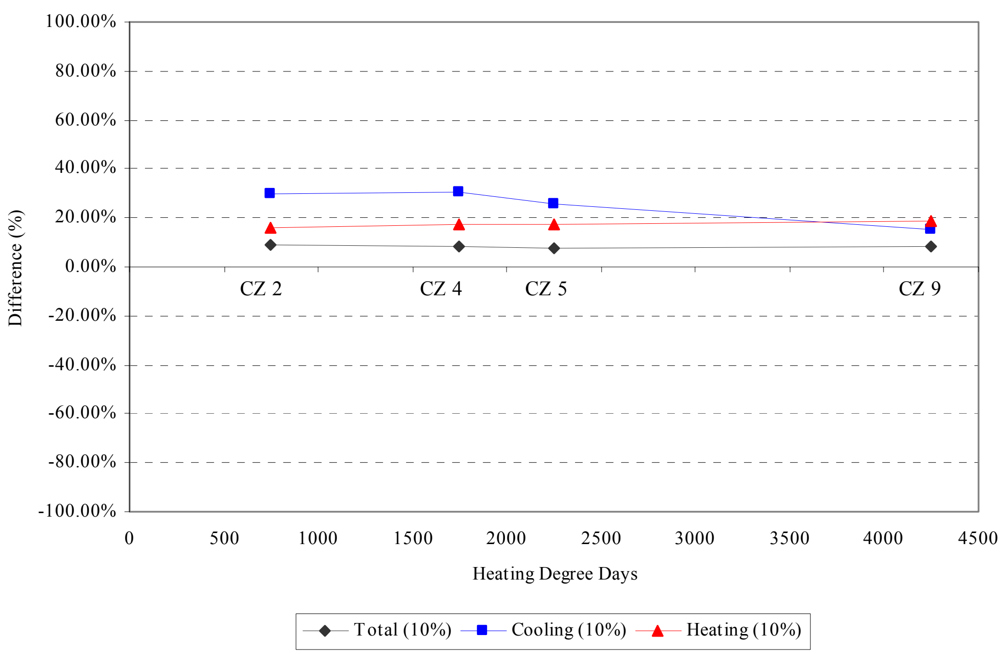


Figure 6.54 Percent difference of annual energy use (base case (0%, SR-8,RR-4) vs. 10% (SR-8,RR-8))

6.4.2.13 Base case (0% DLR, SR-8/RR-4) vs. modified (15% DLR, SR-8/RR-8)

In the case of a 15% duct leakage rate (Figure 6.55), there were total energy use increases of 13.46% for climate zone 9, 13.19% for climate zone 5, 14.40% for climate zone 4 and 15.86% for climate zone 2. For the heating energy use, they showed increase of 29.89% for climate zone 9, 27.69% for climate zone 5, 28.64% for climate zone 4 and 24.57% for climate zone 2, and for cooling energy use, 24.62% for climate zone 9, 44.03% for climate zone 5, 52.38% for climate zone 4 and 51.34% for climate zone 2 were increased due to the duct leakage rates.

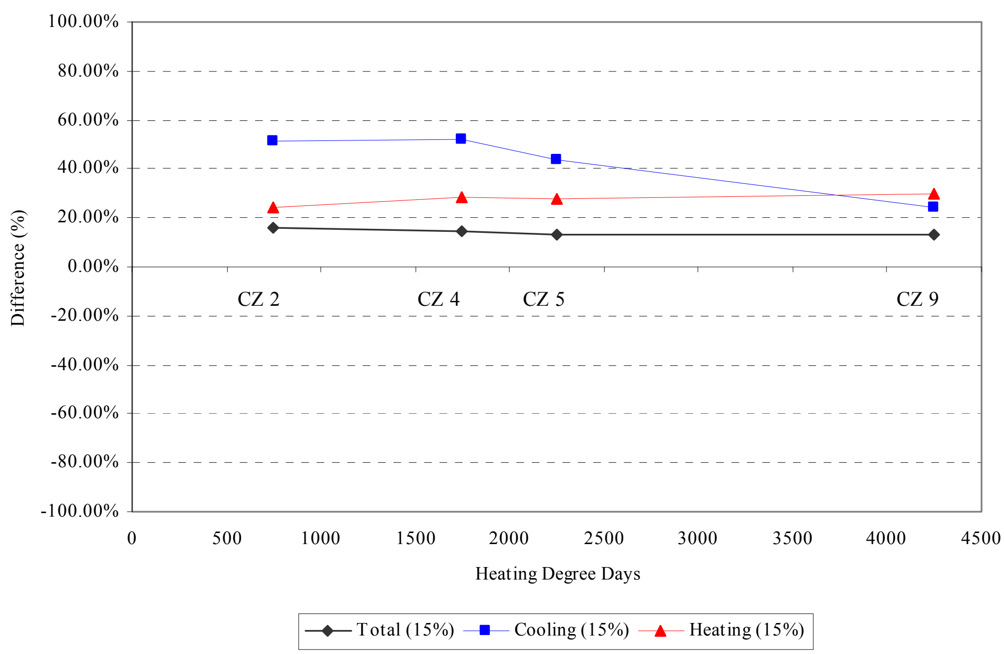


Figure 6.55 Percent difference of annual energy use (base case (0%, SR-8,RR-4) vs. 15% (SR-8,RR-8))

6.4.2.14 Base case (0% DLR, SR-8/RR-4) vs. modified (20% DLR, SR-8/RR-8)

Using a 20% duct leakage rate (Figure 6.56), they also showed increase of 19.52% for climate zone 9, 19.88% for climate zone 5, 22.17% for climate zone 4 and 24.32% for climate zone 2 in the total energy use. For the heating energy use, there were also increases of 43.20% for climate zone 9, 40.17% for climate zone 5, 40.92% for climate zone 4 and 36.13% for climate zone 2, and for the cooling energy use, there were increases of 35.38% for climate zone 9, 68.55% for climate zone 5, 82.74% for climate zone 4 and 79.91% for climate zone 2.

Figure 6.57 shows the annual energy use of SR-8 and RR-8 vs. SR-8 and RR-4 according to the duct leakage rate

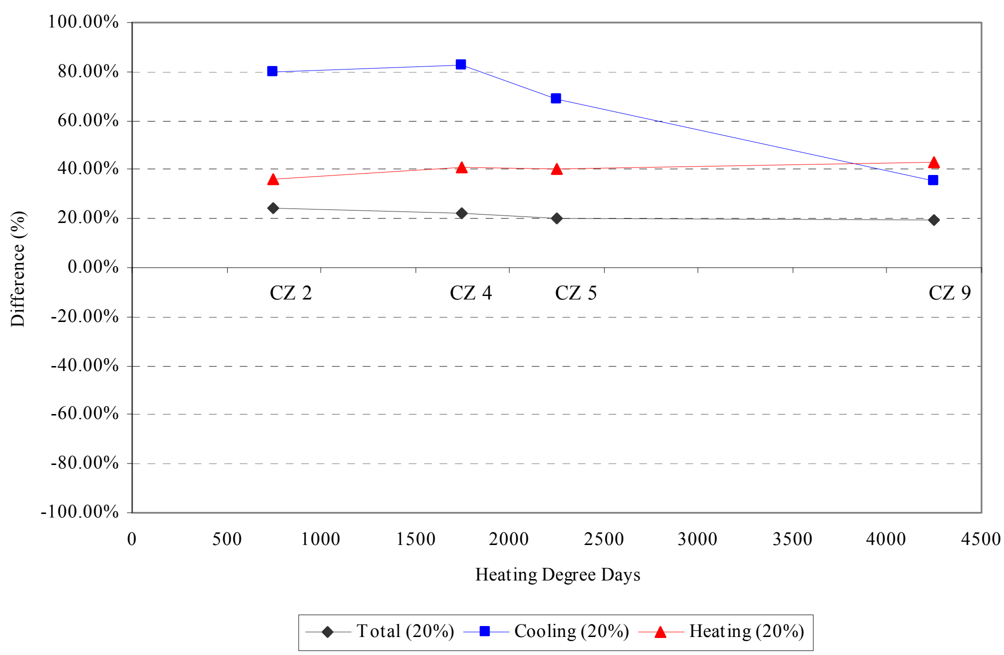


Figure 6.56 Percent difference of annual energy use (base case (0%, SR-8,RR-4) to 20% (SR-8,RR-8))

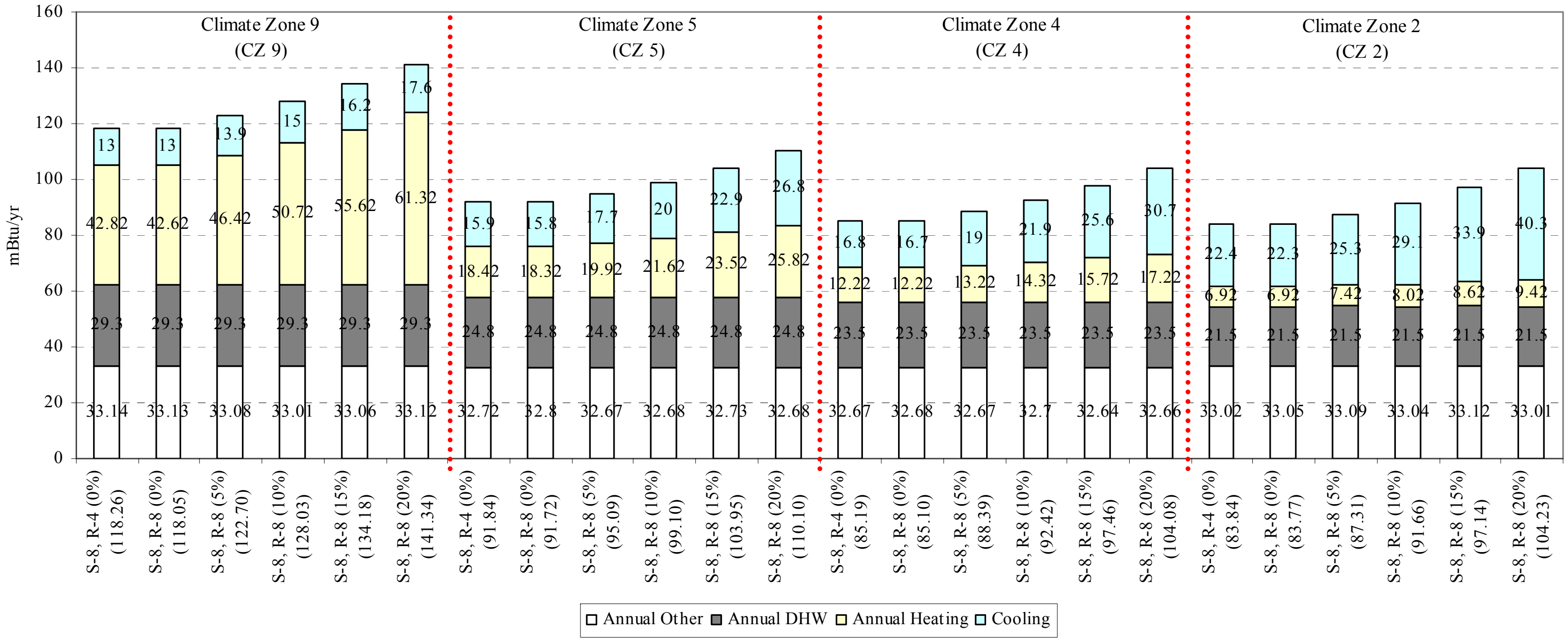


Figure 6.57 Annual energy use of SR-8 and RR-8 vs. SR-8 and RR-4 according to the duct leakage rate

When the duct insulation levels were increased to R-10 for the supply and return from the base-case house and the duct leakage rate was changed from 0% to 20% in increments of 5%.

6.4.2.15 Base case (0% DLR, SR-8/RR-4) vs. modified (0% DLR, SR-10/RR-10)

Improving R-value for supply and return (R-10) with the same duct leakage rate of the base-case house produced reductions for all types of the energy use compared to the base-case house (Figure 6.58). For the total energy use, the results showed reductions of 0.96% for climate zone 9, 0.77% for climate zone 5, 0.75% for climate zone 4 and 0.78% for climate zone 2. Heating energy use decreased by 1.63% for climate zone 9, 1.63% for climate zone 5, 1.64% for climate zone 4 and 1.45% for climate zone 2. Cooling energy use decreased by 2.31% for climate zone 9, 2.52% for climate zone 5, 2.98% for climate zone 4 and 2.65% for climate zone 2.

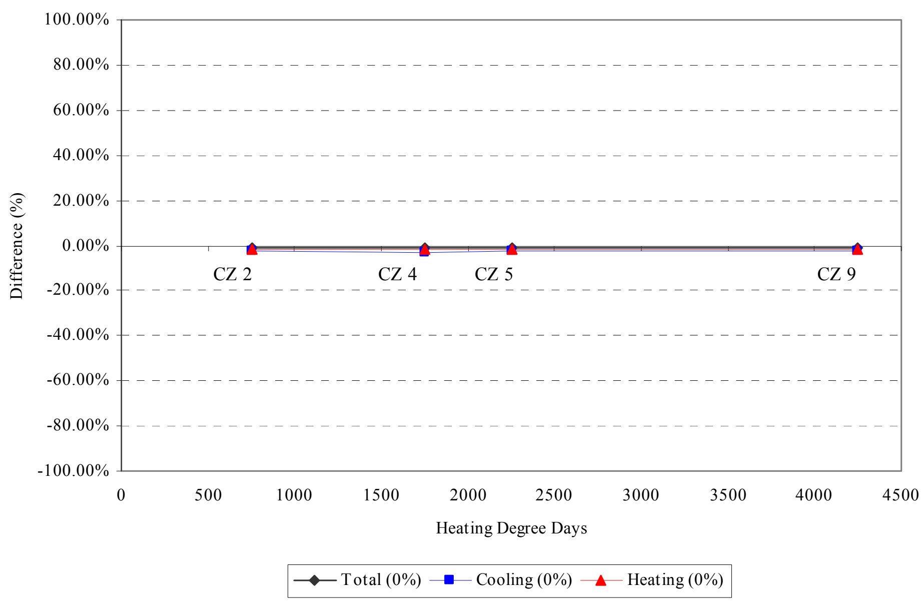


Figure 6.58 Percent difference of annual energy use (base case (0%, SR-8,RR-4) to 0% (SR-10,RR-10))

6.4.2.16 Base case (0% DLR, SR-8/RR-4) vs. modified (5% DLR, SR-10/RR-10)

When a duct leakage rate was increased to 5% (Figure 6.59), the total energy use increased by 2.90% for climate zone 9, 2.80% for climate zone 5, 2.99% for climate zone 4 and 3.29% for climate zone 2. The heating energy use increased by 6.77% for climate zone 9, 6.51% for climate zone 5, 6.55% for climate zone 4 and 5.78% for climate zone 2. The cooling energy use also increased by 4.62% for climate zone 9, 8.18% for climate zone 5, 10.12% for climate zone 4 and 10.27% for climate zone 2.

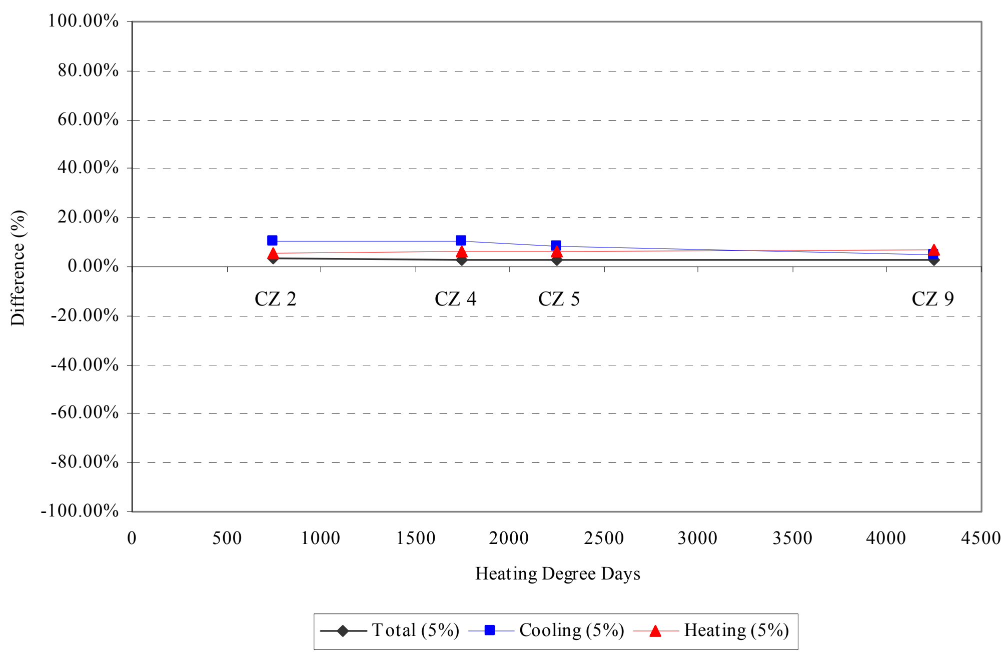


Figure 6.59 Percent difference of annual energy use (base case (0%, SR-8,RR-4) to 5% (SR-10,RR-10))

6.4.2.17 Base case (0% DLR, SR-8/RR-4) vs. modified (10% DLR, SR-10/RR-10)

When a 10% duct leakage rate was used in the simulations (Figure 6.60), there were increases of 7.32% for climate zone 9, 7.01% for climate zone 5, 7.54% for climate zone 4 and 8.29% for climate zone 2 for the total energy use. For the heating energy use, the results showed a 16.58% increase for climate zone 9, a 15.74% increase for climate zone 5, a 16.37% increase for climate zone 4 and a 14.45% increase for climate zone 2. For the cooling energy use, the results also showed a 12.31% increase for climate zone 9, a 22.01% increase for climate zone 5, a 26.19% increase for climate zone 4 and a 26.34% increase for climate zone 2.

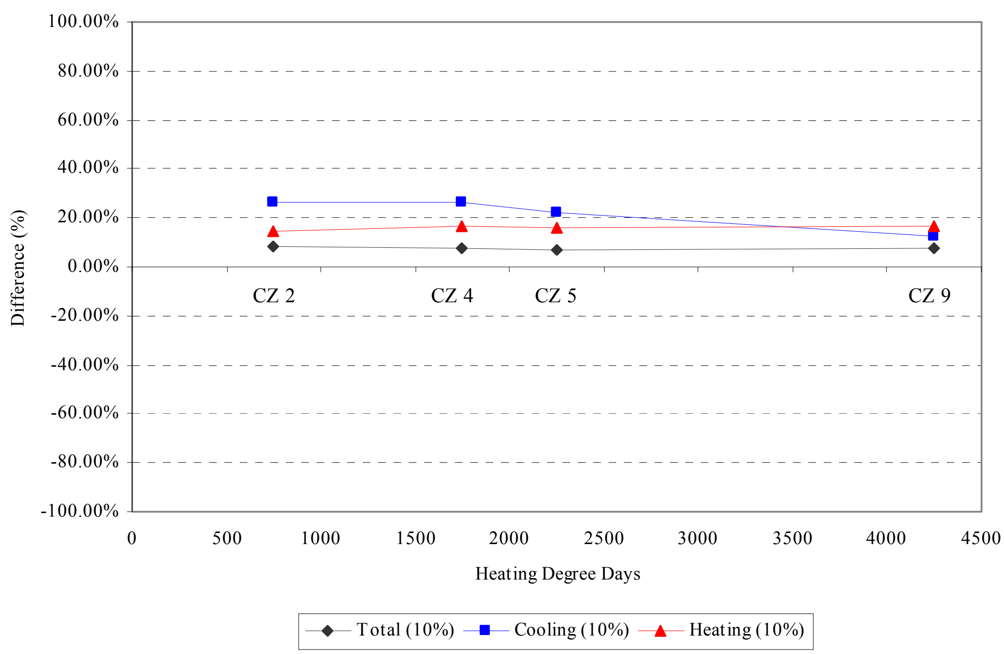


Figure 6.60 Percent difference of annual energy use (base case (0%, SR-8, RR-4) to 10% (SR-10, RR-10))

6.4.2.18 Base case (0% DLR, SR-8/RR-4) vs. modified (15% DLR, SR-10/RR-10)

In the case of a 15% duct leakage rate (Figure 6.61), there were total energy use increases of 12.41% for climate zone 9, 12.11% for climate zone 5, 13.19% for climate zone 4 and 14.53% for climate zone 2. For the heating energy use, the results showed an increase of 28.02% for climate zone 9, 26.60% for climate zone 5, 27.00% for climate zone 4 and 23.12% for climate zone 2. For the cooling energy use, 21.54% for climate zone 9, 39.62% for climate zone 5, 47.02% for climate zone 4 and 46.88% for climate zone 2 were increased due to the duct leakage rates.

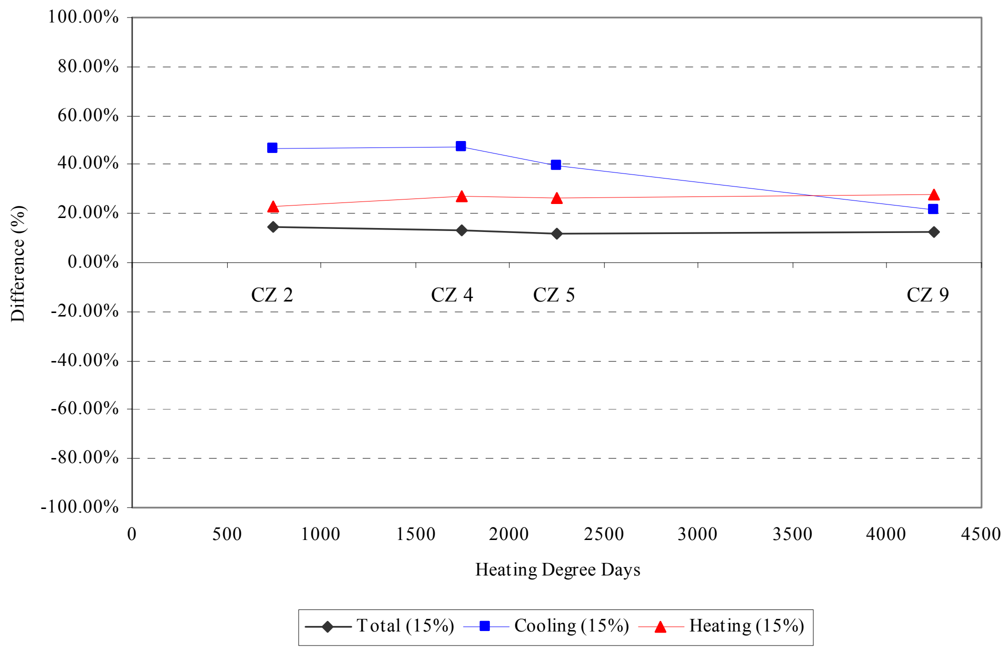


Figure 6.61 Percent difference of annual energy use (base case(0%, SR-8,RR-4) to 15%(SR-10,RR-10))

6.4.2.19 Base case (0% DLR, SR-8/RR-4) vs. modified (20% DLR, SR-10/RR-10)

When a 20% duct leakage rate was used in the simulations (Figure 6.62), there were increases of 18.33% for climate zone 9, 18.47% for climate zone 5, 20.53% for climate zone 4 and 22.55% for climate zone 2 for the total energy use. For the heating energy use, the results showed a 41.10% increase for climate zone 9, 38.55% increase for climate zone 5, 39.28% increase for climate zone 4 and 34.68% increase for climate zone 2, and for the cooling energy use, the results also showed a 31.54% increase for climate zone 9, a 62.26% increase for climate zone 5, a 75.60% increase for climate zone 4 and a 73.66% increase for climate zone 2.

Figure 6.63 shows the annual energy use of SR-10 and RR-10 vs. SR-8 and RR-4 according to the duct leakage rate.

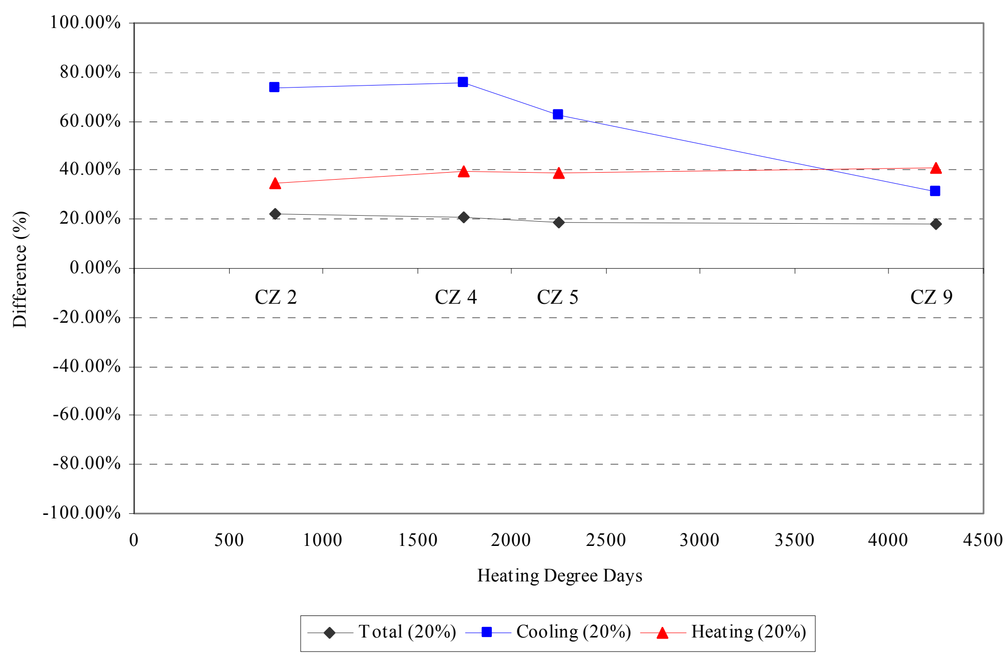


Figure 6.62 Percent difference of annual energy use (base case (0%, SR-8,RR-4) to 20% (SR-10, RR-10))

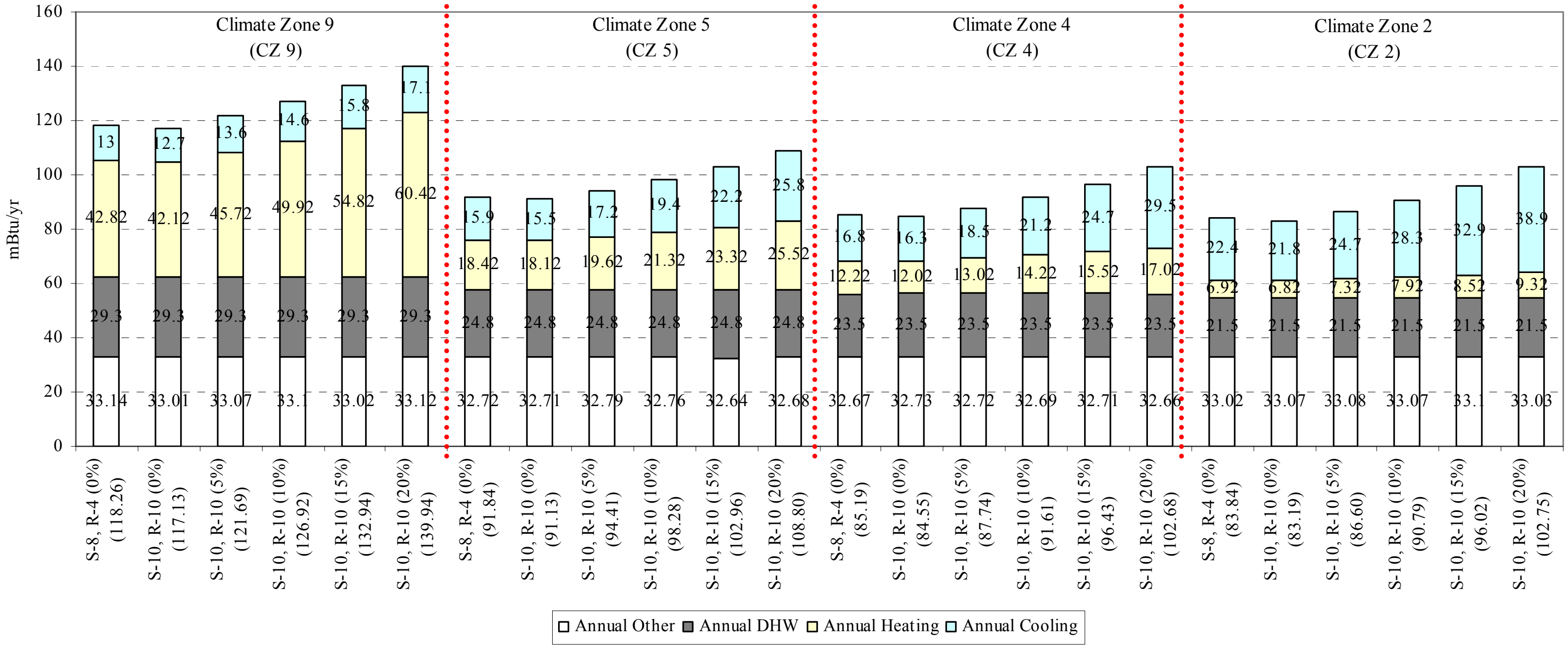


Figure 6.63 Annual energy use of SR-10 and RR-10 vs. SR-8 and RR-4 according to the duct leakage rate

Finally, when duct insulation levels were increased to R-12 for the supply and return with a 0% duct leakage rate from the base-case house which had R-8 for the supply, R-4 for the return and 0% duct leakage rates.

6.4.2.20 Base case (0% DLR, SR-8/RR-4) vs. modified (0% DLR, SR-12/RR-12)

The improvement of R-value (R-12) showed reductions of the total energy use, heating energy use and cooling energy use compared to the base-case house (Figure 6.64). Total energy use decreased by 1.45% for climate zone 9, 1.20% for climate zone 5, 1.16% for climate zone 4 and 1.23% for climate zone 2. Heating energy use decreased by 2.57% for climate zone 9, 2.17% for climate zone 5, 2.45% for climate zone 4 and 1.45% for climate zone 2. Cooling energy use decreased by 3.85% for climate zone 9, 4.40% for climate zone 5, 4.17% for climate zone 4 and 4.02% for climate zone 2.

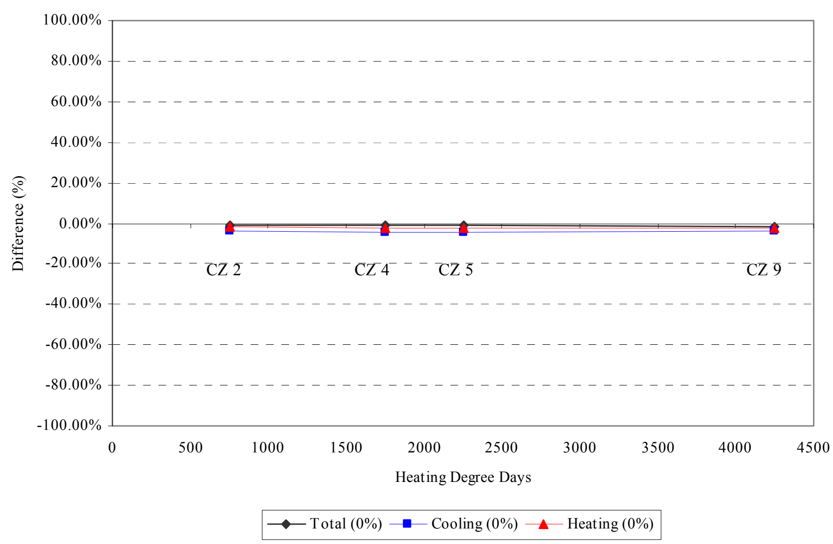


Figure 6.64 Percent difference of annual energy use (base case (0%, SR-8,RR-4) to 0% (SR-12, RR-12))

6.4.2.21 Base case (0% DLR, SR-8/RR-4) vs. modified (5% DLR, SR-12/RR-12)

For a 5% duct leakage rate (Figure 6.65), there were increases of 2.35% for climate zone 9, 2.31% for climate zone 5, 2.49% for climate zone 4 and 2.76% for climate zone 2 compared to the base-case house for the total energy consumptions. For the heating energy use, there were also increases of 5.84% for climate zone 9, 5.97% for climate zone 5, 5.73% for climate zone 4 and 5.78% for climate zone 2. For the cooling energy use, 2.31% for climate zone 9, 6.29% for climate zone 5, 8.33% for climate zone 4 and 8.48% for climate zone 2 were increased, respectively.

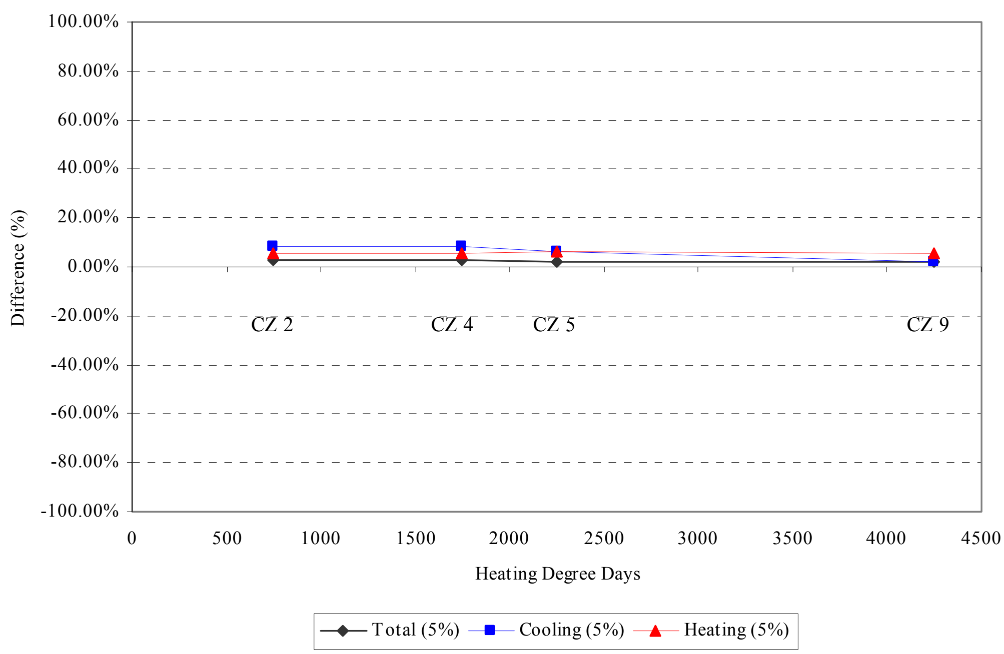


Figure 6.65 Percent difference of annual energy use (base case (0%, SR-8,RR-4) to 5% (SR-12, RR-12))

6.4.2.22 Base case (0% DLR, SR-8/RR-4) vs. modified (10% DLR, SR-12/RR-12)

When a 10% leakage was used in the simulations (Figure 6.66), there were increases of 6.71% for climate zone 9, 6.45% for climate zone 5, 6.93% for climate zone 4 and 7.61% for climate zone 2 in the total annual energy use. For the annual heating energy use, there were increases of 15.65% for climate zone 9, 15.20% for climate zone 5, 15.55% for climate zone 4 and 13.01% for climate zone 2. For the annual cooling energy use, there were also increases of 10.00% for climate zone 9, 20.13% for climate zone 5, 23.81% for climate zone 4 and 24.11% for climate zone 2.

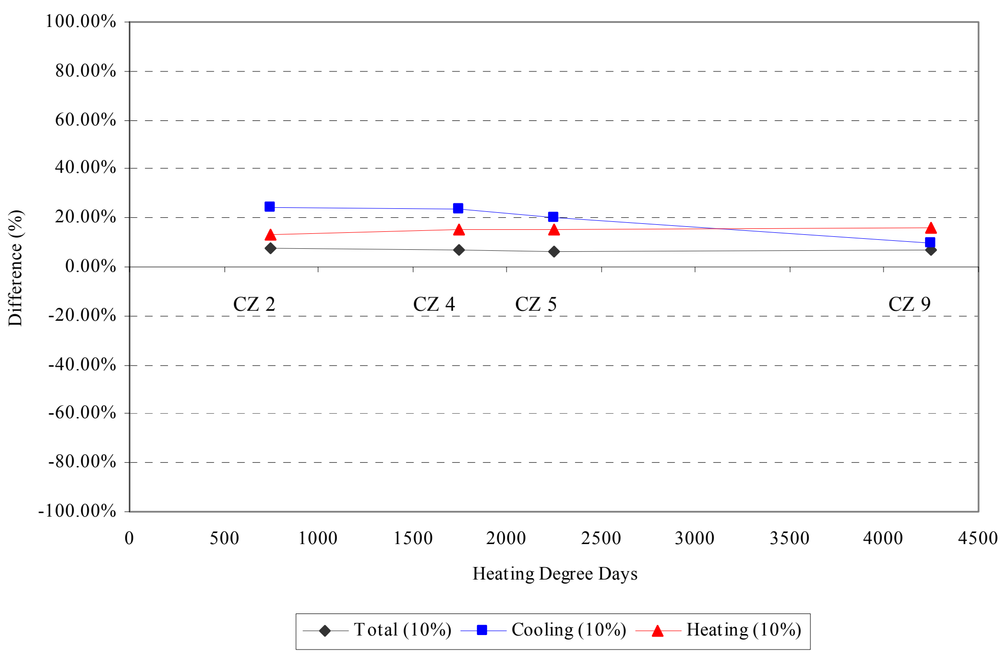


Figure 6.66 Percent difference of annual energy use (base case(0%, SR-8,RR-4) to 10% (SR-12,RR-12))

6.4.2.23 Base case (0% DLR, SR-8/RR-4) vs. modified (15% DLR, SR-12/RR-12)

In the case of a 15% duct leakage rate (Figure 6.67), there were total energy use increases of 11.73% for climate zone 9, 11.41% for climate zone 5, 12.43% for climate zone 4 and 13.67% for climate zone 2. For the heating energy use, the results showed an increase of 26.86% for climate zone 9, 25.52% for climate zone 5, 26.19% for climate zone 4 and 23.12% for climate zone 2, and for the cooling energy use, 19.23% for climate zone 9, 36.48% for climate zone 5, 44.05% for climate zone 4 and 44.20% for climate zone 2 were increased due to the duct leakage rates.

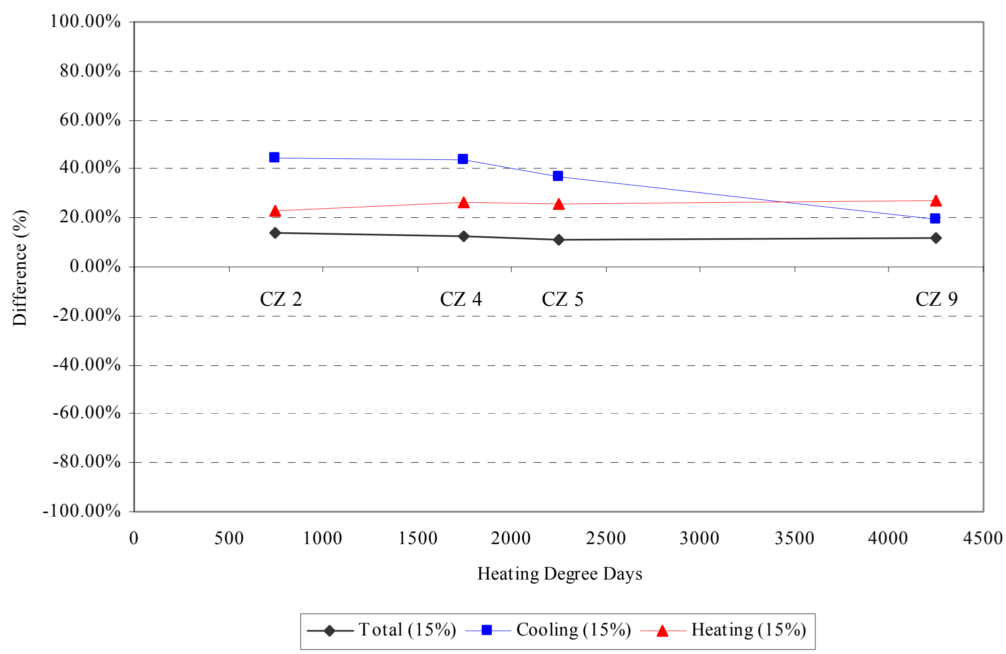


Figure 6.67 Percent difference of annual energy use (base case(0%, SR-8,RR-4) to 15% (SR-12,RR-12))

6.4.2.24 Base case (0% DLR, SR-8/RR-4) vs. modified (20% DLR, SR-12/RR-12)

Using a 20% duct leakage rate (Figure 6.68), the results showed increases of 17.57% for climate zone 9 and 5, 19.51% for climate zone 4 and 21.43% for climate zone 2. For the heating energy use, there were also increases of 39.70% for climate zone 9, 37.46% for climate zone 5, 38.46% for climate zone 4 and 33.24% for climate zone 2, and for the cooling energy use, there were increases of 29.23% for climate zone 9, 58.49% for climate zone 5, 71.43% for climate zone 4 and 69.64% for climate zone 2.

Figure 6.69 shows the annual energy use of SR-12 and RR-12 vs. SR-8 and RR-4 according to the duct leakage rate.

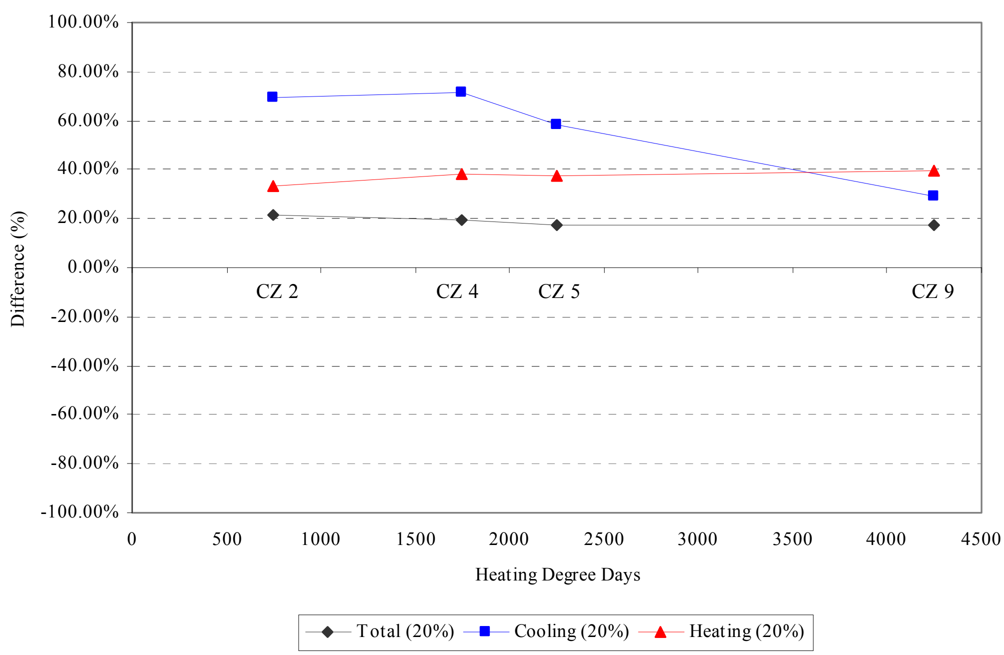


Figure 6.68 Percent difference of annual energy use (base case(0%, SR-8,RR-4) to 20% (SR-12, RR-12)

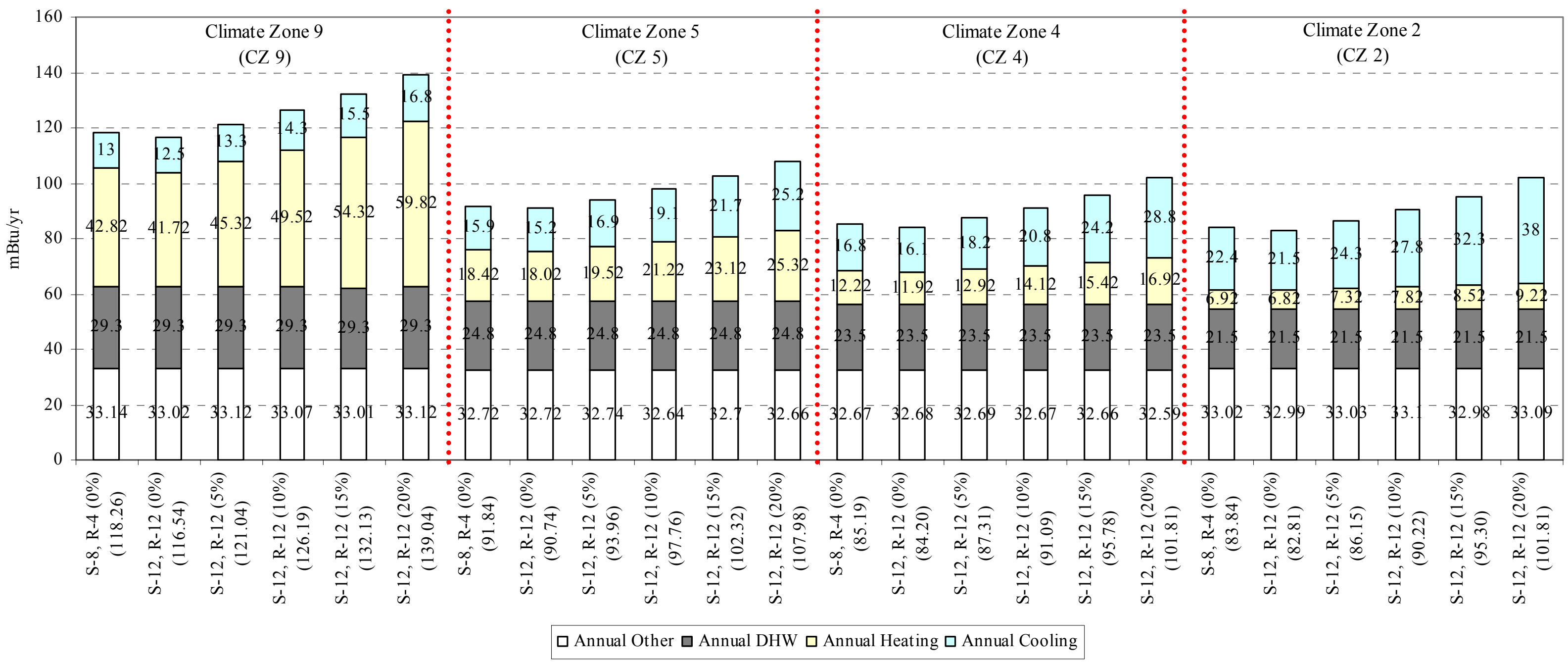


Figure 6.69 Annual energy use of SR-12 and RR-12 vs. SR-8 and RR-4 according to the duct leakage rate

6.4.3 Analysis of the Air conditioner Efficiency

In order to find the savings from an air conditioner's efficiency, the annual energy use was plotted from the SEER-10 (the base-case house) to the SEER-17 in increments of 1. All other properties were kept the same as in the base-case house. The following are detailed explanations of the results obtained when using the different levels of the SEER in the simulations.

6.4.3.1 Base case (SEER-10) vs. modified (SEER-11)

When using the SEER-11 instead of the SEER-10 (the base-case house) in the simulations (Figure 6.70), the SEER-11 air conditioner resulted in a 1.06 % decrease in the total annual energy use for climate zone 9, a 1.84% decrease for climate zone 5, a 2.16% decrease for climate zone 4 and a 2.89% decrease for climate zone 2 compared to the base-case house. For the cooling energy use, the SEER-11 air conditioner also resulted in a 9.33% decrease in the total annual energy use for climate zone 9, a 9.45% decrease for climate zone 5, a 8.68% decrease for climate zone 4 and a 9.25% decrease for climate zone 2.

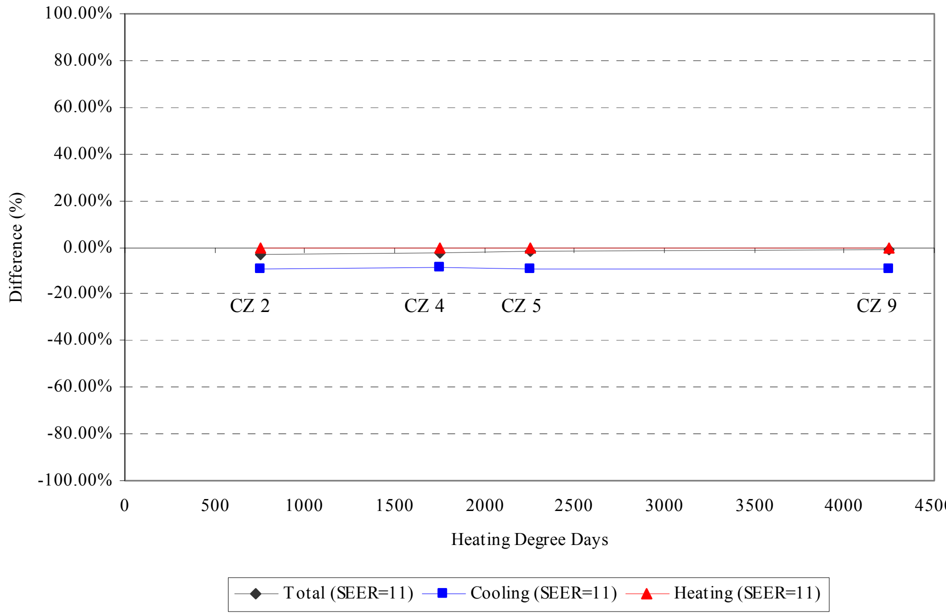


Figure 6.70 Percent difference of annual energy use (base case (SEER 10) vs. SEER 11)

6.4.3.2 Base case (SEER-10) vs. modified (SEER-12)

The SEER-12 air conditioner (Figure 6.71) produced a 1.95% reduction in the total annual energy use for climate zone 9, a 3.38% reduction for climate zone 5, a 3.96% reduction for climate zone 4 and a 5.31% reduction for climate zone 2, and a 16.67% reduction in the cooling energy use for climate zone 9, a 16.92% reduction for climate zone 5, a 16.44% reduction for climate zone 4 and a 16.78% reduction for climate zone 2.

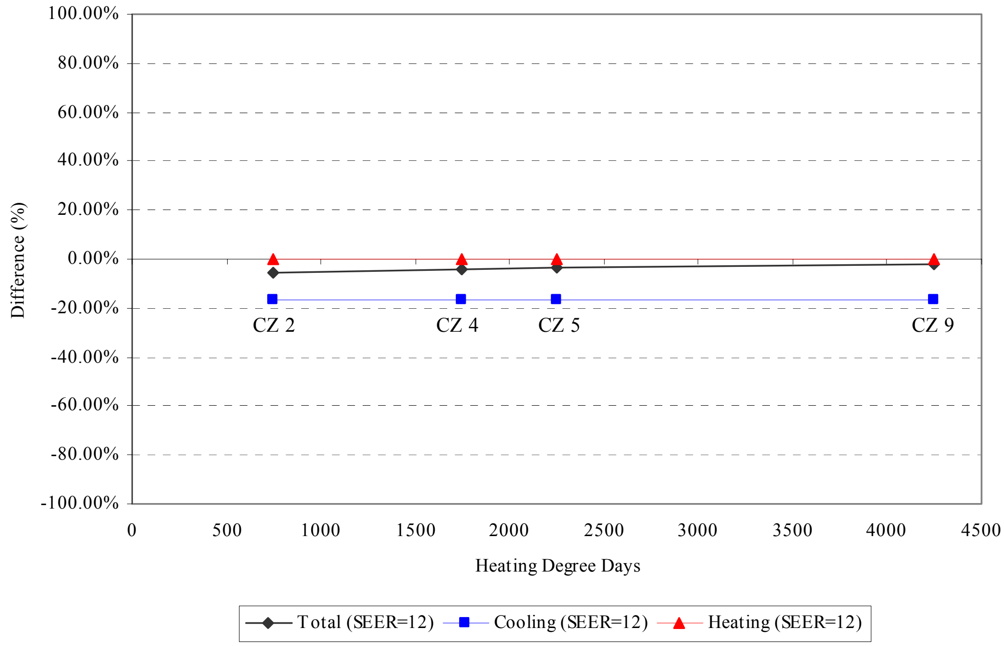


Figure 6.71 Percent difference of annual energy use (base case (SEER 10) vs. SEER 12)

6.4.3.3 Base case (SEER-10) vs. modified (SEER-13)

Simulations using the SEER-13 air conditioner (Figure 6.72) resulted in a 2.70% reduction in the total annual energy use for climate zone 9, a 4.66% reduction for climate zone 5, a 5.48% reduction for climate zone 4 and a 7.35% reduction for climate zone 2. This yielded a 23.33% reduction in the cooling energy use for climate zone 9, a 23.38% reduction for climate zone 5, a 22.83% reduction for climate zone 4 and a 22.95% reduction for climate zone 2.

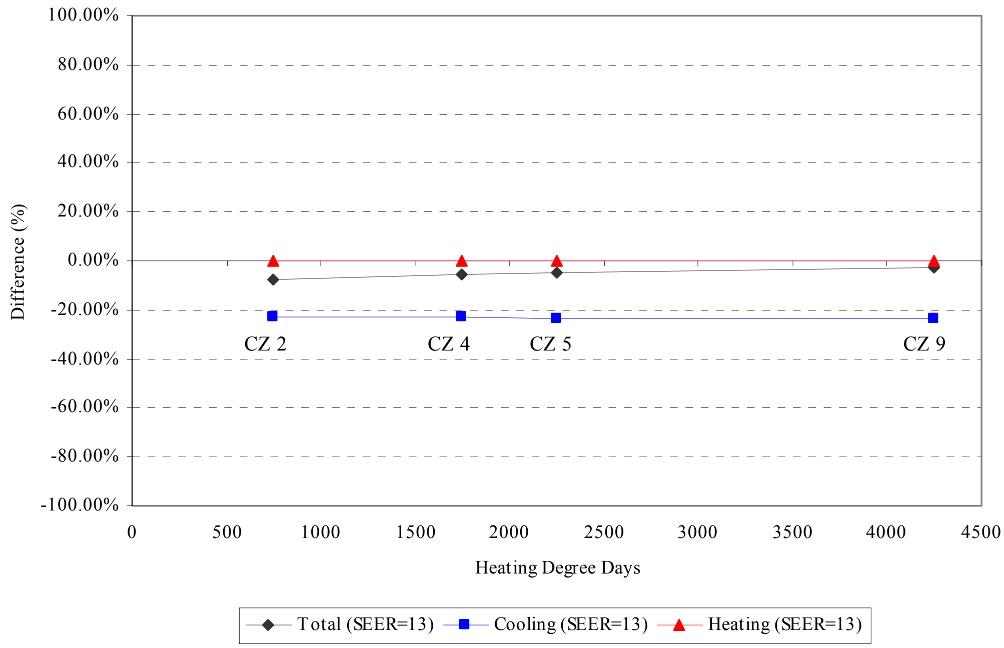


Figure 6.72 Percent difference of annual energy use (base case (SEER 10) vs. SEER 13)

6.4.3.4 Base case (SEER-10) vs. modified (SEER-14)

The SEER-14 air conditioner (Figure 6.73) produced a 3.34% drop of the total annual energy use for climate zone 9, a 5.77% drop for climate zone 5, a 6.78% drop for climate zone 4 and a 9.09% drop for climate zone 2, and a 28.67% drop in the cooling energy use for climate zone 9, a 28.86% drop for climate zone 5, a 28.31% drop for climate zone 4 and a 28.42% drop for climate zone 2.

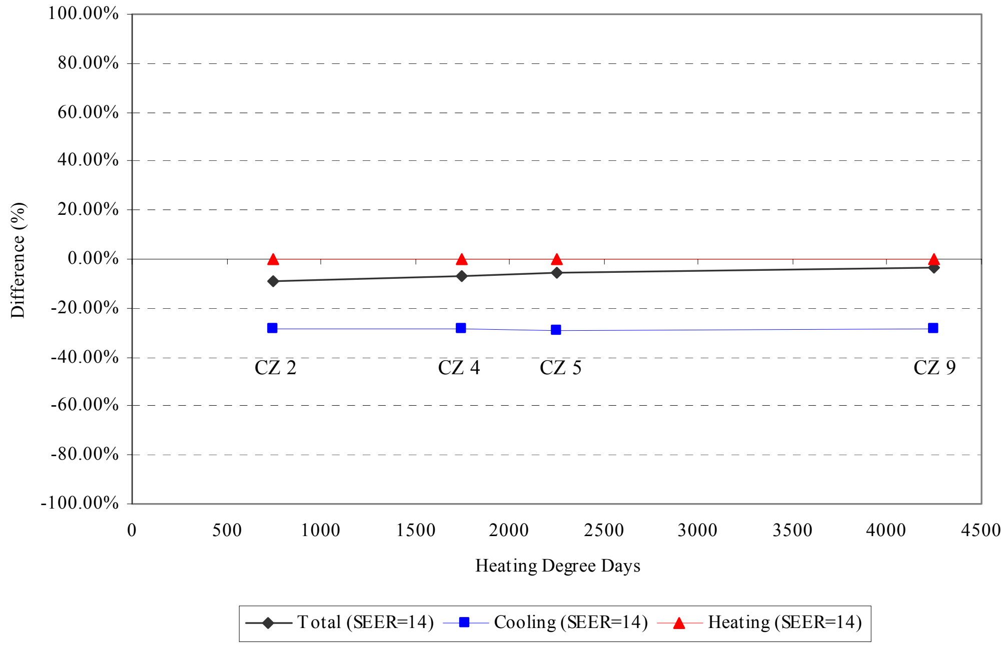


Figure 6.73 Percent difference of annual energy use (base case (SEER 10) vs. SEER 14)

6.4.3.5 Base case (SEER-10) vs. modified (SEER-15)

When the SEER-15 air conditioner was used in the simulation (Figure 6.74), the results showed 3.90% total energy savings for climate zone 9, 6.74% for climate zone 5, 7.91% for climate zone 4 and 10.60% for climate zone 2, and 33.33% cooling energy savings for climate zone 9, 5 and 4 and 33.22% for climate zone 2, respectively.

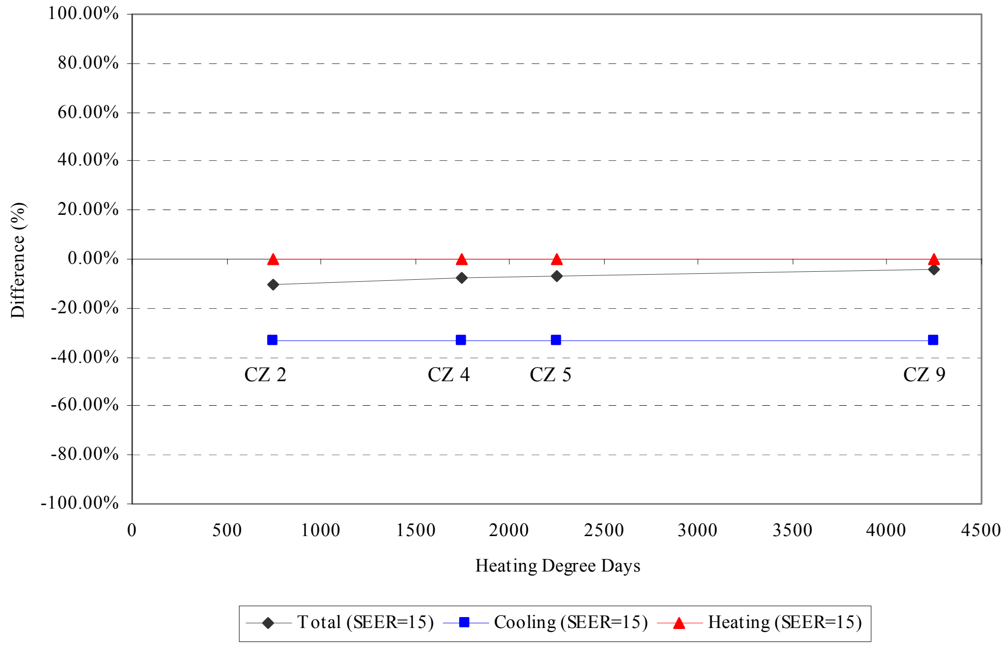


Figure 6.74 Percent difference of annual energy use (base case (SEER 10) vs. SEER 15)

6.4.3.6 Base case (SEER-10) vs. modified (SEER-16)

The SEER-16 air conditioner (Figure 6.75) produced a 4.38% reduction in the total energy use for climate zone 9, a 7.59% reduction for climate zone 5, a 8.89% reduction for climate zone 4 and a 11.93% reduction for climate zone 2, and a 37.33% reduction in cooling energy use for climate zone 9, a 37.81% reduction for climate zone 5, a 37.44% reduction for climate zone 4 and a 37.67% reduction for climate zone 2.

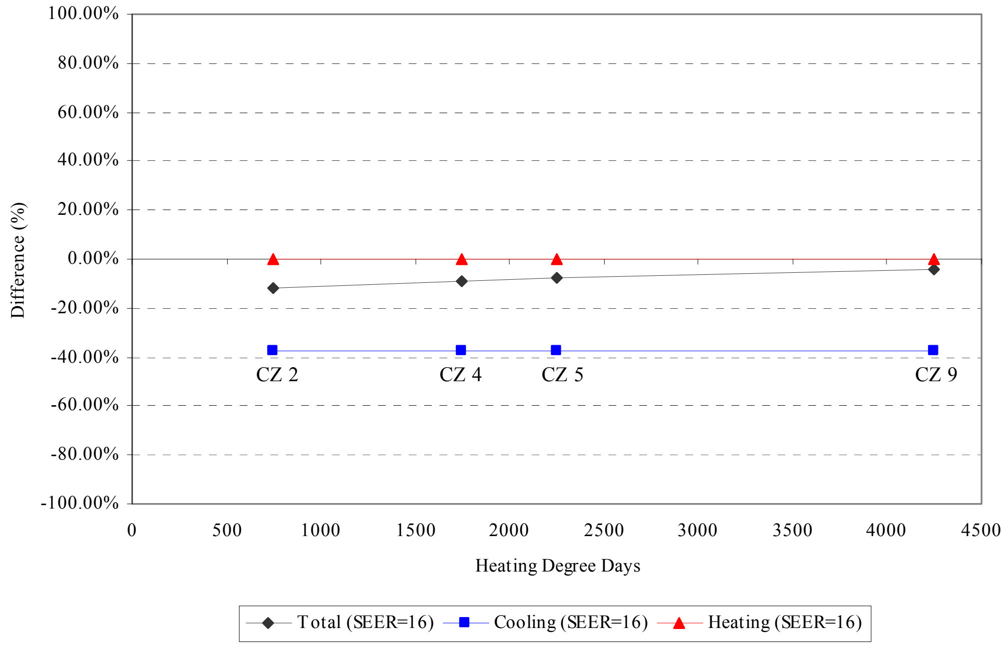


Figure 6.75 Percent difference of annual energy use (base case (SEER 10) vs. SEER 16)

6.4.3.7 Base case (SEER-10) vs. modified (SEER-17)

Finally, when the SEER-17 air conditioner (Figure 6.76) was simulated, it produced a 4.81% reduction in the total energy use for climate zone 9, a 8.32% reduction for climate zone 5, a 9.77% reduction for climate zone 4 and a 13.10% reduction for climate zone 2, and a 41.33% reduction in the cooling energy use for climate zone 9, a 41.29% reduction for climate zone 5, a 41.10% reduction for climate zones 4 and 2. Figure 6.77 shows the annual energy use of different air conditioner efficiency

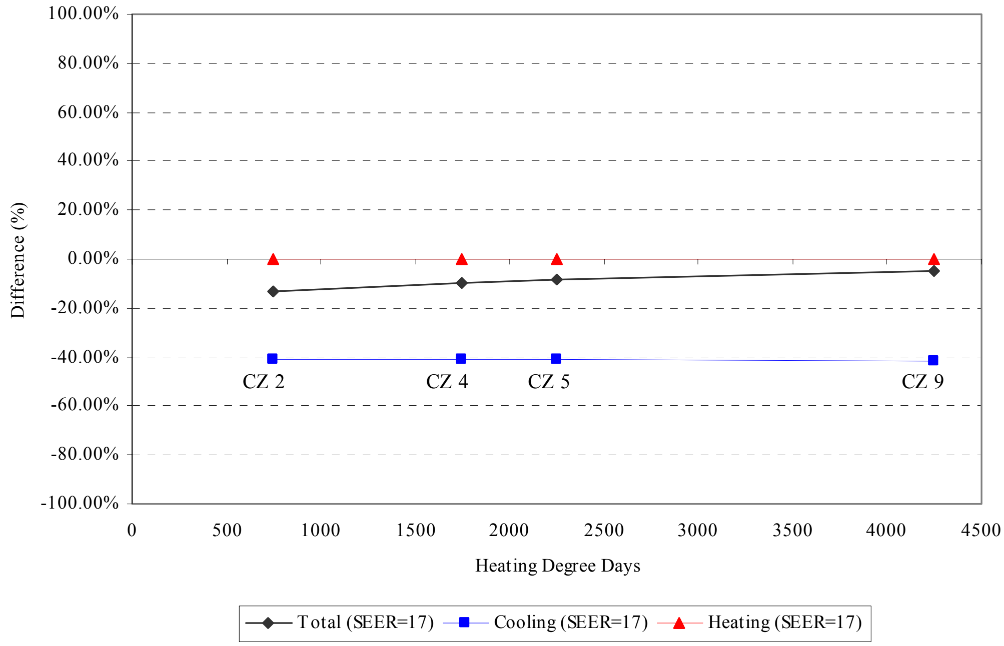


Figure 6.76   Percent difference of annual energy use (base case (SEER 10) vs. SEER 17)

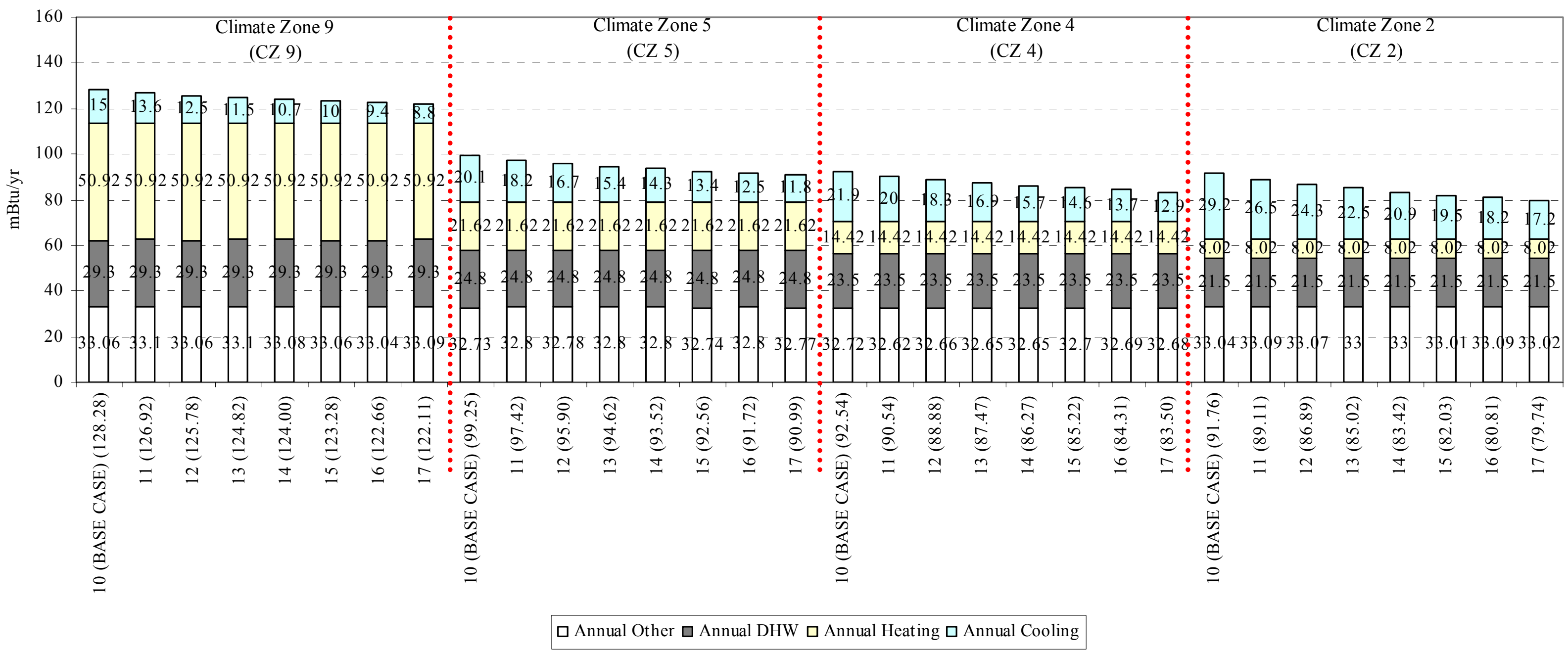


Figure 6.77 Annual energy use of different air conditioner efficiency

6.4.4 Analysis of the Gas Furnace Efficiency

The following plots showed the annual total energy use, heating and the total energy savings by changing the gas-furnace's efficiency. The percent savings were plotted against heating degree days according to the climate zones. In order to find the savings from gas-furnace efficiency, the annual energy use was plotted by changing it from 0.78 AFUE to 0.90 AFUE in increments of 0.05. The other properties remained the same as in the base-case house.

The total energy savings aa compared to the base-case house from climate zone 2 (the hotter climate) to climate zone 9 (the colder climate) were higher, because heating energy use from climate zone 2 to climate zone 9 was higher. It was also found that energy savings from an energy efficienct furnace was significant where the climate was cold, whereas energy savings from an energy efficient furnace was insignificant where the climate was hot and less heating energy was needed.

The following are detailed explanations of the results obtained when using different levels of AFUE for the furnace in the simulations.

6.4.4.1 Base case (AFUE 0.78) vs. modified (AFUE 0.80)

When applying AFUE 0.80 to the base-case (Figure 6.78), the total annual energy use and heating energy use started showing reductions. For the total energy use, there were reductions of 0.99% for climate zone 9, 0.55% for climate zone 5, 0.39% for climate zone 4 and 0.22% for climate zone 2. For the heating energy use, there were also reductions of 2.55% for climate zone 9, 2.31% for climate zone 5, 2.77% for climate zone 4 and 2.49% for climate zone 2.

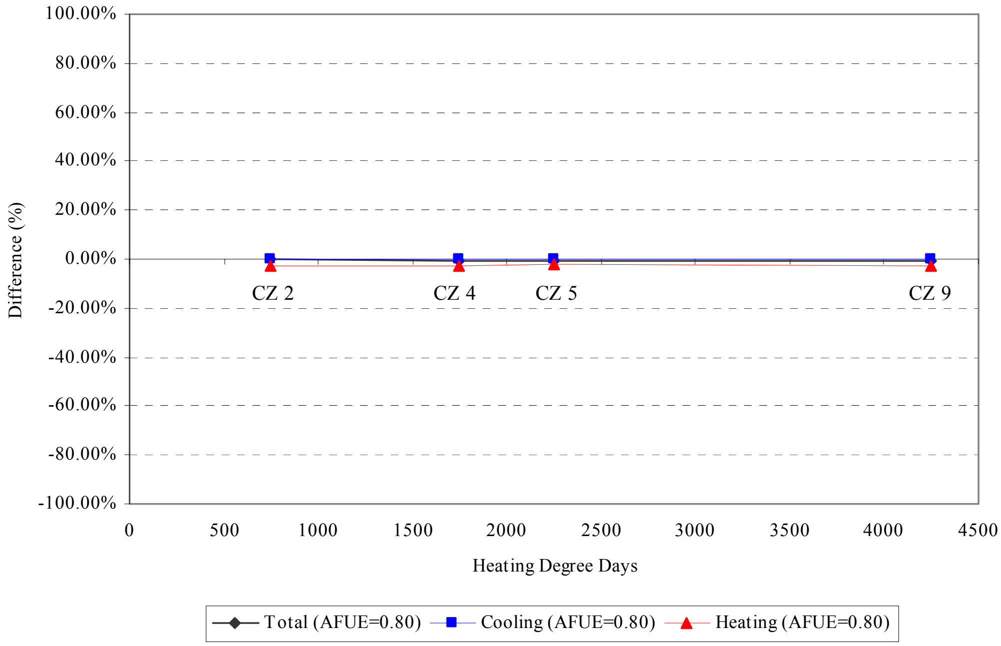


Figure 6.78 Percent difference of annual energy use (base case (AFUE 0.78) vs. AFUE 0.80)

6.4.4.2 Base case (AFUE 0.78) vs. modified (AFUE 0.85)

Using AFUE 0.85 (Figure 6.79) resulted in a 3.27% reduction for climate zone 9, a 1.80% reduction for climate zone 5, a 1.29% reduction for climate zone 4 and a 1.17% reduction for climate zone 2 in the total energy use. There were also a 8.25% reduction for climate zone 9, a 7.86% reduction for climate zone 5, a 8.32% reduction for climate zone 4 and a 8.73% reduction for climate zone 2 in the heating energy use.

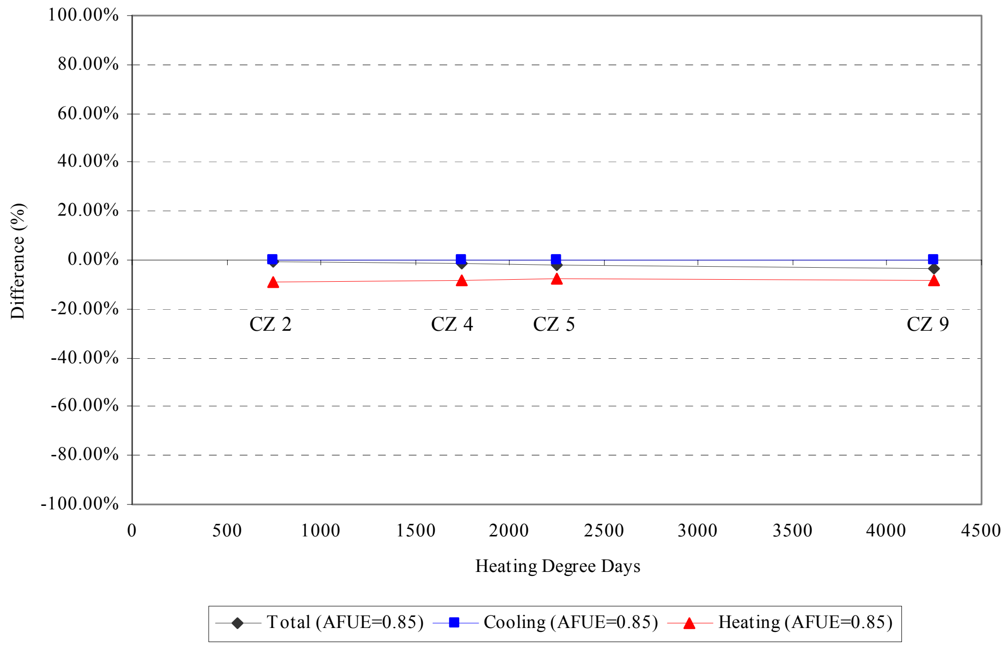


Figure 6.79 Percent difference of annual energy use (base case (AFUE 0.78) vs. AFUE 0.85)

6.4.4.3 Base case (AFUE 0.78) vs. modified (AFUE 0.90)

AFUE 0.90 furnace (Figure 6.80) produced a 5.30% drop for climate zone 9, a 2.92% drop for climate zone 5, a 2.09% drop for climate zone 4 and a 1.17% drop for climate zone 2 in the total annual energy use, and a 13.35% drop for climate zone 9, a 12.95% drop for climate zone 5, a 13.18% drop for climate zone 4 and a 13.72% drop for climate zone 2 in the heating energy use. Figure 6.81 shows the annual energy use of different gas furnace efficiency.

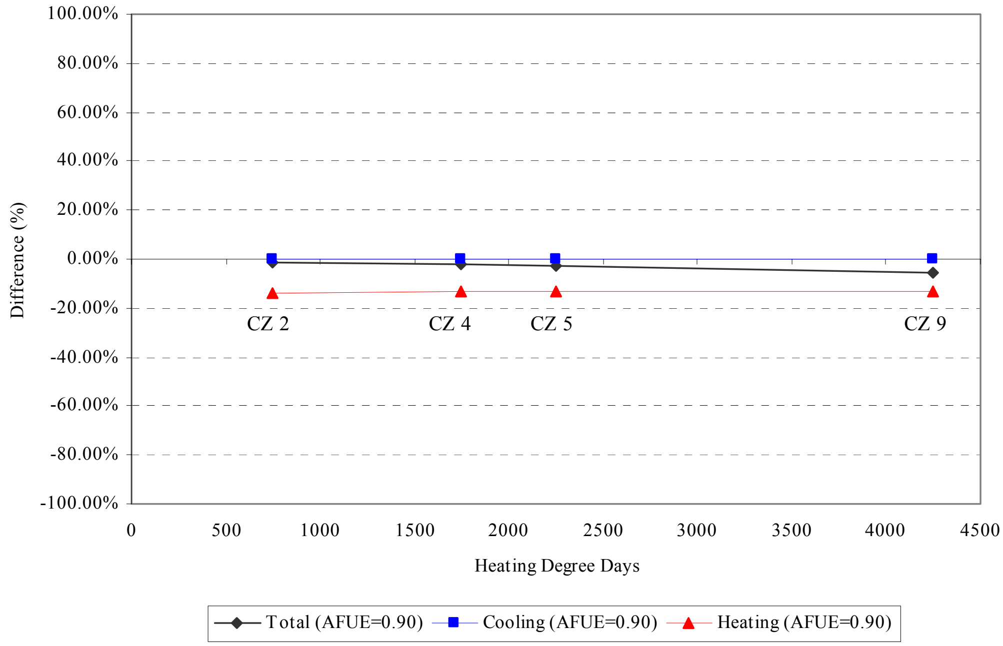


Figure 6.80 Percent difference of annual energy use (base case (AFUE 0.78) vs. AFUE 0.90)

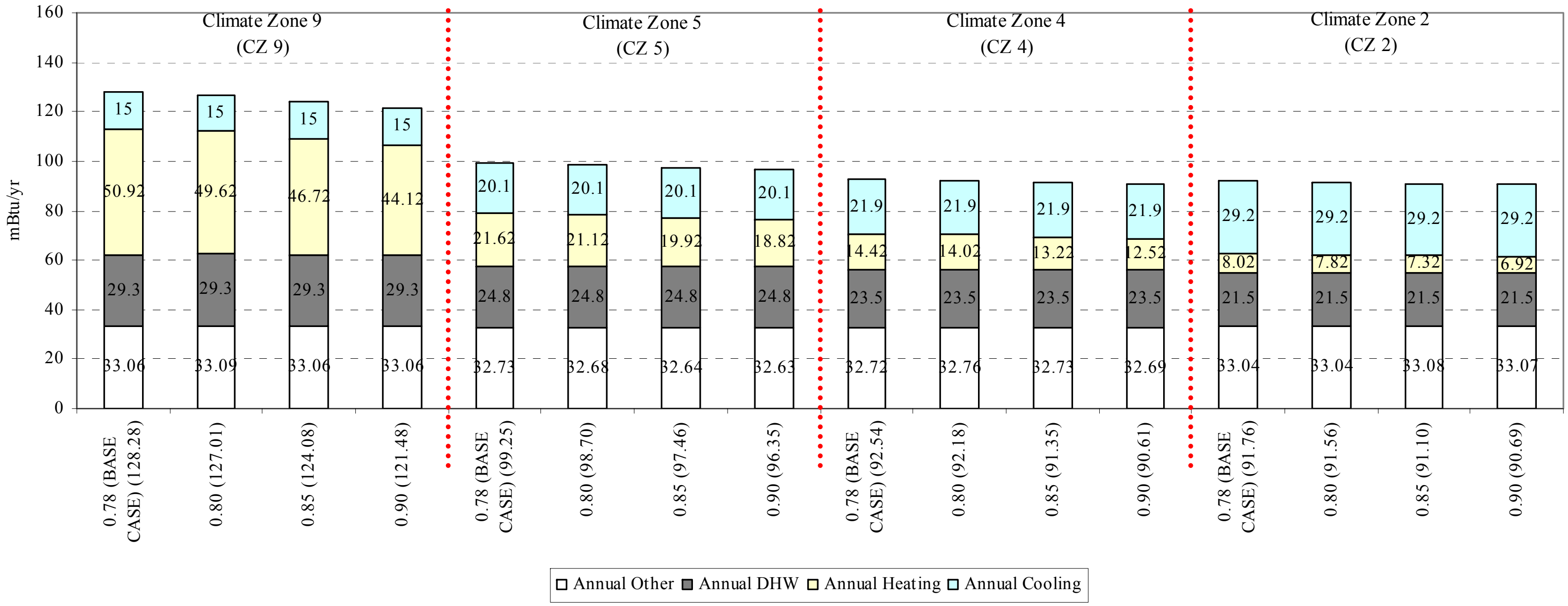


Figure 6.81 Annual energy use of different gas furnace efficiency

6.4.5 Analysis of the Heat Pump Efficiency

The following shows the annual total energy use and the heating and total energy savings by changing the heat pump's efficiency. The percent savings were plotted against the heating degree days according to the climate zones. In order to find the savings from the heat pump's efficiency, the annual energy use was plotted by changing the levels from 6.8 HSPF to 8.0 HSPF in increments of 0.5. The other properties remained the same as in the base-case house.

The pattern of the total energy savings against the base-case house was similar to the results of the gas-furnace. It was found that the total energy savings got higher as it moved from climate zone 2 (a hotter climate) to climate zone 9 (a colder climate). It was also found that energy savings from an energy-efficient heat pump was insignificant where there were less space heating uses.

The following are detailed explanations of the results obtained when using different level of HSPF for the heat pump in the simulations.

6.4.5.1 Base case (HSPF 6.8) vs. modified (HSPF 7.0)

When using HSPF 7.0 (Figure 6.82), the total annual energy use and heating energy use showed decreases. For the total annual energy use, there were reductions of 0.81% for climate zone 9, 0.48% for climate zone 5, 0.35% for climate zone 4 and 0.21% for climate zone 2. For the heating annual energy use, there were also reductions of 2.19% for climate zone 9, 2.02% for climate zone 5, 2.19% for climate zone 4 and 3.03% for climate zone 2.

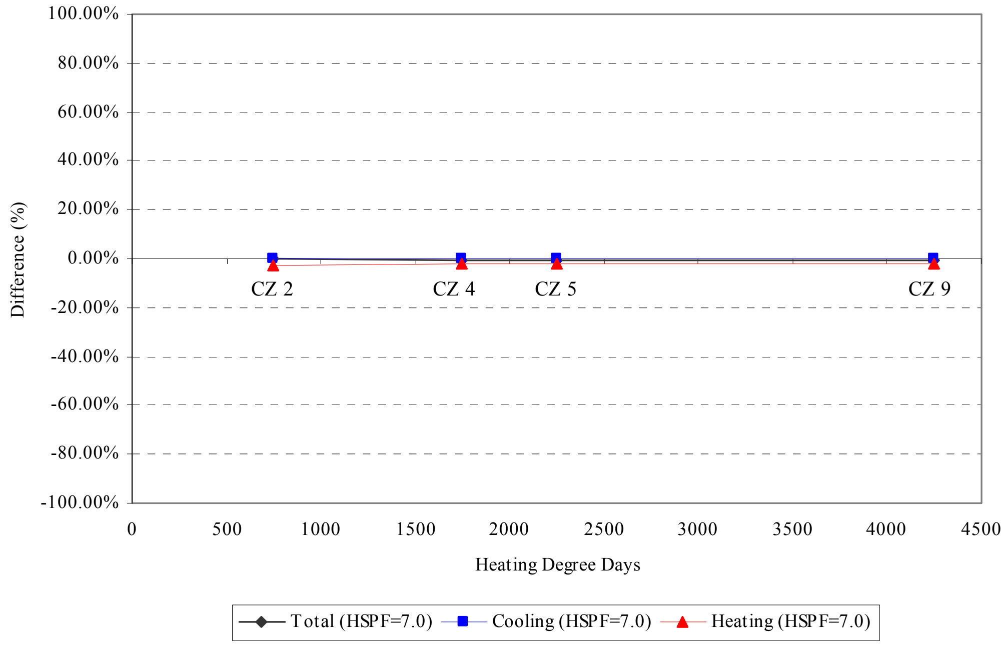


Figure 6.82 Percent difference of annual energy use (base case (HSPF 6.8) vs. HSPF 7.0)

6.4.5.2 Base case (HSPF 6.8) vs. modified (HSPF 7.5)

Applying HSPF 7.5 (Figure 6.83) resulted in a 2.63% reduction for climate zone 9, a 1.58% reduction for climate zone 5, a 1.14% reduction for climate zone 4 and a 0.67% reduction for climate zone 2 in the total annual energy use. There were also a 6.78% reduction for climate zone 9, a 7.58% reduction for climate zone 5, a 7.30% reduction for climate zone 4 and a 9.09% reduction for climate zone 2 in the heating annual energy use.

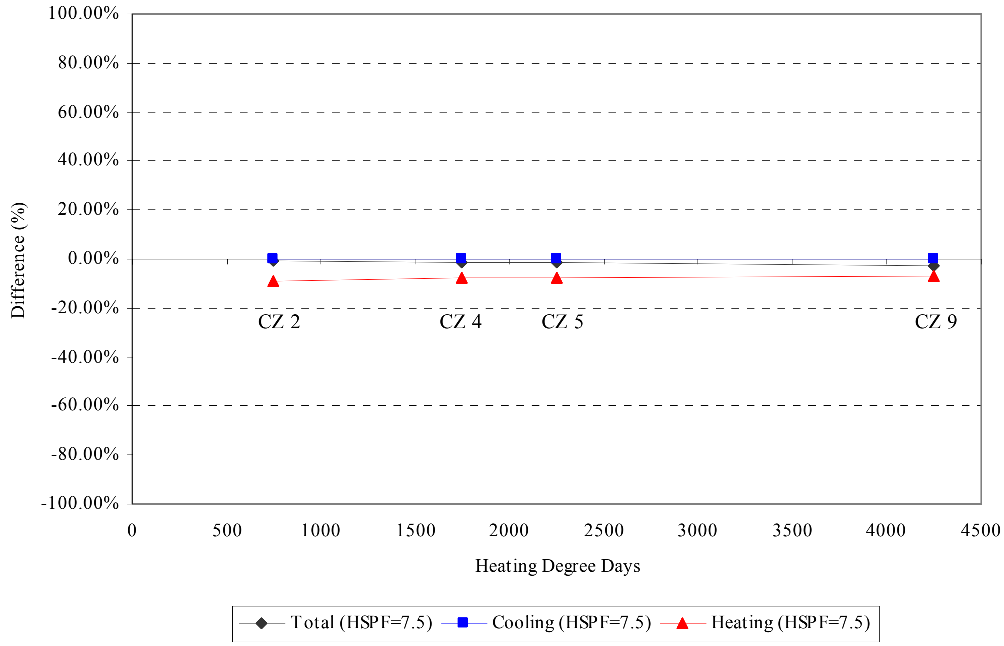


Figure 6.83 Percent difference of annual energy use (base case (HSPF 6.8) vs. HSPF 7.5)

6.4.5.3 Base case (HSPF 6.8) vs. modified (HSPF 8.0)

HSPF 8.0 heat pump (Figure 6.84) produced a 4.22% drop for climate zone 9, a 2.55% drop for climate zone 5, a 1.85% drop for climate zone 4 and a 1.08% drop for climate zone 2 in the total energy use, and a 10.94% drop for climate zone 9, a 12.12% drop for climate zone 5, a 11.68% drop for climate zone 4 and a 15.15% drop for climate zone 2 in the cooling annual energy use. Figure 6.85 Annual energy use of different heat pump efficiency.

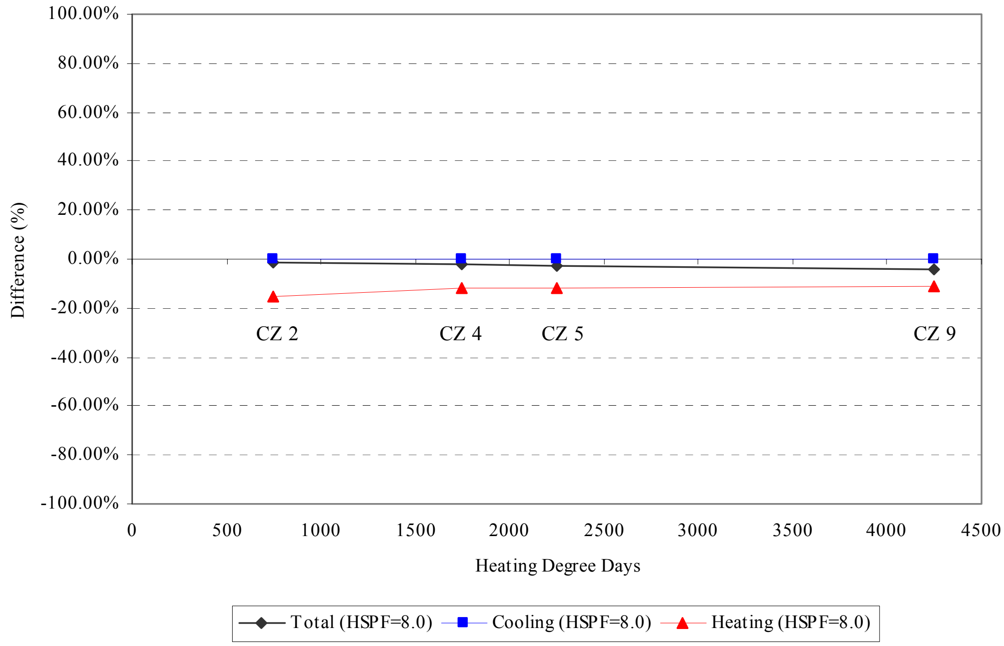


Figure 6.84 Percent difference of annual energy use (base case (HSPF 6.8) vs. HSPF 8.0)

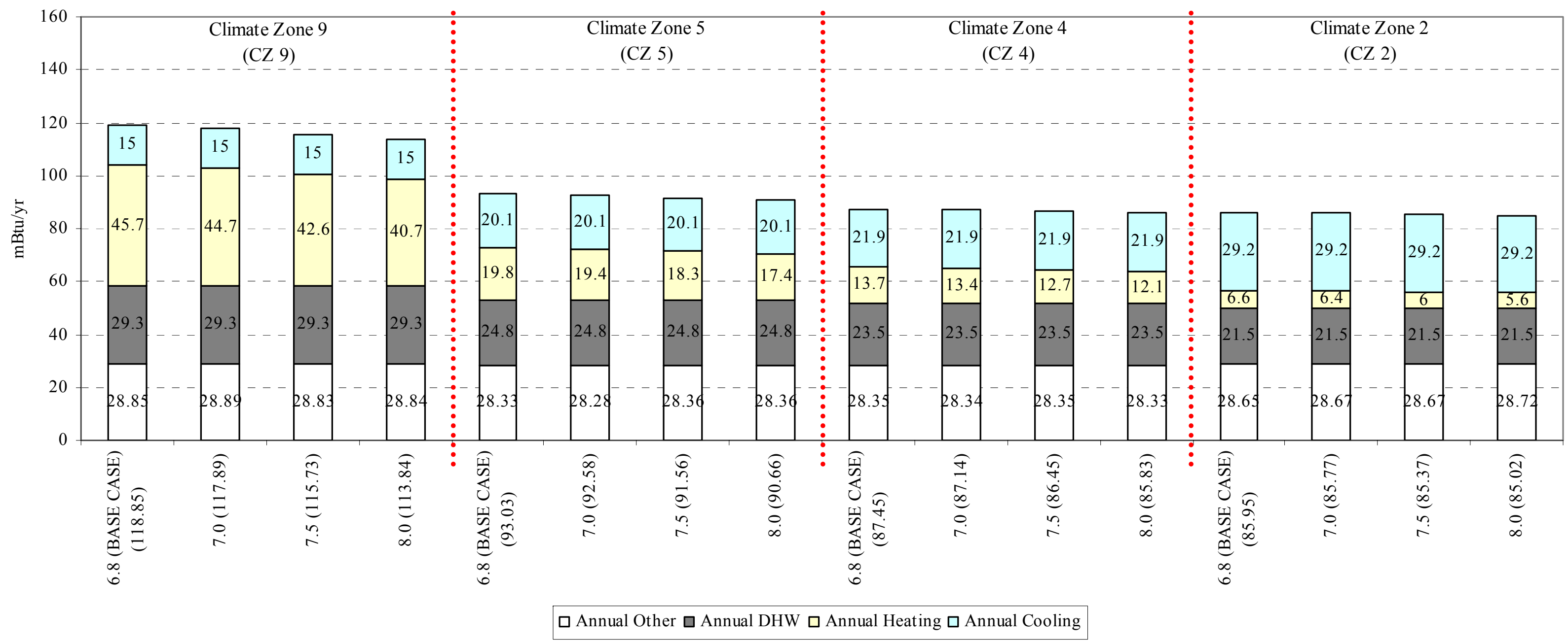


Figure 6.85 Annual energy use of different heat pump efficiency

6.4.6 Analysis of the Domestic Hot Water Heater Efficiency

The following show the annual total energy use and domestic hot water energy use, as well as the total energy and domestic hot water savings obtained by changing the domestic hot water efficiency (Energy Factor or EF). The percent savings were plotted against the heating degree days according to the climate zones. In order to find the savings from the domestic hot water efficiency, the annual energy use was plotted by changing 0.55 EF to 0.80 EF in increments of 0.05. The other properties were the same as in the base-case house.

It was found that the total energy savings and domestic hot water energy savings were constant through all the climate zones. This means that the domestic hot waster energy use was hardly influenced by the different climates. However, energy efficient water heaters offered significant savings potentials in all climate zones.

The following are detailed explanations of the results obtained when different levels of EF were applied to the simulations.

6.4.6.1 Base case (0.55 EF) vs. modified (0.60 EF)

Applying a 0.60 EF water heater (Figure 6.86) resulted in a 1.90% reduction for climate zone 9, a 2.09% reduction for climate zone 5, a 2.12% reduction for climate zone 4 and a 1.95% reduction for climate zone 2 in the total energy use. This yielded a 8.53% reduction in the domestic hot water energy use for climate zone 9, a 8.47% reduction for climate zone 5, a 8.51% reduction for climate zone 4 and a 8.37% reduction for climate zone 2.

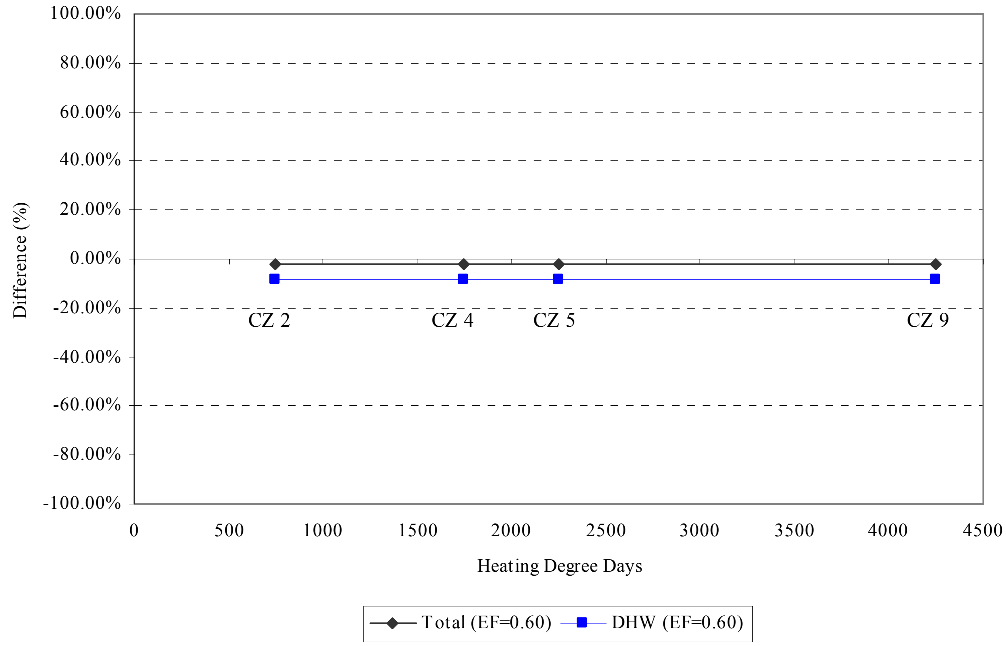


Figure 6.86 Percent difference of annual energy use (base case (0.55 EF) vs. 0.60 EF)

6.4.6.2 Base case (0.55 EF) vs. modified (0.65 EF)

On going from the base case to 0.65 EF (Figure 6.87), the total annual energy consumptions reduced by 3.51% for climate zone 9, 3.85% for climate zone 5, 3.91% for climate zone 4 and 3.60% for climate zone 2, and the domestic hot water energy consumptions decreased by 15.36% for climate zone 9, 15.32% for climate zone 5, 15.32% for climate zone 4 and 15.35% for climate zone 2.

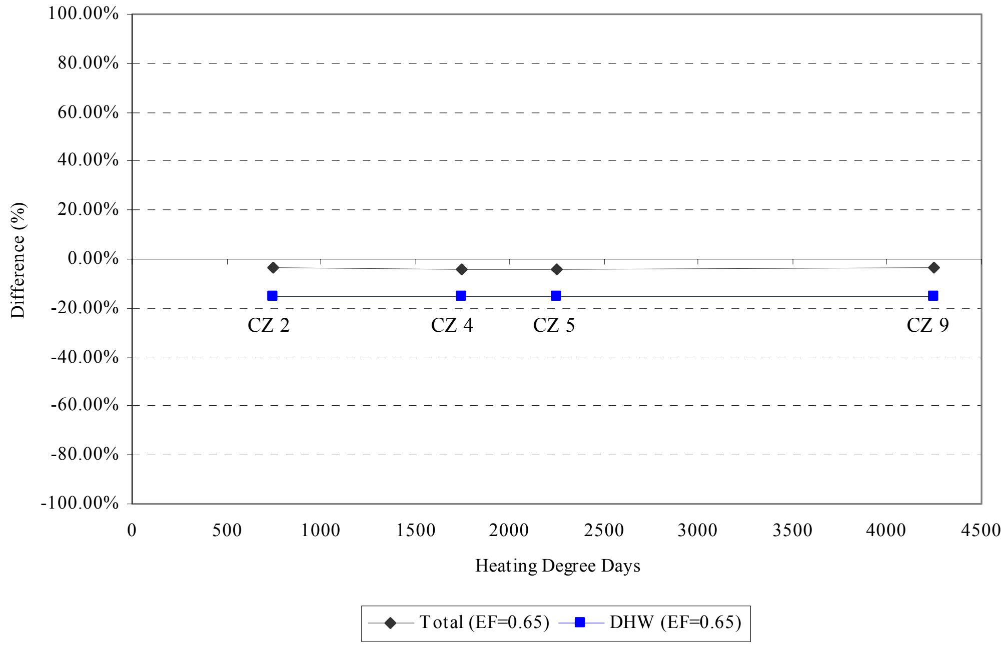


Figure 6.87 Percent difference of annual energy use (base case (0.55 EF) vs. 0.65 EF)

6.4.6.3 Base case (0.55 EF) vs. modified (0.70 EF)

A 0.70 EF water heater (Figure 6.88) produced a 4.89% drop for climate zone 9, a 5.36% drop for climate zone 5, a 5.44% drop for climate zone 4 and a 5.01% drop for climate zone 2 in the total annual energy use, and a 21.50% drop for climate zone 9, a 21.37% drop for climate zone 5, a 21.70% drop for climate zone 4 and a 21.40% drop for climate zone 2 in the domestic hot water energy use.

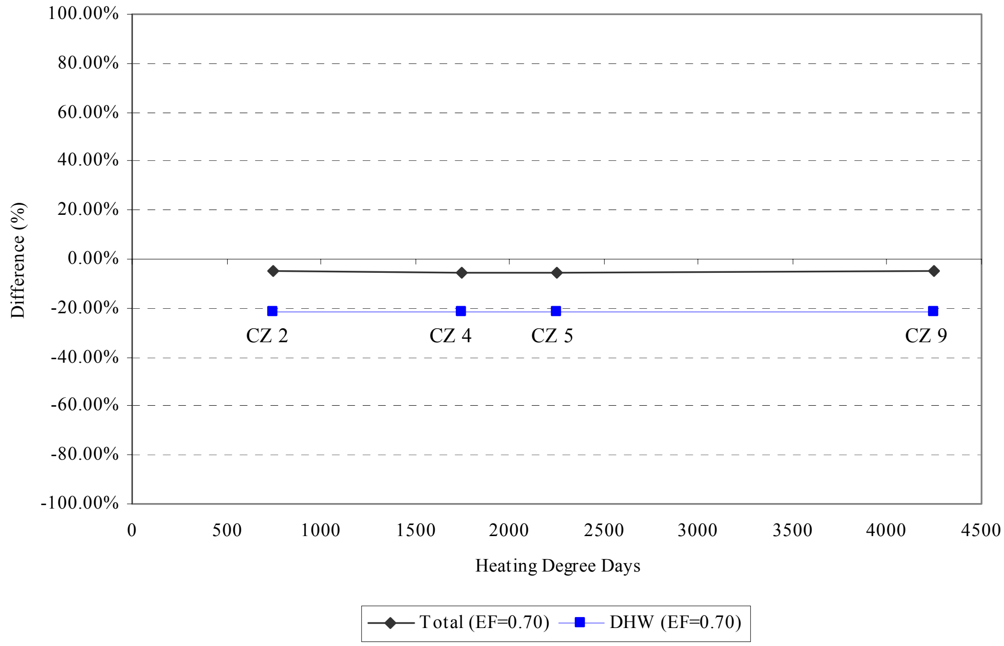


Figure 6.88 Percent difference of annual energy use (base case (0.55 EF) vs. 0.70 EF)

6.4.6.4 Base case (0.55 EF) vs. modified (0.75 EF)

Application of 0.75 EF water heater (Figure 6.89) resulted in 6.08% total energy savings for climate zone 9, 6.67% for climate zone 5, 6.76% for climate zone 4 and 6.23% for climate zone 2, and 26.62% domestic hot water energy savings for climate zone 9, 26.61% for climate zone 5, 26.81% for climate zone 4 and 36.98% for climate zone 2, respectively.

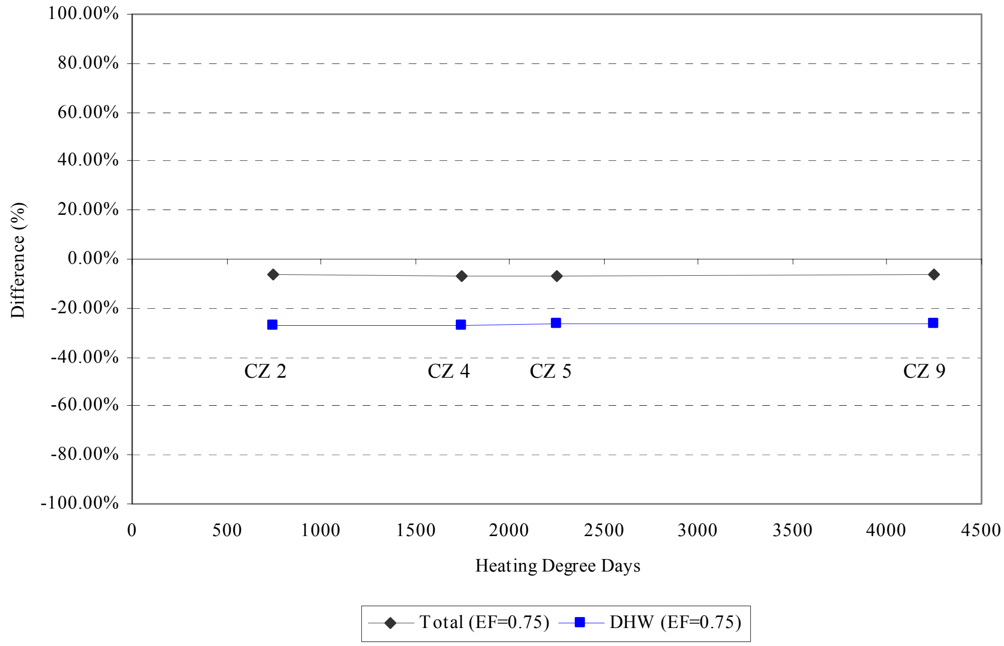


Figure 6.89 Percent difference of annual energy use (base case (0.55 EF) vs. 0.75 EF)

6.4.6.5 Base case (0.55 EF) vs. modified (0.80 EF)

When a 0.80 EF water heater was simulated (Figure 6.90), it produced a 7.13% drop for climate zone 9, a 7.82% drop for climate zone 5, a 7.93% drop for climate zone 4 and a 7.31% drop for climate zone 2 in the total energy use, and a 31.40% drop for climate zone 9, a 31.05% drop for climate zone 5, a 31.49% drop for climate zone 4 and a 31.16% drop for climate zone 2 in the domestic hot water energy use.

Figure 6.91 shows the annual energy use of different domestic hot water efficiency.

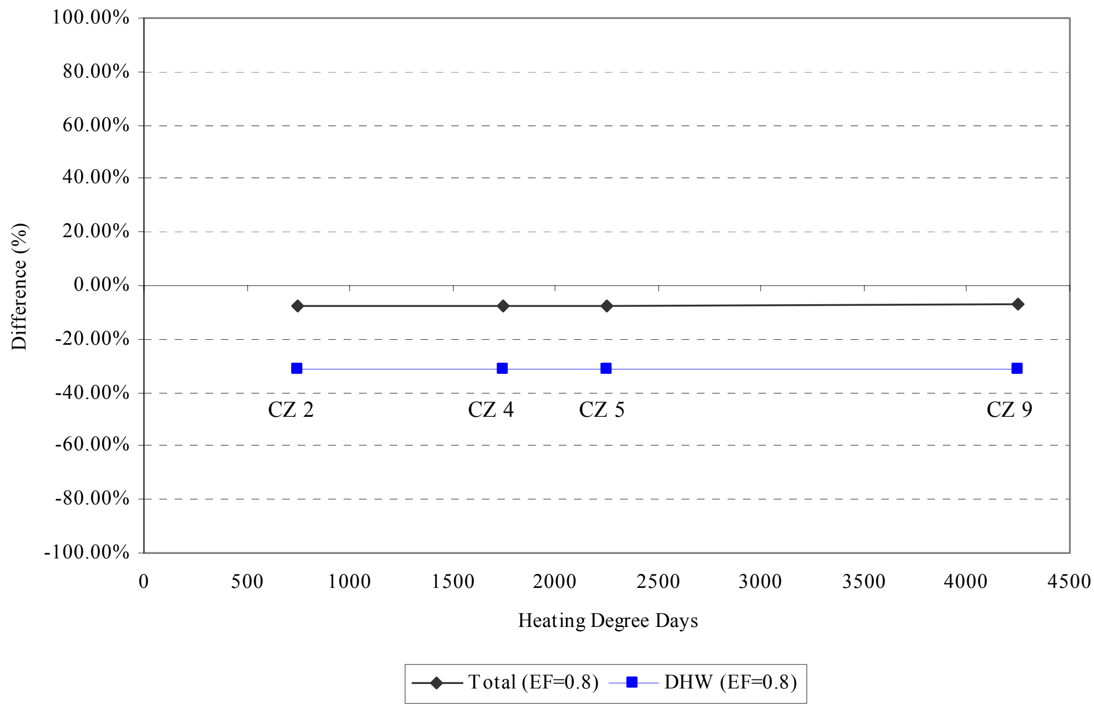


Figure 6.90 Percent difference of annual energy use (base case (0.55 EF) vs. 0.80 EF)

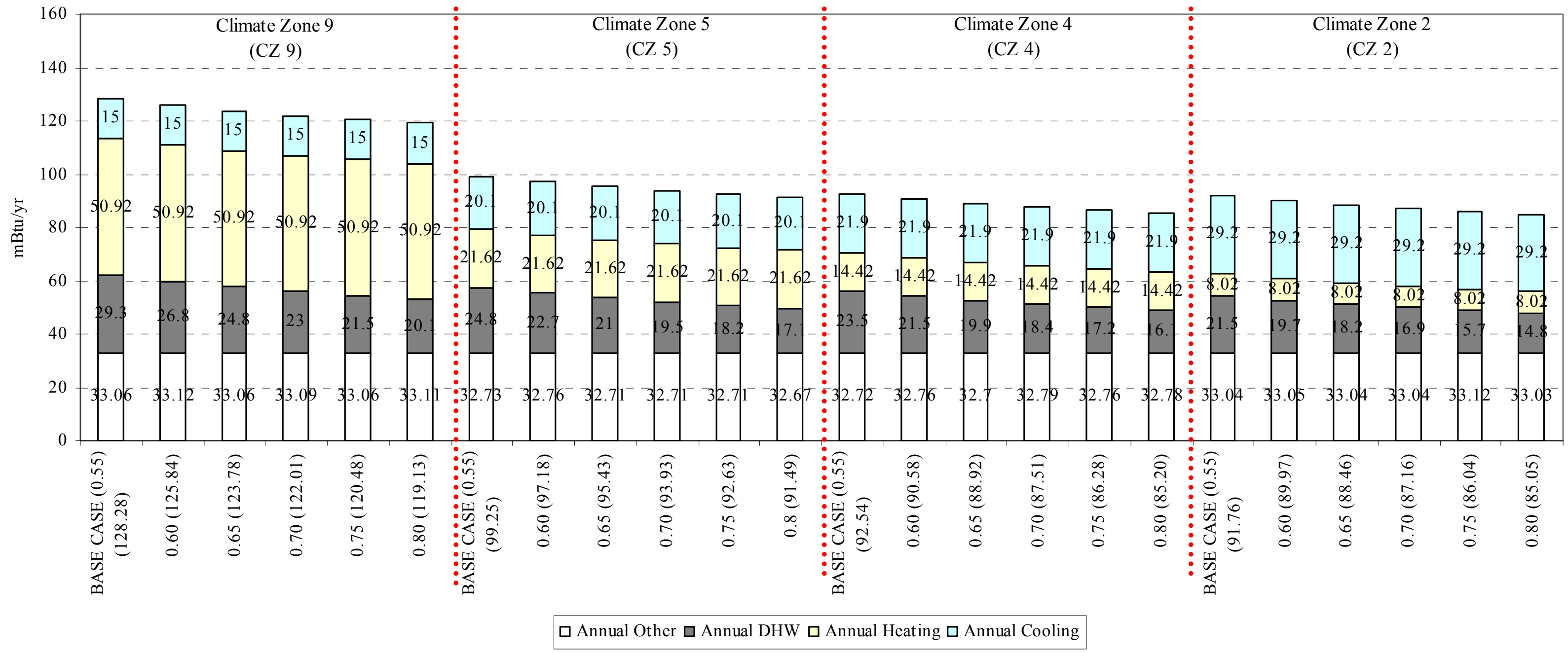


Figure 6.91 Annual energy use of different domestic hot water efficiency

6.4.7 Analysis of the Location of the HVAC Systems

In an attempt to evaluate the effects of placing the ducts in the conditioned space as opposed to the attic space, the duct leakage rates were varied from 0% to 20% for those HVAC systems located in the attic space and as well as in the conditioned space.

The following show the annual total energy use, total energy, heating energy and cooling energy savings by placing the duct in the conditioned space and by changing the duct leakage rate from 0% to 20% in increments of 5%. The other properties remained the same as in the base-case house. Both energy uses in the attic space and the conditioned space with the same duct leakage rate were compared in order to investigate the energy use difference between the attic space and the conditioned space.

The following are detailed explanations of the results obtained according to the duct locations and the duct leakage rate in each of the simulations. It was found that climate zone 9 produced the highest total energy savings and heating energy savings, and climate zone 5 produced the highest cooling energy savings.

6.4.7.1 0% DLR, the attic space vs. 0% DLR, the conditioned space

In the case of 0% duct leakage rate (Figure 6.92), the total energy use decreased by 1.44% for climate zone 9, 0.97% for climate zone 5, 0.82% for climate zone 4 and 0.63% for climate zone 2 when duct location was changed from the attic space to the conditioned space. The heating energy use also decreased by 3.27% for climate zone 9, 2.71% for climate zone 5, 2.45% for climate zone 4 and 1.45% for climate zone 2. The cooling energy use decreased by 1.54% for climate zone 9, 2.52% for climate zone 5, 2.38% for climate zone 4 and 1.79% for climate zone 2.

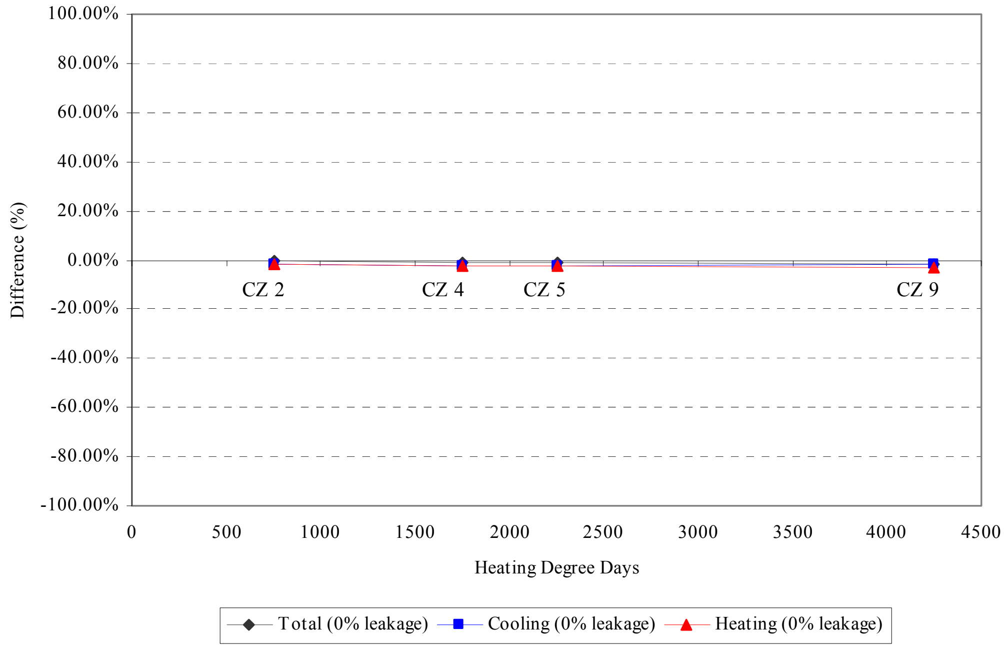


Figure 6.92 Percent difference according to HVAC location (the attic space vs. the conditioned space (0% duct leakage rate))

6.4.7.2 5% DLR, the attic space vs. 5% DLR, the conditioned space

The results using a 5% duct leakage rate (Figure 6.93) showed reductions of 2.90% for climate zone 9, 2.16% for climate zone 5, 1.91% for climate zone 4 and 1.50% for climate zone 2. Results of heating energy use produced a 6.44% drop for climate zone 9, a 5.02% drop for climate zone 5, a 5.30% drop for climate zone 4 and a 4.04% drop for climate zone 2. For the cooling energy use, there were also reductions of 3.60% for climate zone 9, 6.18% for climate zone 5, 5.24% for climate zone 4 and 3.94% for climate zone 2.

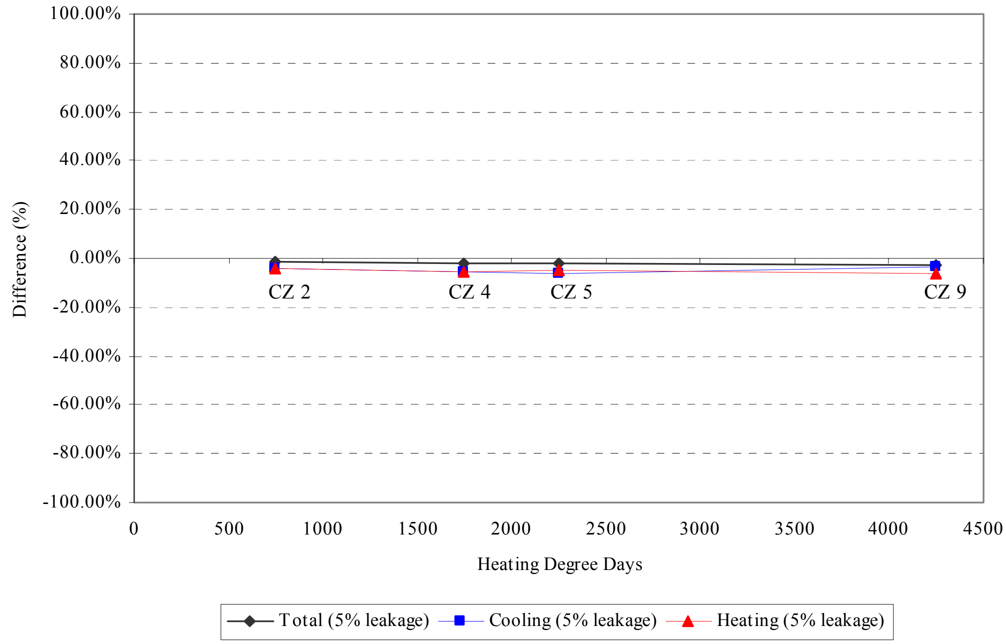


Figure 6.93 Percent difference according to HVAC location (the attic space vs. the conditioned space (5% duct leakage rate))

6.4.7.3 10% DLR, the attic space vs. 10% DLR, the conditioned space

When a 10% duct leakage rate was used in the simulation (Figure 6.94), there were reductions of 4.52% for climate zone 9, 3.60% for climate zone 5, 3.27% for climate zone 4 and 2.64% for climate zone 2 for total energy use. For the heating energy use, there were also reductions of 9.62% for climate zone 9, 7.86% for climate zone 5, 8.32% for climate zone 4 and 6.23% for climate zone 2. For the cooling energy use, there were reductions of 6.00% for climate zone 9, 9.45% for climate zone 5, 8.22% for climate zone 5 and 6.85% for climate zone 2.

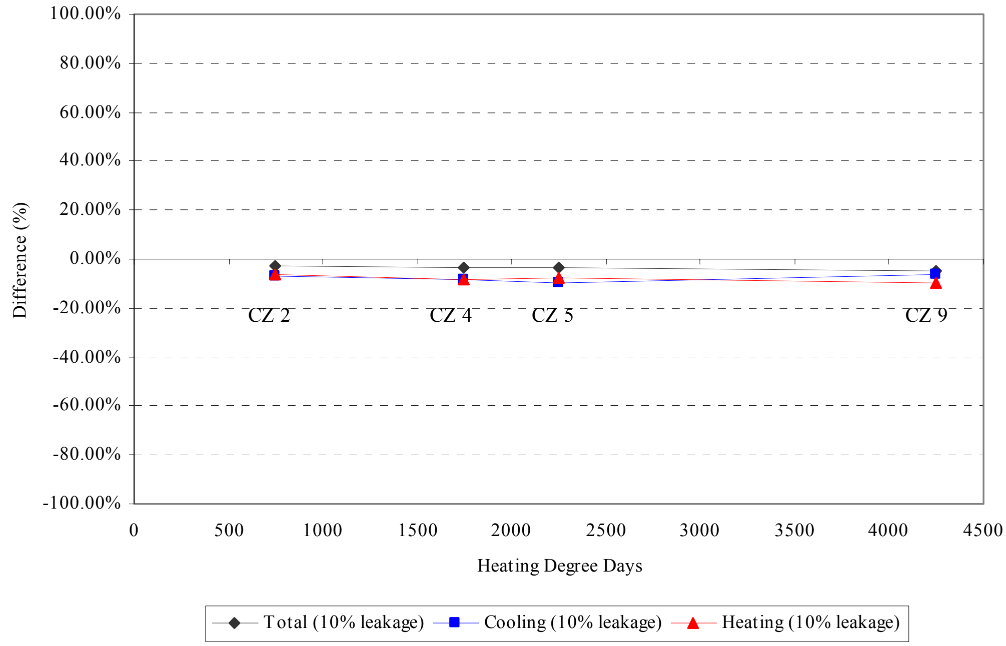


Figure 6.94 Percent difference according to HVAC location (the attic space vs. the conditioned space (10% duct leakage rate))

6.4.7.4 15% DLR, the attic space vs. 15% DLR, the conditioned space

A 15% duct leakage rate (Figure 6.95) produced reductions of 6.30% for climate zone 9, 5.36% for climate zone 5, 5.04% for climate zone 4 and 4.13% for climate zone 2 in the total energy use. For the heating energy use, there were 12.72% decrease for climate zone 9, 10.58% for climate zone 5, 10.81% for climate zone 4 and 6.96% for climate zone 2. In the case of the cooling energy use, there were also decreases of 8.02% for climate zone 9, 13.48% for climate zone 5, 12.45% for climate zone 4 and 9.71% for climate zone 2.

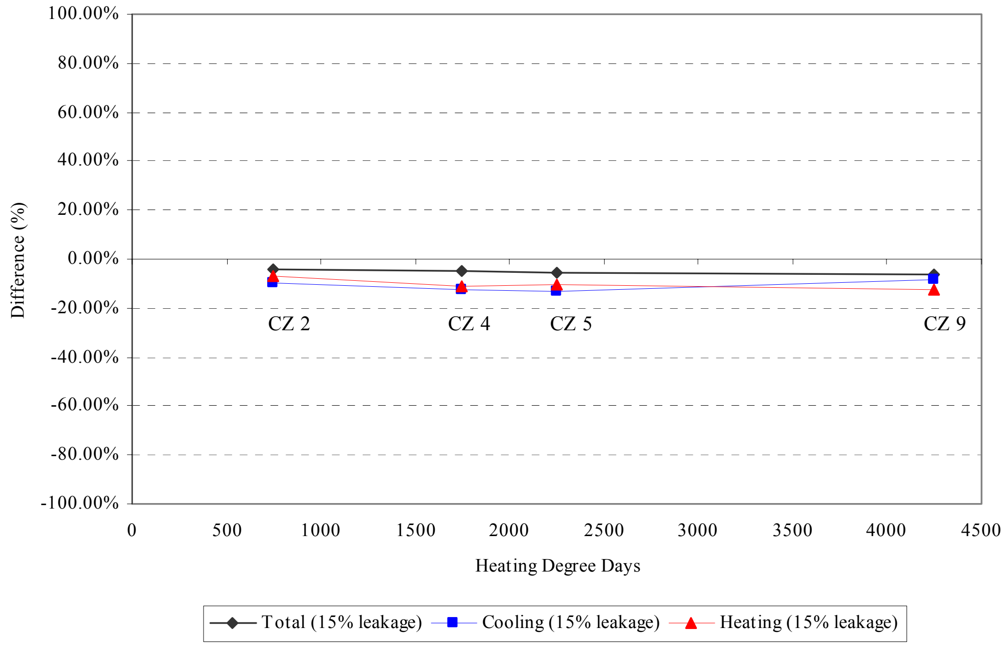


Figure 6.95 Percent difference according to HVAC location (the attic space vs. the conditioned space (15% duct leakage rate))

6.4.7.5 20% DLR, the attic space vs. 20% DLR, the conditioned space

In the case of 20% duct leakage rate (Figure 6.96), there were reductions of 8.25% for climate zone 9 which was the largest savings, 7.68% for climate zone 5, 7.47% for climate zone 4 and 6.17% for climate zone 2 for the total energy use. For the heating energy use, there were also decreases of 15.90% for climate zone 9 which was the largest savings, 13.50% for climate zone 5, 13.86% for climate zone 4 and 9.55% for climate zone 2. For the cooling energy use, there were reductions of 10.73% for climate zone 9 and 18.59% for climate zone 5 which was the largest saving, 17.53% for climate zone 4 and 13.61% for climate zone 2.

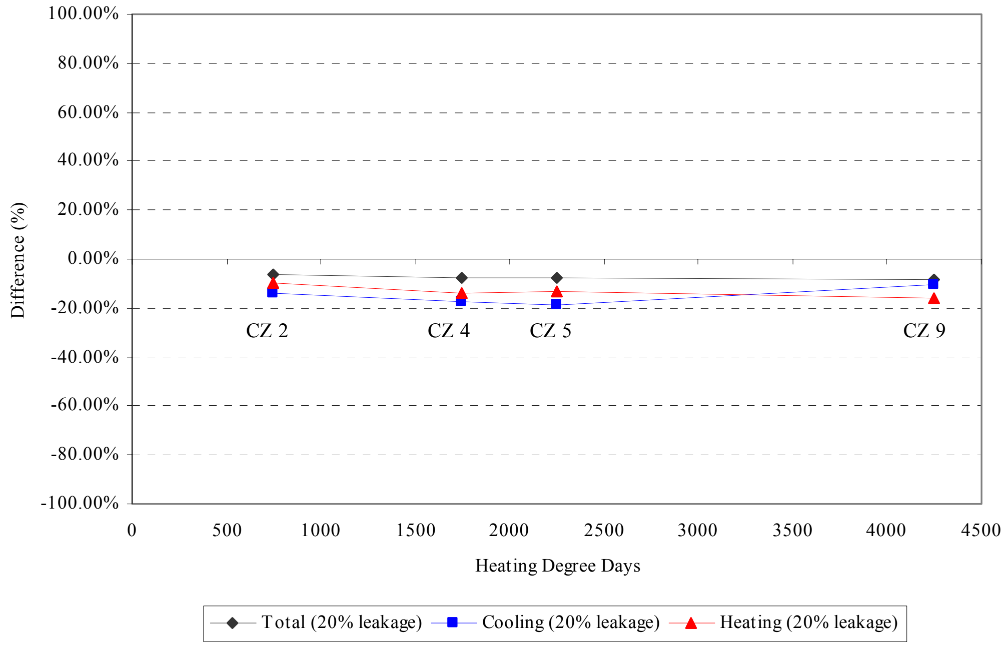


Figure 6.96 Percent difference according to HVAC location (the attic space vs. the conditioned space (20% duct leakage rate))

According to the IECC Chapter 402.1.3.9, the heating/cooling system efficiency should be proportionately adjusted for portions of the ductwork located outside or inside the conditioned space. According to the IECC, if the duct system was relocated from outside to inside, there could be 20% savings for the heating and cooling energy.

From this analysis, it was found that there were savings variations from 1.54% to 18.59% for the cooling system, from 1.45% to 15.90% for the heating system depending on the amount of the duct leakage rates and the climate zones. Nevertheless, the current 2000/2001 IECC defines the fixed adjustment factor. Therefore, the new version of the IECC needs to consider system adjustment factors according to different conditions.

Figure 6.97 shows the annual energy use according to the locations of the HVAC systems.

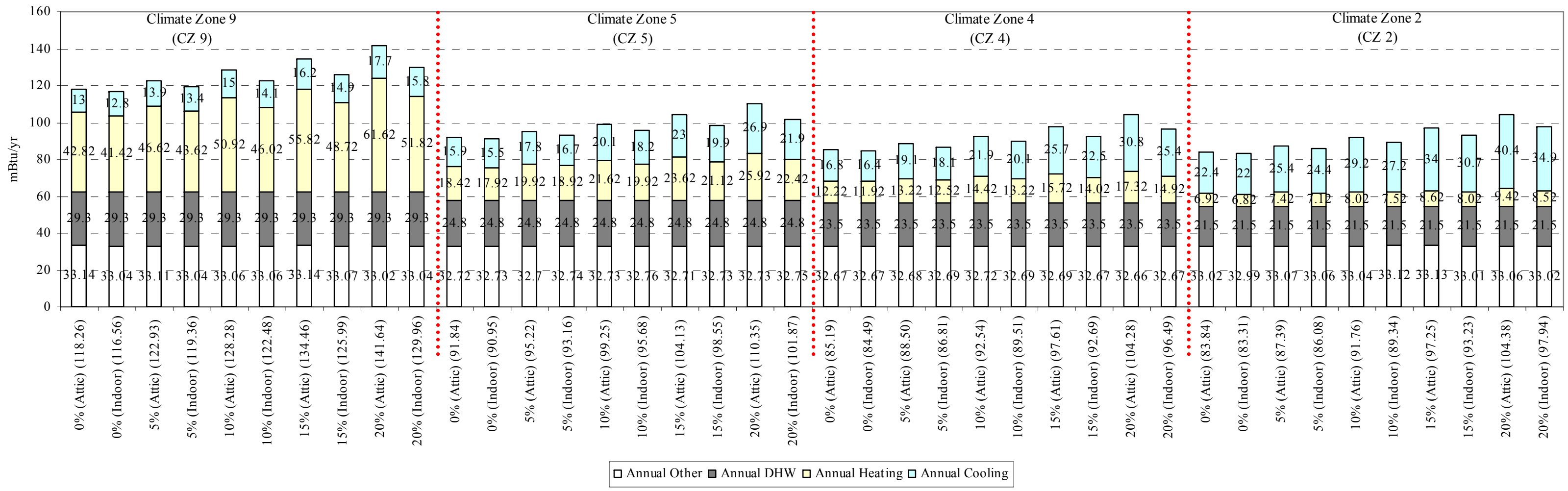


Figure 6.97   Annual energy use according to the locations of the HVAC systems

6.4.8 Analysis of the Tree Shading Impacts

The following results include two different types of graphs to show the effect of tree shading. The annual energy use was plotted by changing the tree shading type from the base case (no shading). The other properties remained the same as in the base case house. From the simulations, the following were observed:

1) Cooling energy savings from evergreen tree shading on the east and west sides were the highest for all climate zones. However, this tree shading resulted in the largest energy use for heating because the tree shading blocked much of the solar heat gain throughout the year.

2) Heating energy savings from deciduous tree shading on the west side were the highest for all climate zones. However, this tree shading also offered less cooling energy savings than any other tree shading because this tree shading allowed solar heat gain to enter the house in the summer season.

3) Total energy savings from deciduous trees on the east and west sides were the highest for climate zones 9, 5, and 4, and total savings from the east and west sides of evergreen trees was the highest for climate zone 2. For climate zones 9, 5 and 4, the results showed a large reduction of the cooling energy and a small increase for heating energy use. There were compensations for each other due primarily to the east and west deciduous tree shading leading to the highest total energy savings. However, the east and west side of evergreen tree shading provided the most benefits to climate zone 2 because climate zone 2 was the hottest climate zone in this analysis, and the resulting cooling energy savings was higher than any other tree shading option.

The following are detailed explanations of the results obtained from the different simulation conditions according to the tree shading types.

6.4.8.1 Base case (no shading) vs. modified (shading on the ease side, live oak tree)

In the case of the east side live oak tree shadings (Figure 6.98), there was a decrease in total energy use for climate zones 9, 5, 4 and 2 compared to the base-case house. For the heating energy use, all climate zones showed an increase in the heating energy use. However, there was a reduction in the cooling energy for all climate zones. For the total energy use, there were reductions of 0.01% for climate zone 9, 0.64% for climate zone 5, 0.69% for climate zone 4 and 1.24% for climate zone 2. For the heating energy use, there were increases of 3.14% for climate zone 9, 3.24% for climate zone 5, 2.77% for climate zone 4 and 1.25% for climate zone 2, and for the cooling energy use, there were reductions of 10.00% for climate zone 9, 5.97% for climate zone 5, 4.57% for climate zone 4 and 4.11% for climate zone 2.

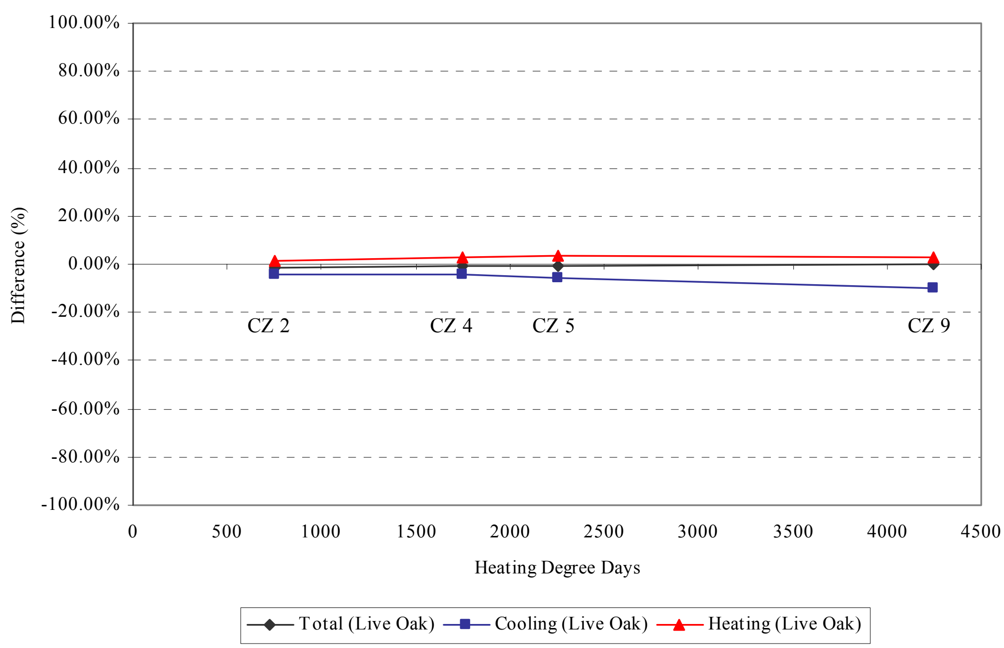


Figure 6.98 Percent difference of annual energy use (base case (no shading) vs. east side shading of live oak))

6.4.8.2 Base case (no shading) vs. modified (shading on the ease side, deciduous tree)

In the case of the east side deciduous tree shading (Figure 6.99), the total energy use decreased by 0.63% for climate zone 9, 1.05% for climate zone 5, 0.94% for climate zone 4 and 1.26% for climate zone 2. The heating energy use increased by 1.57% for climate zone 9, 1.39% for climate zone 5 and 4, no change for climate zone 2. The cooling energy use decreased by 10.00% for climate zone 9, 5.97% for climate zone 5, 4.11% for climate zone 4 and 3.77% for climate zone 2.

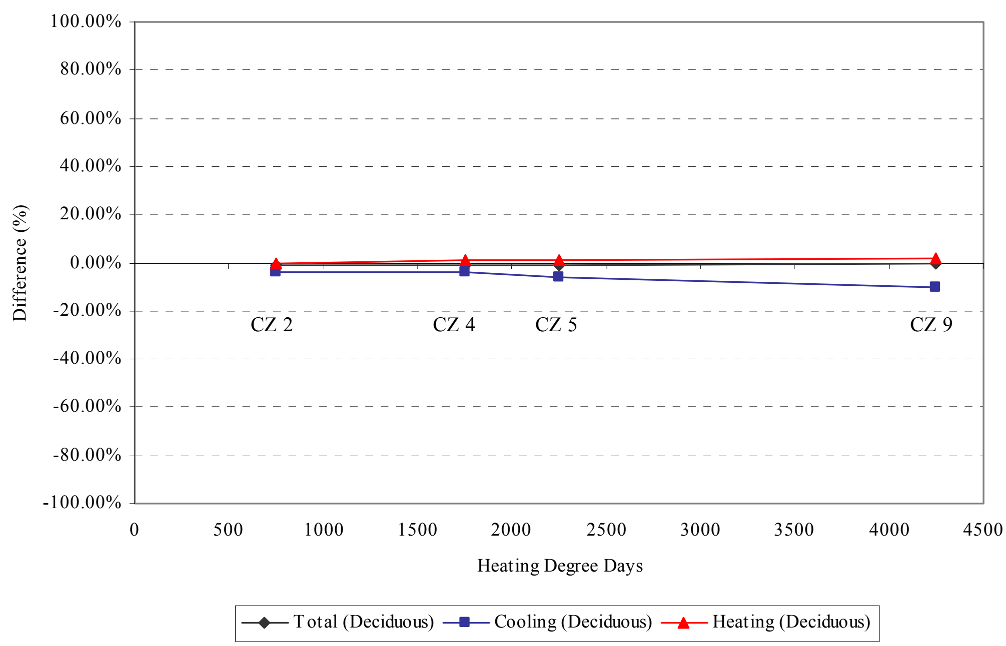


Figure 6.99 Percent difference of annual energy use (base case (no shading) vs. east side shading of deciduous tree))

6.4.8.3 Base case (no shading) vs. modified (shading on the ease side, evergreen tree)

When using the east side evergreen tree shading (Figures 6.100 and 6.101), there were a 0.06% increase for climate zone 9, a 0.70% decrease for climate zone 5, a 0.72% decrease for climate zone 4 and a 1.31% decrease for climate zone 2 in the total energy use. The heating energy showed a 3.34% increase for climate zone 9, a 3.24% increase for climate zone 5, a 2.77% increase for climate zone 4 and a 1.25% increase for climate zone 2. The cooling energy showed a 10.00% drop in climate zone 9, a 6.47% drop in climate zone 5, a 4.57% drop for climate zone 4 and a 4.11% drop for climate zone 2.

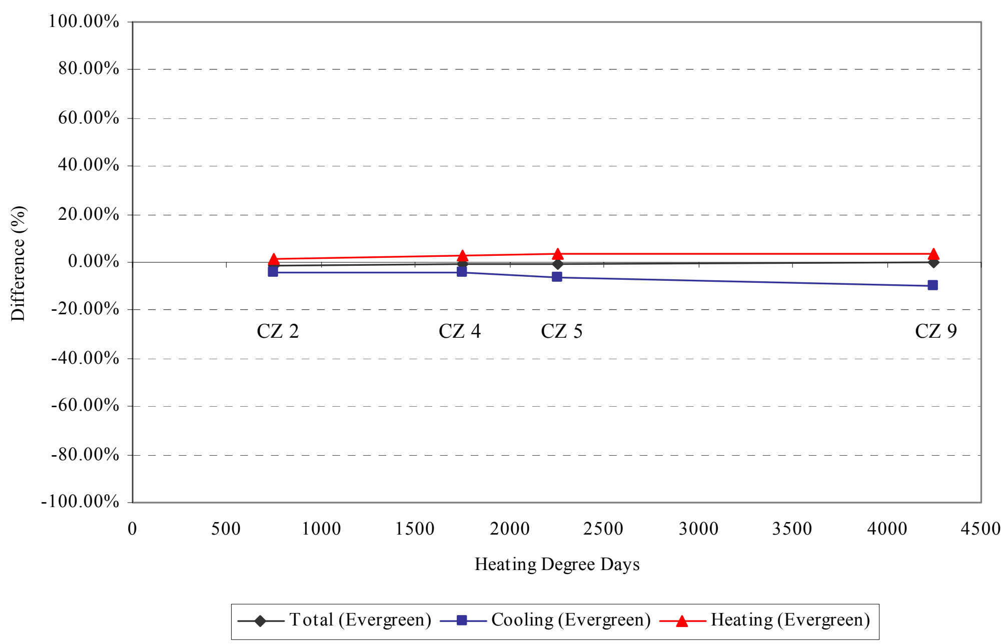


Figure 6.100 Percent difference of annual energy use (base case (no shading) vs. east side shading of evergreen))

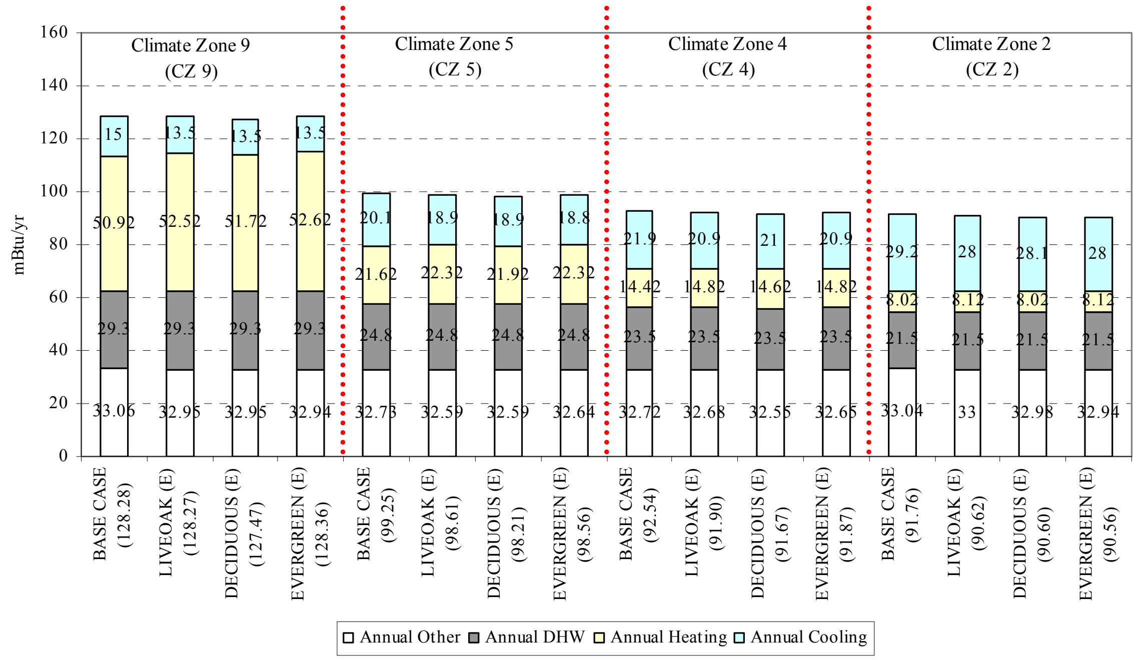


Figure 6.101 Annual energy use of east side tree shading

6.4.8.4 Base case (no shading) vs. modified (shading on the west side, live oak tree)

In case of the west side live oak tree shading (Figure 6.102), the total energy use decreased by 0.14% for climate zone 9, 0.40% for climate zone 5, 0.38% for climate zone 4 and 0.50% for climate zone 2. For the heating energy use, the results showed increases of 0.59% for climate zone 9, 0.93% for climate zone 5 and 0.69% for climate zone 4. There was no change for climate zone 2. For the cooling energy use, the results showed reductions of 2.67% for climate zone 9, 2.99% for climate zone 5, 1.83% for climate zone 4 and 1.71% for climate zone 2.

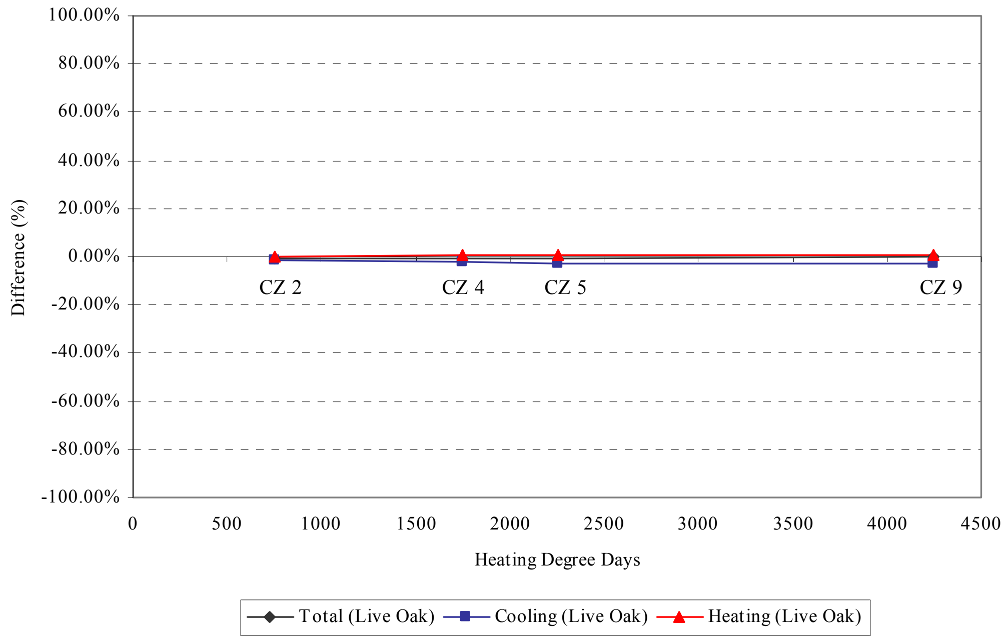


Figure 6.102 Percent difference of annual energy use (base case (no shading) vs. west side shading of live oak))

6.4.8.5 Base case (no shading) vs. modified (shading on the west side, deciduous tree)

Application of the deciduous tree shading (Figure 6.103) produced a 0.27% reduction for climate zone 9, a 0.50% reduction for climate zone 5, a 0.46% reduction for climate zone 4 and a 0.51% reduction for climate zone 2 in the total energy use. The heating energy use increased by 0.20% for climate zone 9 and 0.46% for climate zone 5, and there were no changes for climate zone 4 and 2. The cooling energy use decreased by 2.67% for climate zone 9, 2.99% for climate zone 5, 1.83% for climate zone 4, 1.71% for climate zone 2.

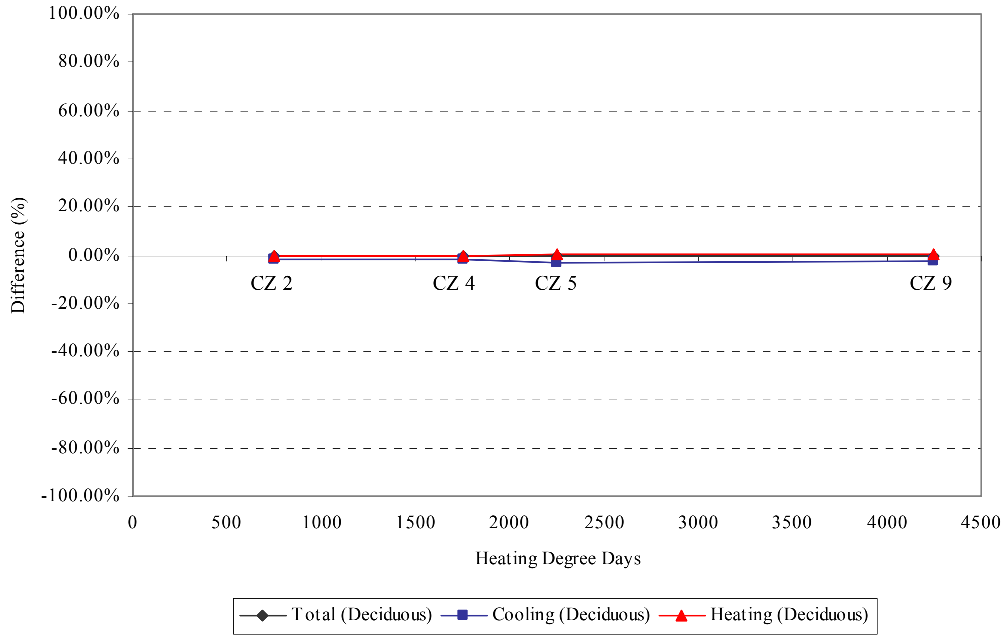


Figure 6.103 Percent difference of annual energy use (base case (no shading) vs. west side shading of deciduous))

6.4.8.6 Base case (no shading) vs. modified (shading on the west side, evergreen tree)

The results with the evergreen tree shading (Figure 6.104) showed reductions of 0.14% for climate zone 9, 0.41% for climate zone 5 and 4, 0.53% for climate zone 2 in the total energy use. Results of the heating energy use produced a 0.59% increase for climate zone 9, a 0.93% increase for climate zone 5, a 0.69% increase for climate zone 4 and there was no change for climate zone 2. For the cooling energy use, there were reductions of 3.33% for climate zone 9, 2.99% for climate zone 5, 1.83% for climate zone 4 and 1.71% for climate zone 2.

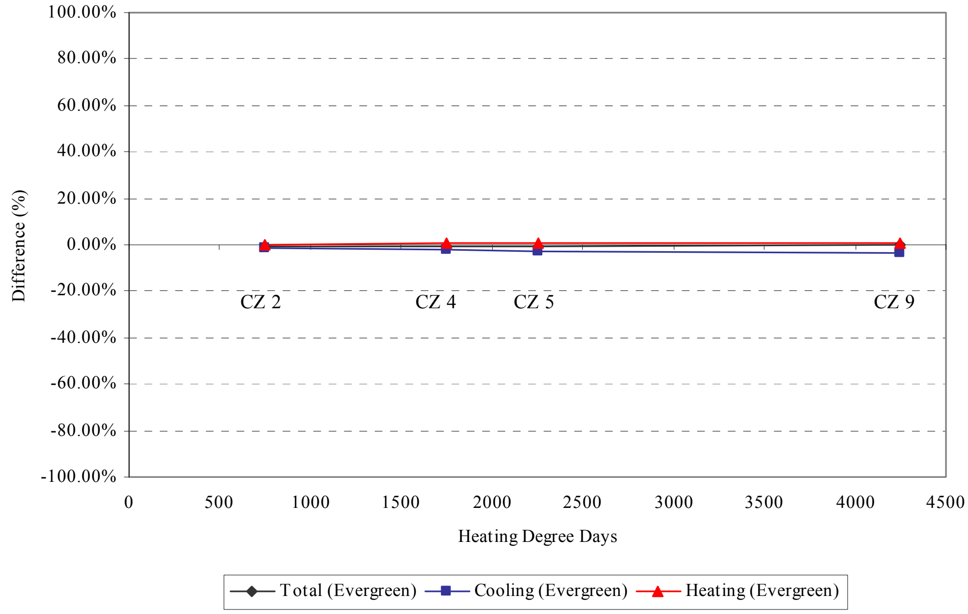


Figure 6.104 Percent difference of annual energy use (base case (no shading) vs. west side shading of evergreen))

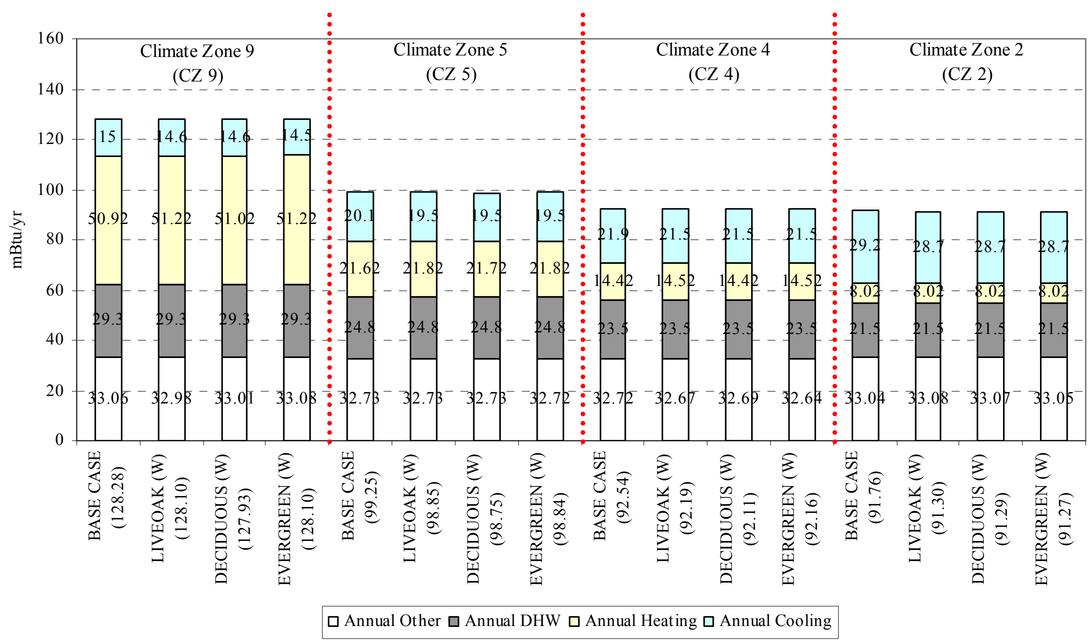


Figure 6.105 Annual energy use of west side tree shading

6.4.8.7 Base case (no shading) vs. modified (shading on the east/west side, live oak tree)

In case of both the east and west side live oak tree shading (Figure 6.106), the total annual energy decreased by 0.14% for climate zone 9, 1.00% for climate zone 5, 1.10% for climate zone 4 and 1.74% for climate zone 2. There were increases of 3.73% for climate zone 9, 4.16% for climate zone 5, 3.47% for climate zone 4 and 2.49% for climate zone 2 in the heating energy use, and there were 12.67% decrease in for climate zone 9, 8.46% in climate zone 5, 6.39% in climate zone 4 and 5.82% in climate zone 2.

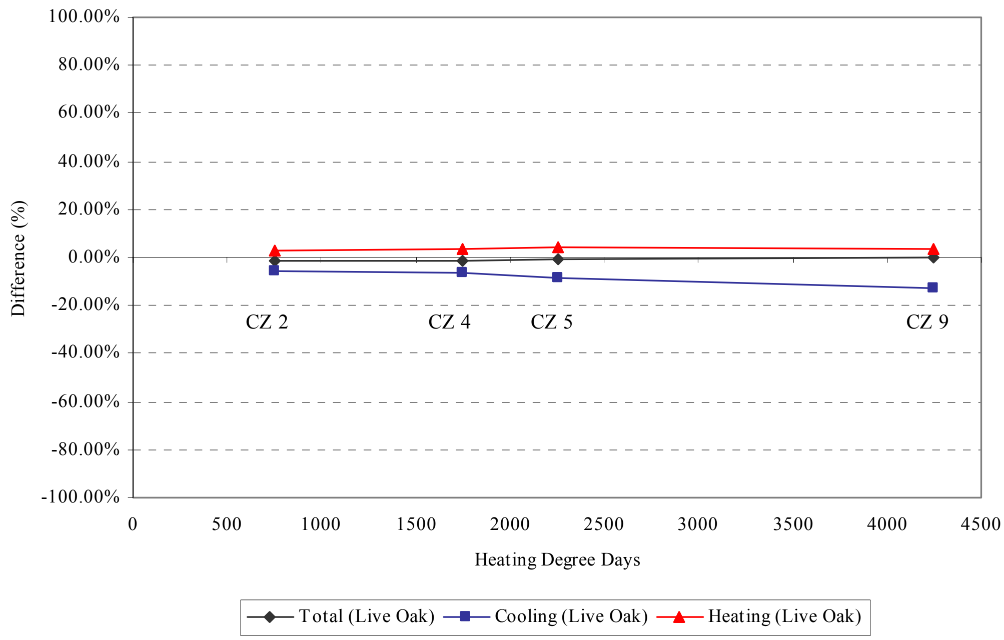


Figure 6.106 Percent difference of annual energy use (base case (no shading) vs. both (east and west) side shading of live oak))

6.4.8.8 Base case (no shading) vs. modified (shading on the east/west side, deciduous tree)

For the east and west side shading with the deciduous trees (Figure 6.107), the total annual energy use yielded a 0.86% drop for climate zone 9, a 1.51% drop for climate zone 5, a 1.40% drop for climate zone 4 and a 1.77% drop for climate zone 2. The heating energy use yielded a 1.77% increase for climate zone 9, a 1.85% increase for climate zone 5, a 1.39% increase for climate zone 4 and there was no change for climate zone 2. The cooling energy use yielded a 12.67% drop for climate zone 9, a 8.46% drop for climate zone 5, a 6.39% drop for climate zone 4 and a 5.48% drop for climate zone 2.

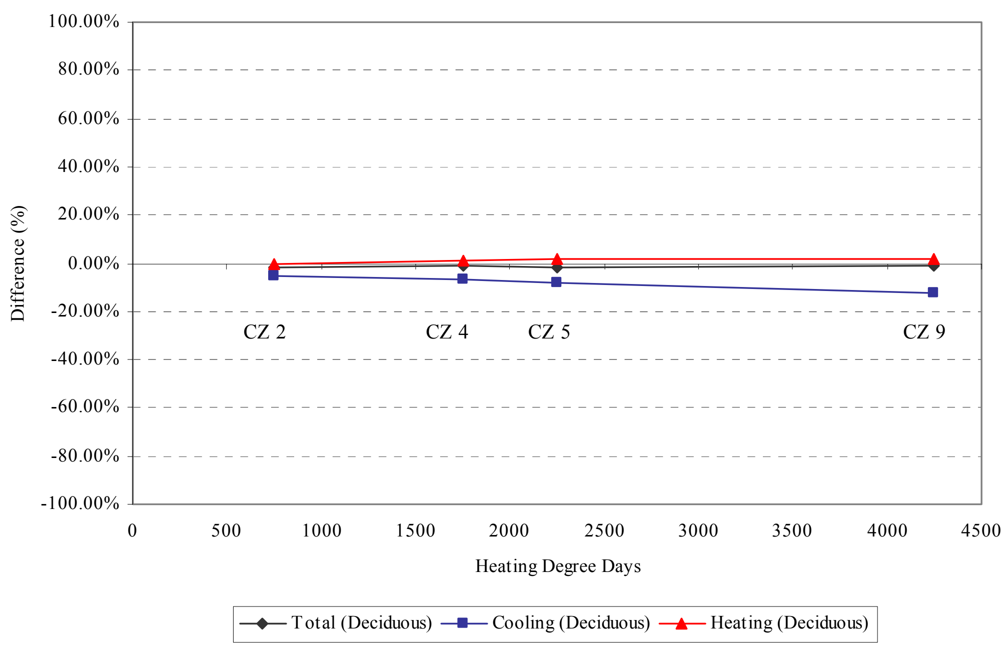


Figure 6.107 Percent difference of annual energy use (base case (no shading) vs. both (east and west) side shading of deciduous))

6.4.8.9 Base case (no shading) vs. modified (shading on the east and west side, evergreen tree)

Finally, using the evergreen tree on both the east and west side (Figures 6.108 and 6.109) produced a 0.06% reduction for climate zone 9, a 1.07% reduction for climate zone 5, a 1.16% reduction for climate zone 4 and a 1.83% reduction for climate zone 2 in the total energy use. For the heating energy use, there were increases of 3.93% for climate zone 9, 4.16% for climate zone 5 and 4, and 2.49% for climate zone 2. Cooling energy use decreased by 13.33% for climate zone 9, 8.96% for climate zone 5, 6.85% for climate zone 4 and 5.82% for climate zone 2.

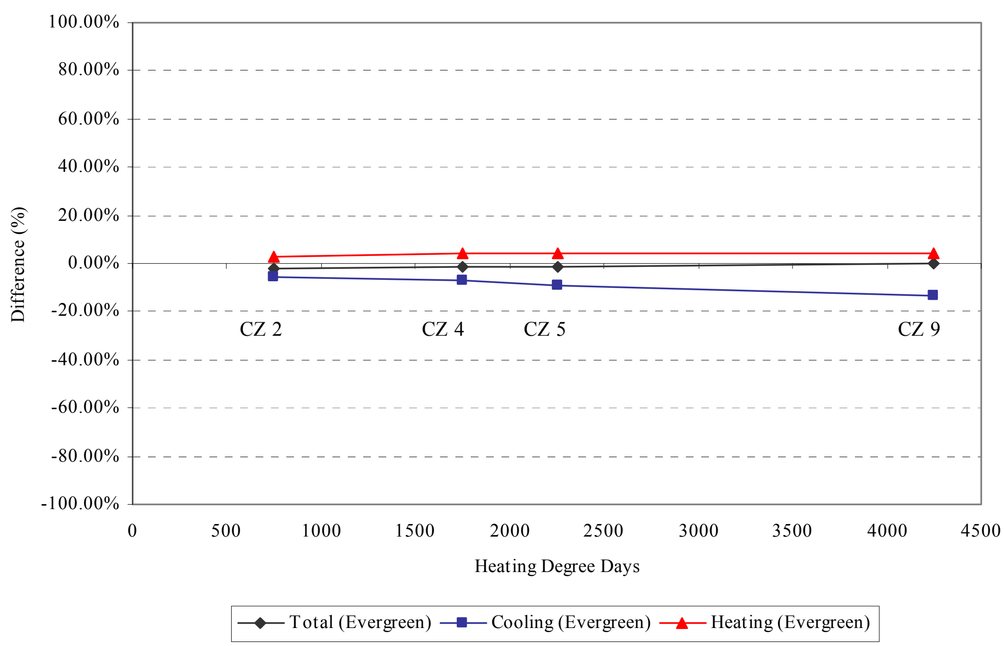


Figure 6.108 Percent difference of annual energy use (base case (no shading) vs. both (east and west) side shading of evergreen))

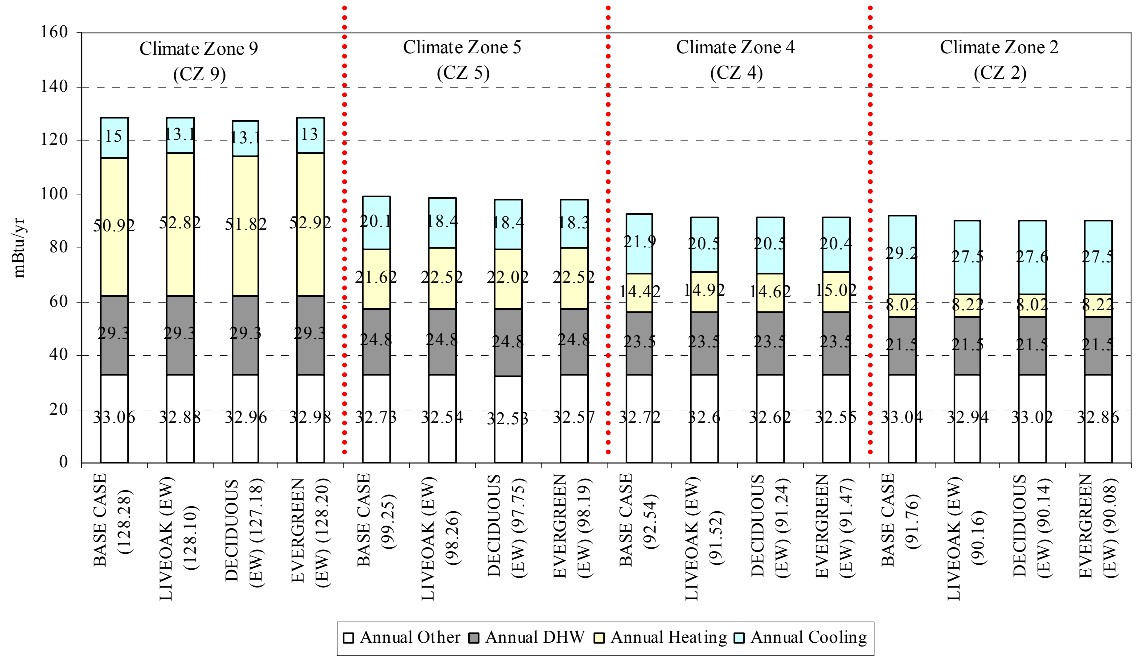


Figure 6.109 Annual energy use of both (east and west) side tree shading

6.5 Summary

This chapter has presented and discussed the IECC-compliant simulation model including a thermal mass analysis and a window input mode analysis. For the thermal mass analysis, a quick construction wall and six thermal mass construction wall types were simulated to investigate their impact on the annual, cooling and heating energy use. It was found that the quick construction mode usually overestimated the total, the cooling and the heating energy use. For the window input mode analysis, the simulations of the SC (Shading Coefficient) method and the Window-5 method were compared. Simulations were also performed based on the two different construction modes (the quick construction mode and the thermal mass construction mode). It was observed that the percent savings obtained from the Window-5 method were usually greater than those from the SC method in almost all the cases. In comparing the percent savings based on the two construction modes, the savings from the quick construction mode were usually greater than the percent savings from the thermal mass construction mode.

Using the IECC-compliant simulation model, efficiency tests were performed. Results from the fenestration properties suggested that cooling energy savings could be achieved from decreasing only the SHGC, and heating energy savings could be achieved from decreasing only the U-value. However, the combination of proper SHGC and U-values produced the largest total energy savings. From duct properties simulations, it was found that duct leakage rates affected the cooling and heating energy use more than duct insulation levels. From a system efficiency simulation of an air conditioner, furnace and heat pump, it was found that a highly efficient air conditioner has a high potential energy savings in a hot climate zone, whereas a highly efficient furnace and heat pump have a high potential for energy savings in a cold climate zone. From domestic hot water efficiency simulations, it was found that an energy efficient water heater had a significant savings potential regardless of the climate zones. The results of the different locations of the HVAC system suggested that the HVAC system in the conditioned space could produce cooling and heating energy savings up to 18.59% and 15.90%. Finally, the results from the simulations of various tree shadings could provide the highest cooling energy savings with east and west side evergreen tree shading, and a total annual energy savings with east and west deciduous tree shading.

CHAPTER VII

SUMMARY AND FUTURE RECOMMENDATIONS

7.1 Summary of the Methodology

A methodology was developed for the purpose of creating a code-traceable IECC simulation model. Before creating the code-traceable IECC simulation model, a base-case model was created and calibrated with measured data collected from the case-study house to obtain a simulation model that would more accurately represent the case-study house. The calibrated model was then used to verify the accuracy of the new simulation methods against previous models and the measured data. These methods include:

- An application of multi-layered window models (i.e., Window-5) combined with improved thermal mass modeling (i.e., DOE-2's Custom Weighting Factors)
- The development of a duct model in an attic space using ASHRAE Standard 152-2004 using DOE-2.1e FUNCTION commands (ASHRAE 2004).
- The application of new, more accurate residential HVAC system performance curves (Henderson et al. 2000).
- The application of a new, more accurate domestic hot water system curve (NREL 2001).
- The application of improved underground surface heat transfer calculations (Winkelmann 1998).

The measurements in the case-study house in Bryan, TX, were performed from January to December of 2004. These measurements were used to validate various aspects of the results taked from the improved simulation model of the base-case house. After the validation was accomplished, the improved model was then used to simulate the various types of energy-conserving features of a single-family residence that could not be simulated with the previous version of the DOE-2 input file.

7.2 Summary of the Results

This section consists of two types of results obtained from this dissertation: 1) the results from the calibrated simulation of the case-study house, and 2) the results from the use of the improved IECC simulation model.

7.2.1 The Results of the Case-Study House

The results obtained from these analyses include measurement results and DOE-2 simulations of the base-case house.

- In order to verify the accuracy of the base-case house simulation model, measurements of the indoor and outdoor environmental condition and energy consumption were used to calibrate the new model. The results show that the new model had an improved calibration of CV (RMSE) (24.7%) and MBE (-0.79%) over the previous model of CV (RMSE) (40.24%) and MBE (-29.10%) of the house.
- Three-parameter change-point (3P) cooling and heating models using ASHRAE's Inverse Model Tool Kit (IMT) were developed to compare the annual electricity and natural gas use of the case-study house with a similarly sized IECC-compliant house. The comparison showed that if the base-case house had been built to the 2000/2001 IECC standard, the annual electricity and natural gas use could be reduced by 9.2% and 20.0% respectively.
- From the measurements of the HVAC and duct systems in the attic during the summer periods, it was found that the fluctuating conditions in the unconditioned space played a very significant role in the duct heat loss or gain which requires an improved thermal mass simulations.

- For the base-case house simulation, the results from the new model agreed well with the measurements from the base-case model. The improved methods in the new model include:
    - The development of a duct model using DOE-2.1e FUNCTION commands, and ASHRAE 152-2004 equations. After applying the duct model to the base-case house simulation model, the simulated energy use provided a better match to the measured energy use than the previous simulation results that did not include a duct model. Thus the improved simulation input file with the duct model can properly evaluate the impact of duct properties in residential energy use, which could not have been considered in the previous residential simulation model.
    - Three new performance curves (good, typical and poor) were tested to improve the A/C system simulations from Henderson et al. (2000) along with two new DOE-2 performance (the new SDL-C17 and the old SDL-C17) performance curves. After applying these residential A/C system performance curves, it was found that the cooling energy use from the new A/C system performance curves better matched the measured performance data than did the previous model. Therefore, simulations using the new system performance curves could investigate cooling energy use more accurately than did the previous model.
    - In order to investigate a new method of designing a domestic hot water system, simulations of four different results were compared: 1) the measured data from the case-study house, 2) a calculation using the ASHRAE 90.2 (2001a) method, 3) simulation results using a new method suggested by NREL, and 4) simulation results using the previous DOE-2 default method. It was found that the results from the NREL method were the closest to the results of both the measured data and the

ASHRAE 90.2 (2001a) calculations. Therefore, a simulation of the DHW using an EF is now recommended for residential houses.

- In order to investigate a more accurate method to calculate the underground surface heat transfer, simulations for an underground surface were performed using LBNL's U-EFFECTIVE method (Winkelmann 1998). The results showed that the use of U-EFFECTIVE, when combined with TRY ground temperatures, offered a significant improvement in the accuracy of the simulation of the heating energy uses of the case-study house. Thus, the simulation with LBNL's U-EFFECTIVE method should be used to calculate the heat transfer from the underground surface.

7.2.2 The Results of the IECC-Compliant Simulation Model

The results obtained from the IECC-compliant simulation include an improved thermal mass analysis, an improved window input mode analysis, and an improved efficiency analysis.

Thermal mass analysis

- The IECC simulation model was used to perform a thermal mass analysis with the "quick" construction mode (i.e., pre-calculated ASHRAE weighting factors) and a thermal mass construction model (i.e., DOE-2's custom weighting factors with layered walls, roof, etc.). For this analysis, seven wall construction types were created according to the 2000/2001 IECC: 1) a quick mode wall that uses U-values instead of layered materials, 2) a 2x4, wood-framed wall with studs 16" O.C. with insulation between the studs, 3) a 3" facia brick wall with a 2 x 4 wood-frame with studs 16" O.C. with insulation between the studs, 4) an 8" concrete block wall with perlite fill in the cells of the block and insulation between the block and the interior gypsum board, 5) an 8" concrete block wall with perlite and concrete fill in the cells of the block and insulation between the block and the interior gypsum board, 6) an 8" concrete block wall with perlite fill in the cells of the block and insulation outside the block, covered by stucco, and 7) an 8” concrete block with perlite and concrete fill in the cells of the block and insulation outside the block, covered by stucco.

- It was found that the quick construction mode usually over-estimated the total, cooling and heating energy uses when compared to the thermal mass mode. In the case of the total annual energy use, an 8” concrete block wall with perlite fill in the cells of the block and insulation between the block and the interior gypsum board was the most energy-conserving wall. The results from this wall type showed a 2.54% total annual savings compared to the base-case wall type, which was a 2 x 4, wood-framed wall with studs 16” O.C. with insulation between the studs.

Window input mode analysis

- A window input mode analysis was also performed using DOE-2’s SC input method and the Window-5 input method which compared single-pane, double-pane and low-e glass, using the quick construction mode and the thermal mass construction mode. The results showed that the annual percent savings obtained from the Window-5 method were usually greater than the annual percent savings obtained from the SC method in almost all cases.
- It was also found that the savings from the “quick” construction mode (i.e., pre-calculated ASHRAE weighting factors) were usually greater than the percent savings from the thermal mass construction mode (i.e., DOE-2’s custom weighting factors).
- Several researches proved that the W-5 method calculated the window heat transfer more accurately than the SC method. Performing the simulations in this study, this research found that there were differences between the two methods even though exactly the same thermal window properties were used for the simulations. However, since the current IECC provides only a U-value and an SHGC for the window properties, the SC method must still be used for analyzing the IECC-code compliant house. Thus, the LBNL needs to provide an

automatic Window-5 preprocessor that allows for Window-5 files to be produced given only U-values, SHGC and several assumptions about frame size, type, etc.

Efficiency analysis

An Efficiency analysis using the IECC-compliant traceable simulation model was performed with varying fenestration properties, duct properties, air conditioner efficiencies, furnace efficiencies, heat pump efficiencies, domestic hot water heater efficiencies, locations of the HVAC system, and tree shading effects.

- Results from the fenestration properties showed that additional annual cooling energy savings could be achieved by decreasing the SHGC. Heating energy savings could be achieved by decreasing the U-value. However, the combination of the proper SHGC and U-values produced the largest total energy savings.
- From the duct simulations, it was found that duct leakage rates affected the cooling and heating energy use more than did duct insulation levels.
- From the system efficiency simulations of air conditioners, furnaces and heat pumps, it was found that a highly efficient air conditioner had substantial potential for energy savings in the hot-humid climate zones, whereas a high efficiency furnacess and heat pumps had the most energy savings in cold climate zones.
- From the domestic hot water efficiency simulations, energy efficient water heaters had significant savings potential regardless of the climate zones.
- The results of the simulation using different locations of the HVAC system suggested that an HVAC system in a conditioned space could produce significant cooling and heating energy savings because duct losses could be eliminated.

- Finally, the results from simulations of tree shading showed the highest cooling energy savings with evergreen trees shading the east and west sides, and the highest total annual energy savings with deciduous trees shading the east and west sides of a building.

7.3 Impacts of the Study

This research was performed to improve an existing IECC-compliant simulation model for Texas and to analyze the energy efficiency of a single family residential house, which could not have been evaluated to the same extent using the previous residential simulation model. After testing and verifying the new and improved simulation methodologies, it became possible to provide an improved residential simulation model in order to make recommendations for changes in residential construction and HVAC installation that could save energy in residential housing according to climate variations.

Since it was found that a highly efficient air conditioner offered more potential energy savings in hot climate zones as compared to cold climate zones, highly efficient air conditioners should be considered for use in hot climate zones when installing a cooling system. On the other hand, it was found that highly efficient gas furnaces and heat pump had more energy savings potential in cold climate zones compared to hot climate zones in Texas. Therefore, a highly efficient gas furnace and heat pump need to be considered when installing a heating system in a cold climate zone. In addition, DHW system efficiency was found to be an important factor in energy savings regardless of the climate zones. Therefore, it is recommended that highly efficient DHW systems be installed in all climate zones for energy savings in residential construction.

Duct leakage rates were found to be a significantly important factor in increasing energy consumption in unconditioned space. Thus, sealing or repairing leaky ducts could immensely reduce energy consumption in all climate zones. Changing the locations of duct systems from unconditioned spaces to conditioned spaces also has a significant effect on energy savings. Currently, most of the duct systems in Texas are located in unconditioned spaces (i.e., the attic). Therefore, relocating these duct systems to conditioned spaces needs to be considered for possible energy savings when designing residential houses.

In case of window installation, it was found that both the U-value and the SHGC influence energy consumption in opposite ways. Thus, combinations of improved U-values and SHGCs need to be considered when selecting window types.

Lastly, tree shading effects showed a slight influence on energy savings depending upon the type of tree shading. Although the amount of energy savings might be more minor than that taken from other components stated above, it can be a cost-effective way of saving energy by using existing natural resources.

7.4 Recommendations for Future Research

Although this study developed, tested and used a number of simulation features of the DOE-2 program, many simulation features still remain that are outside the capabilities of the DOE-2.1e program, including:

Simulation of a multi-story house with varying shapes

This study was performed using a one-story, single-family house with a slab-on-grade. Therefore, a two-story house and a multi-family house were not considered for analyses in this study. This study did not investigate the effects of different building configurations in terms of form, orientation, or different window sizes. Therefore, an analysis considering different types of residential houses and building configurations is recommended.

A duct model with an improved radiant model of the interior of the attic

The new duct model didn’t consider the radiation effects from the inside surface of the roof, since the duct model in the analysis followed the methodology of the ASHRAE 152-2004

(2004). Therefore, future research concerning the radiation effects on the duct model is recommended.

Analysis with an improved ground heat transfer model

The newest version of the underground heat transfer methodology by Huang et al. (2000) was not applied in this study because the version of the DOE-2 used in this analysis did not have the capability to apply the new methodology. Therefore, it is recommended that the new methodology (Huang et al. 2000) needs to be tested.

Direct conversion of SC to Window-5 model

For the efficiency analysis using the IECC-compliant simulation model, the SHGC of the windows must be converted to a Shading Coefficient (SC) in order to be entered into the DOE-2 simulations. As discussed in Chapter 6.3, for more accurate simulations of any window, a generic Window-5 library needs to be used for the IECC-compliant simulation. Unfortunately, this cannot be accomplished with the current version of the Window-5 program.

Use of an improved thermal mass model

It was found that the delayed construction mode (i.e., DOE-2's custom weighting factors or CWFs) calculated energy consumption more accurately than the quick mode construction mode (i.e., pre-calculated ASHRAE weighting factors). Unfortunately, the current 2000/2001 IECC defines construction using only R-values and a fixed floor weight, which makes it difficult to use CWFs. Therefore, the IECC needs to be rewritten to allow for proper treatment of thermal mass using CWFs.

Combined effects of system sizing and reduced loads

In the current study, the system size was auto-sized with the DOE-2 program (SNGFAM2ST.INP). However, a more realistic analysis would resize the HVAC system as the heating and cooling loads decreased. Therefore, a combined analysis should be conducted.

Analysis of the IECC with varying duct locations

The results from the different duct locations (conditioned space vs. unconditioned space) and varying duct leakage rates showed that there could be a difference from 1.54% to 18.59% in saving varying by climate zone and duct leakage rates when changing the duct location from that which is in unconditioned space to that which is in conditioned space. Nevertheless, the current 2000/2001 IECC has a fixed adjustment factor at 0.80. Therefore, it is recommended that the new version of the IECC considers various system adjustment factors when changing duct locations according to climate zone and duct leakage rate.

Application of the ACH rate (air-change / hour) in the attic space to the IECC-code compliant simulation model

From the temperature calibration procedures with measured data in the attic space, it was found that the air-change rate with the adjusted infiltration schedules for both the daytime and nighttime showed the most reasonable results. However, for the IECC-code compliant simulations, the fixed air-change rate was used in the attic space for all climate zones because of the lack of available measured data. If there were no measurement data for the model calibration, it was recommended that other infiltration calculation methods of the DOE-2 (INF-METHOD: CRACK, RESIDENTIAL, and S-G) could be considered.

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APPENDIX A

CALIBRATION OF MEASURING DEVICES

A.1. Calibration of Temperature Sensors

A.2. Statistical Evaluation of the Calibration Results.

A.3. Calibration of Relative Humidity Sensors

A.4. Portable Data Loggers

A.5. Calibration of Solar Radiation Sensors: Pyramometer

A.6. Comparison of Supply and Duct Temperature Sensors

With the exception of the newly installed sensors in the attics, the sensors at the case study house were installed as part of a previous study by Kootin-Sanwu (2004). Therefore, all sensors were inspected and recalibrated. NIST (National Institute of Standards and Technology) and ASTM (American Society for Testing and Materials) calibration methods were used for the calibration procedures.

A.1. Calibration of Temperature Sensors

In order to measure temperature and humidity, Vaisala HMD60Y duct mounted relative humidiy and temperature sensors were used. Those sensors have a range from -4°F to 176°F, and ± 0.2-0.6°F accuracy on temperature measurements (Vaisala 2003). In order to convert the temperature measurement (°F) into an electronic signal, a correctly calibrated scale and offset must be calculated. To accomplish this, an ASTM certificated liquid-in-glass thermometer and Type-T thermocouple (RTD thermometer) with the Synergistics portable data logger (C180-XP, Figure A.1) were used for the reference temperature. Type-T thermocouple was calibrated using an ice point and a boiling point (ASTM E 77–98 2001) using an ASTM certificated liquid-in-glass thermometer and distilled water to make the ice and boiling water. Figure A.2 shows the calibration of the RTD thermometer that was calibrated. After calibrating the RTD sensor, the Vaisala relative humidity and temperature sensors and calibrated RTD sensor is connected to the data logger and placed in a glass container to perform the calibration of the temperature and relative humidity. This container and the sensors were then placed to the refrigerator to maintain a constant temperature (Figure A.3). In order to change the temperature, a 60W incandescent lamp and small fan were used in the refrigerator. The temperature of the refrigerator was then set to three different temperature conditions: 1) low temperature which represents the lowest temperature position of the refrigerator's thermostat, 2) room temperature (the refrigerator was off), and 3) a high temperature where the 60W incandescent lamp was turned on. During these three different conditions, a small fan was used to maintain a uniform temperature in the refrigerator. The calibration of the humidity was performed at the same time.

In the case-study house, there are five Vaisala sensors which measure: 1) attic, 2) return, 3) supply, 4) duct, and 5) outside condition. Figures A.4 to A.18 compare the temperatures of each Vaisala sensor agianst calibrated RTD thermometer before and after the calibration. The graphs provide the time seriese plot of the RTD thermometer vs. the Vaisala sensors and a residual plot of the five Vaisala sensors. Table A.1 lists the scale and offset parameters for all 5 sensors before and after calibration.

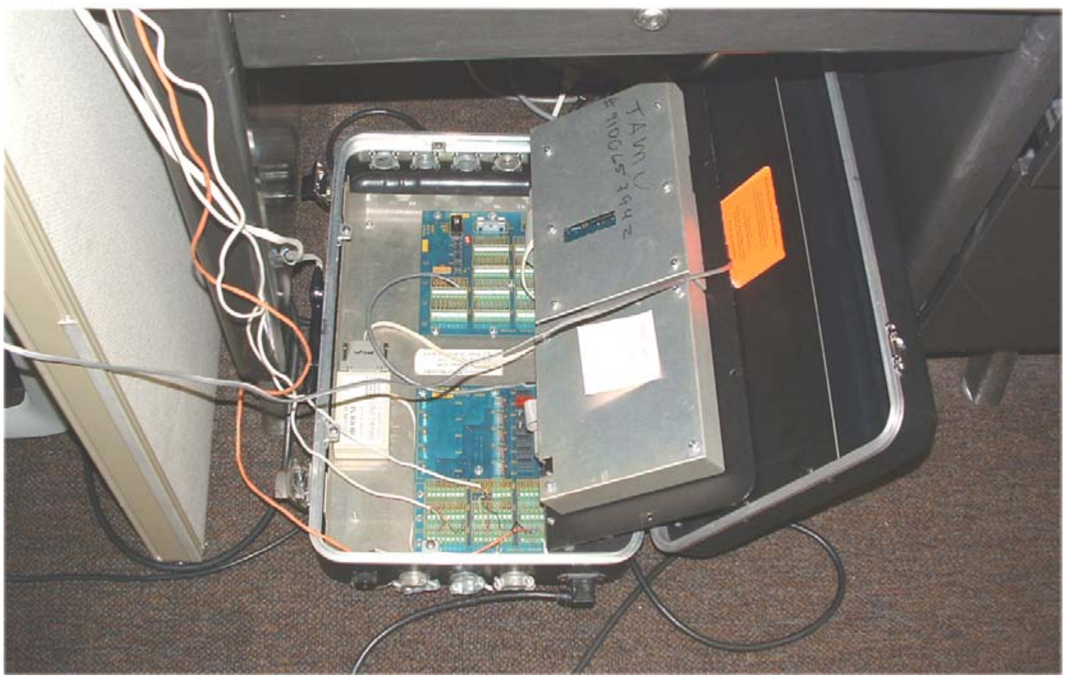


Figure A.1 Synergistics portable data logger (C180-XP) used for the calibration procedure

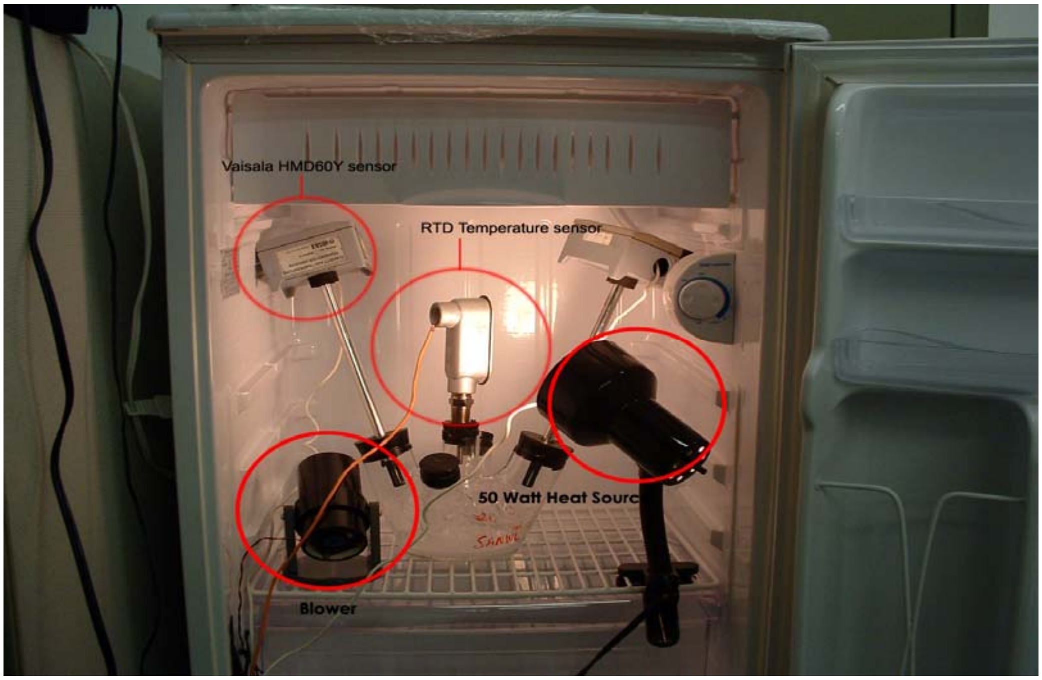


Figure A.2 Experimental setting showing the Vaisala and RTD sensors

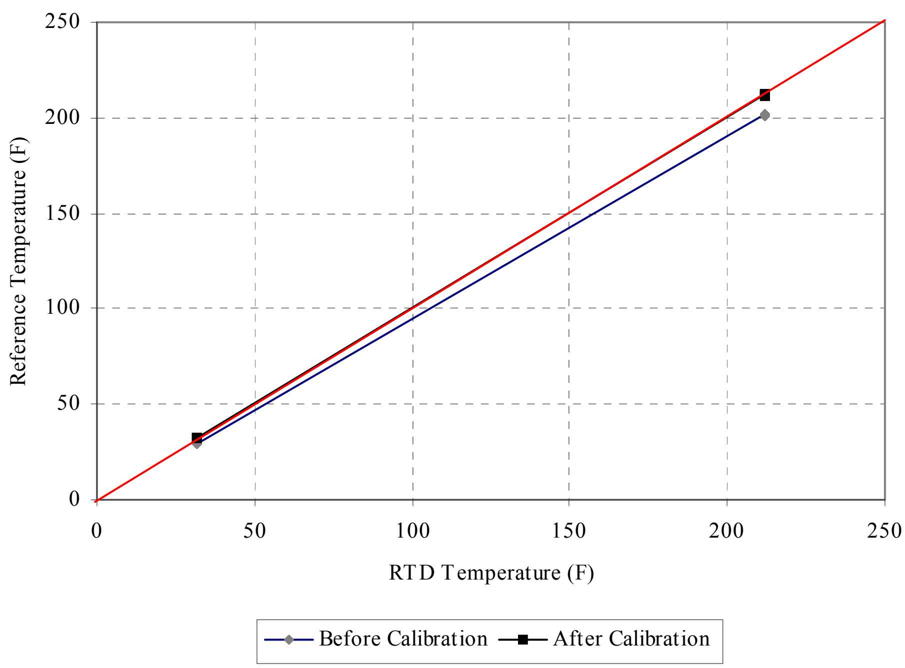


Figure A.3 Calibration of the RTD sensor (Before and after calibration)

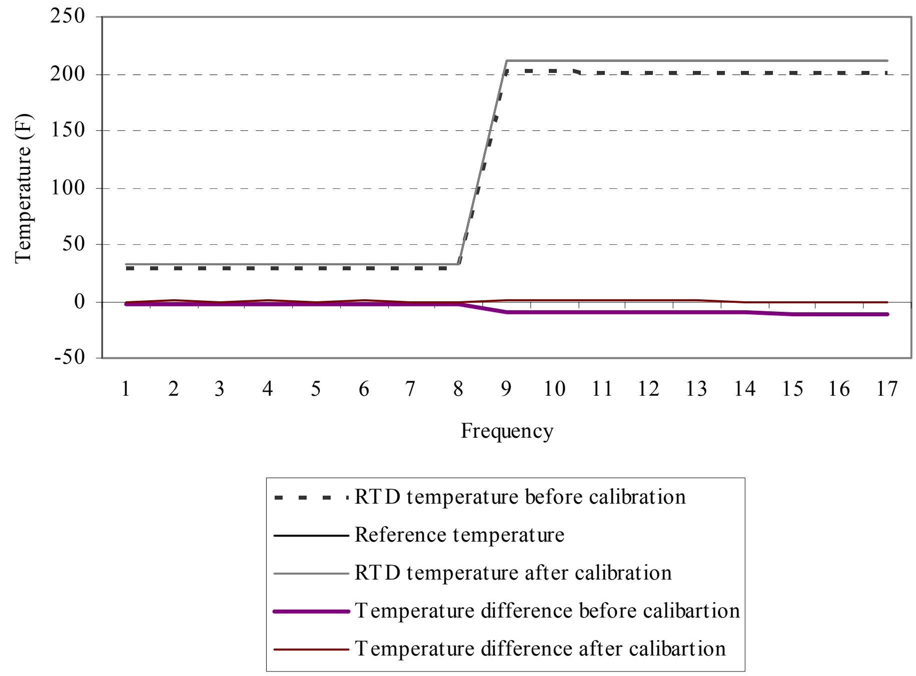


Figure A.4 Residual plot of the RTD sensor against reference temperature

A.1.1 Sensor No.1

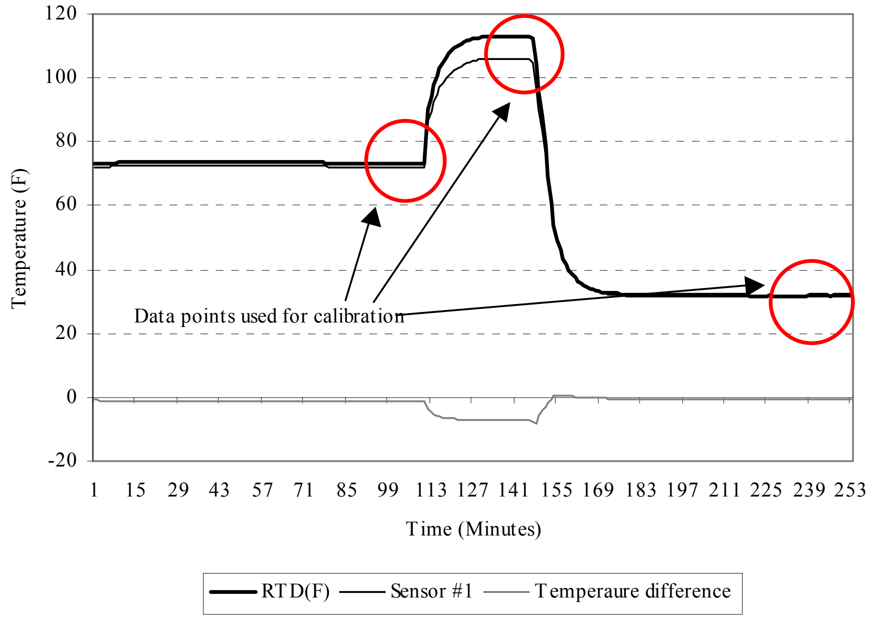


Figure A.5   Time series and residual plot of the RTD sensor and sensor #1 before calibration

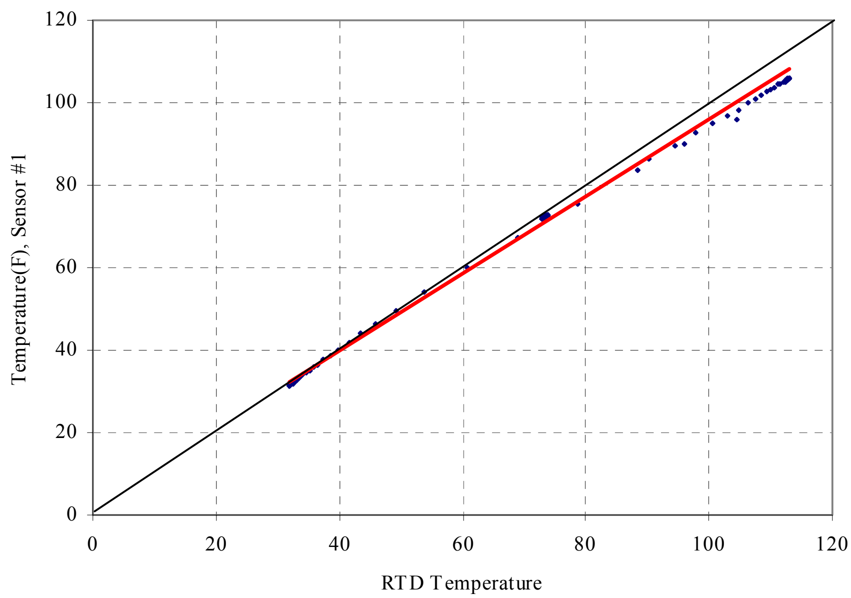


Figure A.6   Comparison of sensor #1 against the RTD sensor before calibration

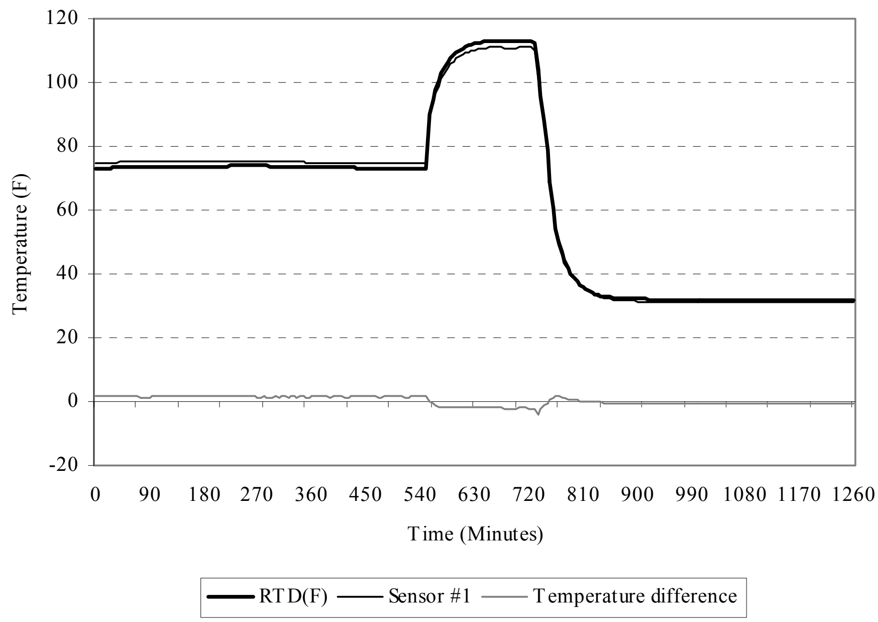


Figure A.7   Time series and residual plot of the RTD sensor and sensor #1 after calibration

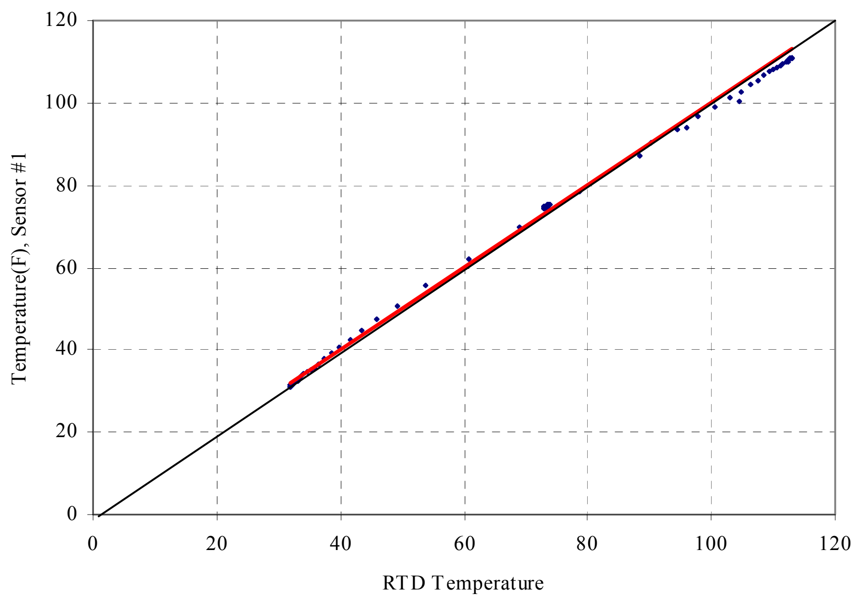


Figure A.8   Comparison of sensor #1 against RTD temperature after calibration

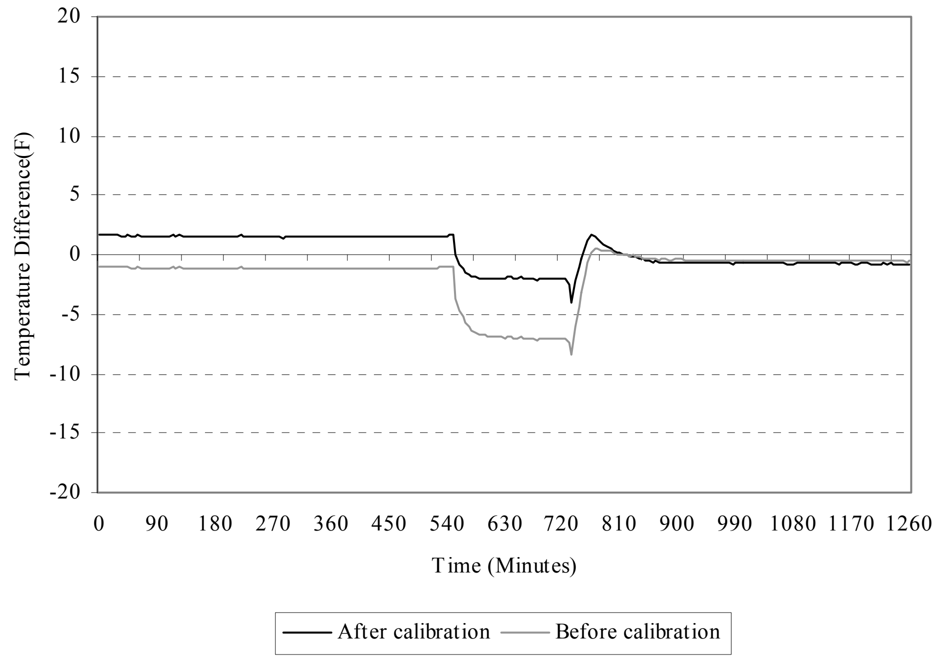


Figure A.9 Residual plot of before and after calibration

A.1.2. Sensor No.2

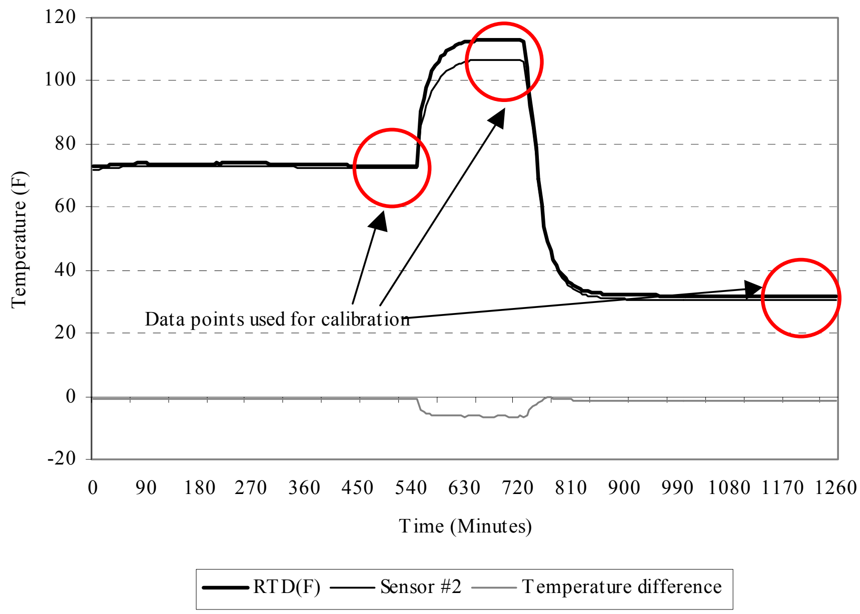


Figure A.10 Time series and residual plot of the RTD sensor and sensor #2 before calibration

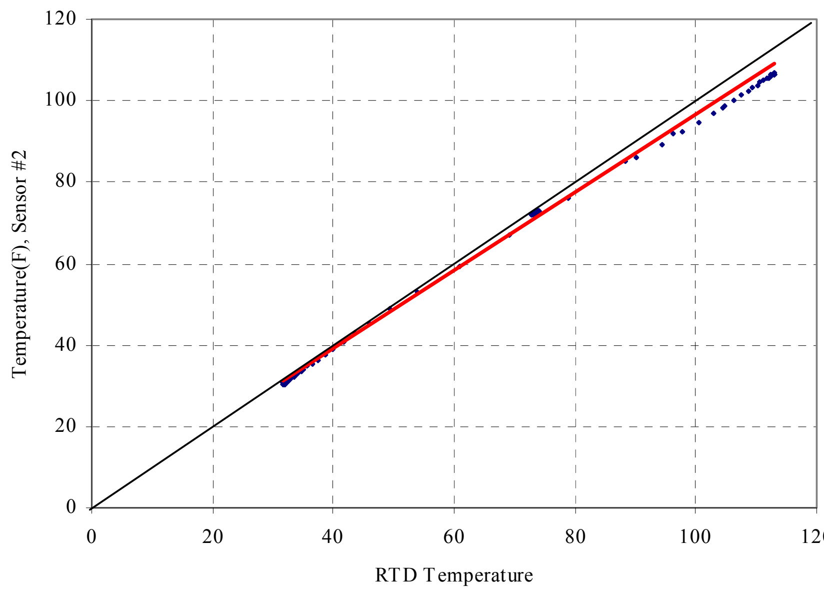


Figure A.11 Comparison of sensor #2 against RTD temperature before calibration

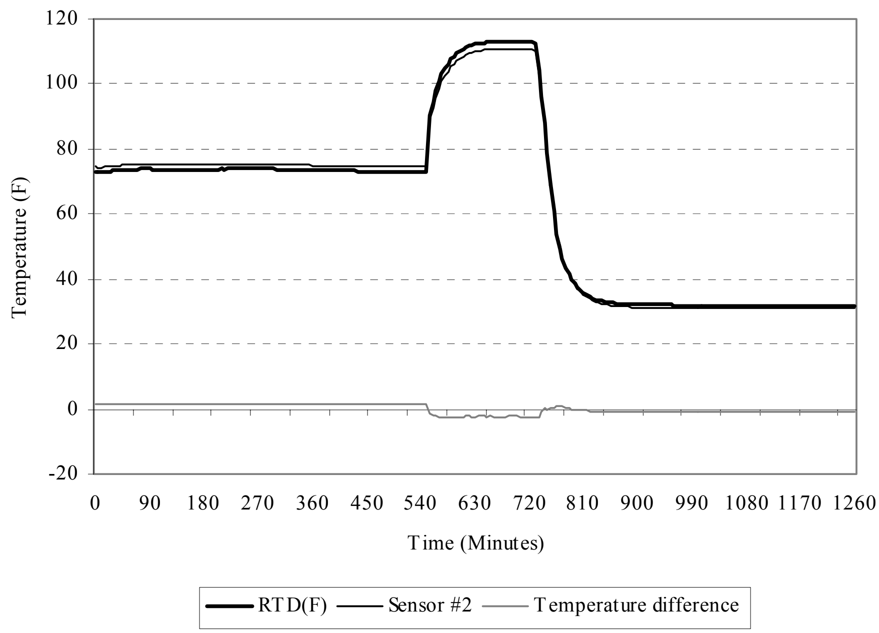


Figure A.12 Time series and residual plot of the RTD sensor and sensor #2 after calibration

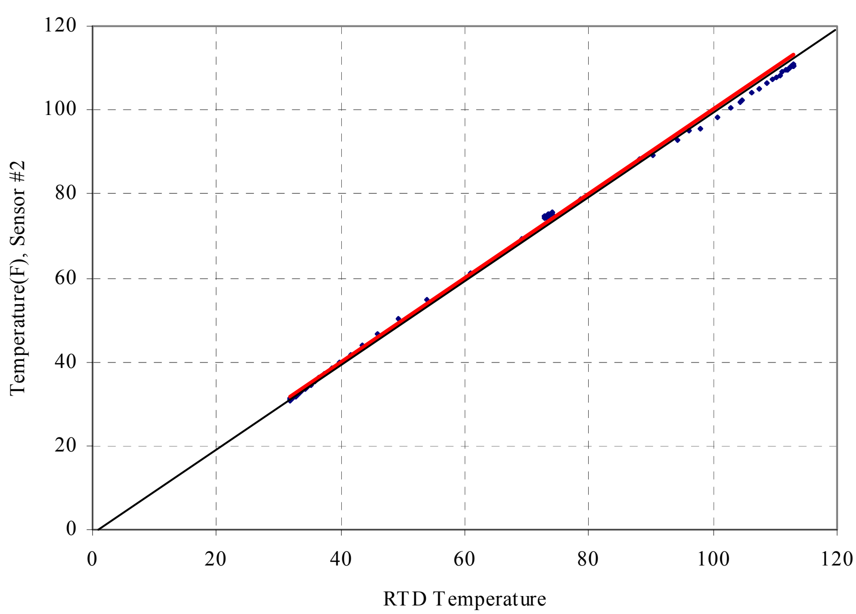


Figure A.13 Comparison of sensor #2 against RTD temperature after calibration

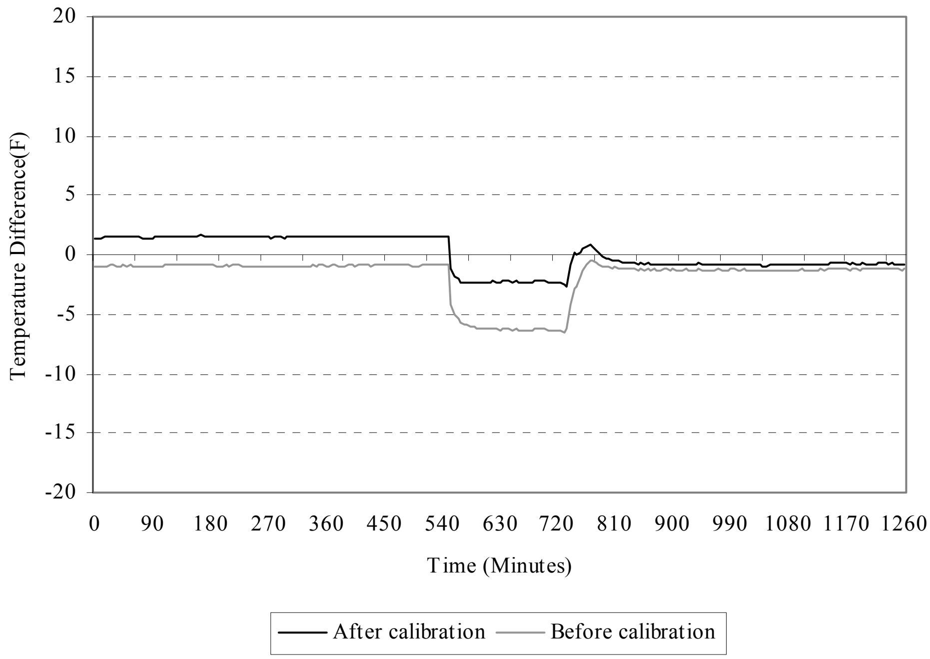


Figure A.14 Residual plot of before and after calibration

A.1.3. Sensor No.3.

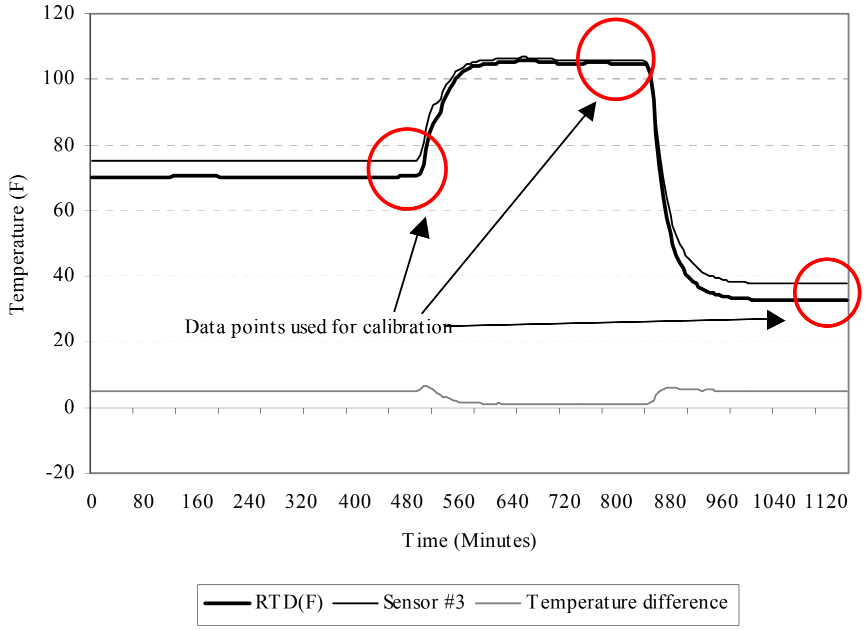


Figure A.15 Time series and residual plot of the RTD sensor and sensor #3 before calibration

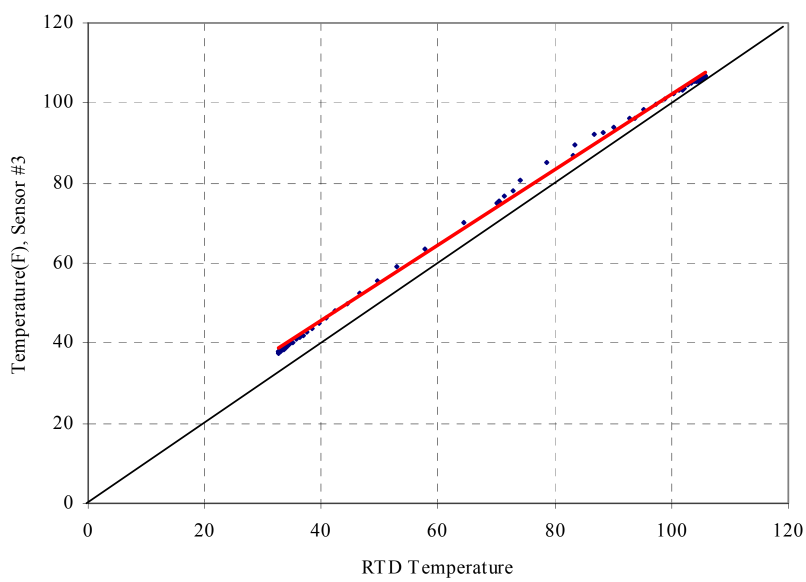


Figure A.16 Comparison of sensor #3 against RTD temperature before calibration

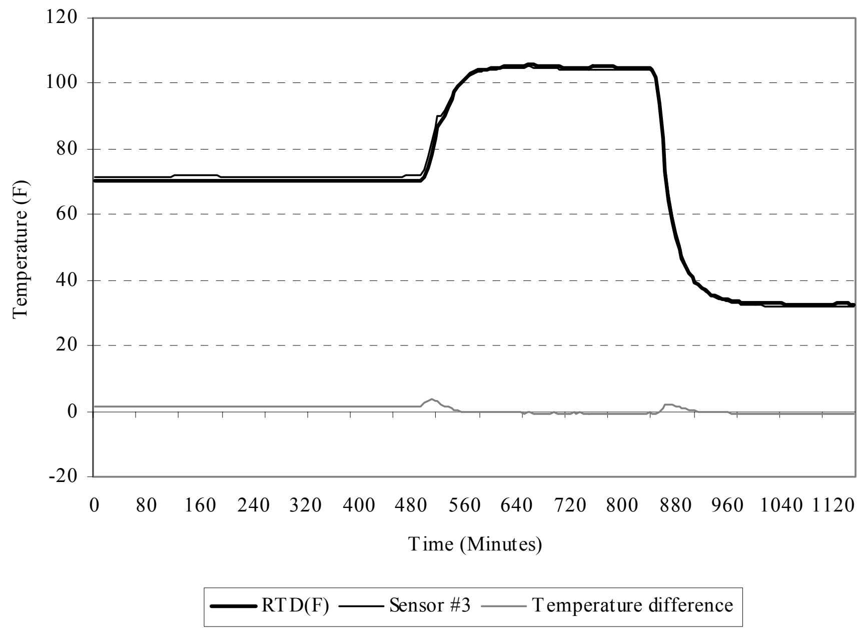


Figure A.17 Time series and residual plot of the RTD sensor and sensor #3 after calibration

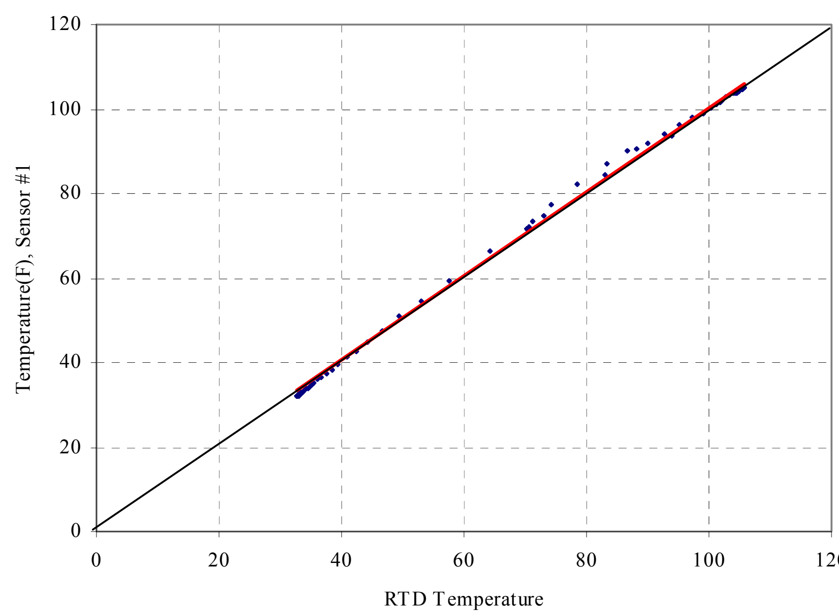


Figure A.18 Comparison of sensor #3 against RTD temperature after calibration

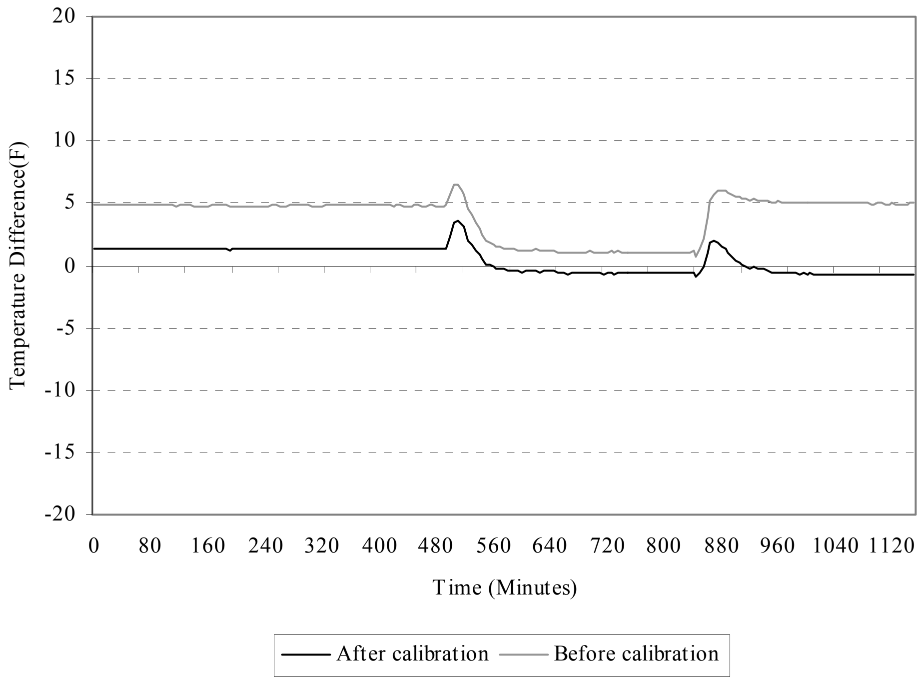


Figure A.19 Residual plot of before and after calibration

A.1.4. Sensor #4

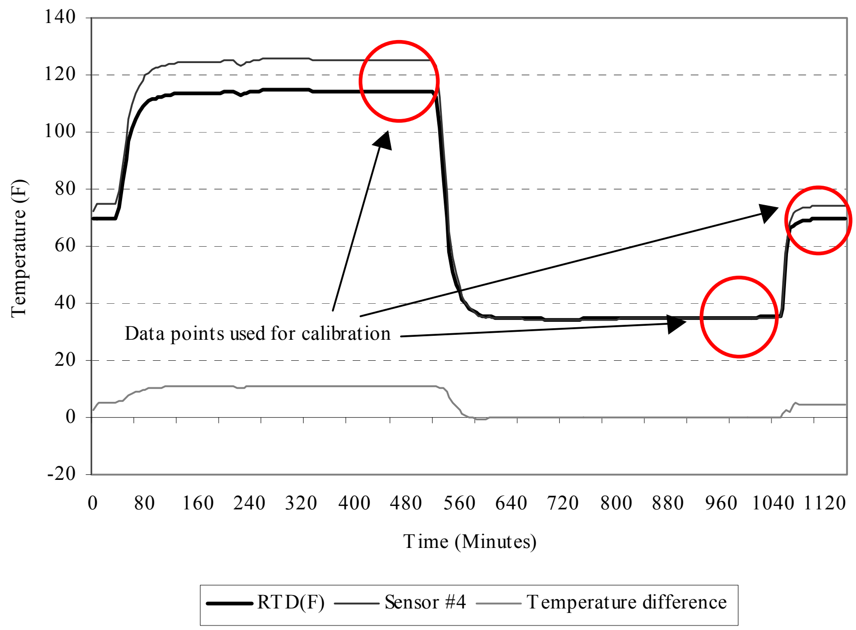


Figure A.20 Time series and residual plot of the RTD sensor and sensor #4 before calibration

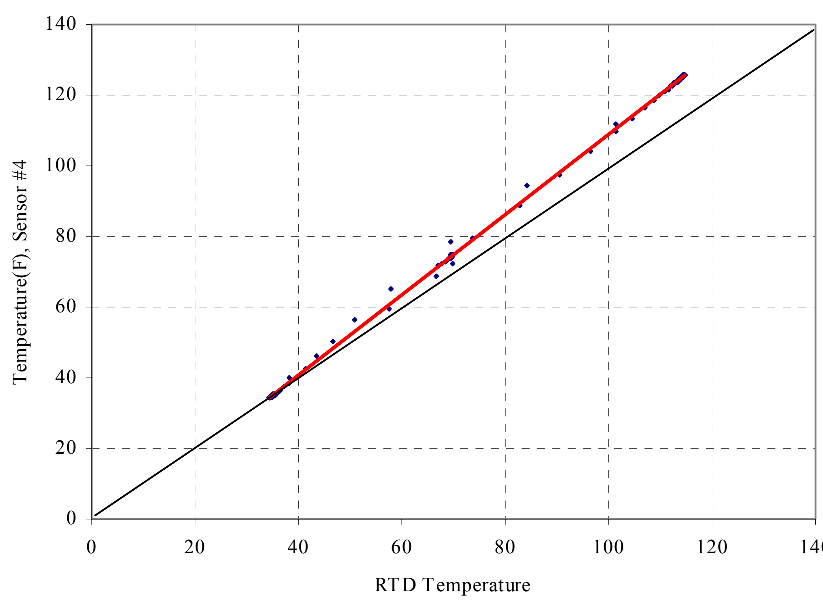


Figure A.21 Comparison of sensor #4 against RTD temperature before calibration

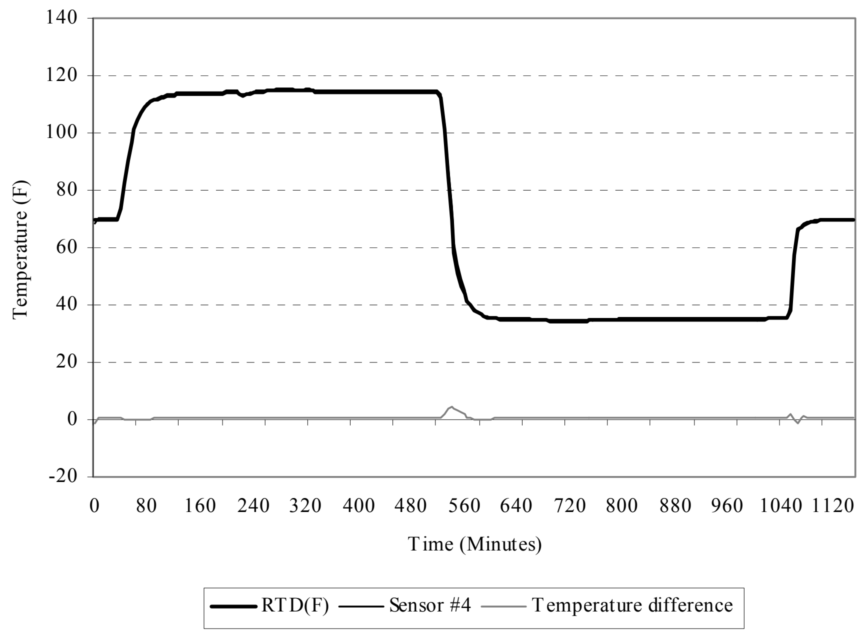


Figure A.22 Time series and residual plot of the RTD sensor and sensor #4 after calibration

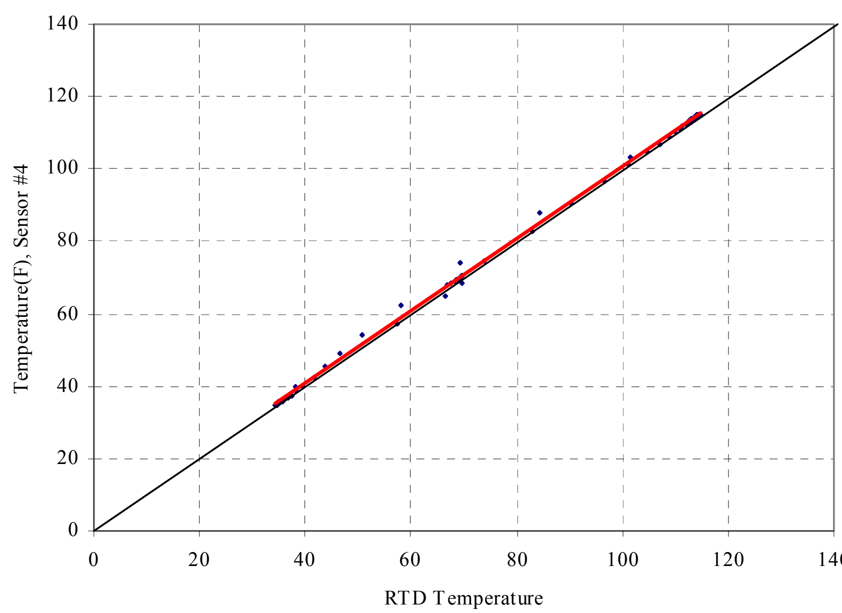


Figure A.23 Comparison of sensor #4 against RTD temperature after calibration

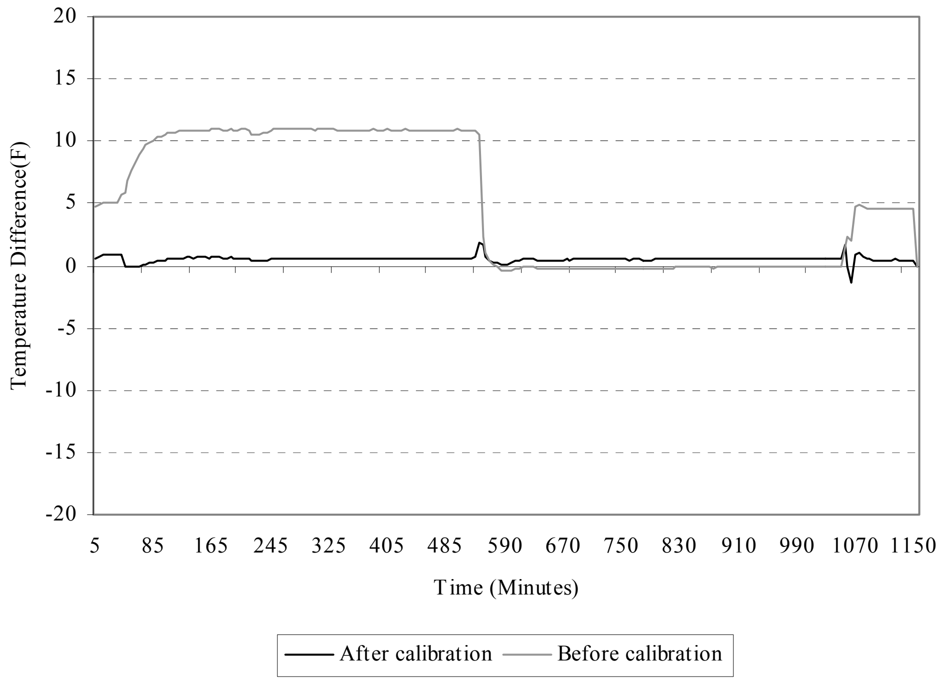


Figure A.24 Residual plot of before and after calibration

A.1.5. Sensor #5

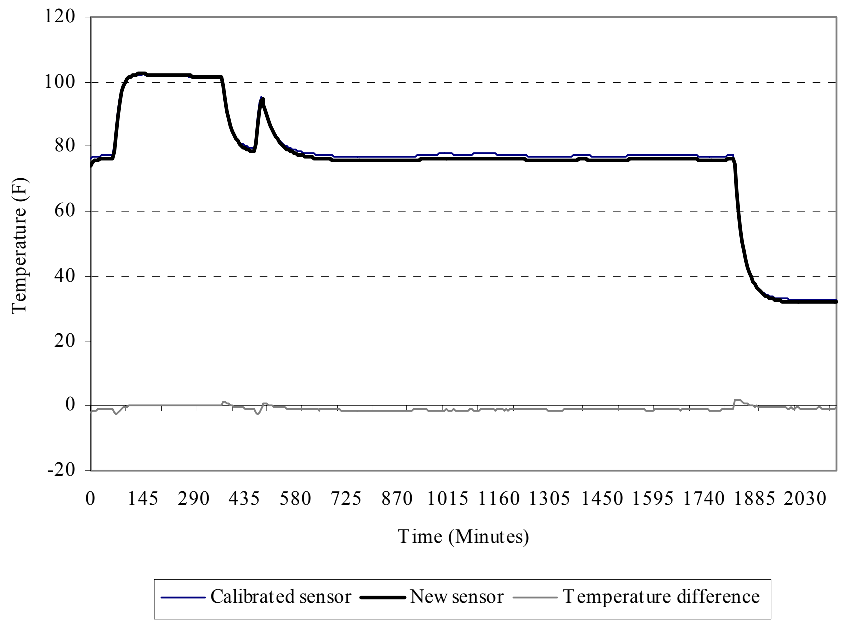


Figure A.25 Time series plot of new sensor #5 and calibrated sensor#1

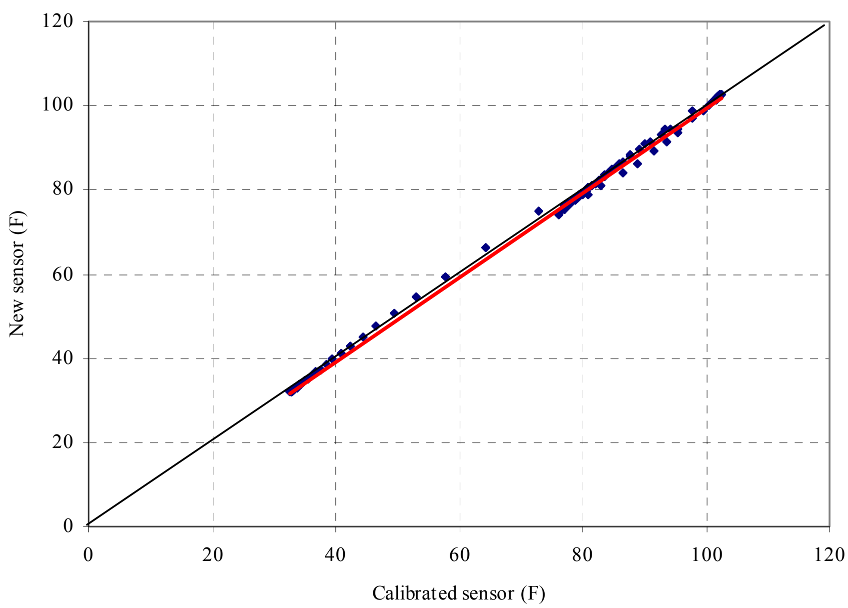


Figure A.26 Comparison of new sensor #5 against calibrated sensor #1

A.2. Statistical Evaluation of the Calibration Results.

After the calibration process, the Mean Bias Error (MBE) and the coefficient of variation of the root Mean Square Error (CV (RMSE)) were calculated. The Mean Bias Error, MBE (%) (Kreider and Haberl 1994a, b; Haberl and Thamilseran, 1996) determines the non-dimensional bias measure (the sum of errors) between the simulated data and the measured data. For the sensor calibration procedure, the simulated data were data from Vaisala sensors and measured data were from reference sensor.

$$MBE = \left[\left(\sum y_{pred,i} - \sum y_{data,i}\right)/(n-p)\right]/\,\bar{y}_{data} \times 100$$

The coefficient of variation of the root mean squared error, CV (RMSE) (%) (Draper and Smith 1981) is essentially the root mean squared error divided by the measured mean of all the data, a convenient way of reporting a non-dimensional result. CV(RMSE) allows one to determine how well a model fits the data; the lower the CV(RMSE), the better the calibration.

$$CV(RMSE)(\%) = \left[\left(\sum y_{pred,i} - \sum y_{data,i}\right)^2 /(n-p)\right]^{1/2} /\,\bar{y}_{data} \times 100$$

Where

$y_{pred,i}$ is a predicted dependent variable value for the same set of independent varialbles.

$y_{data,i}$ is a data value of the dependent variable corresponding to a particular set of the independent varialbles.

y_{data} is the mean value of the dependent variable of the data set

n is the number of data points in the data set

p is the total number of regression parameters in the model (arbitually assigned as 1 for all models)

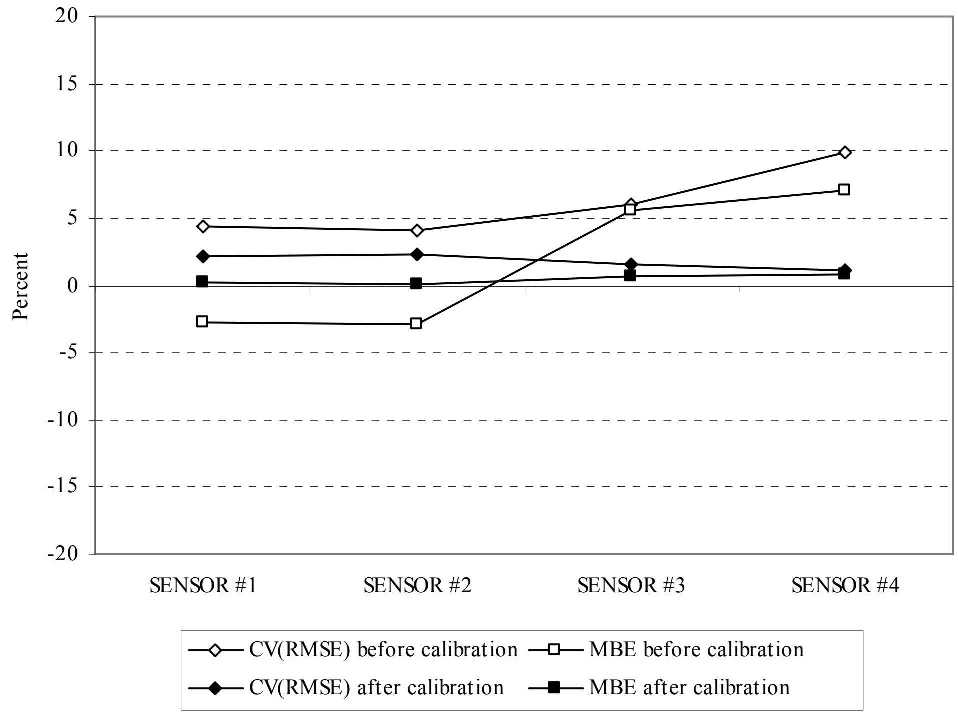


Figure A.27 CV(RMSE) and MBE plot before and after calibration.

Table A.1 Scale and Offset parameters for temperature

Sensor No.	Before Calibration		After Calibration	
	Scale	Offset	Scale	Offset
1	56.39	-48.98	60.37	-54.88
2	56.39	-48.98	59.03	-52.26
3	56.39	-48.98	59.74	-59.84
4	56.39	-48.98	56.79	-51.59
5			56.39	-48.98

A.3. Calibration of Relative Humidity Sensors

The sensor for measuring the relative humidity on case study house has a range from 0% to 100%, and ± 2% accuracy (Vaisala 2003). The methodology for calibrating the relative humidity sensor was followed by ASTM E 104–85 (2001), Standard practice for maintaining constant relative humidity by means of aqueous solutions. This standard states that saturated salt solutions were used to generate a known humidity in the sealed flask. According to ASTM E 104–85 (2001), Lithium Chloride generates low humidity (11.3% ± 0.3), Magnesium Chloride generates medium humidity (33.1% ± 0.2) and Sodium Chloride generates high humidity (75.5% ± 0.1), and Greenspan (1977) collected data on salt solutions from various studies and provide the equations of the experimentally determined relative humilities for the different salts at various temperature conditions. He also provided the following equation according to the temperature for these three saturated salt solutions.

Table A.2 Summary of Least Square Fits to RH= $\sum_{i=0}^{3} A_i t^i$ ***for selected saturated salt* solutions (t is in °C)**

Salt	A_0	A_1	A_2	A_3
Lithium Chloride	11.2323	-0.00824245	$-0.214890 * 10^{-3}$	
Magnesium Chloride	33.6686	-0.00797397	$-0.108988 * 10^{-2}$	
Sodium Chloride	75.5164	0.0398321	$-0.265459 * 10^{-2}$	$0.284800 * 10^{-4}$

The experiment was performed by using these three types of aqueous salt solutions. In order to generate constant relative humidity, each saturated salt solution in the container was put in the container, and then Vaisala HMD 60Y sensors and RTD thermometer were located above the salt solution in the container (Figure A.3). As I mentioned earlier, for each solution, the procedures for calibration of temperature and relative humidity such as three different temperatures were performed at the same time.

There are 4 sensors that are going to measure the relative humidity; 1) return, 2) supply, 3) attic, and 4) outside air on case study house. The following graphs (from Figures A.19 to A.30) provide the time seriese plot of relative humidity according to ambient temeprature, time seriese plot of each solution, and calibration procedures. Table A.3 lists the scale and offset parameters for 5 sensors for the relative humidity before and after calibration.

A.3.1. Sensor No.1

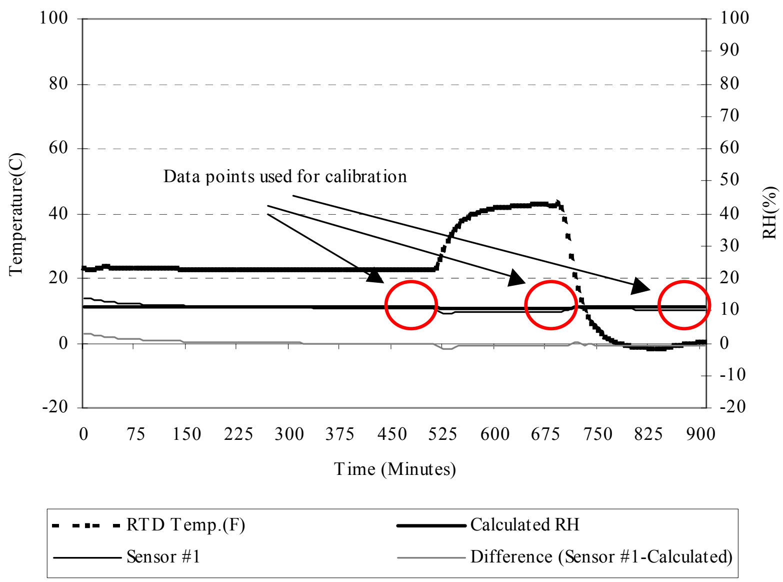


Figure A.28 Time series and residual plot of sensor #1 and calculated RH for Lithium Chloride before calibration

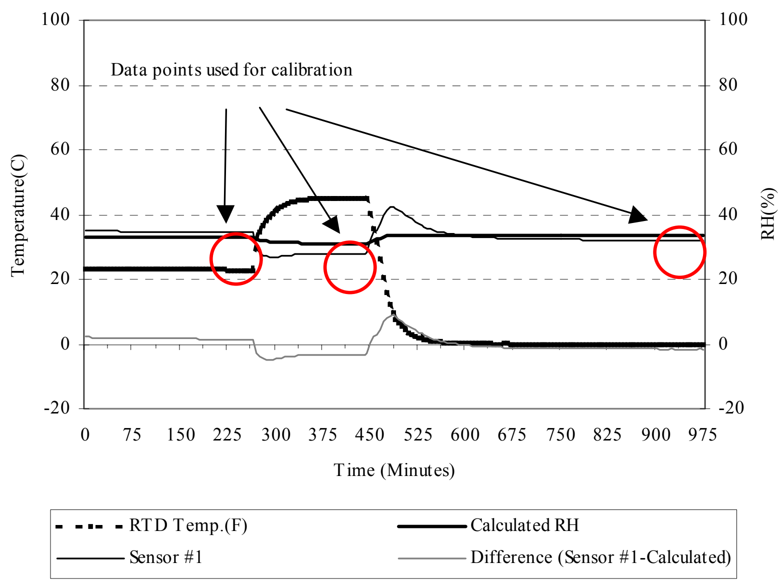


Figure A.29 Time series and residual plot of sensor #1 and calculated RH for Magnesium Chloride before calibration

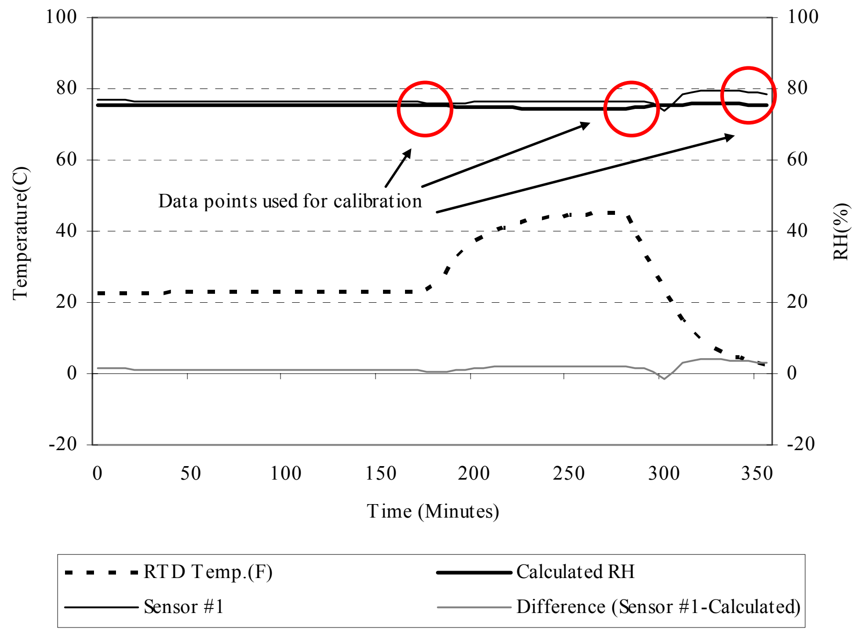


Figure A.30   Time series and residual plot of sensor #1 and calculated RH for Sodium Chloride before calibration

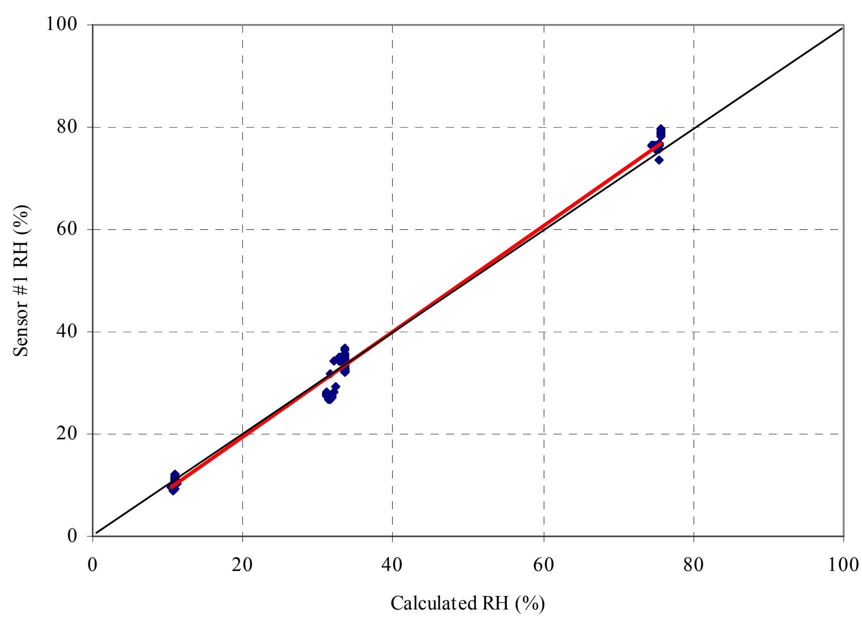


Figure A.31   Comparison of sensor #1 against calculated RH before calibration

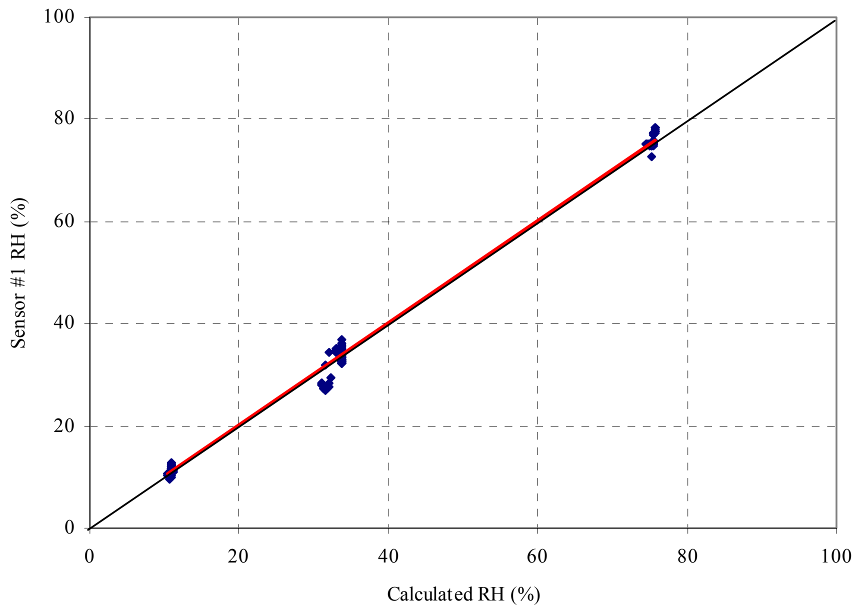


Figure A.32 Comparison of sensor #1 against calculated RH after calibration

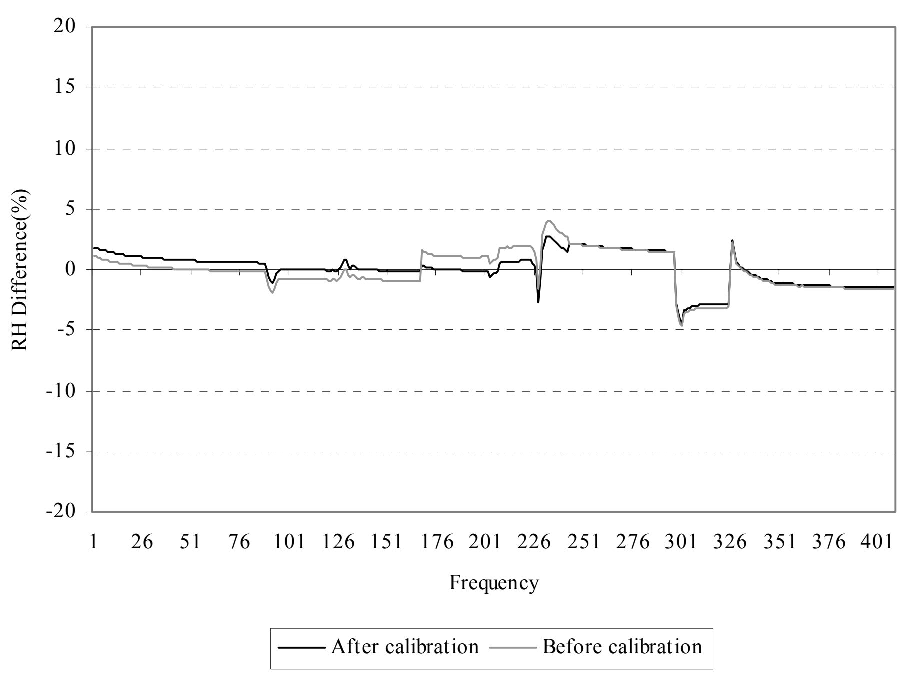


Figure A.33 Residual plot before and after calibration

A.3.2. Sensor No.2

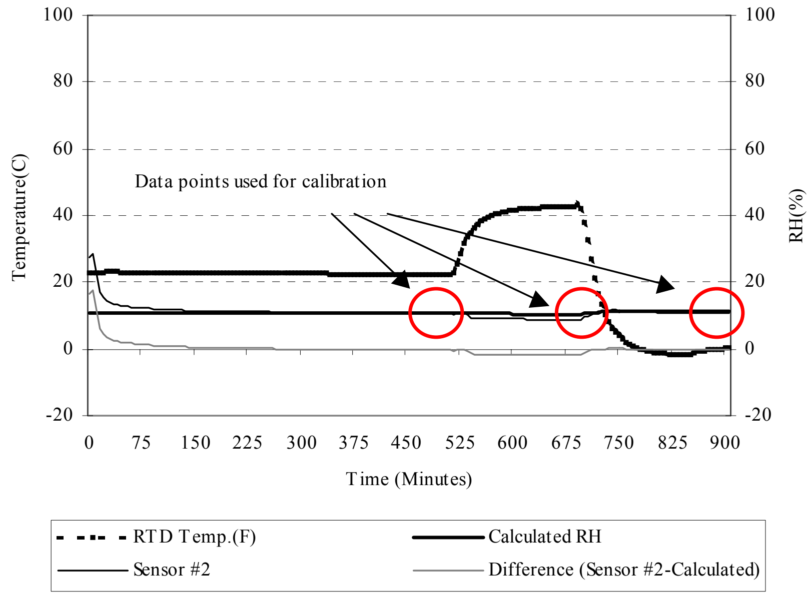


Figure A.34 Time series and residual plot of sensor #2 and calculated RH for Lithium Chloride before calibration

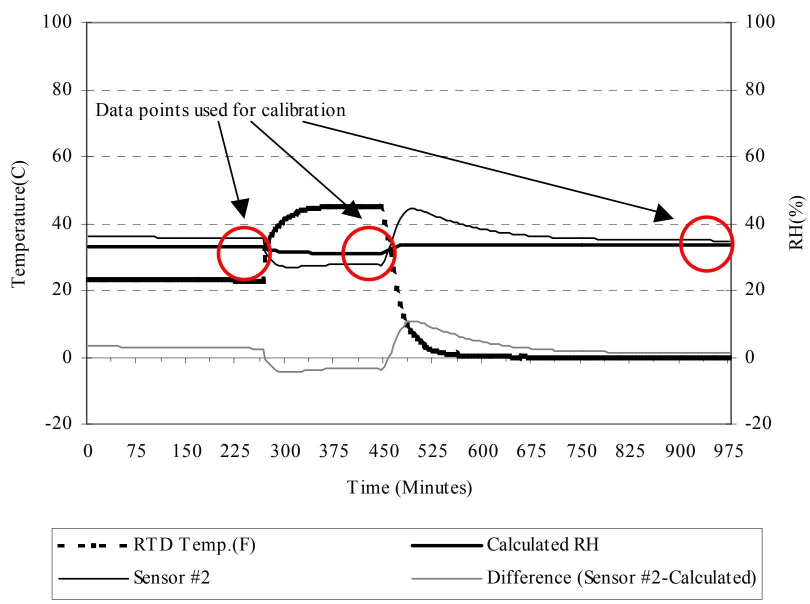


Figure A.35 Time series and residual plot of sensor #2 and calculated RH for Magnesium Chloride before calibration

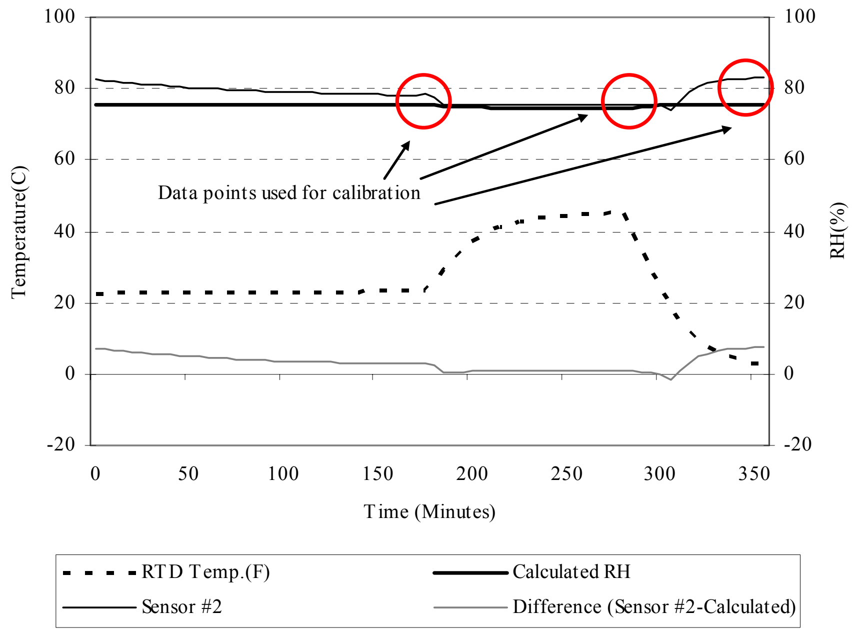


Figure A.36 Time series and residual plot of sensor #2 and calculated RH for Sodium Chloride before calibration

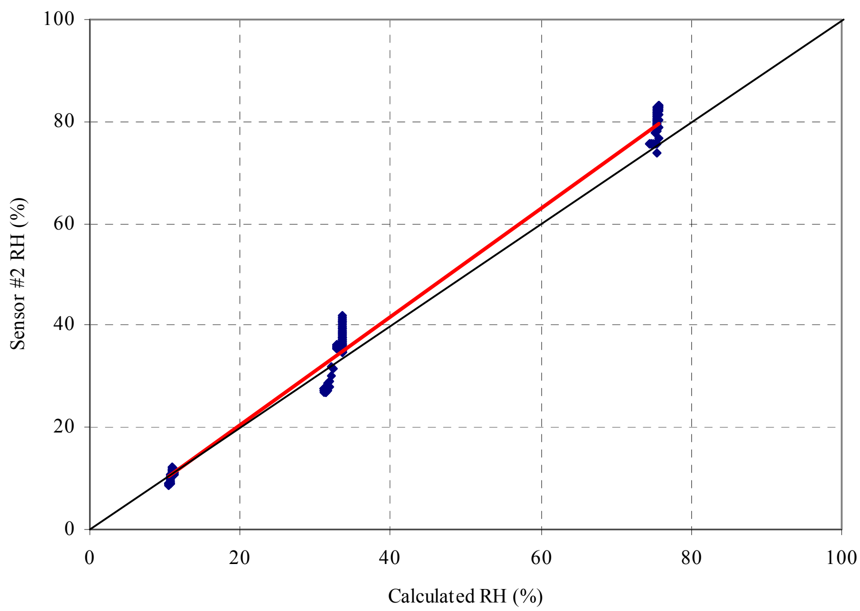


Figure A.37 Comparison of sensor #2 against calculated RH before calibration

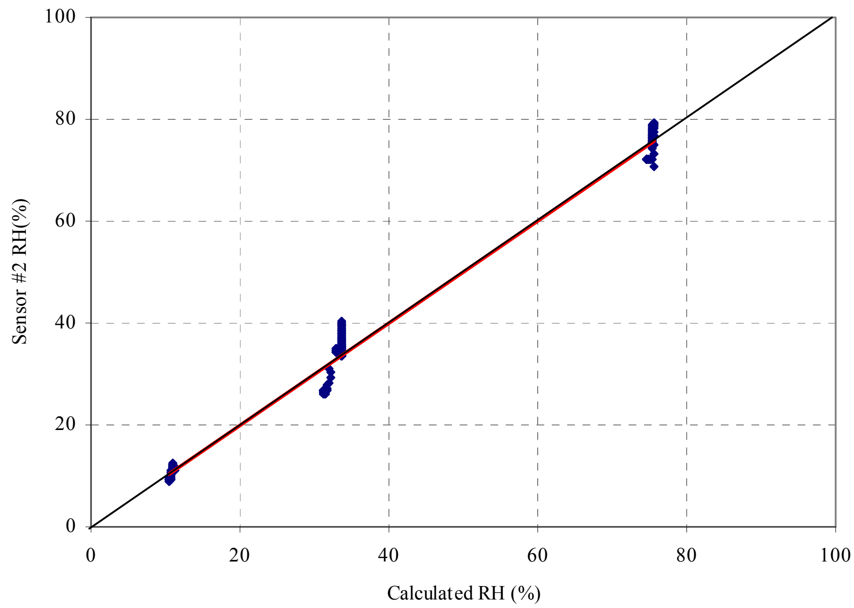


Figure A.38   Comparison of sensor #2 against calculated RH after calibration

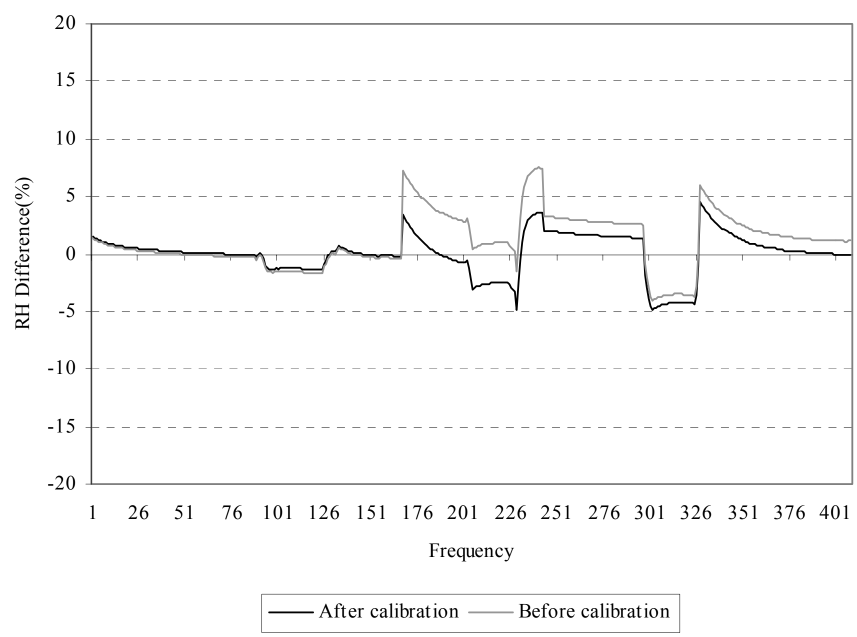


Figure A.39   Residual plot before and after calibration

A.3.3. Sensor No.3

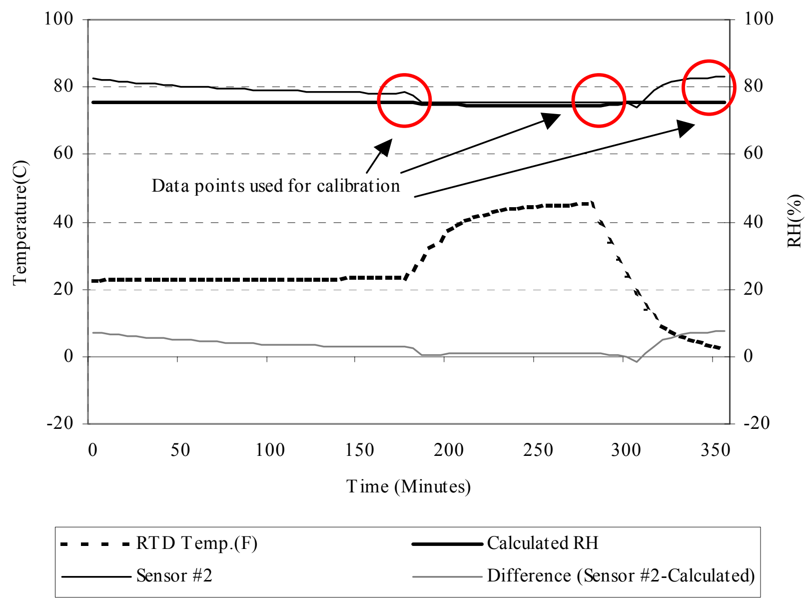


Figure A.40 Time series and residual plot of sensor #3 and calculated RH for Lithium Chloride before calibration

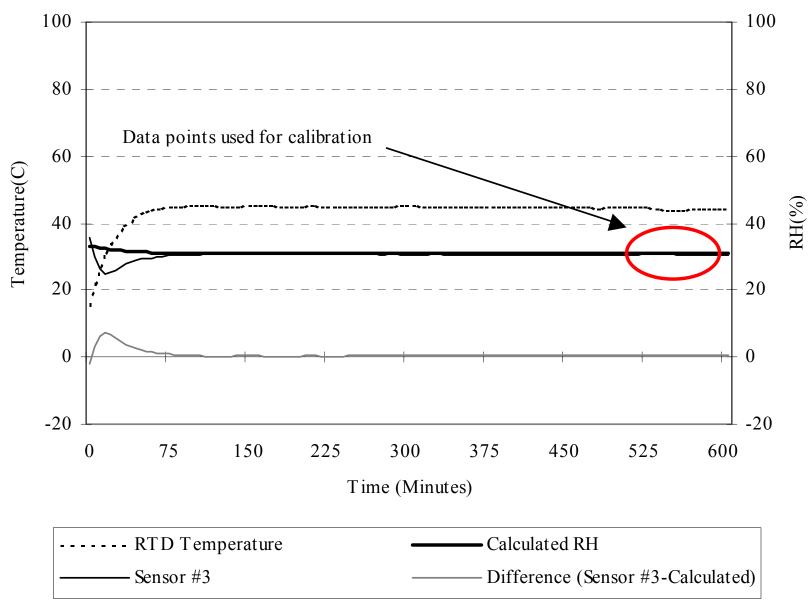


Figure A.41 Time series and residual plot of sensor #3 and calculated RH for Magnesium Chloride before calibration

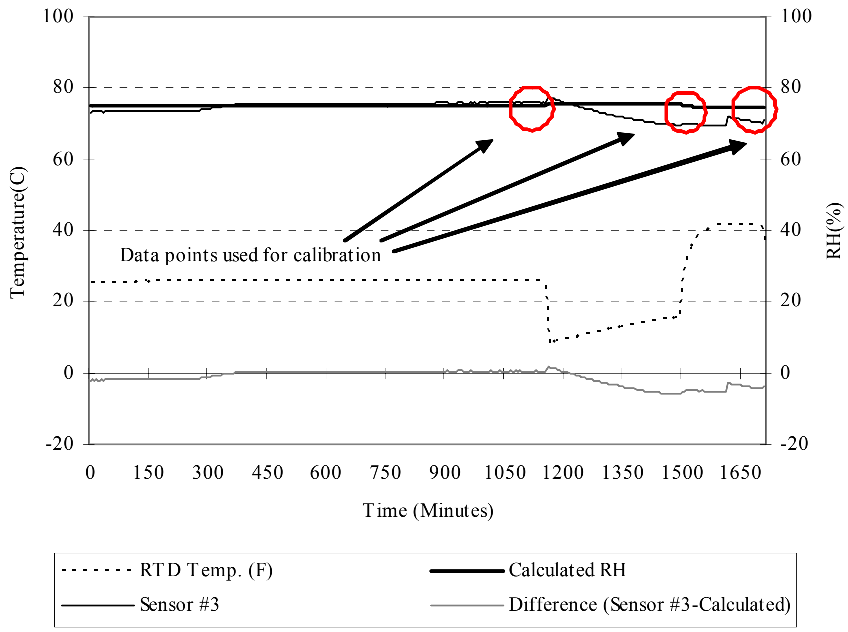


Figure A.42 Time series and residual plot of sensor #3 and calculated RH for Sodium Chloride before calibration

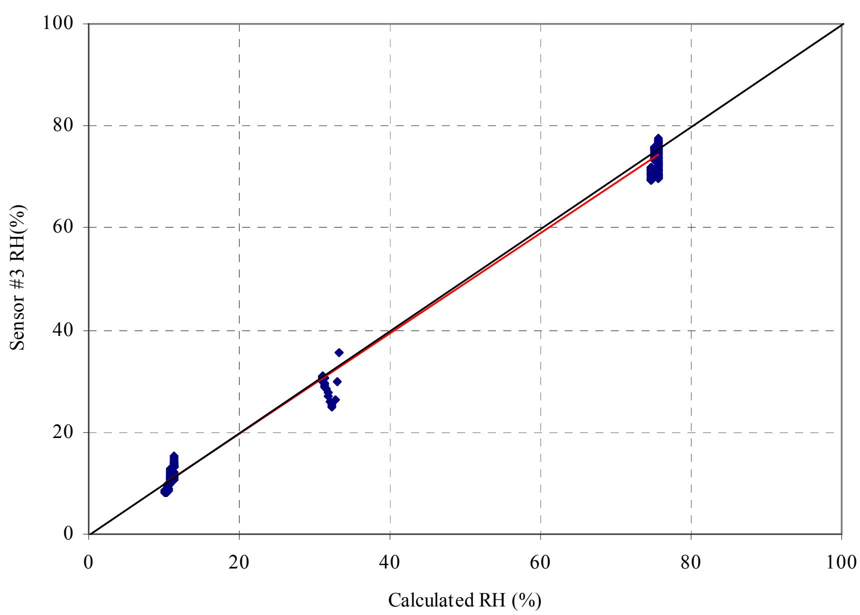


Figure A.43 Comparison of sensor #3 against calculated RH before calibration

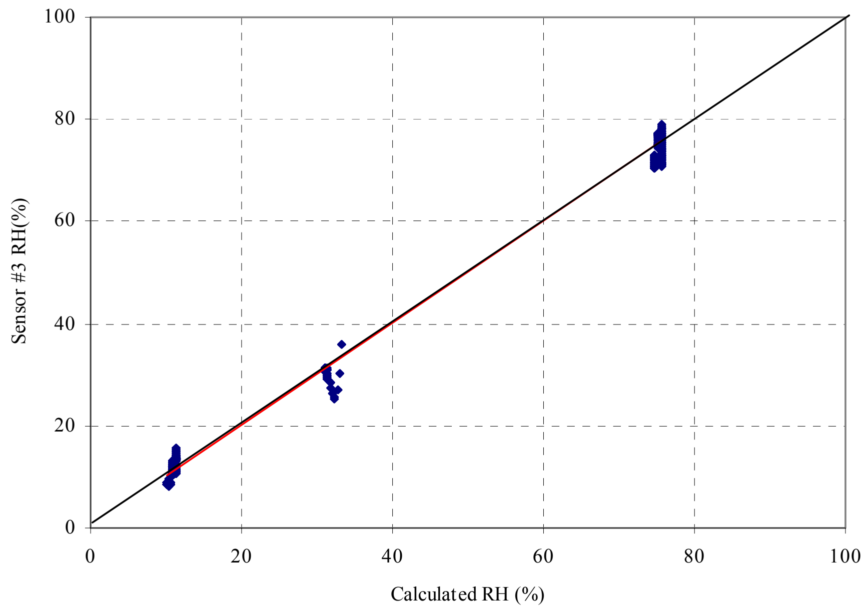


Figure A.44   Comparison of sensor #3 against calculated RH after calibration

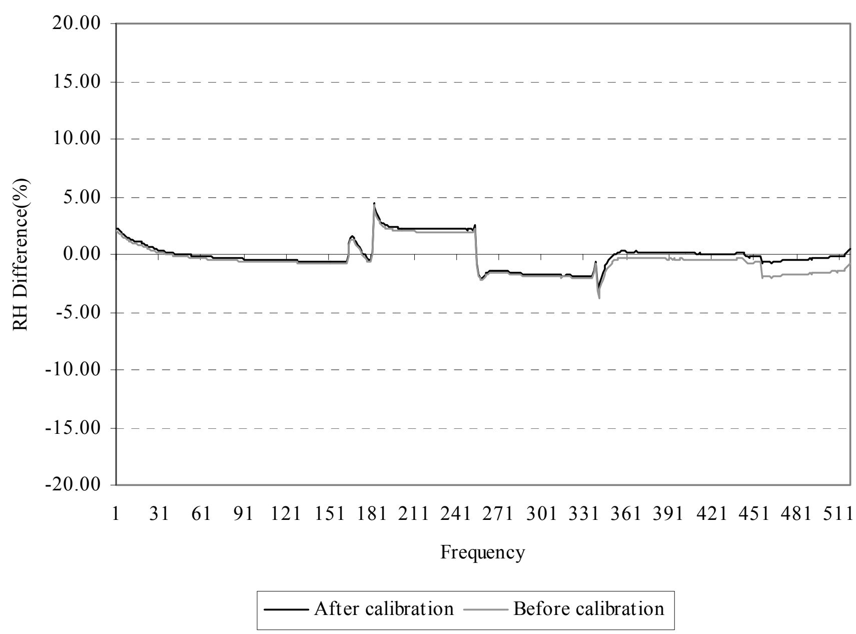


Figure A.45 Residual plot before and after calibration

A.3.4. Sensor No.5

Since sensor #5 is a new sensor, it was calibrated against a previously calibrated sensor (#1). The data matched well each other (R^2 is 0.9959). Therefore, there was no calibration procedure for sensor #5.

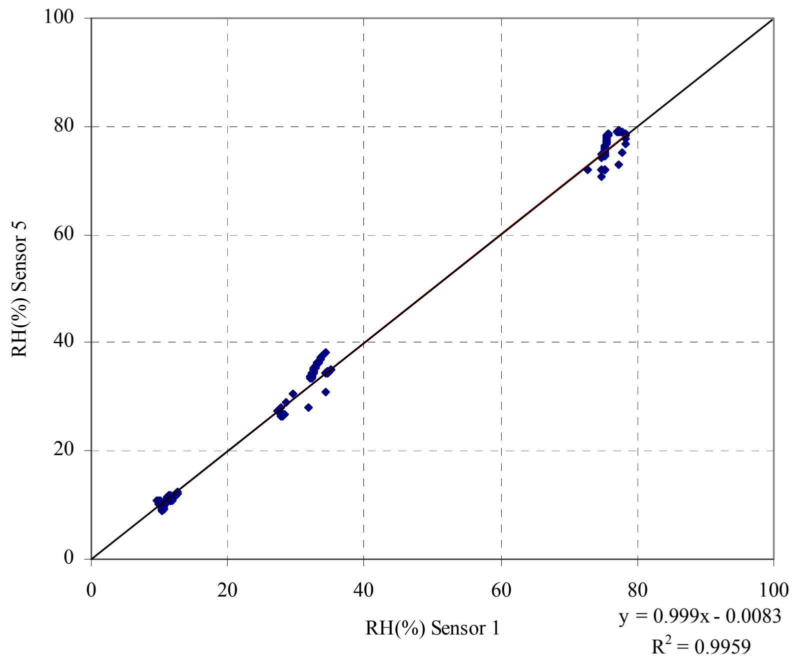


Figure A.46 Comparison plot of sensor #5 vs. sensor #1

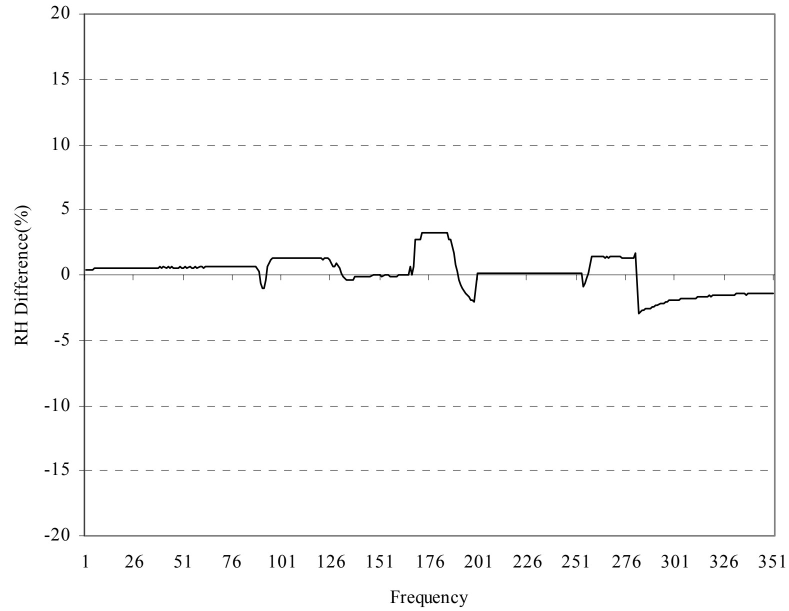


Figure A.47 Difference plot of sensor #5 and sensor #1

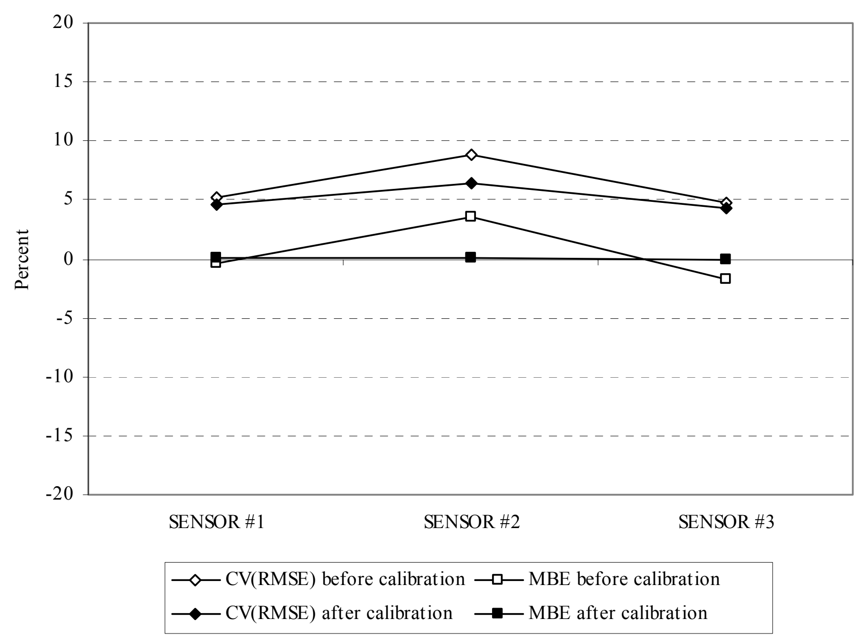


Figure A.48 CV(RMSE) and MBE plot before and after calibration

Table A.3 Scale and Offset parameters for relative humidity

Sensor No.	Before Calibration		After Calibration	
	Scale	Offset	Scale	Offset
1	31.25	-25.00	30.34	-23.21
2	31.25	-25.00	29.47	-22.77
3	31.25	-25.00	31.30	-27.19
4	N/A (Sensor 4 measures only temperature)			
5	31.25	-25.00	31.25	-25.00

A.4. Portable Data Loggers

In order to measure the underside roof surface temperature in the attic space, three Onset portable data loggers are used with type J thermocouple sensor. These data loggers have a range from 32°F to 482°F, and accuracy of ±5.7°F at 257°F. Since data from portable data logger should match with measurement from the calibrated Vaisala sensor, the measurement test was performed between portable loggers and Vaisala sensor that will measure attic temperature. To accomplish this test, temperature was adjusted to three different temperatures (low, medium, and high temperature) using the same procedure for calibrating temperature and humidity sensors. Figure A.41 shows the time series plot according to three different temperature conditions and Figure A.42 shows each portable data logger vs. Vaisala HMD 60Y temperature and humidity sensor.

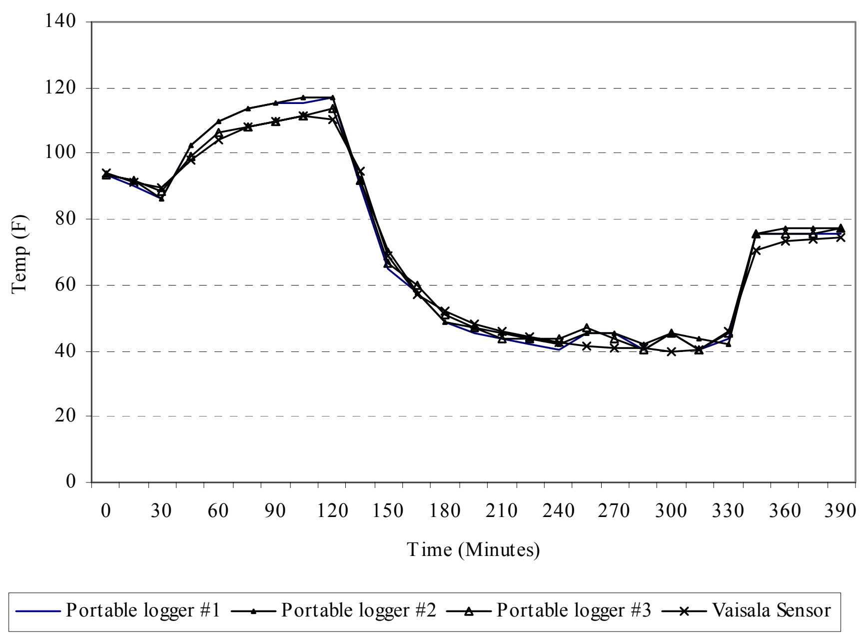


Figure A.49 Temperature plots of the three Onset portable data loggers versus the Vaisala sensor

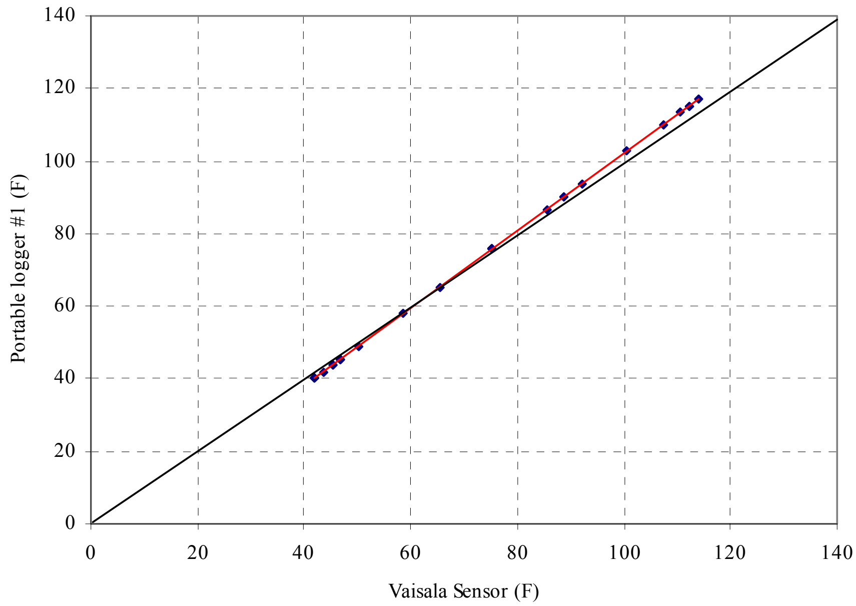


Figure A.50   Comparison of portable data logger #1 and Vaisala sensor before calibration.

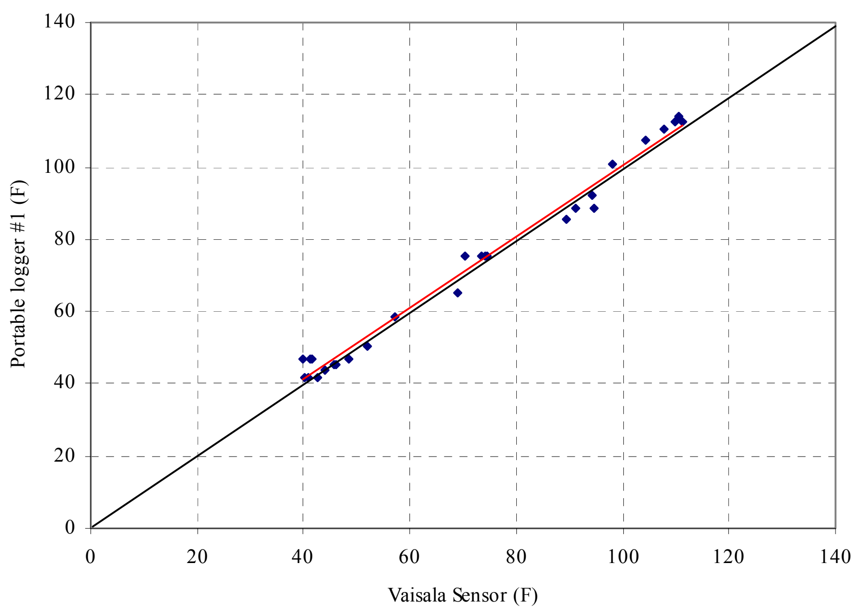


Figure A.51   Comparison of portable data logger #1 and Vaisala sensor after calibration.

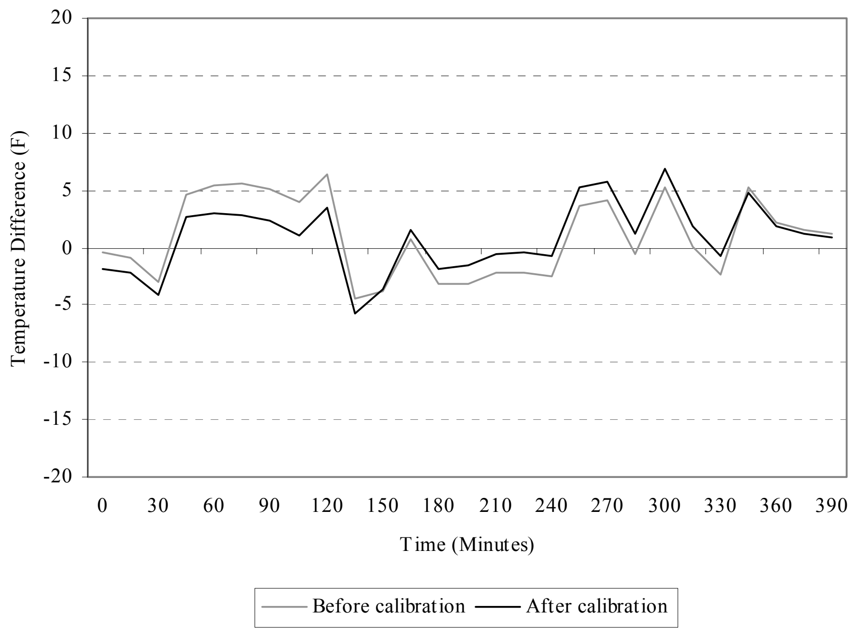


Figure A.52 Residual plot before and after calibration.

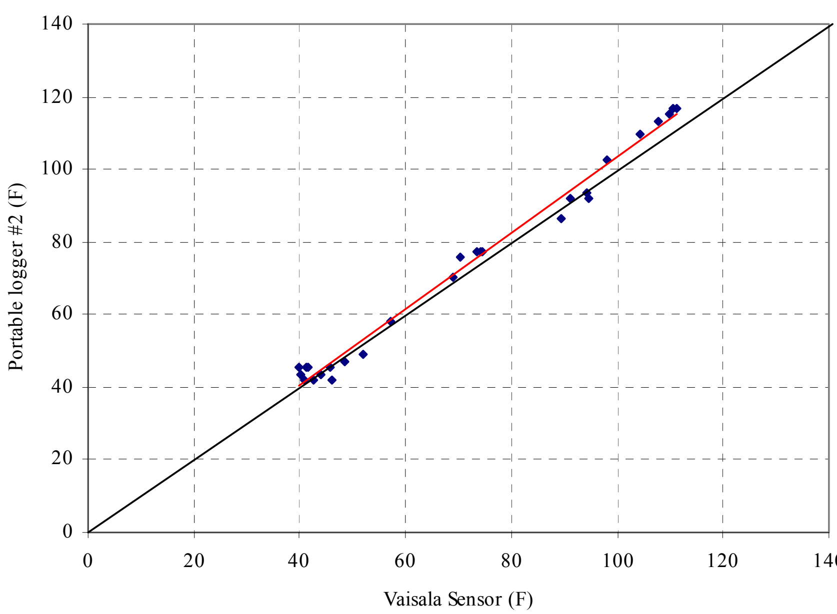


Figure A.53 Comparison of portable data logger #2 and Vaisala sensor before calibration.

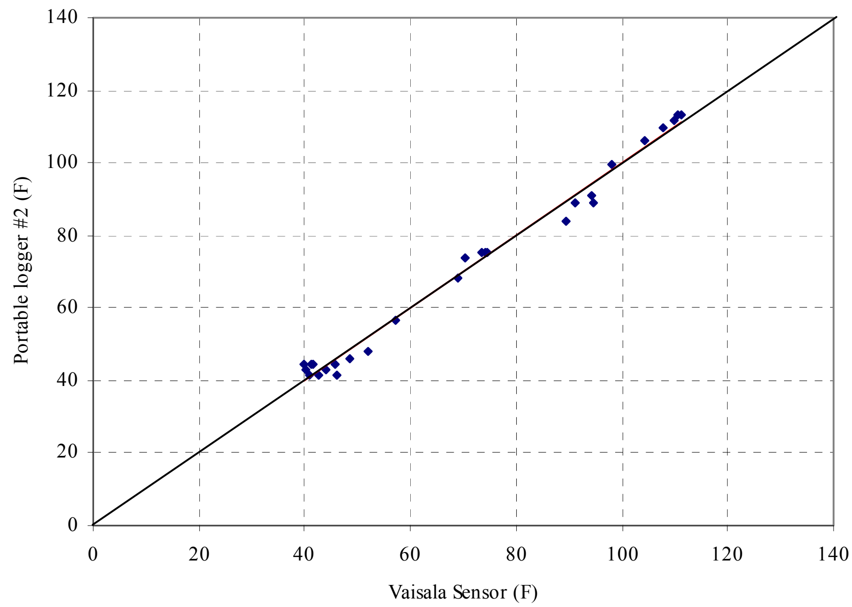


Figure A.54 Comparison of portable data logger #2 and Vaisala sensor after calibration.

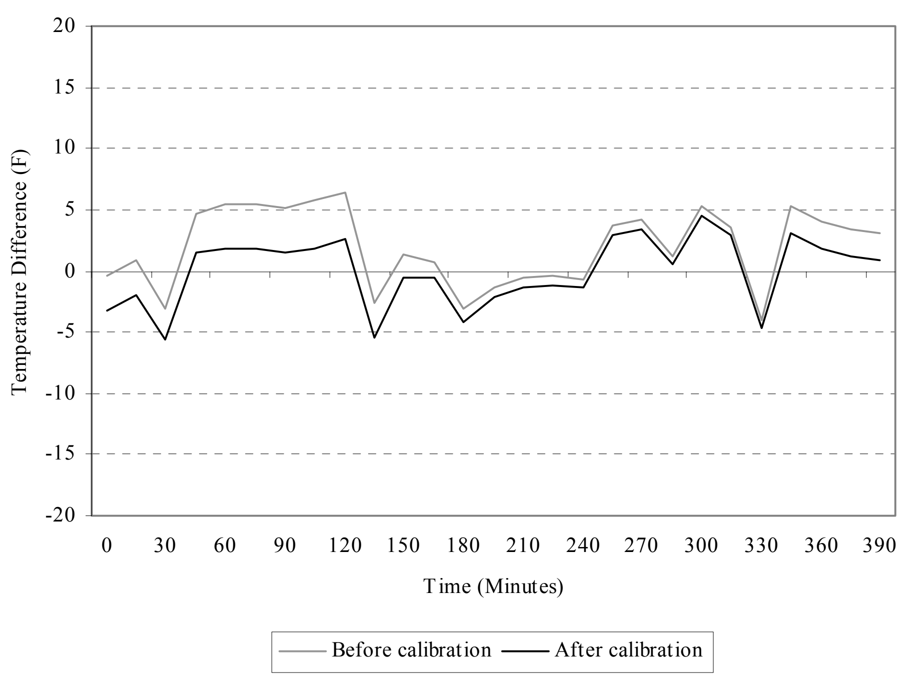


Figure A.55 Residual plot before and after calibration.

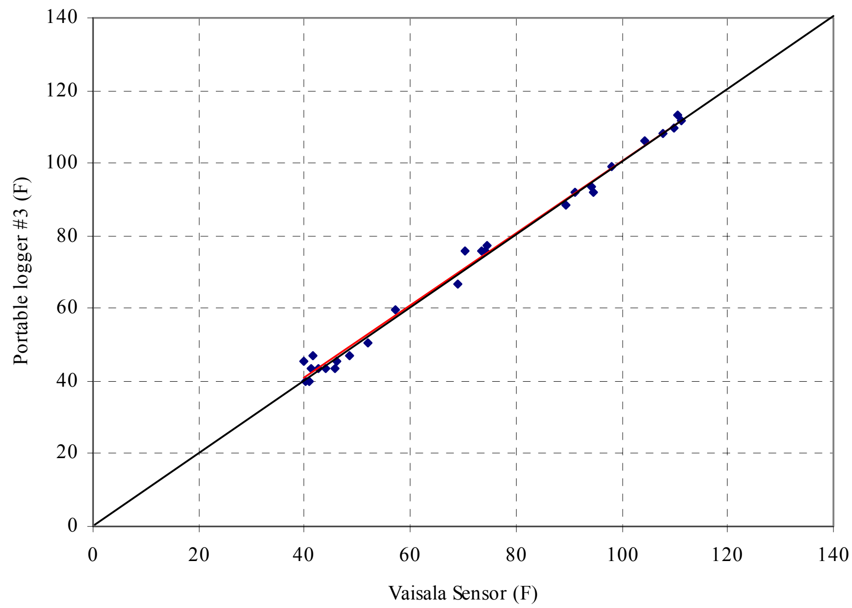


Figure A.56 Comparison of portable data logger #3 and Vaisala sensor before calibration.

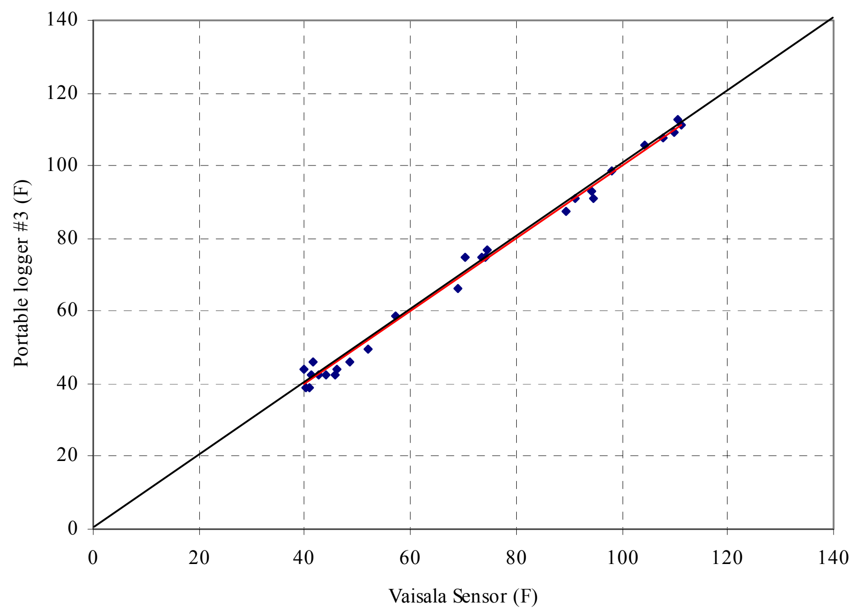


Figure A.57 Comparison of portable data logger #3 and Vaisala sensor after calibration.

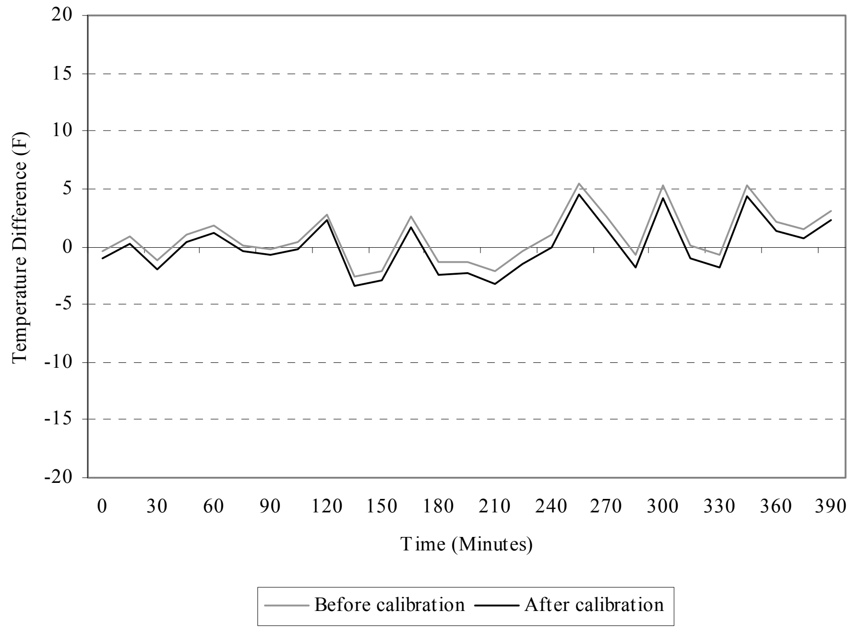


Figure A.58   Residual plot before and after calibration.

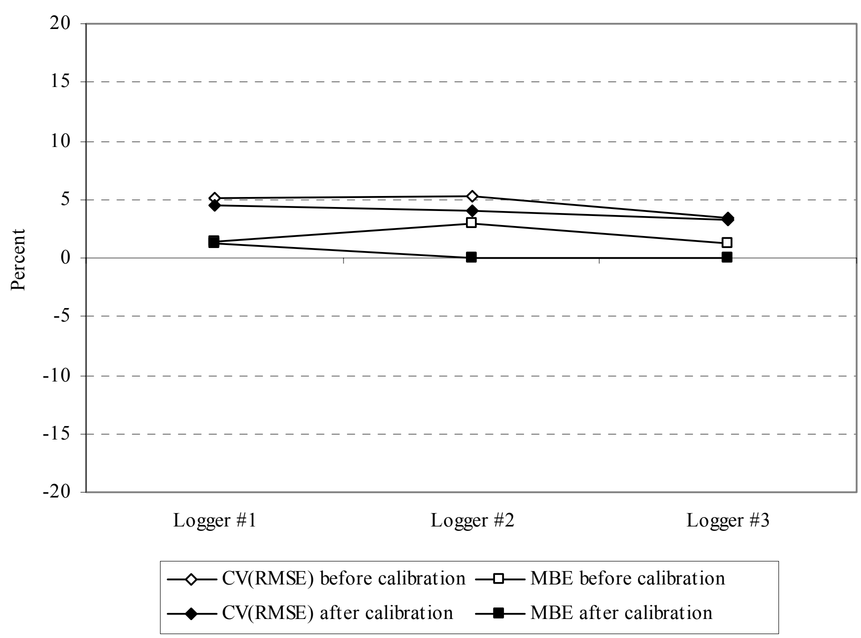


Figure A.59   CV(RMSE) and MBE plot before and after calibration.

A.5. Calibration of Solar Radiation Sensors: Pyramometer

A photovoltaic-type sensor (Li-Cor LI-200SA pyranometer solar radiation sensor) was installed to measure horizontal solar radiation (W/m^2) at the weather station on case study house. Since the installed Li-Cor sensor's output is 0-20 millivolt, a millivolt transmitter was attached to convert the signal to a 4-20 milliamps signal. This current was then transmitted to the data logger (Synergestic C-180E) and converted to a voltage signal using 200 Ohm resistor.

Klima (2000) and Rasisuttha (2004) calibrated Li-Cor sensors against an Eppley Precision Spectral Pyranometer (PSP) at solar test bench at Langford Architecture building that was reconditioned by the Eppley Laboratory and compared a NIST-traceable Epply Precision Spectral Pyranometer (PSP).

According to LI-COR, inc. (2004), the Li-Cor pyranometer has been calibrated against an Eppley Precision Spectral Pyranometer (PSP) under natural daylight conditions in units of watts per squre meter (W/m^2). Under most conditions of natural daylight, the erros is less than 5%.

For the research, an Eppley Precision Spectral Pyranometer (PSP) at solar test bench at River Side campus was used for reference sensor for calibrating Li-Cor of case study house. Several clear days were selected. Figures A.60 to A.64 show time series and x-y plot of the PSP and the Li-Cor data every 15-minute for 3 clear days before and after the calibration procedure.

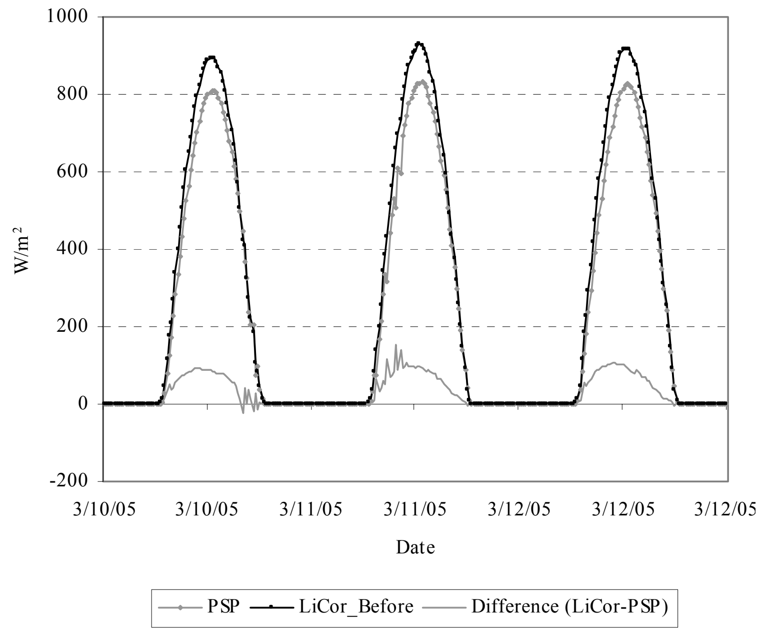


Figure A.60 PSP and Li-Cor time series plot before calibration.

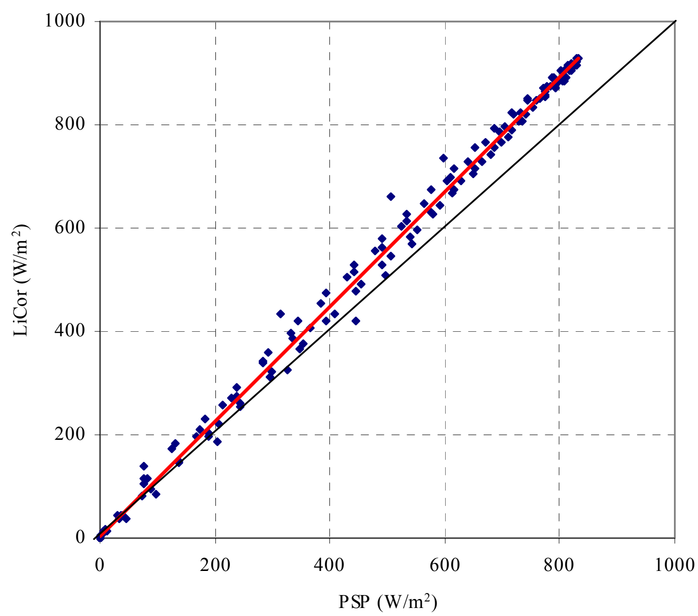


Figure A.61 PSP versus Li-Cor before calibration.

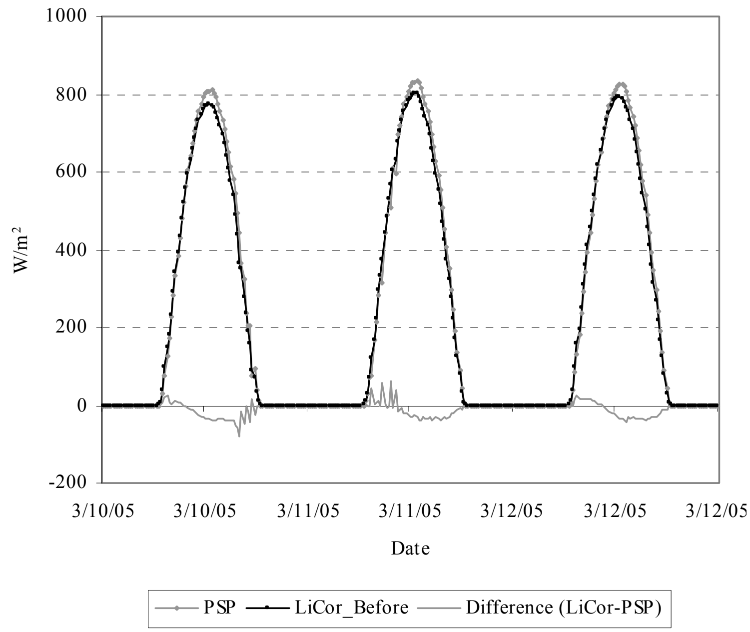


Figure A.62   PSP and Li-Cor time series plot after calibration.

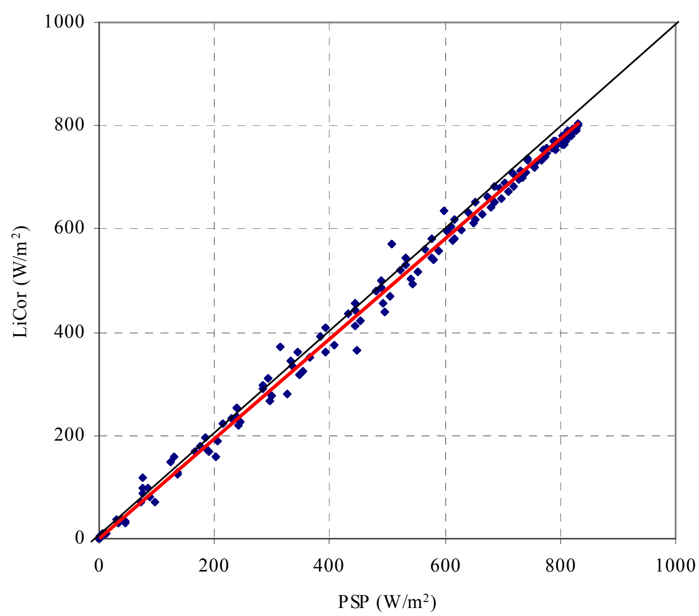


Figure A.63   PSP versus Li-Cor after calibration.

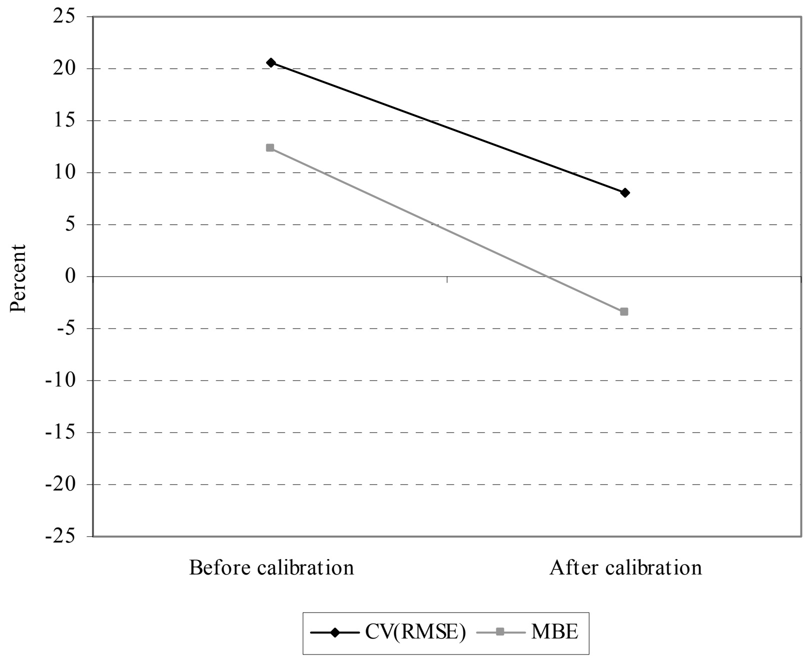


Figure A.64   CV(RMSE) and MBE plot before and after calibration.

A.6. Comparison of Supply and Duct Temperature Sensors

Two temperature sensors were installed in order to measure the supply side and the diffuser side to investigate the heat loss / gain to duct system from the attic space. The locations of sensors were explained in Chapter 4.2.2.2. After one-year measurement, two-sensors were tested to verify the data using RTD temperature sensor. Installment procedure of sensors for the calibration was explained in Section A.1.

The comparison between the measurements of the RTD temperature sensor and two Vaisala sensors showed a response time difference varying the environment temperatures. From Figures A.65 and A.70, it was found that the supply temperature and the duct temperature were 2°F and 3°F higher respectively than the reading from the RTD temperature sensor at temperatures of 130°F to 140°F. Decreasing the temperature to 45°F showed a 2°F and 3°F lower temperatures respectively than the reading from RTD temperature sensor. Temperatures at 70°F were in good agreement.

These differences may be attributed to the heating/cooling of the transducers. According to Sparks et al. (1992), the temperature of the transducer can affect the error in the measurements in the case of the severe environmental conditions. Their results showed that while the temperature dependency of analog measurements was slight in the conditions normally found in a building's mechanical room, a logger exposed to very cold climate temperatures showed a 2°F+ temperature difference.

Since the Vaisla tranducers were located at the attic space where the temperature reached up to 135°F in the summer, there could be potential errors of measuring temperatures. Therefore, in order to prevent the potential bias of the measurements in the hot or cold space, 3 or 4-wire RTD temperature sensor are recommened for measuring attic temperature in future experiments.

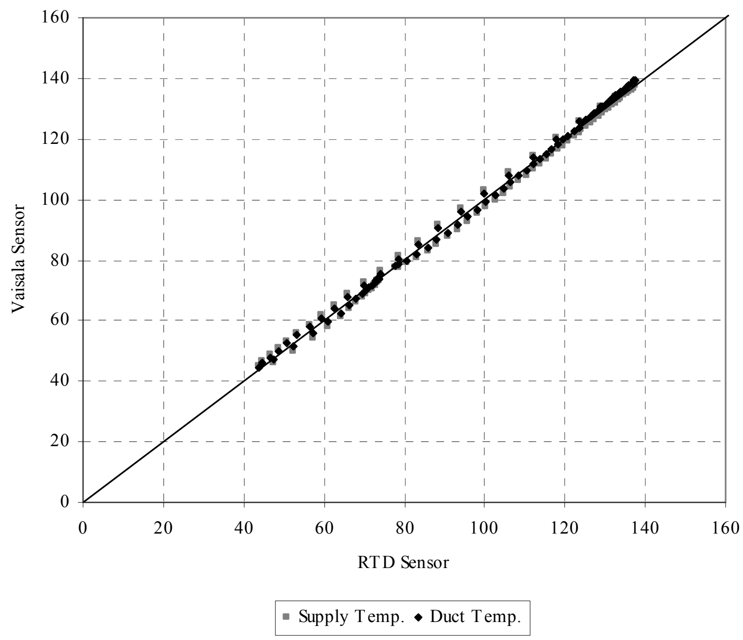


Figure A.65 RTD sensor temperature vs. Vaisala temperature sensor

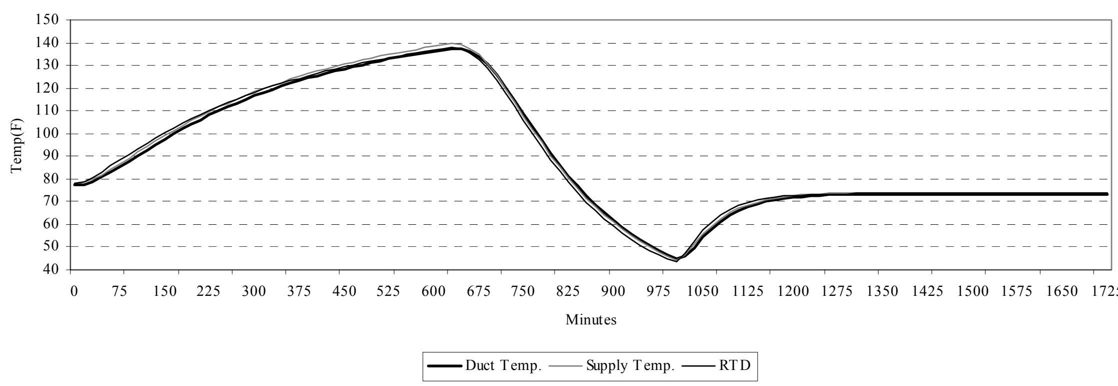


Figure A.66 Time series plot of RTD sensor vs. Vaisala sensor

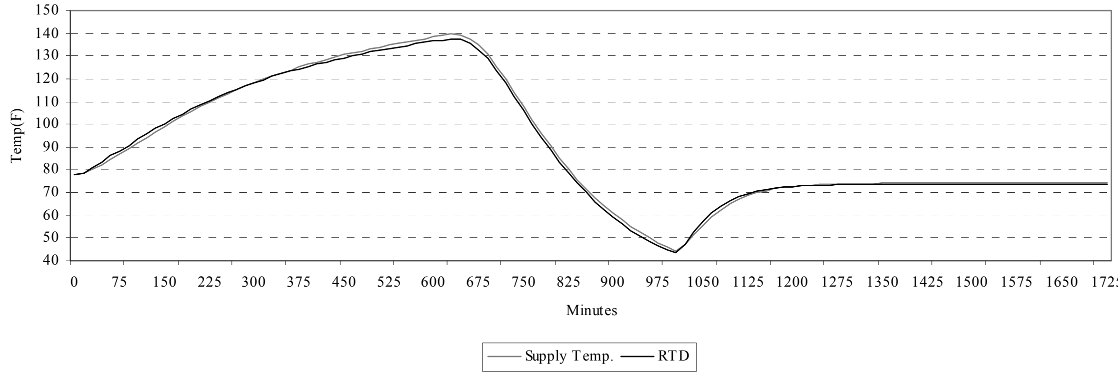


Figure A.67 Time series plot of supply sensor vs. RTD sensor

Figure A.68 Residual plot between supply and RTD sensor

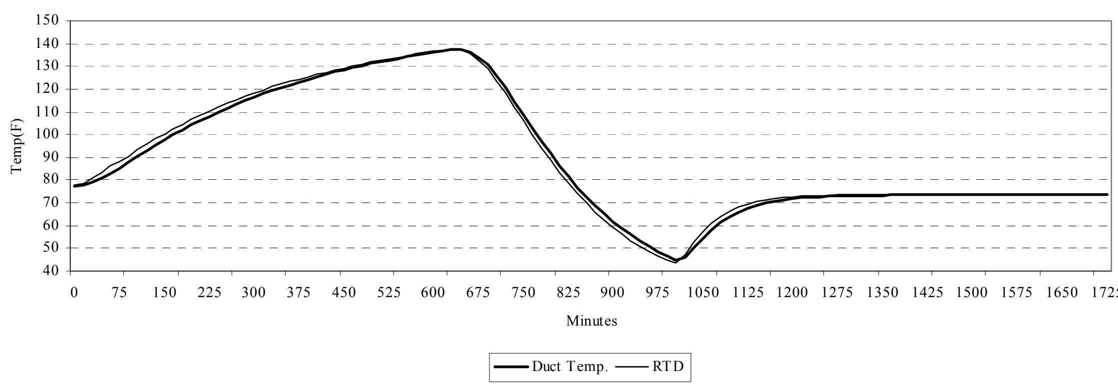


Figure A.69 Time series plot of duct sensor vs. RTD sensor

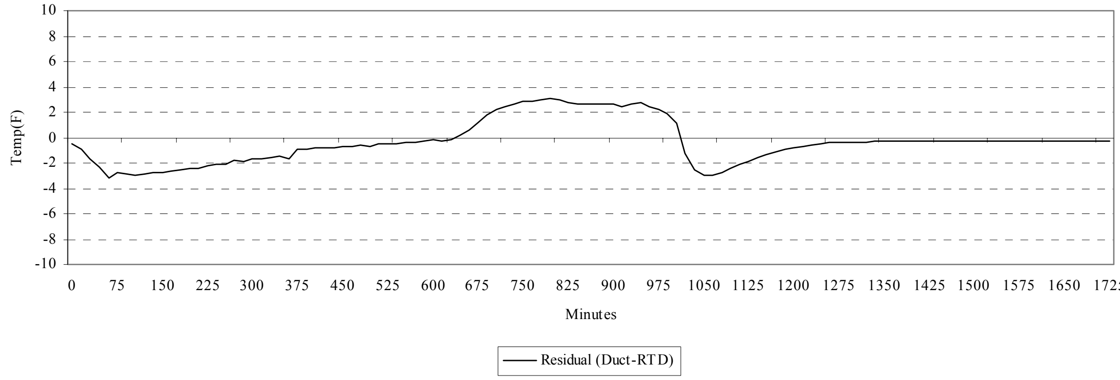


Figure A.70 Residual plot between duct and RTD sensor

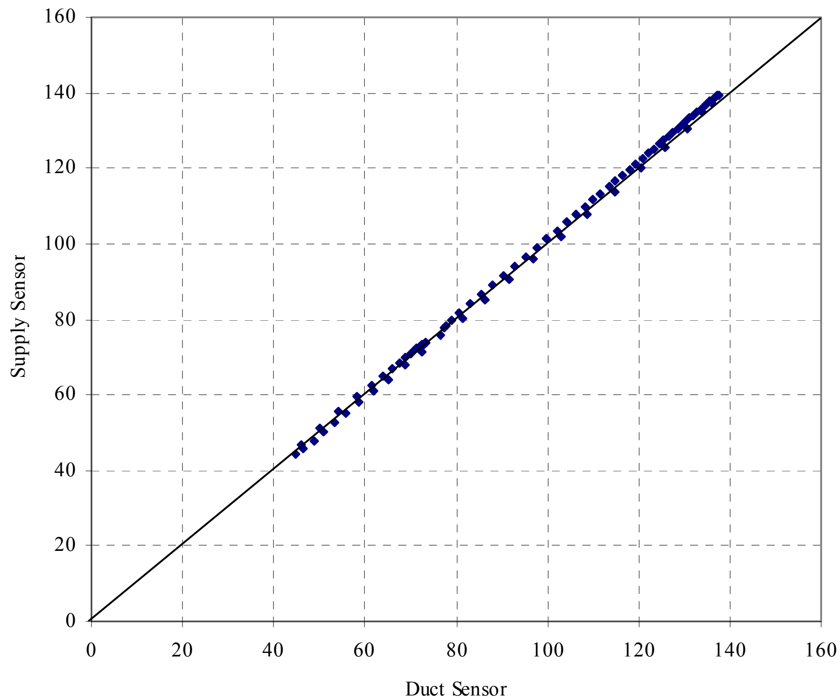


Figure A.71 Supply sensor temperature vs. duct sensor temperature

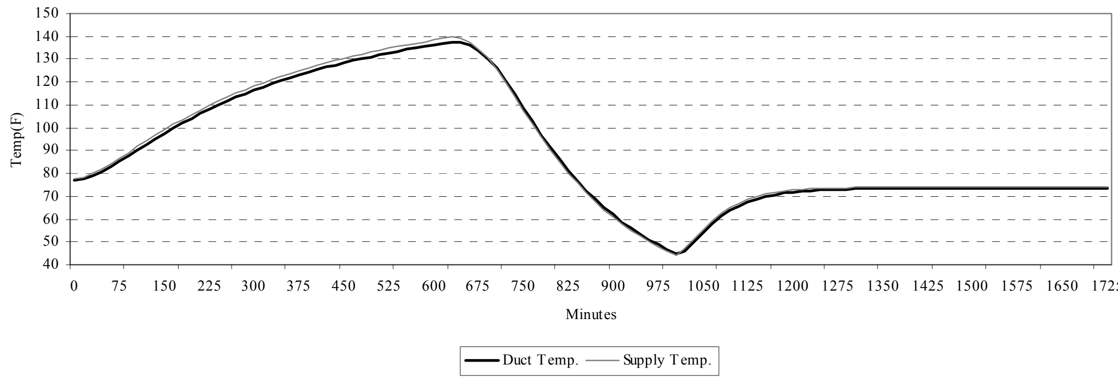


Figure A.72 Time series plot of supply sensor vs. duct sensor

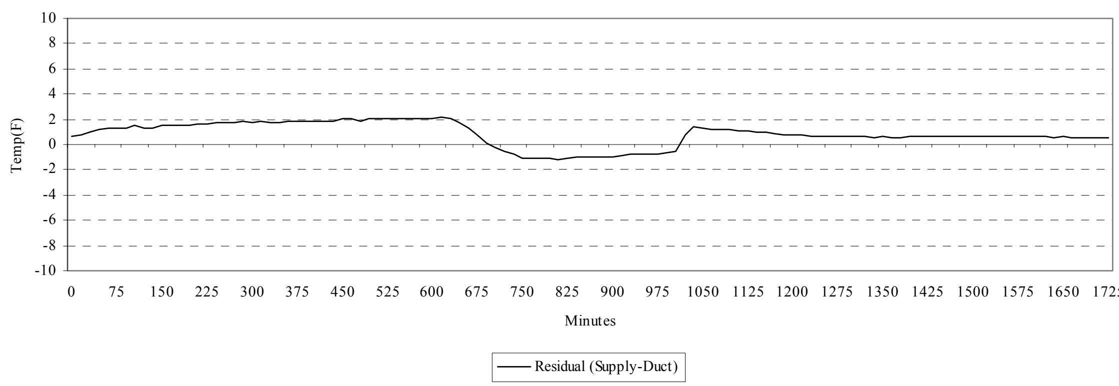


Figure A.73 Residual plot between supply and duct sensor

REFERENCES

Greenspan, L. 1976. Humidity fixed points of binary saturated aqueos solutions. *Journal of Research* 81(1): 89-96.

Klima, P.M., 2000. Improving the reliablility and accuracy of a multipyranometer array measuring solar radiation. M.S. Thesis, Texas A&M University, College Station.

LI-COR Inc. 2004, LI-200SA pyranometer sensor. Lincoln, NE: LI-COR Biosciences. <http://www.licor.com/env/PDF_Files/sensors.pdf>

Modera, M. and B. Treidler. 1995. Improved modeling of HVAC system/envelope interactions in residential buildings. *The ASME International Solar Energy Conference* March, 19-24.

Rasisuttha, S. 2004. The development ofimproved energy efficient housing for Thailand utilizing renewable energy technolody. Ph.D. Dissertation, Texas A&M University, College Station.

Sparks, R., J. Haberl, S. Bhattacharyya, M. Rayaprolu, J. Wang, and S. Vadlamani. 1992. Testing of data acquisition systems for use in monitoring building energy conservation systems. *In Proceedings of the 8th Symposium on Improving Building Systems in Hot and Humid Climates*: 197-204.

APPENDIX B

DUCT MODEL FUNCTION FOR DOE-2.1e

B.1. Concept of Duct Model

ASHRAE developed ASHRAE Standard 152-2004 – Method of Test for Determining the Design and Seasonal Efficiencies of Residential Thermal Distribution Systems (ASHRAE 2004) to estimate design and seasonal efficiency for residential building systems. This calculation considers the impacts of duct leakage, location, insulation level, climate, etc.

Figure B.1 shows the concept of duct works which are located in two buffer zones, one for return side and one for the supply side (Palmiter and Francisco 1996) and this concept was applied to DOE-2.1e simulation program using DOE-2 FUNCTION commands. Detailed procedures for duct model were explained at this chapter in detail.

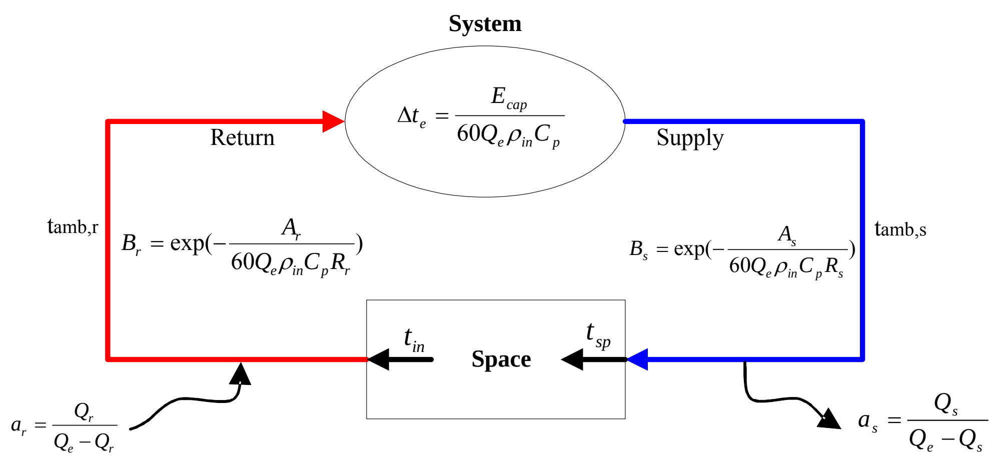


Figure B.1 Schematic diagram of duct model (ASHRAE 152-2004)

Following equations show the procedure of calculation of the delivery efficiency of the heating and cooling systems considering conduction loss and air leakage of supply duct and return duct side.

$$DE_{heating} = a_s B_s - a_s B_s (1 - B_r a_r) \frac{\Delta t_r}{\Delta t_e} - a_s (1 - B_s) \frac{\Delta t_s}{\Delta t_e} \tag{B.1}$$

$$DE_{cooling} = \frac{a_s Q_e \rho_{in}}{E_{cap}} \left(\frac{E_{cap}}{60 Q_e \rho_{in}} + (1 - a_r)(h_{amb,r} - h_{in}) + a_r C_p (B_r - 1)\Delta t_r + C_p (B_s - 1)(t_{sp} - t_{amb,s}) \right) \tag{B.2}$$

where,

B_s = conduction efficiency of supply duct = $\exp(\frac{-A_s}{60Q_e\rho_{in}C_pR_s}))$, (B.3)

B_r = conduction efficiency of return duct = $\exp(\frac{-A_r}{60Q_e\rho_{in}C_pR_r}))$, (B.4)

a_s = air leakage efficiency of the duct of supply duct = $(\frac{Q_e-Q_s}{Q_e})$, (B.5)

a_r = air leakage efficiency of the duct of return duct = $(\frac{Q_e-Q_r}{Q_e})$, (B.6)

E_{cap} = capacity of the equipment (Btu/hr),
Q_e = system air flow (CFM),
C_p = specific heat (Btu/(lb$_m$·ºF)),
Δt_e = temperature rise across the equipment (ºF) = $\frac{E_{cap}}{60Q_e\rho_{in}C_p}$, (B.7)

Δt_s = temperature difference between the building and the ambient temperature surrounding the supply (ºF) $= t_{in} - t_{amb,s}$, (B.8)

Δt_r = temperature difference between the building and the ambient temperature surrounding the return (ºF) $= t_{in} - t_{amb,r}$, (B.9)

t_{in} = temperature of indoor air (ºF),
t_{sp} = supply plenum air temperature (ºF),
$t_{amb,s}$ = ambient temperature for supply ducts (ºF),
$t_{amb,r}$ = ambient temperature for return ducts (ºF),
$h_{amb,r}$ = enthalpy of ambient air for return (Btu/hr),
h_{in} = enthalpy of air inside conditioned space (Btu/hr),
A_s = supply duct area (ft^2),
A_r = return duct area (ft^2),
ρ_{in} = density of air (lb/ft^3),
R_s = thermal resistance of supply duct (hr-ft^2-ºF /Btu),
R_r = thermal resistance of return duct (hr-ft^2-ºF /Btu).

Figures B.2 and B.3 show the procedures of the function method developed for the DOE-2.1e to apply the duct model using concepts of ASHRAE 152-2004. Three function methods (SAVETEMP, DUCT, and DUCT 2) are used. This section of the appendix contains DOE-2 commands of the duct model, which were explained in the section 4.2.3.3.

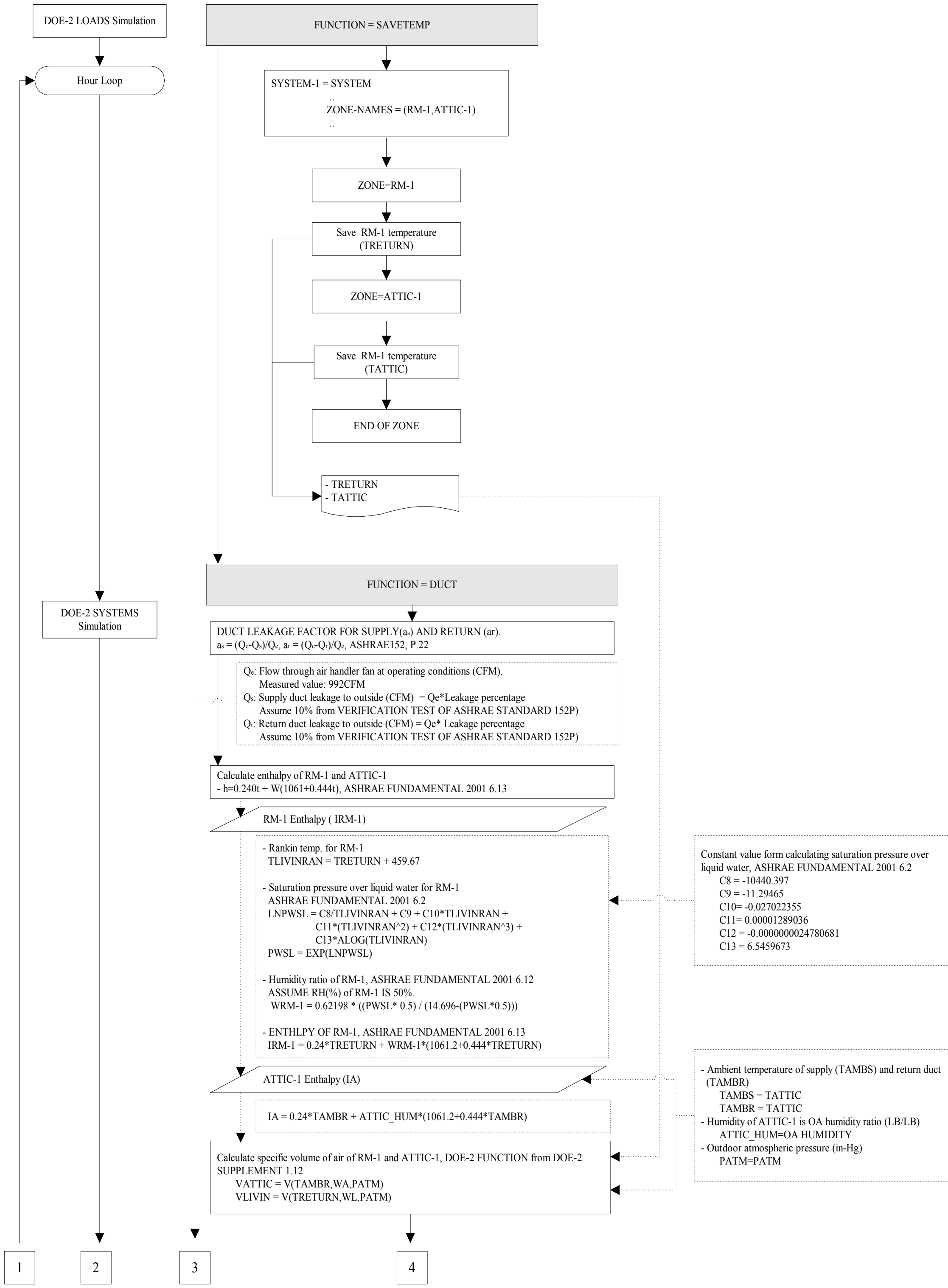


Figure B.2 Diagram of DOE-2 FUNCTION command for ASHRAE 152-2004 duct loss model (a)

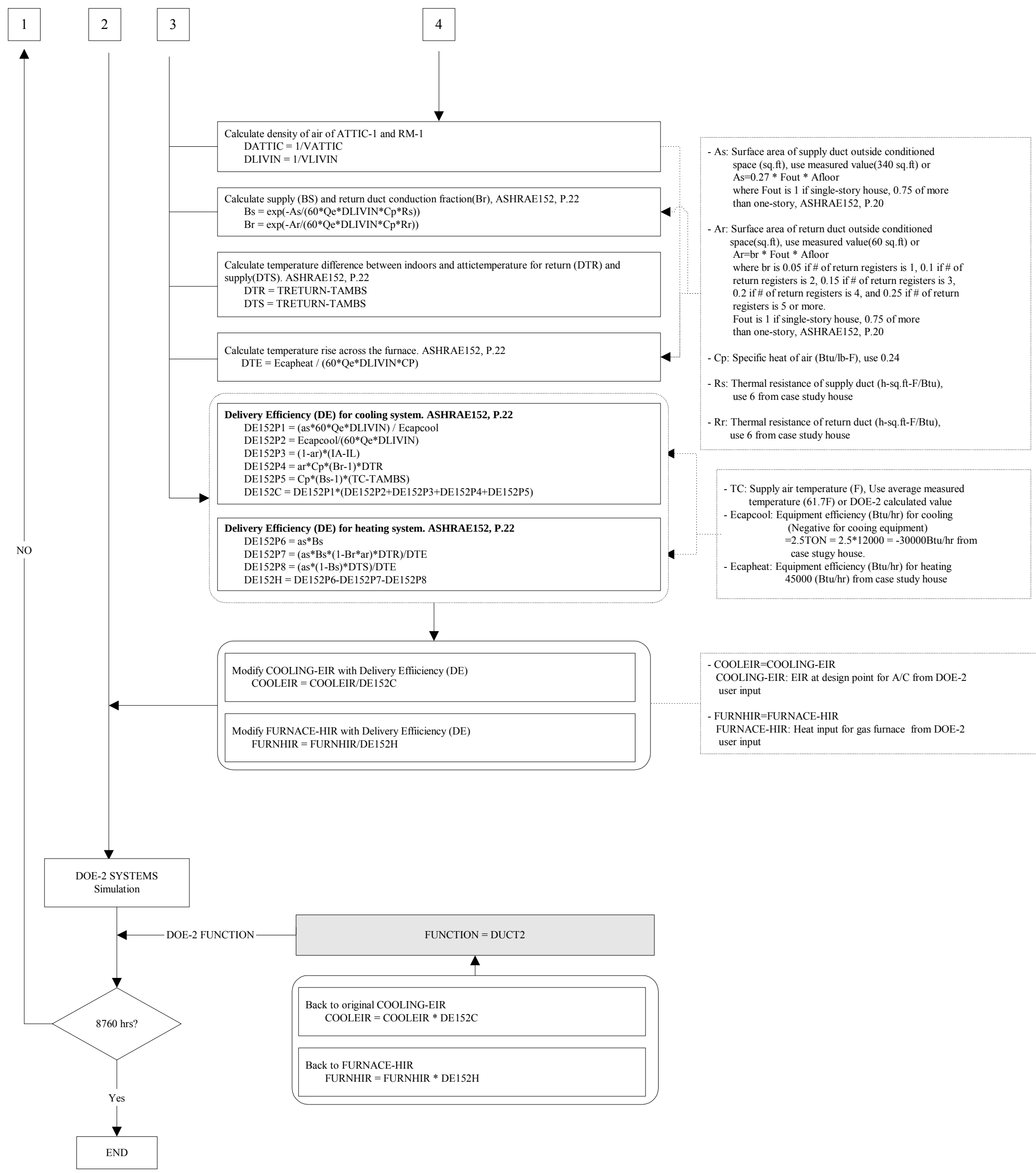


Figure B.3 Diagram of DOE-2 FUNCTION command for ASHRAE 152-2004 duct loss model (B)

B.2. Duct Model FUNCTION for DOE-2.1e

```
INPUT SYSTEMS  ..

SUBR-FUNCTIONS      RESYS-0=*DUCT*
                    RESYS-3Z=*SAVETEMP*
                    DAYCLS-4=*DUCT2*  ..

TITLE           LINE-1 *HABITAT FOR HUMANITY HOUSE, BRYAN,TEXAS*
                LINE-2 *1126 COMMERCE STREET, BRYAN TX 77803*
                LINE-3 *PH.D. DISSERTATION BY SEONGCHAN KIM*  ..

$************************************************************************************************
$       PROGRAM:                        DOE-2 SIMULATION INPUT FILE
$
$       LANGUAGE:                       DOE-2.1E BDL VERSION 119
$
$       SPONSOR:                        TEXAS STATE LEGISLATURE
$
$       PURPOSE:                        This input file is a duct loss simulation using function
$                                       method of DOE-2.1e version 119 program.
$                                       The calculation methods follow ASHRAE 152-2004 (Method of Test
$                                       for Determining the Design and Seasonal Efficiencies of
$                                       Residential Thermal Distribution Systems).
$                                       To simulate duct loss on DOE-2 program, the following
$                                       parameter need to be specified;
$                                       1)SUPPLY AIR(CFM), 2)SUPPLY LEAKAGE, 3)RETURN LEAKAGE
$                                       4)SUPPLY AREA(SQ.FT), 5)RETURN AREA(SQ.FT),
$                                       6)R-VALUE FOR SUPPLY DUCT, 7)R-VALUE FOR RETURN DUCT
$                                       8)COOLING CAPACITY(BTU/HR), 9)HEATING CAPACITY(BTU/HR)
$
$       COPYRIGHT:                      TEES, 2006.
$                                       This program bears a copyright notice to prevent rights
$                                       from being claimed by any other party. This program
$                                       shall not be redistributed or sold without written
$                                       approval from the Texas Engineering Experiment Station
$                                       (TEES).
$
$                                       The program is distributed "as is". TEES DOES NOT
$                                       WARRANT THAT THE OPERATION OF THE PROGRAM WILL BE
$                                       UNINTERRUPTED OR ERROR-FREE, AND MAKES NO
$                                       REPRESENTATIONS OR OTHER WARRANTIES, EXPRESS OR IMPLIED,
$                                       INCLUDING BUT NOT LIMITED TO THE IMPLIED WARRANTIES
$                                       OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE.
$
$                                       No support service will be provided unless
$                                       written arrangements have been made to do so. Certain
$                                       manufacturers and trade names are mentioned in this code
$                                       for the purpose of describing  their product parameters
$                                       Such reference does not constitute an
$                                       endorsement or recommendation of such equipment, but is
$                                       provided for informational purposes only.
$
$       DEVELOPER:                      SEONGCHAN KIM
$                                       Graduate Assistant Research
$                                       Department of Architecture
$                                       Energy Systems Laboratory
$                                       Texas A&M University, College Station, TX 77843
$
$                                       JEFF HABERL  Ph.D, P.E
$                                       Professor
$                                       Department of Architecture
$                                       Energy Systems Laboratory
$                                       Texas A&M University, College Station, TX 77843
$                                       PHONE: (979)458-4315,   FAX: (979)862-2457
$                                       Email: jhaberl@esl.tamu.edu
$
$************************************************************************************************

FUNCTION NAME = DUCT  ..
ASSIGN MON=IMO
       DAY=IDAY
       HR=IHR
       HUMRAT=HUMRAT
       PATM=PATM
       TRETURN = XXX24 $ RM-1 TEMP
       TATTIC = XXX25 $ ATTIC TEMP
       DE152C=XXX40
       DE152H=XXX41
       PDE152H=XXX42
       HPDE152H=XXX43
       DE152HHEATPUMP=XXX44
```

```
       FURNHIR=FURNACE-HIR
       COOLEIR=COOLING-EIR
       HEATEIR=HEATING-EIR
       NZ=NZ
       TC=TC       $SUPPLY TEMPERATURE
       CP=0.24     $SPECIFIC HEAT OF AIR, BTU/LB.F
       QSPL=P-SUPPLYAIR[]   $MEASURED, SUPPLY AIR(CFM),SY12
       SLF=P-SUPPLYLEAK[]     $SUPPLY LEAKAGE FRACTION(FROM "VERIFICATION TEST OF ASHRAE STANDARD 152P"),SY13
       RLF=P-RETURNLEAK[]     $RETURN LEAKAGE FRACTION(FROM "VERIFICATION TEST OF ASHRAE STANDARD 152P"),SY14
       AS=P-SUPPLYAREA[]      $MEASURED, SUPPLY DUCT AREA OF OUTSIDE CONDITIONED SPACE,SY15
       AR=P-RETURNAREA[]       $MEASURED, RETURN DUCT AREA OF OUTSIDE CONDITIONED SPACE,SY16
       RS=P-RSUPPLY[]        $THERMAL RESISTANCE OF SUPPLY DUCT (H-SQ.FT-F/BTU),SY17
       RR=P-RRETURN[]        $THERMAL RESISTANCE OF RETURN DUCT (H-SQ.FT-F/BTU),SY18
       ECAPCOOL=P-ECAPCOOL[] $2.5TON = 2.5*12000 = 30000BTU/HR, SY19
       ECAPHEAT=P-ECAPHEAT[] $SY20
       ..

 CALCULATE  ..

C DUCT LEAKAGE FACTOR FOR SUPPLY
       aas = (QSPL-(QSPL*SLF))/QSPL

C DUCT LEAKAGE FACTOR FOR RETURN
       aar = (QSPL-(QSPL*RLF))/QSPL

C CONSTANT VALUE FOR CALCULATING ENTHALPY, ASHRAE FUNDAMENTAL 2001 6.2
       C8 = -10440.397
       C9 = -11.29465
       C10= -0.027022355
       C11= 0.00001289036
       C12 = -0.0000000024780681
       C13 = 6.5459673

C AMBIENT TEMP. OF SUPPLY AND RETURN DUCT, ATTIC TEMP
       TAMBS = TATTIC
       TAMBR = TATTIC

C CALCULATION FOR ENTHALPY OF AMBIENT TEMP. FOR RETURN DUCT(ATTIC) FROM ASHRAE FUNDAMENTAL 2001 6.2

C      ENTHALPY OF ATTIC, ASHRAE FUNDAMENTAL 2001 6.13
       IA = 0.24*TAMBR + HUMRAT*(1061.2+0.444*TAMBR)

C      AMBIENT RANKIN TEMP. FOR LIVING SPACE
       TLIVINRAN = TRETURN + 459.67

C      SATURATION PRESSURE OVER LIQUID WATER FOR LIVING SPACE, ASHRAE FUNDAMENTAL 2001 6.2
       LNPWSL = C8/TLIVINRAN + C9 + C10*TLIVINRAN + C11*(TLIVINRAN**2) +
     + C12*(TLIVINRAN**3) + C13*ALOG(TLIVINRAN)
       PWSL = EXP(LNPWSL)

C      HUMIDITY RATIO OF LIVING SPACE, ASHRAE FUNDAMENTAL 2001 6.12
C      ASSUME RH(%) IS 50% ON LIVING SPACE
       WL = 0.62198 * ((PWSL* 0.5) / (14.696-(PWSL*0.5)))

C      ENTHLPY OF LIVING SPACE, ASHRAE FUNDAMENTAL 2001 6.13
       IL = 0.24*TRETURN + WL*(1061.2+0.444*TRETURN)


C      SPECIFIC VOLUME OF AIR FOR ATTIC AND LIVING SPACE, DOE-2 SUPPLEMENT 1.12
       VATTIC = V(TAMBR,WA,PATM)
       VLIVIN = V(TRETURN,WL,PATM)

C      DENSITY OF AIR FOR ATTIC AND LIVING SPACE
       DATTIC = 1/VATTIC
       DLIVIN = 1/VLIVIN

C      SUPPLY CONDUCTION FRACTION
       BS1 = -AS/(60*QSPL*DLIVIN*CP*RS)
       BS = EXP(BS1)

C      RETURN CONDUCTION FRACTION
       BR1 = -AR/(60*QSPL*DLIVIN*CP*RR)
       BR = EXP(BR1)

C      TEMPERATURE DIFFERENCE BETWEEN INDOORS AND AMBIENT FOR THE RETURN(F)
       DTR = TRETURN-TAMBS
       DTS = TRETURN-TAMBS

C      DTE, THE TEMPERATURE RISE ACROSS THE FURNACE
       DTE = ECAPHEAT / (60*QSPL*DLIVIN*CP)
C
       DE152P1 = (aas*60*QSPL*DLIVIN) / ECAPCOOL
       DE152P2 = ECAPCOOL/(60*QSPL*DLIVIN)
       DE152P3 = (1-aar)*(IA-IL)
       DE152P4 = aar*CP*(BR-1)*DTR
       DE152P5 = CP*(BS-1)*(TC-TAMBS)
       DE152C = DE152P1*(DE152P2+DE152P3+DE152P4+DE152P5)

       DE152P6 = aas*BS
       DE152P7 = (aas*BS*(1-BR*aar)*DTR)/DTE
```

```
       DE152P8 = (aas*(1-BS)*DTS)/DTE
       DE152H = DE152P6-DE152P7-DE152P8
       DE152HHEATPUMP = DE152P6-DE152P7-DE152P8
       PDE152H = FURNHIR/100
       HPDE152H = HEATEIR/2

98     IF (DE152C .GT. 1) DE152C = 1
       IF (DE152C .LT. COOLEIR) DE152C = COOLEIR
       COOLEIR = COOLEIR/DE152C

99     IF (DE152H .GT. 1) DE152H = 1
       IF (DE152H .LT. PDE152H) DE152H = PDE152H
       IF (DE152HHEATPUMP .LT. HPDE152H) DE152HHEATPUMP = HPDE152H
       FURNHIR = FURNHIR/DE152H
       HEATEIR = HEATEIR/DE152HHEATPUMP

C       PRINT 20,
C     + MON,DAY,HR,TATTIC,DE152C,DE152H,CFMINFATT
C20     FORMAT
C     + (3F3.0,' ',F5.1,' ',F5.3,' ',F5.3,' ',F6.0)

100    CONTINUE

       END

END-FUNCTION  ..
```

FUNCTION NAME = DUCT2 ..

```
ASSIGN MON=IMO
       DAY=IDAY
       HR=IHR
       TC=TC
       TH=TH
       FURNHIR=FURNACE-HIR
       COOLEIR=COOLING-EIR
       HEATEIR=HEATING-EIR
       TRETURN = XXX24 $ RM-1 TEMP
       TATTIC = XXX25 $ ATTIC TEMP
       DE152C=XXX40
       DE152H=XXX41
       ..

 CALCULATE  ..

       IF (DE152C .NE. 0 .AND. TC .GT. 0.1) GOTO 98
       IF (DE152C .EQ. 0) GOTO 100

98     COOLEIR = COOLEIR*DE152C

       IF (ABS(QH) .GT. 0.1) GOTO 99
       IF (DE152H .EQ. 0) GOTO 100

99     FURNHIR = FURNHIR*DE152H
       HEATEIR = HEATEIR*DE152H

100    CONTINUE
       END

END-FUNCTION  ..
```

```
FUNCTION NAME = SAVETEMP  ..
ASSIGN TRETURN = XXX24  $ RM-1 TEMP
       TATTIC = XXX25   $ ATTIC TEMP
       TNOW=TNOW
       NZ=NZ ..
 CALCULATE ..
       IF (NZ .EQ. 1) TRETURN=TNOW
       IF (NZ .EQ. 2) TATTIC=TNOW
      END

END-FUNCTION ..

FUNCTION NAME = SAVETEMP2 ..

ASSIGN TRETURN = XXX24  $ RM-1 TEMP
       TATTIC = XXX25   $ ATTIC TEMP
       TNOW=TNOW
       NZ=NZ ..
 CALCULATE ..
        IF (NZ .EQ. 1) TRETURN=TNOW
        IF (NZ .EQ. 2) TATTIC=TNOW
      END

END-FUNCTION  ..
```

REFERENCES

ASHRAE (American Society of Heating, Refrigerating, and Air-conditioning Engineers). 2004. *Method of test for determining the design and seasonal efficiencies of residential thermal distribution systems (ASHRAE Standard 152-2004)*. Atlanta, GA: American Society of Heating, Ventilation and Air-conditioning Engineer.

Palmiter, L., and P.W. Francisco. 1996. A practical method for estimating the thermal efficiency of residential forced-air distribution systems. *Proceedings of the 1996 ACEEE Summer Study on Energy-Efficient Buildings*: 96-112.

APPENDIX C

EXAMPLES OF BDI AND GAWK PROGRAMS

C.1. BDI spreadsheet for the efficiency test (THESIS_DUCTLOCATION.xls)

C.2. Include file generated by the BDI program.

C.3. BDI program to run DOE-2 simulation in batch mode.

C.4. Commands of GAWK program to extract the data from the BEPS of DOE-2 output generated by BDI runs

C.5. Batch file run to extract data using commands of GAWK from DOE-2 output

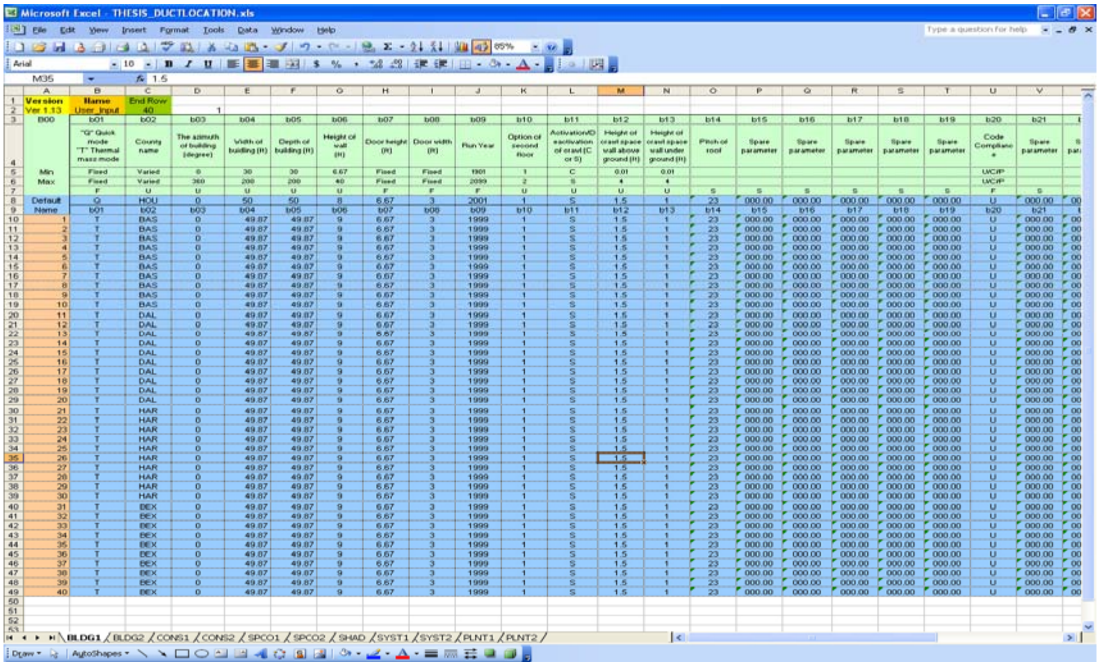
C.6. Summary output after extracting specific output from DOE-2 output using GAWK and batch file run

C.7. Data from summary output using EXCEL spreadsheet

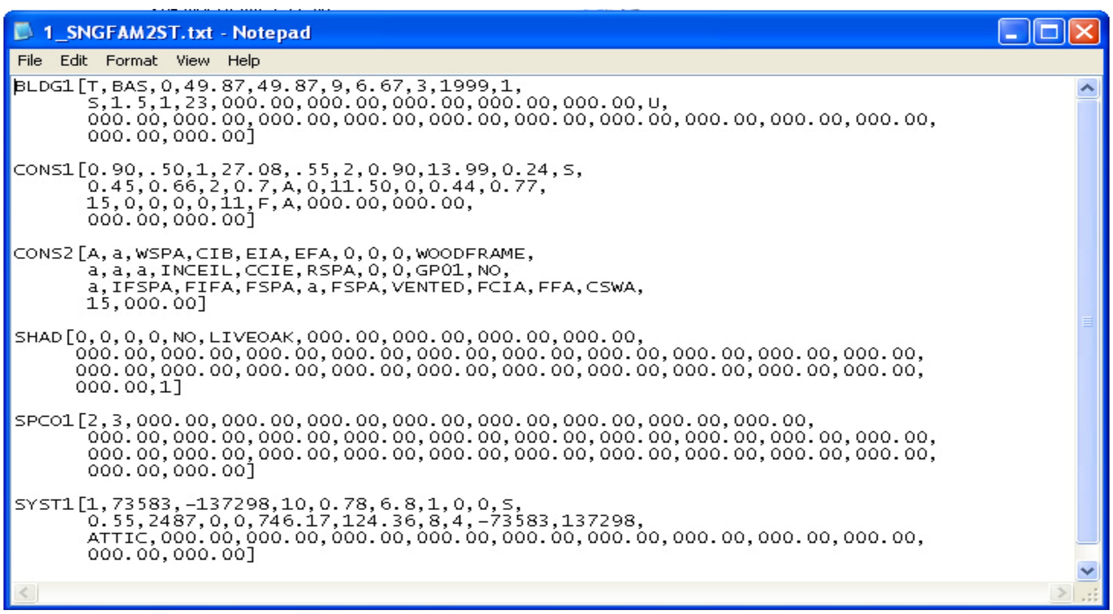
The Batch DOE-2 Input (BDI) program developed by ESL was used to perform the DOE-2 simulation in the batch model. Gawk program was used to extract required output from BEPU and hourly report from output file generated by BDI program.

This section presents a specially prepared spreadsheet to assign values to all PARAMETERS, INCLUDE file generated by BDI program, DOE-2 run in the batch mode and GAWK commands to extract data from DOE-2 output, which were explained in the section 4.2.3.3.

C.1. BDI spreadsheet for the efficiency test (THESIS_DUCTLOCATION.xls)



C.2. Include file generated by the BDI program.



1_SNGFAM2ST.txt - Notepad

```
BLDG1[T,BAS,0,49.87,49.87,9,6.67,3,1999,1,
      S,1.5,1,23,000.00,000.00,000.00,000.00,000.00,U,
      000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00]

CONS1[0.90,.50,1,27.08,.55,2,0.90,13.99,0.24,S,
      0.45,0.66,2,0.7,A,0,11.50,0,0.44,0.77,
      15,0,0,0,0,11,F,A,000.00,000.00,
      000.00,000.00]

CONS2[A,a,WSPA,CIB,EIA,EFA,0,0,0,WOODFRAME,
      a,a,a,INCEIL,CCIE,RSPA,0,0,GP01,NO,
      a,IFSPA,FIFA,FSPA,a,FSPA,VENTED,FCIA,FFA,CSWA,
      15,000.00]

SHAD[0,0,0,0,NO,LIVEOAK,000.00,000.00,000.00,000.00,
     000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
     000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
     000.00,1]

SPCO1[2,3,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00]

SYST1[1,73583,-137298,10,0.78,6.8,1,0,0,S,
      0.55,2487,0,0,746.17,124.36,8,4,-73583,137298,
      ATTIC,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,000.00,
      000.00,000.00]
```

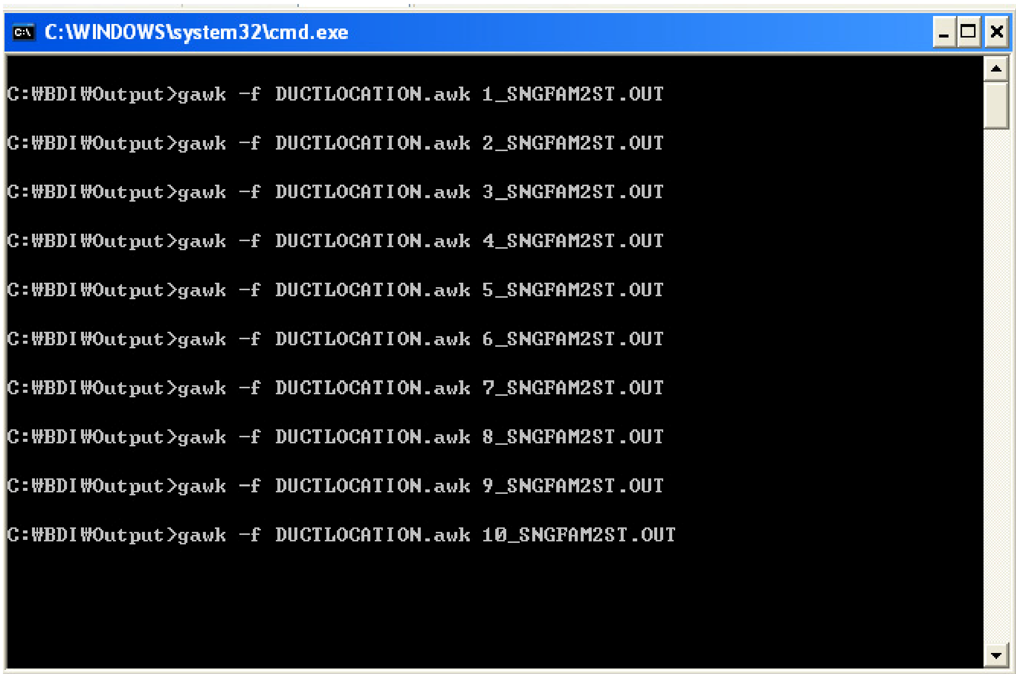
C.3. BDI program to run DOE-2 simulation in batch mode.

```
C:\BDI\BDI.exe
BDI Version: 1.8
Enter an input spreadsheet: THESIS_DUCTLOCATION
Enter the scenario: SNGFAM2ST
Reading from Excel Sheet: ............ Done
Choose I for Injection mode and D for Desktop mode: D

C:\DOE2\install DOE2\input>set DOE2_DR=C:\DOE2\INSTAL~1

C:\DOE2\install DOE2\input>set DOE2_EX=C:\DOE2\INSTAL~1\21e\exe_dvf

C:\DOE2\install DOE2\input>set PATH=C:\WINDOWS\command;C:\WINDOWS

C:\DOE2\install DOE2\input>if exist C:\WINDOWS\system32 set PATH=C:\WINDOWS\syst
em32;C:\WINDOWS

C:\DOE2\install DOE2\input>set PATH=C:\DOE2\INSTAL~1\21e\exe_dvf;C:\WINDOWS\syst
em32;C:\WINDOWS

C:\DOE2\install DOE2\input>doe21e SNGFAM2ST ATT
===== doe21e SNGFAM2ST ATT        ==== Start ========
Using working directory SNGFAM2ST.tmp
_
```

C.4. Commands of GAWK program to extract the data from the BEPS of DOE-2 output generated by BDI runs

```
DUCTLOCATION.awk - Notepad
File  Edit  Format  View  Help
BEGIN {
 }
 {
  HEATINGS[NR] = $4;
  COOLINGS[NR] = $3;
  DHWS[NR] = $4;
  HEATINGU[NR] = $4;
  COOLINGU[NR] = $3;
  TOTAL[NR] = $4;
  PEAKCOOLHR[NR] = $2;
  PEAKCOOLDAY[NR] = $2;

  if (($1 == "REPORT-") && ($2 == "BEPS"))
                    {i= NR+15; j= NR+17; d= NR+23; k= NR+30}

  if (($1 == "REP1") && ($3 == "HOURLY-REPORT") && ($4 == "PAGE231"))
                    {l= NR+24; m= NR+36}

  if (($1 == "REPORT-") && ($2 == "BEPU"))
                    {n= NR+15; o= NR+17}
 }

 END {
             print COOLINGS[j],HEATINGS[i],DHWS[d],TOTAL[k],PEAKCOOLHR[l],
             PEAKCOOLDAY[m],COOLINGU[o],HEATINGU[n] >> "DUCTLOCATION.out"
}
```

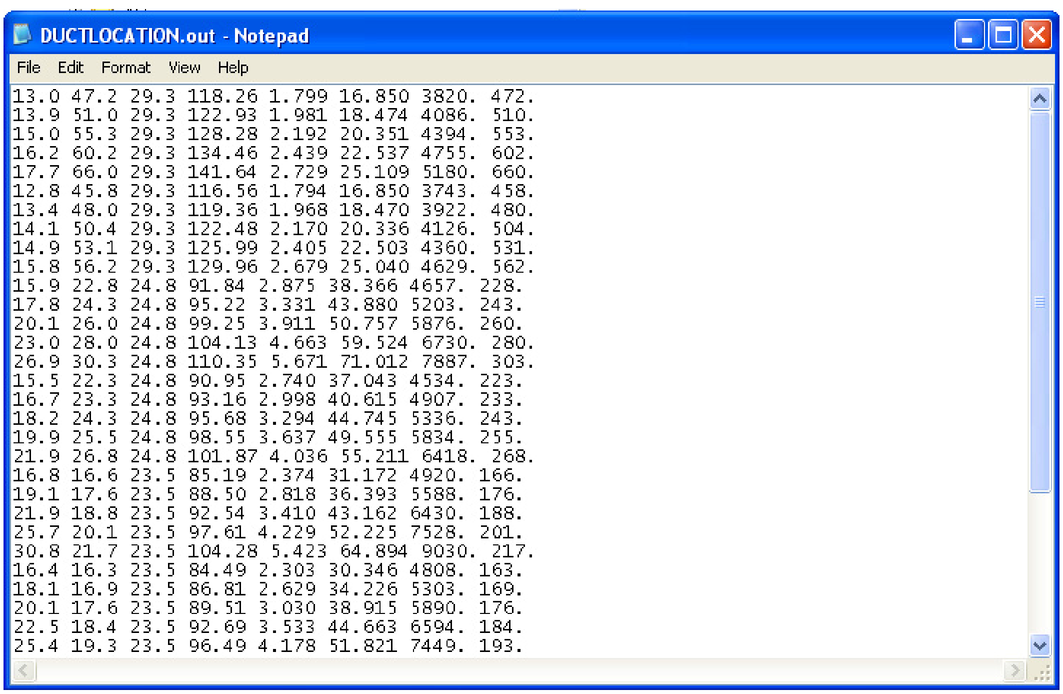
C.5. Batch file run to extract data using commands of GAWK from DOE-2 output



C:\WINDOWS\system32\cmd.exe

```
C:\BDI\Output>gawk -f DUCTLOCATION.awk 1_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f DUCTLOCATION.awk 2_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f DUCTLOCATION.awk 3_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f DUCTLOCATION.awk 4_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f DUCTLOCATION.awk 5_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f DUCTLOCATION.awk 6_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f DUCTLOCATION.awk 7_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f DUCTLOCATION.awk 8_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f DUCTLOCATION.awk 9_SNGFAM2ST.OUT

C:\BDI\Output>gawk -f DUCTLOCATION.awk 10_SNGFAM2ST.OUT
```

C.6. Summary output after extracting specific output from DOE-2 output using GAWK and batch file run

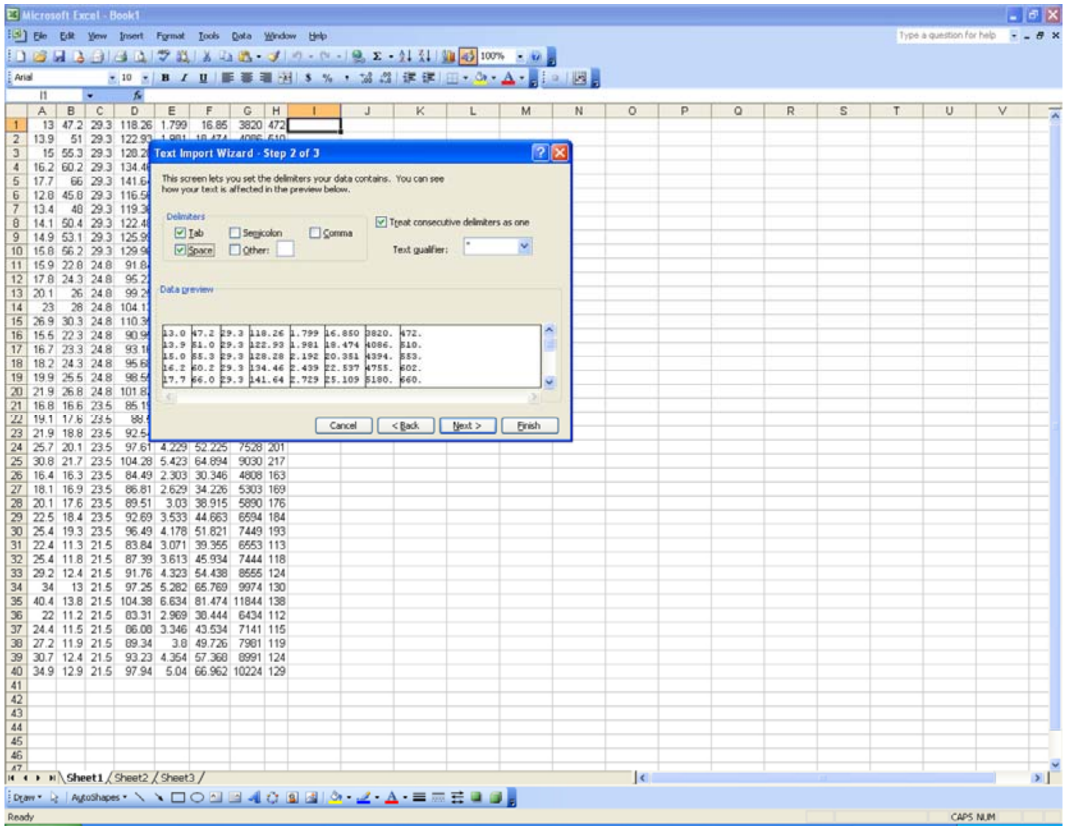


DUCTLOCATION.out - Notepad

File Edit Format View Help

```
13.0 47.2 29.3 118.26 1.799 16.850 3820. 472.
13.9 51.0 29.3 122.93 1.981 18.474 4086. 510.
15.0 55.3 29.3 128.28 2.192 20.351 4394. 553.
16.2 60.2 29.3 134.46 2.439 22.537 4755. 602.
17.7 66.0 29.3 141.64 2.729 25.109 5180. 660.
12.8 45.8 29.3 116.56 1.794 16.850 3743. 458.
13.4 48.0 29.3 119.36 1.968 18.470 3922. 480.
14.1 50.4 29.3 122.48 2.170 20.336 4126. 504.
14.9 53.1 29.3 125.99 2.405 22.503 4360. 531.
15.8 56.2 29.3 129.96 2.679 25.040 4629. 562.
15.9 22.8 24.8 91.84 2.875 38.366 4657. 228.
17.8 24.3 24.8 95.22 3.331 43.880 5203. 243.
20.1 26.0 24.8 99.25 3.911 50.757 5876. 260.
23.0 28.0 24.8 104.13 4.663 59.524 6730. 280.
26.9 30.3 24.8 110.35 5.671 71.012 7887. 303.
15.5 22.3 24.8 90.95 2.740 37.043 4534. 223.
16.7 23.3 24.8 93.16 2.998 40.615 4907. 233.
18.2 24.3 24.8 95.68 3.294 44.745 5336. 243.
19.9 25.5 24.8 98.55 3.637 49.555 5834. 255.
21.9 26.8 24.8 101.87 4.036 55.211 6418. 268.
16.8 16.6 23.5 85.19 2.374 31.172 4920. 166.
19.1 17.6 23.5 88.50 2.818 36.393 5588. 176.
21.9 18.8 23.5 92.54 3.410 43.162 6430. 188.
25.7 20.1 23.5 97.61 4.229 52.225 7528. 201.
30.8 21.7 23.5 104.28 5.423 64.894 9030. 217.
16.4 16.3 23.5 84.49 2.303 30.346 4808. 163.
18.1 16.9 23.5 86.81 2.629 34.226 5303. 169.
20.1 17.6 23.5 89.51 3.030 38.915 5890. 176.
22.5 18.4 23.5 92.69 3.533 44.663 6594. 184.
25.4 19.3 23.5 96.49 4.178 51.821 7449. 193.
```

C.7. Data from summary output using EXCEL spreadsheet



APPENDIX D

DOE-2 INPUT COMMANDS FOR THERMAL MASS ANALYSIS

D.1. DOE-2 code of a 2x4, wood-framed wall with studs 16” O.C. with insulation between the studs

D.2. DOE-2 code of a 3” facia brick wall with 2x4 wood-framed with studs 16” O.C. with insulation between the studs

D.3. DOE-2 code of an 8” concrete block wall with perlite fill in the cells of the block and insulation between the block and the interior gypsum board (I)

D.4. DOE-2 code of an 8” concrete block wall with perlite and concrete fill in the cells of the block and insulation between the block and the interior gypsum board (II)

D.5. DOE-2 code of an 8” concrete block wall with perlite fill in the cells of the block and insulation outside the block, covered by stucco (III)

D.6. DOE-2 code of an 8” concrete block with perlite and concrete fill in the cells of the block and insulation outside the block, covered by stucco (IV)

This study evaluated both the quick and the delayed methods since the 2000/2001 IECC specifies the thermal properties of the wall and roof for normal and thermal mass walls.

Therefore, the effect of different construction type was analyzed for different building configurations to find the effect of high thermal materials in the IECC including: 1) a quick mode wall that uses U-values instead of the layered materials, 2) a 2x4, wood-framed wall with studs 16” O.C. with insulation between the studs, 3) a 3” facia brick wall with 2x4 wood-framed with studs 16” O.C. with insulation between the studs, 4) an 8” concrete block wall with perlite fill in the cells of the block and insulation between the block and the interior gypsum board, 5) an 8” concrete block wall with perlite and concrete fill in the cells of the block and insulation between the block and the interior gypsum board, 6) an 8” concrete block wall with perlite fill in the cells of the block and insulation outside the block, covered by stucco, and 7) an 8” concrete block with perlite and concrete fill in the cells of the block and insulation outside the block, covered by stucco.

This section presents the DOE-2 commands of each wall type, which were explained in the section 4.3.6.6.

D.1. DOE-2 code of a 2x4, wood-framed wall with studs 16” O.C. with insulation between the studs

```
VINYL-TILE          = MATERIAL                    $DOE2.1E(MATERIALS LIBRARY)
                    RESISTANCE   = .05            $(HR.FT^2.F/BTU)
                    SPECIFIC-HEAT= .30  ..        $(BTU/LB.F)

PLY-WOOD            = MATERIAL                     $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .0417           $(FT)
                    CONDUCTIVITY = .0667           $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 34              $(LB/FT^3)
                    SPECIFIC-HEAT = .29   ..       $(BTU/LB.F), PW03

INSULATION-R15      = MATERIAL                    $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .405           $(FT)
                    CONDUCTIVITY = .027           $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 0.6            $(LB/FT^3)
                    SPECIFIC-HEAT= .20  ..        $(BTU/LB.F)

GYPSUM-BOARD        = MATERIAL                     $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .0417           $(FT)
                    CONDUCTIVITY = .0926           $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 50              $(LB/FT^3)
                    SPECIFIC-HEAT = .2   ..        $(BTU/LB.F), GP01

STUD               = MATERIAL                     $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .3333          $(FT)
                    CONDUCTIVITY = .0667          $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 32             $(LB/FT^3)
                    SPECIFIC-HEAT= .33  ..        $(BTU/LB.F)

WA-1 = LAYERS
       MATERIAL = (VINYL-TILE, PLY-WOOD,
                   INSULATION-R15, GYPSUM-BOARD)  ..
              $ Insulation Part of Wall
              $ VINYL-TILE = Asbestos Vinyl Siding
              $ PLY-WOOD = Plywood 1/2"
              $ INSULATION-R15 = MINERAL WOOL/FIBER
              $ GYPSUM-BOARD = Gypsum Board 1/2"
              $ The percentage of WA-1 = 87.5 %

WA-2 = LAYERS
       MATERIAL = (VINYL-TILE, PLY-WOOD,
                   STUD, GYPSUM-BOARD)  ..
              $ Stud Part of Wall
              $ VINYL-TILE = Asbestos Vinyl Siding
              $ PLY-WOOD = Plywood 1/2"
              $ STUD = 2*4 STUD
              $ GYPSUM-BOARD = Gypsum Board 1/2"
              $ The percentage of WA-2 = 12.5 %

WALL-1    = CONSTRUCTION
            LAYERS = WA-1   ..

WALL-2    = CONSTRUCTION
            LAYERS = WA-2   ..
```

D.2. DOE-2 code of a 3" facia brick wall with 2x4 wood-framed with studs 16" O.C. with insulation between the studs

```
BRICK-BK04          = MATERIAL                     $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .25             $(FT)
                    CONDUCTIVITY = .7576           $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 130             $(LB/FT^3)
                    SPECIFIC-HEAT= .22  ..         $(BTU/LB.F)

PLY-WOOD            = MATERIAL                      $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .0417            $(FT)
                    CONDUCTIVITY = .0667            $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 34               $(LB/FT^3)
                    SPECIFIC-HEAT = .29   ..        $(BTU/LB.F), PW03

INSULATION-R15      = MATERIAL                     $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .405            $(FT)
                    CONDUCTIVITY = .027            $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 0.6             $(LB/FT^3)
                    SPECIFIC-HEAT= .20  ..         $(BTU/LB.F)

STUD               = MATERIAL                      $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .3333           $(FT)
                    CONDUCTIVITY = .0667           $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 32              $(LB/FT^3)
                    SPECIFIC-HEAT= .33  ..         $(BTU/LB.F)

GYPSUM-BOARD        = MATERIAL                      $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .0417            $(FT)
                    CONDUCTIVITY = .0926            $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 50               $(LB/FT^3)
                    SPECIFIC-HEAT = .2   ..         $(BTU/LB.F), GP01

WA-1 = LAYERS
       MATERIAL = (BRICK-BK04, PLY-WOOD,
                   INSULATION-R15, GYPSUM-BOARD)  ..
              $ Insulation Part of Wall
              $ BRICK = 3 INCH FACE BRICK
              $ PLY-WOOD = Plywood 1/2"
              $ INSULATION-R15 = MINERAL WOOL/FIBER
              $ GYPSUM-BOARD = Gypsum Board 1/2"
              $ The percentage of WA-1 = 87.5 %

WA-2 = LAYERS
       MATERIAL = (BRICK-BK04, PLY-WOOD,
                   STUD, GYPSUM-BOARD)  ..
              $ Stud Part of Wall
              $ BRICK = 3 INCH FACE BRICK            $ PLY-WOOD = Plywood 1/2"
              $ STUD = 2*4 STUD
              $ GYPSUM-BOARD = Gypsum Board 1/2"
              $ The percentage of WA-2 = 12.5 %

WALL-1    = CONSTRUCTION
            LAYERS = WA-1   ..

WALL-2    = CONSTRUCTION
            LAYERS = WA-2   ..
```

D.3. DOE-2 code of an 8" concrete block wall with perlite fill in the cells of the block and insulation between the block and the interior gypsum board (I)

```
BLOCK-CB33          = MATERIAL                   $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = 0.6667        $(FT)
                    CONDUCTIVITY = 0.1141        $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 56            $(LB/FT^3)
                    SPECIFIC-HEAT= .20  ..       $(BTU/LB.F)

INSULATION-IN34     = MATERIAL                   $DOE2.1E(MATERIALS LIBRARY), R-5.21
                    THICKNESS    = 0.1042        $(FT)
                    CONDUCTIVITY = 0.02          $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 1.8           $(LB/FT^3)
                    SPECIFIC-HEAT= .29  ..       $(BTU/LB.F)

GYPSUM-BOARD        = MATERIAL                    $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .0417          $(FT)
                    CONDUCTIVITY = .0926          $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 50             $(LB/FT^3)
                    SPECIFIC-HEAT = .2   ..       $(BTU/LB.F), GP01

WA-3 = LAYERS
       MATERIAL = (BLOCK-CB33, INSULATION-IN34, GYPSUM-BOARD)  ..
              $ BLOCK-CB33 – PERLITE FILLED CONCRETE BLCOK
              $ INSULATON-IN34 – R5.21
              $ GYPSUM-BOARD = Gypsum Board 1/2"

WALL-3    = CONSTRUCTION
            LAYERS = WA-3   ..
```

D.4. DOE-2 code of an 8" concrete block wall with perlite and concrete fill in the cells of the block and insulation between the block and the interior gypsum board (II)

```
BLOCK-CB35          = MATERIAL                    $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = 0.6667         $(FT)
                    CONDUCTIVITY = 0.2413         $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 77             $(LB/FT^3)
                    SPECIFIC-HEAT= .20  ..        $(BTU/LB.F)

INSULATION-IN35     = MATERIAL                    $DOE2.1E(MATERIALS LIBRARY), R-8.33
                    THICKNESS    = 0.158          $(FT)
                    CONDUCTIVITY = 0.02           $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 1.8            $(LB/FT^3)
                    SPECIFIC-HEAT= .29  ..        $(BTU/LB.F)

GYPSUM-BOARD        = MATERIAL                     $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .0417           $(FT)
                    CONDUCTIVITY = .0926           $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 50              $(LB/FT^3)
                    SPECIFIC-HEAT = .2   ..        $(BTU/LB.F), GP01

WA-3 = LAYERS
       MATERIAL = (BLOCK-CB35, INSULATION-IN35, GYPSUM-BOARD)  ..
              $ BLOCK-CB35 – CONCRETE AND PERLITE FILLED
              $ INSULATON-IN35 – R8.33
              $ GYPSUM-BOARD = Gypsum Board 1/2"

WALL-3    = CONSTRUCTION
            LAYERS = WA-3   ..
```

D.5. DOE-2 code of an 8” concrete block wall with perlite fill in the cells of the block and insulation outside the block, covered by stucco (III)

```
STUCCO-SC01         = MATERIAL                      $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = 0.0833           $(FT)
                    CONDUCTIVITY = 0.4167           $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 166              $(LB/FT^3)
                    SPECIFIC-HEAT= .20  ..          $(BTU/LB.F)

INSULATION-IN31     = MATERIAL                      $DOE2.1E(MATERIALS LIBRARY), R-2.08
                    THICKNESS    = 0.01             $(FT)
                    CONDUCTIVITY = 0.027            $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 0.6              $(LB/FT^3)
                    SPECIFIC-HEAT= .29  ..          $(BTU/LB.F)

BLOCK-CB33          = MATERIAL                      $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = 0.6667           $(FT)
                    CONDUCTIVITY = 0.1141           $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 56               $(LB/FT^3)
                    SPECIFIC-HEAT= .20  ..          $(BTU/LB.F)

AIR-AL21             = MATERIAL                       $DOE2.1E(MATERIALS LIBRARY)
                    RESISTANCE   = .89  ..          $(HR.FT^2.F/BTU)

GYPSUM-BOARD        = MATERIAL                       $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .0417             $(FT)
                    CONDUCTIVITY = .0926             $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 50                $(LB/FT^3)
                    SPECIFIC-HEAT = .2   ..          $(BTU/LB.F), GP01

STUD1               = MATERIAL                       $DOE2.1E(MATERIALS LIBRARY)
                    THICKNESS    = .167             $(FT)
                    CONDUCTIVITY = .0667            $(BTU.FT/HR.FT^2.F)
                    DENSITY      = 32               $(LB/FT^3)
                    SPECIFIC-HEAT= .33  ..          $(BTU/LB.F)

WA-1 = LAYERS
       MATERIAL = (STUCCO-SC01, INSULATION-IN31,
                   BLOCK-CB33, AIR-AL21, GYPSUM-BOARD)  ..
              $ AIR Part of Wall
              $ STUCC0-SC01 – 1”
              $ INSULATION-IN31 – R-2.08
             $ BLOCK 8 INCH – PERLITE FILLED
             $ AIR-AL21 – FOR VERTICAL WALL
             $ GYPSUM-BOARD = Gypsum Board 1/2”
              $ The percentage of WA-1 = 87.5 %

WA-2 = LAYERS
       MATERIAL = (STUCCO-SC01, INSULATION-IN31,
                   BLOCK-CB33, STUD1, GYPSUM-BOARD)  ..
              $ STUD Part of Wall
              $ STUCC0-SC01 – 1”
              $ INSULATION-IN31 – R-2.08
             $ BLOCK 8 INCH – PERLITE FILLED
             $ STUD – 2*2”
             $ GYPSUM-BOARD = Gypsum Board 1/2”
              $ The percentage of WA-1 = 12.5 %

WALL-1    = CONSTRUCTION
            LAYERS = WA-1   ..

WALL-2    = CONSTRUCTION
            LAYERS = WA-2   ..
```

D.6. DOE-2 code of an 8" concrete block with perlite and concrete fill in the cells of the block and insulation outside the block, covered by stucco (IV)

```
STUCCO-SC01          = MATERIAL                      $DOE2.1E(MATERIALS LIBRARY)
                     THICKNESS    = 0.0833           $(FT)
                     CONDUCTIVITY = 0.4167           $(BTU.FT/HR.FT^2.F)
                     DENSITY      = 166              $(LB/FT^3)
                     SPECIFIC-HEAT= .20  ..          $(BTU/LB.F)

INSULATION-IN31      = MATERIAL                      $DOE2.1E(MATERIALS LIBRARY), R-2.08
                     THICKNESS    = 0.01             $(FT)
                     CONDUCTIVITY = 0.027            $(BTU.FT/HR.FT^2.F)
                     DENSITY      = 0.6              $(LB/FT^3)
                     SPECIFIC-HEAT= .29  ..          $(BTU/LB.F)

BLOCK-CB35           = MATERIAL                      $DOE2.1E(MATERIALS LIBRARY)
                     THICKNESS    = 0.6667           $(FT)
                     CONDUCTIVITY = 0.2413           $(BTU.FT/HR.FT^2.F)
                     DENSITY      = 77               $(LB/FT^3)
                     SPECIFIC-HEAT= .20  ..          $(BTU/LB.F)
                                                     $8"
AIR-AL21              = MATERIAL                       $DOE2.1E(MATERIALS LIBRARY)
                     RESISTANCE   = .89  ..          $(HR.FT^2.F/BTU)

GYPSUM-BOARD         = MATERIAL                       $DOE2.1E(MATERIALS LIBRARY)
                     THICKNESS    = .0417             $(FT)
                     CONDUCTIVITY = .0926             $(BTU.FT/HR.FT^2.F)
                     DENSITY      = 50                $(LB/FT^3)
                     SPECIFIC-HEAT = .2   ..          $(BTU/LB.F), GP01

STUD1                = MATERIAL                       $DOE2.1E(MATERIALS LIBRARY)
                     THICKNESS    = .167             $(FT)
                     CONDUCTIVITY = .0667            $(BTU.FT/HR.FT^2.F)
                     DENSITY      = 32               $(LB/FT^3)
                     SPECIFIC-HEAT= .33  ..          $(BTU/LB.F)

WA-1 = LAYERS
       MATERIAL = (STUCCO-SC01, INSULATION-IN31,
                   BLOCK-CB35, AIR-AL21, GYPSUM-BOARD)  ..
              $ AIR Part of Wall
              $ STUCC0-SC01 - 1"
              $ INSULATION-IN31 - R-2.08
             $ BLOCK 8 INCH - PERLITE AND CONCRETE FILLED
             $ AIR-AL21 - FOR VERTICAL WALL
             $ GYPSUM-BOARD = Gypsum Board 1/2"
              $ The percentage of WA-1 = 87.5 %

WA-2 = LAYERS
       MATERIAL = (STUCCO-SC01, INSULATION-IN31,
                   BLOCK-CB35, STUD1, GYPSUM-BOARD)  ..
              $ STUD Part of Wall
              $ STUCC0-SC01 - 1"
              $ INSULATION-IN31 - R-2.08
             $ BLOCK 8 INCH - PERLITE AND CONCRETE FILLED
             $ STUD - 2*2"
             $ GYPSUM-BOARD = Gypsum Board 1/2"
              $ The percentage of WA-1 = 12.5 %

WALL-1    = CONSTRUCTION
            LAYERS = WA-1   ..

WALL-2    = CONSTRUCTION
            LAYERS = WA-2   ..
```

APPENDIX E

WINDOW-5 OUTPUT FILES

E.1. Single-Pane Clear Glass

E.2. Double-Pane Clear Glass

E.3. Double Pane Low-e Glass

This study investigated methods of modeling windows in the DOE-2 program: Window Library method and the Shading Coefficient (SC) method. In order to compare the differences between the two methods, Window-5 program was used to create three window types (single-pane clear, double-pane clear and double-pane low-e glass) which were explained in the section 4.3.6.8.

This section presents the window properties created by Window-5 program which were converted to WIN.DAT library in the DOE-2 program.

E.1. Single-Pane Clear Glass

```
Window 5.2a  v5.2.17a  DOE-2 Data File

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : SNG CLEAR(S.KIM
Window ID   : 1000
Tilt        : 90.0
Glazings    : 1
Frame       :  1 Al no break          10.790
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1500.0 mm
Total Width : 1200.0 mm
Glass Height: 1385.7 mm
Glass Width : 1085.7 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1              0       0      0      0      0      0       0      0       0
2              0       0      0      0      0      0       0      0       0
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  0.834 0.833 0.831 0.827 0.818 0.797 0.749 0.637 0.389 0.000 0.753
Abs1  0.091 0.092 0.094 0.096 0.100 0.104 0.108 0.110 0.105 0.000 0.101
Abs2      0     0     0     0     0     0     0     0     0     0     0
Abs3      0     0     0     0     0     0     0     0     0     0     0
Abs4      0     0     0     0     0     0     0     0     0     0     0
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol 0.075 0.075 0.075 0.077 0.082 0.099 0.143 0.253 0.506 1.000 0.136
Rbsol 0.075 0.075 0.075 0.077 0.082 0.099 0.143 0.253 0.506 1.000 0.136
Tvis  0.899 0.899 0.898 0.896 0.889 0.870 0.822 0.705 0.441 0.000 0.822
Rfvis 0.083 0.083 0.083 0.085 0.091 0.109 0.156 0.272 0.536 1.000 0.148
Rbvis 0.083 0.083 0.083 0.085 0.091 0.109 0.156 0.272 0.536 1.000 0.148
SHGC  0.858 0.858 0.857 0.853 0.844 0.825 0.778 0.667 0.418 0.000 0.780
SC: 0.92



Layer ID#          102        0        0        0        0        0
Tir              0.000        0        0        0        0        0
Emis F           0.840        0        0        0        0        0
Emis B           0.840        0        0        0        0        0
Thickness(mm)      3.0        0        0        0        0        0
Cond(W/m2-K     )328.1        0        0        0        0        0
Spectral File   CLEAR_3.DAT           None           None           None           None
None

Overall and Center of Glass Ig U-values (W/m2-K)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-K)
   0        0.00   4.00  3.54  7.16  3.63 3.63  3.67 3.67  3.75 3.75  4.11 4.11
   0        6.71  30.84  3.30  7.26  5.88 5.88  5.51 5.51  5.52 5.52  6.22 6.22
 783        0.00   4.00  3.64  7.08  3.63 3.63  3.67 3.67  3.75 3.75  4.11 4.11
 783        6.71  30.84  3.33  7.25  5.88 5.88  5.51 5.51  5.52 5.52  6.22 6.22
```

E.2. Double-Pane Clear Glass

```
Window 5.2a  v5.2.17a  DOE-2 Data File

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : DBL CLEAN(S.KIM
Window ID   : 2000
Tilt        : 90.0
Glazings    : 2
Frame       :  1 Al no break          10.790
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1500.0 mm
Total Width : 1200.0 mm
Glass Height: 1385.7 mm
Glass Width : 1085.7 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1 Air       12.0 0.02407  7.760  1.722  4.940  1.292 -0.0046  0.720 -0.0002
2              0       0      0      0      0      0       0      0       0
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  0.607 0.606 0.601 0.593 0.577 0.546 0.483 0.362 0.165 0.000 0.510
Abs1  0.167 0.168 0.170 0.175 0.182 0.190 0.200 0.209 0.202 0.000 0.185
Abs2  0.113 0.113 0.115 0.116 0.118 0.119 0.115 0.101 0.067 0.000 0.111
Abs3      0     0     0     0     0     0     0     0     0     0     0
Abs4      0     0     0     0     0     0     0     0     0     0     0
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol 0.114 0.114 0.114 0.115 0.123 0.145 0.201 0.328 0.566 1.000 0.184
Rbsol 0.114 0.114 0.114 0.115 0.123 0.145 0.201 0.328 0.566 1.000 0.184
Tvis  0.786 0.786 0.784 0.779 0.766 0.735 0.663 0.510 0.253 0.000 0.683
Rfvis 0.144 0.144 0.144 0.147 0.157 0.185 0.253 0.403 0.662 1.000 0.229
Rbvis 0.144 0.144 0.144 0.147 0.157 0.185 0.253 0.403 0.662 1.000 0.229
SHGC  0.700 0.699 0.697 0.690 0.676 0.647 0.584 0.455 0.236 0.000 0.605
SC: 0.76



Layer ID#          103      103        0        0        0        0
Tir              0.000    0.000        0        0        0        0
Emis F           0.840    0.840        0        0        0        0
Emis B           0.840    0.840        0        0        0        0
Thickness(mm)      5.7      5.7        0        0        0        0
Cond(W/m2-K     )175.0    175.0        0        0        0        0
Spectral File   CLEAR_6.DAT   CLEAR_6.DAT           None           None           None
None

Overall and Center of Glass Ig U-values (W/m2-K)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-K)
   0        0.00   4.00  3.39  7.00  2.12 2.12  2.24 2.24  2.32 2.32  2.48 2.48
   0        6.71  30.84  3.23  7.08  2.70 2.70  2.79 2.79  2.88 2.88  3.11 3.11
 783        0.00   4.00  3.71  6.39  2.12 2.12  2.24 2.24  2.32 2.32  2.48 2.48
 783        6.71  30.84  3.32  6.78  2.70 2.70  2.79 2.79  2.88 2.88  3.11 3.11
```

E.3. Double Pane Low-e Glass

```
Window 5.2a  v5.2.17a  DOE-2 Data File

Unit System : SI
Name        : DOE-2 WINDOW LIB
Desc        : DBL LOEW(S.KIM)
Window ID   : 2661
Tilt        : 90.0
Glazings    : 2
Frame       :  1 Al no break          10.790
Spacer      :  1 Class1                2.330  -0.010   0.138
Total Height: 1500.0 mm
Total Width : 1200.0 mm
Glass Height: 1385.7 mm
Glass Width : 1085.7 mm
Mullion     : None
Gap        Thick    Cond  dCond    Vis   dVis   Dens   dDens     Pr     dPr
1 Air       12.7 0.02407  7.760  1.722  4.940  1.292 -0.0046  0.720 -0.0002
2              0       0      0      0      0      0       0      0       0
3              0       0      0      0      0      0       0      0       0
4              0       0      0      0      0      0       0      0       0
5              0       0      0      0      0      0       0      0       0
Angle     0    10    20    30    40    50    60    70    80    90 Hemis
Tsol  0.408 0.410 0.404 0.395 0.383 0.362 0.316 0.230 0.106 0.000 0.338
Abs1  0.177 0.180 0.188 0.193 0.195 0.201 0.218 0.239 0.210 0.001 0.201
Abs2  0.060 0.060 0.061 0.061 0.063 0.063 0.061 0.053 0.038 0.000 0.059
Abs3      0     0     0     0     0     0     0     0     0     0     0
Abs4      0     0     0     0     0     0     0     0     0     0     0
Abs5      0     0     0     0     0     0     0     0     0     0     0
Abs6      0     0     0     0     0     0     0     0     0     0     0
Rfsol 0.355 0.350 0.348 0.350 0.359 0.374 0.405 0.478 0.646 0.999 0.392
Rbsol 0.289 0.285 0.283 0.282 0.285 0.296 0.328 0.411 0.594 1.000 0.322
Tvis  0.696 0.700 0.690 0.677 0.660 0.625 0.548 0.399 0.187 0.000 0.581
Rfvis 0.207 0.201 0.198 0.201 0.212 0.234 0.278 0.374 0.582 0.999 0.260
Rbvis 0.180 0.174 0.173 0.176 0.189 0.215 0.271 0.401 0.648 1.000 0.250
SHGC  0.469 0.471 0.466 0.458 0.448 0.427 0.381 0.291 0.152 0.000 0.399
SC: 0.54



Layer ID#          925      103        0        0        0        0
Tir              0.000    0.000        0        0        0        0
Emis F           0.840    0.840        0        0        0        0
Emis B           0.033    0.840        0        0        0        0
Thickness(mm)      3.2      5.7        0        0        0        0
Cond(W/m2-K     )315.0    175.0        0        0        0        0
Spectral File CMFTIR_3.AFG   CLEAR_6.DAT           None           None           None
None

Overall and Center of Glass Ig U-values (W/m2-K)
Outdoor Temperature                 -17.8 C      15.6 C      26.7 C      37.8 C
Solar      WdSpd  hcout hrout  hin
(W/m2)     (m/s)     (W/m2-K)
   0        0.00   4.00  3.31  6.86  1.37 1.37  1.35 1.35  1.38 1.38  1.44 1.44
   0        6.71  30.84  3.21  6.92  1.66 1.66  1.53 1.53  1.56 1.56  1.63 1.63
 783        0.00   4.00  3.63  6.33  1.37 1.37  1.35 1.35  1.38 1.38  1.44 1.44
 783        6.71  30.84  3.29  6.55  1.66 1.66  1.53 1.53  1.56 1.56  1.63 1.63
```

APPENDIX F

LV-H REPORT FROM DOE-2 SIMULATION

In order to verify that the same window thermal properties were simulated by the SC method and the Window-5 library method for window input mode test in the DOE-2 program, LV-H report from DOE-2 outputs was used to compare the window thermal properties from the SC method and the Window-5 library method.

This section presents LV-H reports of three different window types from the SC method and the Window-5 library method, which were explained in the section 4.3.6.8.

F.1. Single Pane Clear

WINDOW-5 METHOD

WINDOW NAME	MULTIPLIER	GLASS AREA (SQFT)	GLASS HEIGHT (FT)	GLASS WIDTH (FT)	LOCATION OF ORIGIN IN SURFACE COORDINATES X (FT)	Y (FT)	FRAME AREA (SQFT)	FRAME U-VALUE (BTU/HR-SQFT-F)
W-F-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-R-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-B-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-L-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905

WINDOW NAME	SETBACK (FT)	X-DIVISIONS	GLASS SHADING COEFF	NUMBER OF PANES	GLASS TYPE CODE	INFILTRATION FLOW COEFF	CENTER-OF-GLASS U-VALUE (BTU/HR-SQFT-F)	GLASS VISIBLE TRANS
W-F-1	0.00	10	0.92	1	1000	0.0	1.120	0.899
W-R-1	0.00	10	0.92	1	1000	0.0	1.120	0.899
W-B-1	0.00	10	0.92	1	1000	0.0	1.120	0.899
W-L-1	0.00	10	0.92	1	1000	0.0	1.120	0.899

SC METHOD

WINDOW NAME	MULTIPLIER	GLASS AREA (SQFT)	GLASS HEIGHT (FT)	GLASS WIDTH (FT)	LOCATION OF ORIGIN IN SURFACE COORDINATES X (FT)	Y (FT)	FRAME AREA (SQFT)	FRAME U-VALUE (BTU/HR-SQFT-F)
W-F-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-R-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-B-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-L-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905

WINDOW NAME	SETBACK (FT)	X-DIVISIONS	GLASS SHADING COEFF	NUMBER OF PANES	GLASS TYPE CODE	INFILTRATION FLOW COEFF	CENTER-OF-GLASS U-VALUE (BTU/HR-SQFT-F)	GLASS VISIBLE TRANS
W-F-1	0.00	10	0.92	1	1	0.0	1.120	0.899
W-R-1	0.00	10	0.92	1	1	0.0	1.120	0.899
W-B-1	0.00	10	0.92	1	1	0.0	1.120	0.899
W-L-1	0.00	10	0.92	1	1	0.0	1.120	0.899

F.2. Double Pane Clear

WINDOW-5 METHOD

WINDOW NAME	MULTIPLIER	GLASS AREA (SQFT)	GLASS HEIGHT (FT)	GLASS WIDTH (FT)	LOCATION OF ORIGIN IN SURFACE COORDINATES X (FT)	Y (FT)	FRAME AREA (SQFT)	FRAME U-VALUE (BTU/HR-SQFT-F)
W-F-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-R-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-B-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-L-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905

WINDOW NAME	SETBACK (FT)	X-DIVISIONS	GLASS SHADING COEFF	NUMBER OF PANES	GLASS TYPE CODE	INFILTRATION FLOW COEFF	CENTER-OF-GLASS U-VALUE (BTU/HR-SQFT-F)	GLASS VISIBLE TRANS
W-F-1	0.00	10	0.76	2	2000	0.0	0.497	0.786
W-R-1	0.00	10	0.76	2	2000	0.0	0.497	0.786
W-B-1	0.00	10	0.76	2	2000	0.0	0.497	0.786
W-L-1	0.00	10	0.76	2	2000	0.0	0.497	0.786

SC METHOD

WINDOW NAME	MULTIPLIER	GLASS AREA (SQFT)	GLASS HEIGHT (FT)	GLASS WIDTH (FT)	LOCATION OF ORIGIN IN SURFACE COORDINATES X (FT)	Y (FT)	FRAME AREA (SQFT)	FRAME U-VALUE (BTU/HR-SQFT-F)
W-F-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-R-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-B-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-L-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905

WINDOW NAME	SETBACK (FT)	X-DIVISIONS	GLASS SHADING COEFF	NUMBER OF PANES	GLASS TYPE CODE	INFILTRATION FLOW COEFF	CENTER-OF-GLASS U-VALUE (BTU/HR-SQFT-F)	GLASS VISIBLE TRANS
W-F-1	0.00	10	0.76	2	1	0.0	0.497	0.786
W-R-1	0.00	10	0.76	2	1	0.0	0.497	0.786
W-B-1	0.00	10	0.76	2	1	0.0	0.497	0.786
W-L-1	0.00	10	0.76	2	1	0.0	0.497	0.786

F.3. Double Pane Low-e

WINDOW-5 METHOD

WINDOW NAME	MULTIPLIER	GLASS AREA (SQFT)	GLASS HEIGHT (FT)	GLASS WIDTH (FT)	LOCATION OF ORIGIN IN SURFACE COORDINATES X (FT)	Y (FT)	FRAME AREA (SQFT)	FRAME U-VALUE (BTU/HR-SQFT-F)
W-F-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-R-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-B-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-L-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905

WINDOW NAME	SETBACK (FT)	X-DIVISIONS	GLASS SHADING COEFF	NUMBER OF PANES	GLASS TYPE CODE	INFILTRATION FLOW COEFF	CENTER-OF-GLASS U-VALUE (BTU/HR-SQFT-F)	GLASS VISIBLE TRANS
W-F-1	0.00	10	0.54	2	2661	0.0	0.302	0.696
W-R-1	0.00	10	0.54	2	2661	0.0	0.302	0.696
W-B-1	0.00	10	0.54	2	2661	0.0	0.302	0.696
W-L-1	0.00	10	0.54	2	2661	0.0	0.302	0.696

SC METHOD

WINDOW NAME	MULTIPLIER	GLASS AREA (SQFT)	GLASS HEIGHT (FT)	GLASS WIDTH (FT)	LOCATION OF ORIGIN IN SURFACE COORDINATES X (FT)	Y (FT)	FRAME AREA (SQFT)	FRAME U-VALUE (BTU/HR-SQFT-F)
W-F-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-R-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-B-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905
W-L-1	1.0	58.63	4.52	12.98	19.95	1.00	8.70	1.905

WINDOW NAME	SETBACK (FT)	X-DIVISIONS	GLASS SHADING COEFF	NUMBER OF PANES	GLASS TYPE CODE	INFILTRATION FLOW COEFF	CENTER-OF-GLASS U-VALUE (BTU/HR-SQFT-F)	GLASS VISIBLE TRANS
W-F-1	0.00	10	0.54	2	1	0.0	0.302	0.696
W-R-1	0.00	10	0.54	2	1	0.0	0.302	0.696
W-B-1	0.00	10	0.54	2	1	0.0	0.302	0.696
W-L-1	0.00	10	0.54	2	1	0.0	0.302	0.696

APPENDIX G

RESULTS OF THE SIMULATION RUNS FOR EFFICIENCY TEST

G.1. Fenestration simulation results

G.2. Duct simulation results

G.3. Air conditioner efficiency simulation results

G.4. Furnace efficiency simulation results

G.5. Heat pump efficiency simulation results

G.6. Domestic hot water heater efficiency simulation results

G.7. Duct location simulation results

G.8. Tree shading simulation results

Over 400 simulations using the IECC-compliant simulation model were performed to compare a base-case building with the same building modified by an energy efficiency strategy during this study.

For energy efficiency analysis, the DOE-2.1e (version 119) program was selected as the simulation program and the modified SNGFAM2ST.INP (version 1.20) was adopted as the DOE-2 simulation model. In order to perform the DOE-2 simulation in the batch mode, the Batch DOE-2 Input (BDI) (version 1.13) was used as explained at Chapter 4.3.5.3.

For the different climate zone simulations, four TMY2 weather data were used: 1) Amarillo TMY2 (climate zone 9), 2) Fort Worth TMY2 (climate zone 5), 3) Houston TMY2 (climate zone 4), and 4) Brownsville TMY2 (climate zone 2).

Following tables were used to present the results for the efficiency analysis using the 2000/2001 IECC-complaint simulation model in Chapter 6.4.

G.1. Fenestration simulation results

No	Location	SEER	AFUE(%)	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%	Duct Insulation	Duct Leakage	Ceiling R-value	ROOF R-value	Glazing U-factor	SHGC	TREE SHADING		Annual Other (mBtu/yr)	Annual DHW (mBtu/yr)	Annual Heating (mBtu/yr)	Annual Cooling (mBtu/yr)	Total (mBtu/yr)	Annual Heating+DHW (mBtu/yr)	Cooling Differ. (%)	Heating Differ. (%)	Total Differ. (%)
		IECC 2000	IECC 2000	ASHRAE 152-2004	ASHRAE 152-2004		ASHRAE 152-2004	IECC 2000	IECC 2000	IECC 2000	IECC 2000											
1	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	BASE CASE	33.14	29.3	42.82	13	118.26	47.2			
2	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.64	NO	SHGC-0.2	32.97	29.3	43.42	12.8	118.49	47.8	2.40%	-1.36%	-0.27%
3	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.62	NO	SHGC-0.4	32.99	29.3	44.02	12.5	118.81	48.4	0.00%	0.00%	0.00%
4	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.428	0.66	NO	ONLY U-VALUE	33.12	29.3	41.92	13.1	117.44	46.3	4.80%	-4.77%	-1.15%
5	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.428	0.64	NO	SHGC-0.2	33.04	29.3	42.52	12.8	117.66	46.9	2.40%	-3.41%	-0.97%
6	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.428	0.62	NO	SHGC-0.4	32.99	29.3	43.02	12.6	117.91	47.4	0.80%	-2.27%	-0.76%
7	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.405	0.66	NO	ONLY U-VALUE	33.07	29.3	41.02	13.2	116.59	45.4	5.60%	-6.82%	-1.87%
8	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.405	0.64	NO	SHGC-0.2	33.05	29.3	41.52	12.9	116.77	45.9	3.20%	-5.68%	-1.72%
9	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.405	0.62	NO	SHGC-0.4	33.1	29.3	42.02	12.6	117.02	46.4	0.80%	-4.54%	-1.51%
10	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.383	0.66	NO	ONLY U-VALUE	33.06	29.3	40.12	13.3	115.78	44.5	6.40%	-8.86%	-2.55%
11	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.383	0.64	NO	SHGC-0.2	33.04	29.3	40.62	13	115.96	45	4.00%	-7.72%	-2.40%
12	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.383	0.62	NO	SHGC-0.4	33.02	29.3	41.12	12.7	116.14	45.5	1.60%	-6.59%	-2.25%
13	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.36	0.66	NO	ONLY U-VALUE	33.11	29.3	39.12	13.3	114.83	43.5	6.40%	-11.13%	-3.35%
14	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.36	0.64	NO	SHGC-0.2	33.03	29.3	39.62	13.1	115.05	44	4.80%	-10.00%	-3.16%
15	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.36	0.62	NO	SHGC-0.4	33.04	29.3	40.12	12.8	115.26	44.5	2.40%	-8.86%	-2.99%
16	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	BASE CASE	32.72	24.8	18.42	15.9	91.84	22.8			
17	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.38	NO	SHGC-0.2	32.72	24.8	18.72	15.6	91.84	23.1	1.96%	-2.09%	0.02%
18	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.36	NO	SHGC-0.4	32.6	24.8	19.12	15.3	91.82	23.5	0.00%	0.00%	0.00%
19	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.618	0.4	NO	ONLY U-VALUE	32.69	24.8	17.82	16	91.31	22.2	4.58%	-6.80%	-0.56%
20	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.618	0.38	NO	SHGC-0.2	32.78	24.8	18.12	15.6	91.3	22.5	1.96%	-5.23%	-0.57%
21	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.618	0.36	NO	SHGC-0.4	32.69	24.8	18.52	15.3	91.31	22.9	0.00%	-3.14%	-0.56%
22	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.585	0.4	NO	ONLY U-VALUE	32.74	24.8	17.22	16	90.76	21.6	4.58%	-9.94%	-1.15%
23	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.585	0.38	NO	SHGC-0.2	32.75	24.8	17.52	15.7	90.77	21.9	2.61%	-8.37%	-1.14%
24	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.585	0.36	NO	SHGC-0.4	32.7	24.8	17.82	15.4	90.72	22.2	0.65%	-6.80%	-1.20%
25	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.555	0.4	NO	ONLY U-VALUE	32.77	24.8	16.62	16.1	90.29	21	5.23%	-13.08%	-1.67%
26	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.555	0.38	NO	SHGC-0.2	32.7	24.8	16.92	15.8	90.22	21.3	3.27%	-11.51%	-1.74%
27	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.555	0.36	NO	SHGC-0.4	32.59	24.8	17.32	15.5	90.21	21.7	1.31%	-9.41%	-1.75%
28	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.52	0.4	NO	ONLY U-VALUE	32.68	24.8	16.02	16.2	89.7	20.4	5.88%	-16.21%	-2.31%
29	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.52	0.38	NO	SHGC-0.2	32.62	24.8	16.32	15.9	89.64	20.7	3.92%	-14.64%	-2.37%
30	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.52	0.36	NO	SHGC-0.4	32.67	24.8	16.62	15.5	89.59	21	1.31%	-13.08%	-2.43%
31	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	BASE CASE	32.67	23.5	12.22	16.8	85.19	16.6			
32	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.38	NO	SHGC-0.2	32.57	23.5	12.52	16.5	85.09	16.9	1.85%	-1.57%	0.13%
33	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.36	NO	SHGC-0.4	32.56	23.5	12.72	16.2	84.98	17.1	0.00%	0.00%	0.00%
34	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.713	0.4	NO	ONLY U-VALUE	32.65	23.5	11.82	16.9	84.87	16.2	4.32%	-7.08%	-0.13%
35	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.713	0.38	NO	SHGC-0.2	32.61	23.5	12.02	16.6	84.73	16.4	2.47%	-5.50%	-0.29%
36	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.713	0.36	NO	SHGC-0.4	32.7	23.5	12.22	16.2	84.62	16.6	0.00%	-3.93%	-0.42%
37	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.675	0.4	NO	ONLY U-VALUE	32.65	23.5	11.32	17	84.47	15.7	4.94%	-11.01%	-0.60%
38	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.675	0.38	NO	SHGC-0.2	32.69	23.5	11.52	16.6	84.31	15.9	2.47%	-9.43%	-0.79%
39	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.675	0.36	NO	SHGC-0.4	32.6	23.5	11.82	16.3	84.22	16.2	0.62%	-7.08%	-0.89%
40	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.638	0.4	NO	ONLY U-VALUE	32.73	23.5	10.92	17	84.15	15.3	4.94%	-14.15%	-0.98%
41	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.638	0.38	NO	SHGC-0.2	32.65	23.5	11.12	16.7	83.97	15.5	3.09%	-12.58%	-1.19%
42	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.638	0.36	NO	SHGC-0.4	32.66	23.5	11.22	16.4	83.78	15.6	1.23%	-11.79%	-1.41%
43	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.6	0.4	NO	ONLY U-VALUE	32.77	23.5	10.32	17.1	83.69	14.7	5.56%	-18.87%	-1.52%
44	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.6	0.38	NO	SHGC-0.2	32.65	23.5	10.62	16.8	83.57	15	3.70%	-16.51%	-1.66%
45	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.6	0.36	NO	SHGC-0.4	32.62	23.5	10.82	16.5	83.44	15.2	1.85%	-14.94%	-1.81%
46	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	BASE CASE	33.02	21.5	6.92	22.4	83.84	11.3			
47	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.38	NO	SHGC-0.2	33.03	21.5	7.02	22	83.55	11.4	1.85%	-1.40%	0.35%
48	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.36	NO	SHGC-0.4	33.04	21.5	7.12	21.6	83.26	11.5	0.00%	0.00%	0.00%
49	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.855	0.4	NO	ONLY U-VALUE	33.06	21.5	6.72	22.4	83.68	11.1	3.70%	-5.62%	0.50%
50	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.855	0.38	NO	SHGC-0.2	32.95	21.5	6.82	22.1	83.37	11.2	2.31%	-4.21%	0.13%
51	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.855	0.36	NO	SHGC-0.4	32.95	21.5	6.92	21.7	83.07	11.3	0.46%	-2.81%	-0.23%
52	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.81	0.4	NO	ONLY U-VALUE	33.04	21.5	6.52	22.5	83.56	10.9	4.17%	-8.43%	0.36%
53	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.81	0.38	NO	SHGC-0.2	33.03	21.5	6.62	22.1	83.25	11	2.31%	-7.02%	-0.01%
54	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.81	0.36	NO	SHGC-0.4	32.98	21.5	6.62	21.8	82.9	11	0.93%	-7.02%	-0.43%
55	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.765	0.4	NO	ONLY U-VALUE	33.1	21.5	6.22	22.6	83.42	10.6	4.63%	-12.64%	0.19%
56	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.765	0.38	NO	SHGC-0.2	33.07	21.5	6.32	22.2	83.09	10.7	2.78%	-11.24%	-0.20%
57	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.765	0.36	NO	SHGC-0.4	33.06	21.5	6.42	21.8	82.78	10.8	0.93%	-9.83%	-0.58%
58	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.72	0.4	NO	ONLY U-VALUE	33.04	21.5	6.02	22.7	83.26	10.4	5.09%	-15.45%	0.00%
59	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.72	0.38	NO	SHGC-0.2	33.03	21.5	6.12	22.3	82.95	10.5	3.24%	-14.04%	-0.37%
60	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.72	0.36	NO	SHGC-0.4	33.04	21.5	6.22	21.9	82.66	10.6	1.39%	-12.64%	-0.72%

G.2. Duct simulation results

No	Location	SEER	AFUE(%)	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%	Duct Insulation	Duct Leakage	Ceiling R-value	Glazing U-factor	SHGC	TREE SHADING		Annual Other (mBtu/yr)	Annual DHW (mBtu/yr)	Annual Heating (mBtu/yr)	Annual Cooling (mBtu/yr)	Total (mBtu/yr)	Annual Heating+DHW (mBtu/yr)	Cooling Differ. (%)	Heating Differ. (%)	Total Differ. (%)
		IECC 2000	IECC 2000	ASHRAE 152-2004	ASHRAE 152-2004		ASHRAE 152-2004	IECC 2000	IECC 2000	IECC 2000											
1	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0	38	0.45	0.66	NO	S-8, R-4 (0%)	33.14	29.3	42.82	13	118.26	47.2			
2	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.05	38	0.45	0.66	NO	S-8, R-4 (5%)	33.11	29.3	46.62	13.9	122.93	51	6.92%	8.87%	3.95%
3	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	NO	S-8, R-4 (10%)	33.06	29.3	50.92	15	128.28	55.3	15.38%	18.92%	8.47%
4	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.15	38	0.45	0.66	NO	S-8, R-4 (15%)	33.14	29.3	55.82	16.2	134.46	60.2	24.62%	30.36%	13.70%
5	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.2	38	0.45	0.66	NO	S-8, R-4 (20%)	33.02	29.3	61.62	17.7	141.64	66	36.15%	43.90%	19.77%
6	Amarillo	10	78	746.17	124.36	SR-6,RR-6	0	38	0.45	0.66	NO	S-6, R-6 (0%)	33.01	29.3	43.72	13.6	119.63	48.1	4.62%	2.10%	1.16%
7	Amarillo	10	78	746.17	124.36	SR-6,RR-6	0.05	38	0.45	0.66	NO	S-6, R-6 (5%)	33.12	29.3	47.52	14.5	124.44	51.9	11.54%	10.98%	5.23%
8	Amarillo	10	78	746.17	124.36	SR-6,RR-6	0.1	38	0.45	0.66	NO	S-6, R-6 (10%)	33.14	29.3	51.92	15.6	129.96	56.3	20.00%	21.25%	9.89%
9	Amarillo	10	78	746.17	124.36	SR-6,RR-6	0.15	38	0.45	0.66	NO	S-6, R-6 (15%)	33.03	29.3	57.02	17	136.35	61.4	30.77%	33.16%	15.30%
10	Amarillo	10	78	746.17	124.36	SR-6,RR-6	0.2	38	0.45	0.66	NO	S-6, R-6 (20%)	33.06	29.3	62.92	18.5	143.78	67.3	42.31%	46.94%	21.58%
11	Amarillo	10	78	746.17	124.36	SR-8,RR-8	0	38	0.45	0.66	NO	S-8, R-8 (0%)	33.13	29.3	42.62	13	118.05	47	0.00%	-0.47%	-0.18%
12	Amarillo	10	78	746.17	124.36	SR-8,RR-8	0.05	38	0.45	0.66	NO	S-8, R-8 (5%)	33.08	29.3	46.42	13.9	122.7	50.8	6.92%	8.41%	3.75%
13	Amarillo	10	78	746.17	124.36	SR-8,RR-8	0.1	38	0.45	0.66	NO	S-8, R-8 (10%)	33.01	29.3	50.72	15	128.03	55.1	15.38%	18.45%	8.26%
14	Amarillo	10	78	746.17	124.36	SR-8,RR-8	0.15	38	0.45	0.66	NO	S-8, R-8 (15%)	33.06	29.3	55.62	16.2	134.18	60	24.62%	29.89%	13.46%
15	Amarillo	10	78	746.17	124.36	SR-8,RR-8	0.2	38	0.45	0.66	NO	S-8, R-8 (20%)	33.12	29.3	61.32	17.6	141.34	65.7	35.38%	43.20%	19.52%
16	Amarillo	10	78	746.17	124.36	SR-10,RR-10	0	38	0.45	0.66	NO	S-10, R-10 (0%)	33.01	29.3	42.12	12.7	117.13	46.5	-2.31%	-1.63%	-0.96%
17	Amarillo	10	78	746.17	124.36	SR-10,RR-10	0.05	38	0.45	0.66	NO	S-10, R-10 (5%)	33.07	29.3	45.72	13.6	121.69	50.1	4.62%	6.77%	2.90%
18	Amarillo	10	78	746.17	124.36	SR-10,RR-10	0.1	38	0.45	0.66	NO	S-10, R-10 (10%)	33.1	29.3	49.92	14.6	126.92	54.3	12.31%	16.58%	7.32%
19	Amarillo	10	78	746.17	124.36	SR-10,RR-10	0.15	38	0.45	0.66	NO	S-10, R-10 (15%)	33.02	29.3	54.82	15.8	132.94	59.2	21.54%	28.02%	12.41%
20	Amarillo	10	78	746.17	124.36	SR-10,RR-10	0.2	38	0.45	0.66	NO	S-10, R-10 (20%)	33.12	29.3	60.42	17.1	139.94	64.8	31.54%	41.10%	18.33%
21	Amarillo	10	78	746.17	124.36	SR-12,RR-12	0	38	0.45	0.66	NO	S-12, R-12 (0%)	33.02	29.3	41.72	12.5	116.54	46.1	-3.85%	-2.57%	-1.45%
22	Amarillo	10	78	746.17	124.36	SR-12,RR-12	0.05	38	0.45	0.66	NO	S-12, R-12 (5%)	33.12	29.3	45.32	13.3	121.04	49.7	2.31%	5.84%	2.35%
23	Amarillo	10	78	746.17	124.36	SR-12,RR-12	0.1	38	0.45	0.66	NO	S-12, R-12 (10%)	33.07	29.3	49.52	14.3	126.19	53.9	10.00%	15.65%	6.71%
24	Amarillo	10	78	746.17	124.36	SR-12,RR-12	0.15	38	0.45	0.66	NO	S-12, R-12 (15%)	33.01	29.3	54.32	15.5	132.13	58.7	19.23%	26.86%	11.73%
25	Amarillo	10	78	746.17	124.36	SR-12,RR-12	0.2	38	0.45	0.66	NO	S-12, R-12 (20%)	33.12	29.3	59.82	16.8	139.04	64.2	29.23%	39.70%	17.57%
26	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0	30	0.65	0.4	NO	S-8, R-4 (0%)	32.72	24.8	18.42	15.9	91.84	22.8			
27	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.05	30	0.65	0.4	NO	S-8, R-4 (5%)	32.7	24.8	19.92	17.8	95.22	24.3	11.95%	8.14%	3.68%
28	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	NO	S-8, R-4 (10%)	32.73	24.8	21.62	20.1	99.25	26	26.42%	17.37%	8.07%
29	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.15	30	0.65	0.4	NO	S-8, R-4 (15%)	32.71	24.8	23.62	23	104.13	28	44.65%	28.23%	13.38%
30	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.2	30	0.65	0.4	NO	S-8, R-4 (20%)	32.73	24.8	25.92	26.9	110.35	30.3	69.18%	40.72%	20.15%
31	Fort Worth	10	78	746.17	124.36	SR-6,RR-6	0	30	0.65	0.4	NO	S-6, R-6 (0%)	32.74	24.8	18.72	16.5	92.76	23.1	3.77%	1.63%	1.00%
32	Fort Worth	10	78	746.17	124.36	SR-6,RR-6	0.05	30	0.65	0.4	NO	S-6, R-6 (5%)	32.68	24.8	20.32	18.5	96.3	24.7	16.35%	10.31%	4.86%
33	Fort Worth	10	78	746.17	124.36	SR-6,RR-6	0.1	30	0.65	0.4	NO	S-6, R-6 (10%)	32.72	24.8	22.02	21	100.54	26.4	32.08%	19.54%	9.47%
34	Fort Worth	10	78	746.17	124.36	SR-6,RR-6	0.15	30	0.65	0.4	NO	S-6, R-6 (15%)	32.71	24.8	24.02	24.2	105.73	28.4	52.20%	30.40%	15.12%
35	Fort Worth	10	78	746.17	124.36	SR-6,RR-6	0.2	30	0.65	0.4	NO	S-6, R-6 (20%)	32.74	24.8	26.32	28.8	112.66	30.7	81.13%	42.89%	22.67%
36	Fort Worth	10	78	746.17	124.36	SR-8,RR-8	0	30	0.65	0.4	NO	S-8, R-8 (0%)	32.8	24.8	18.32	15.8	91.72	22.7	-0.63%	-0.54%	-0.13%
37	Fort Worth	10	78	746.17	124.36	SR-8,RR-8	0.05	30	0.65	0.4	NO	S-8, R-8 (5%)	32.67	24.8	19.92	17.7	95.09	24.3	11.32%	8.14%	3.54%
38	Fort Worth	10	78	746.17	124.36	SR-8,RR-8	0.1	30	0.65	0.4	NO	S-8, R-8 (10%)	32.68	24.8	21.62	20	99.1	26	25.79%	17.37%	7.91%
39	Fort Worth	10	78	746.17	124.36	SR-8,RR-8	0.15	30	0.65	0.4	NO	S-8, R-8 (15%)	32.73	24.8	23.52	22.9	103.95	27.9	44.03%	27.69%	13.19%
40	Fort Worth	10	78	746.17	124.36	SR-8,RR-8	0.2	30	0.65	0.4	NO	S-8, R-8 (20%)	32.68	24.8	25.82	26.8	110.1	30.2	68.55%	40.17%	19.88%
41	Fort Worth	10	78	746.17	124.36	SR-10,RR-10	0	30	0.65	0.4	NO	S-10, R-10 (0%)	32.71	24.8	18.12	15.5	91.13	22.5	-2.52%	-1.63%	-0.77%
42	Fort Worth	10	78	746.17	124.36	SR-10,RR-10	0.05	30	0.65	0.4	NO	S-10, R-10 (5%)	32.79	24.8	19.62	17.2	94.41	24	8.18%	6.51%	2.80%
43	Fort Worth	10	78	746.17	124.36	SR-10,RR-10	0.1	30	0.65	0.4	NO	S-10, R-10 (10%)	32.76	24.8	21.32	19.4	98.28	25.7	22.01%	15.74%	7.01%
44	Fort Worth	10	78	746.17	124.36	SR-10,RR-10	0.15	30	0.65	0.4	NO	S-10, R-10 (15%)	32.64	24.8	23.32	22.2	102.96	27.7	39.62%	26.60%	12.11%
45	Fort Worth	10	78	746.17	124.36	SR-10,RR-10	0.2	30	0.65	0.4	NO	S-10, R-10 (20%)	32.68	24.8	25.52	25.8	108.8	29.9	62.26%	38.55%	18.47%
46	Fort Worth	10	78	746.17	124.36	SR-12,RR-12	0	30	0.65	0.4	NO	S-12, R-12 (0%)	32.72	24.8	18.02	15.2	90.74	22.4	-4.40%	-2.17%	-1.20%
47	Fort Worth	10	78	746.17	124.36	SR-12,RR-12	0.05	30	0.65	0.4	NO	S-12, R-12 (5%)	32.74	24.8	19.52	16.9	93.96	23.9	6.29%	5.97%	2.31%
48	Fort Worth	10	78	746.17	124.36	SR-12,RR-12	0.1	30	0.65	0.4	NO	S-12, R-12 (10%)	32.64	24.8	21.22	19.1	97.76	25.6	20.13%	15.20%	6.45%
49	Fort Worth	10	78	746.17	124.36	SR-12,RR-12	0.15	30	0.65	0.4	NO	S-12, R-12 (15%)	32.7	24.8	23.12	21.7	102.32	27.5	36.48%	25.52%	11.41%
50	Fort Worth	10	78	746.17	124.36	SR-12,RR-12	0.2	30	0.65	0.4	NO	S-12, R-12 (20%)	32.66	24.8	25.32	25.2	107.98	29.7	58.49%	37.46%	17.57%
51	Houston	10	78	746.17	124.36	SR-8,RR-4	0	26	0.75	0.4	NO	S-8, R-4 (0%)	32.67	23.5	12.22	16.8	85.19	16.6			
52	Houston	10	78	746.17	124.36	SR-8,RR-4	0.05	26	0.75	0.4	NO	S-8, R-4 (5%)	32.68	23.5	13.22	19.1	88.5	17.6	13.69%	8.18%	3.89%
53	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	NO	S-8, R-4 (10%)	32.72	23.5	14.42	21.9	92.54	18.8	30.36%	18.00%	8.63%
54	Houston	10	78	746.17	124.36	SR-8,RR-4	0.15	26	0.75	0.4	NO	S-8, R-4 (15%)	32.69	23.5	15.72	25.7	97.61	20.1	52.98%	28.64%	14.58%
55	Houston	10	78	746.17	124.36	SR-8,RR-4	0.2	26	0.75	0.4	NO	S-8, R-4 (20%)	32.66	23.5	17.32	30.8	104.28	21.7	83.33%	41.73%	22.41%
56	Houston	10	78	746.17	124.36	SR-6,RR-6	0	26	0.75	0.4	NO	S-6, R-6 (0%)	32.65	23.5	12.42	17.5	86.07	16.8	4.17%	1.64%	1.03%
57	Houston	10	78	746.17	124.36	SR-6,RR-6	0.05	26	0.75	0.4	NO	S-6, R-6 (5%)	32.63	23.5	13.52	19.9	89.55	17.9	18.45%	10.64%	5.12%
58	Houston	10	78	746.17	124.36	SR-6,RR-6	0.1	26	0.75	0.4	NO	S-6, R-6 (10%)	32.73	23.5	14.62	23	93.85	19	36.90%	19.64%	10.17%
59	Houston	10	78	746.17	124.36	SR-6,RR-6	0.15	26	0.75	0.4	NO	S-6, R-6 (15%)	32.7	23.5	16.02	27.1	99.32	20.4	61.31%	31.10%	16.59%
60	Houston	10	78	746.17	124.36	SR-6,RR-6	0.2	26	0.75	0.4	NO	S-6, R-6 (20%)	32.66	23.5	17.62	32.9	106.68	22	95.83%	44.19%	25.23%
61	Houston	10	78	746.17	124.36	SR-8,RR-8	0	26	0.75	0.4	NO	S-8, R-8 (0%)	32.68	23.5	12.22	16.7	85.1	16.6	-0.60%	0.00%	-0.11%
62	Houston	10	78	746.17	124.36	SR-8,RR-8	0.05	26	0.75	0.4	NO	S-8, R-8 (5%)	32.67	23.5	13.22	19	88.39	17.6	13.10%	8.18%	3.76%
63	Houston	10	78	746.17	124.36	SR-8,RR-8	0.1	26	0.75	0.4	NO	S-8, R-8 (10%)	32.7	23.5	14.32	21.9	92.42	18.7	30.36%	17.18%	8.49%
64	Houston	10	78	746.17	124.36	SR-8,RR-8	0.15	26	0.75	0.4	NO	S-8, R-8 (15%)	32.64	23.5	15.72	25.6	97.46	20.1	52.38%	28.64%	14.40%
65	Houston	10	78	746.17	124.36	SR-8,RR-8	0.2	26	0.75	0.4	NO	S-8, R-8 (20%)	32.66	23.5	17.22	30.7	104.08	21.6	82.74%	40.92%	22.17%
66	Houston	10	78	746.17	124.36	SR-10,RR-10	0	26	0.75	0.4	NO	S-10, R-10 (0%)	32.73	23.5	12.02	16.3	84.55	16.4	-2.98%	-1.64%	-0.75%
67	Houston	10	78	746.17	124.36	SR-10,RR-10	0.05	26	0.75	0.4	NO	S-10, R-10 (5%)	32.72	23.5	13.02	18.5	87.74	17.4	10.12%	6.55%	2.99%
68	Houston	10	78	746.17	124.36	SR-10,RR-10	0.1	26	0.75	0.4	NO	S-10, R-10 (10%)	32.69	23.5	14.22	21.2	91.61	18.6	26.19%	16.37%	7.54%
69	Houston	10	78	746.17	124.36	SR-10,RR-10	0.15	26	0.75	0.4	NO	S-10, R-10 (15%)	32.71	23.5	15.52	24.7	96.43	19.9	47.02%	27.00%	13.19%
70	Houston	10	78	746.17	124.36	SR-10,RR-10	0.2	26	0.75	0.4	NO	S-10, R-10 (20%)	32.66	23.5	17.02	29.5	102.68	21.4	75.60%	39.28%	20.53%
71	Houston	10	78	746.17	124.36	SR-12,RR-12	0	26	0.75	0.4	NO	S-12, R-12 (0%)	32.68	23.5	11.92	16.1	84.2	16.3	-4.17%	-2.45%	-1.16%
72	Houston	10	78	746.17	124.36	SR-12,RR-12	0.05	26	0.75	0.4	NO	S-12, R-12 (5%)	32.69	23.5	12.92	18.2	87.31	17.3	8.33%	5.73%	2.49%
73	Houston	10	78	746.17	124.36	SR-12,RR-12	0.1	26	0.75	0.4	NO	S-12, R-12 (10%)	32.67	23.5	14.12	20.8	91.09	18.5	23.81%	15.55%	6.93%
74	Houston	10	78	746.17	124.36	SR-12,RR-12	0.15	26	0.75	0.4	NO	S-12, R-12 (15%)	32.66	23.5	15.42	24.2	95.78	19.8	44.05%	26.19%	12.43%
75	Houston	10	78	746.17	124.36	SR-12,RR-12	0.2	26	0.75	0.4	NO	S-12, R-12 (20%)	32.59	23.5	16.92	28.8	101.81	21.3	71.43%	38.46%	19.51%
76	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0	19	0.9	0.4	NO	S-8, R-4 (0%)	33.02	21.5	6.92	22.4	83.84	11.3			
77	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.05	19	0.9	0.4	NO	S-8, R-4 (5%)	33.07	21.5	7.42	25.4	87.39	11.8	13.39%	7.23%	4.23%
78	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	NO	S-8, R-4 (10%)	33.04	21.5	8.02	29.2	91.76	12.4	30.36%	15.90%	9.45%
79	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.15	19	0.9	0.4	NO	S-8, R-4 (15%)	33.13	21.5	8.62	34	97.25	13	51.79%	24.57%	15.99%
80	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.2	19	0.9	0.4	NO	S-8, R-4 (20%)	33.06	21.5	9.42	40.4	104.38	13.8	80.36%	36.13%	24.50%
81	Brownsville	10	78	746.17	124.36	SR-6,RR-6	0	19	0.9	0.4	NO	S-6, R-6 (0%)	33.08	21.5	7.02	23.2	84.8	11.4	3.57%	1.45%	1.15%
82	Brownsville	10	78	746.17	124.36	SR-6,RR-6	0.05	19	0.9	0.4	NO	S-6, R-6 (5%)	33.04	21.5	7.52	26.5	88.56	11.9	18.30%	8.67%	5.63%
83	Brownsville	10	78	746.17	124.36	SR-6,RR-6	0.1	19	0.9	0.4	NO	S-6, R-6 (10%)	33.1	21.5	8.12	30.5	93.22	12.5	36.16%	17.34%	11.19%
84	Brownsville	10	78	746.17	124.36	SR-6,RR-6	0.15	19	0.9	0.4	NO	S-6, R-6 (15%)	33.02	21.5	8.82	35.8	99.14	13.2	59.82%	27.46%	18.25%
85	Brownsville	10	78	746.17	124.36	SR-6,RR-6	0.2	19	0.9	0.4	NO	S-6, R-6 (20%)	33.11	21.5	9.52	42.8	106.93	13.9	91.07%	37.57%	27.54%
86	Brownsville	10	78	746.17	124.36	SR-8,RR-8	0	19	0.9	0.4	NO	S-8, R-8 (0%)	33.05	21.5	6.92	22.3	83.77	11.3	-0.45%	0.00%	-0.08%
87	Brownsville	10	78	746.17	124.36	SR-8,RR-8	0.05	19	0.9	0.4	NO	S-8, R-8 (5%)	33.09	21.5	7.42	25.3	87.31	11.8	12.95%	7.23%	4.14%
88	Brownsville	10	78	746.17	124.36	SR-8,RR-8	0.1	19	0.9	0.4	NO	S-8, R-8 (10%)	33.04	21.5	8.02	29.1	91.66	12.4	29.91%	15.90%	9.33%
89	Brownsville	10	78	746.17	124.36	SR-8,RR-8	0.15	19	0.9	0.4	NO	S-8, R-8 (15%)	33.12	21.5	8.62	33.9	97.14	13	51.34%	24.57%	15.86%
90	Brownsville	10	78	746.17	124.36	SR-8,RR-8	0.2	19	0.9	0.4	NO	S-8, R-8 (20%)	33.01	21.5	9.42	40.3	104.23	13.8	79.91%	36.13%	24.32%
91	Brownsville	10	78	746.17	124.36	SR-10,RR-10	0	19	0.9	0.4	NO	S-10, R-10 (0%)	33.07	21.5	6.82	21.8	83.19	11.2	-2.68%	-1.45%	-0.78%
92	Brownsville	10	78	746.17	124.36	SR-10,RR-10	0.05	19	0.9	0.4	NO	S-10, R-10 (5%)	33.08	21.5	7.32	24.7	86.6	11.7	10.27%	5.78%	3.29%
93	Brownsville	10	78	746.17	124.36	SR-10,RR-10	0.1	19	0.9	0.4	NO	S-10, R-10 (10%)	33.07	21.5	7.92	28.3	90.79	12.3	26.34%	14.45%	8.29%
94	Brownsville	10	78	746.17	124.36	SR-10,RR-10	0.15	19	0.9	0.4	NO	S-10, R-10 (15%)	33.1	21.5	8.52	32.9	96.02	12.9	46.88%	23.12%	14.53%
95	Brownsville	10	78	746.17	124.36	SR-10,RR-10	0.2	19	0.9	0.4	NO	S-10, R-10 (20%)	33.03	21.5	9.32	38.9	102.75	13.7	73.66%	34.68%	22.55%
96	Brownsville	10	78	746.17	124.36	SR-12,RR-12	0	19	0.9	0.4	NO	S-12, R-12 (0%)	32.99	21.5	6.82	21.5	82.81	11.2	-4.02%	-1.45%	-1.23%
97	Brownsville	10	78	746.17	124.36	SR-12,RR-12	0.05	19	0.9	0.4	NO	S-12, R-12 (5%)	33.03	21.5	7.32	24.3	86.15	11.7	8.48%	5.78%	2.76%
98	Brownsville	10	78	746.17	124.36	SR-12,RR-12	0.1	19	0.9	0.4	NO	S-12, R-12 (10%)	33.1	21.5	7.82	27.8	90.22	12.2	24.11%	13.01%	7.61%
99	Brownsville	10	78	746.17	124.36	SR-12,RR-12	0.15	19	0.9	0.4	NO	S-12, R-12 (15%)	32.98	21.5	8.52	32.3	95.3	12.9	44.20%	23.12%	13.67%
100	Brownsville	10	78	746.17	124.36	SR-12,RR-12	0.2	19	0.9	0.4	NO	S-12, R-12 (20%)	33.09	21.5	9.22	38	101.81	13.6	69.64%	33.24%	21.43%

G.3. Air conditioner efficiency simulation results

No	Location	SEER	AFUE(%)	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%	Duct Insulation	Duct Leakage	Ceiling R-value	ROOF R-value	Glazing U-factor	SHGC	TREE SHADING		Annual Other (mBtu/yr)	Annual DHW (mBtu/yr)	Annual Heating (mBtu/yr)	Annual Cooling (mBtu/yr)	Total (mBtu/yr)	Annual Heating+DHW (mBtu/yr)	Cooling Differ. (%)	Heating Differ. (%)	Total Differ. (%)
		IECC 2000	IECC 2000	ASHRAE 152-2004	ASHRAE 152-2004		ASHRAE 152-2004	IECC 2000	IECC 2000	IECC 2000	IECC 2000											
1	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	10 (BASE CASE)	33.06	29.3	50.92	15	128.28	55.3			
2	Amarillo	11	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	11	33.1	29.3	50.92	13.6	126.92	55.3	8.80%	0.00%	0.91%
3	Amarillo	12	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	12	33.06	29.3	50.92	12.5	125.78	55.3	0.00%	0.00%	0.00%
4	Amarillo	13	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	13	33.1	29.3	50.92	11.5	124.82	55.3	-8.00%	0.00%	-0.76%
5	Amarillo	14	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	14	33.08	29.3	50.92	10.7	124	55.3	-14.40%	0.00%	-1.42%
6	Amarillo	15	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	15	33.06	29.3	50.92	10	123.28	55.3	-20.00%	0.00%	-1.99%
7	Amarillo	16	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	16	33.04	29.3	50.92	9.4	122.66	55.3	-24.80%	0.00%	-2.48%
8	Amarillo	17	78	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	17	33.09	29.3	50.92	8.8	122.11	55.3	-29.60%	0.00%	-2.92%
9	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	10 (BASE CASE)	32.73	24.8	21.62	20.1	99.25	26			
10	Fort Worth	11	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	11	32.8	24.8	21.62	18.2	97.42	26	8.98%	0.00%	1.58%
11	Fort Worth	12	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	12	32.78	24.8	21.62	16.7	95.9	26	0.00%	0.00%	0.00%
12	Fort Worth	13	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	13	32.8	24.8	21.62	15.4	94.62	26	-7.78%	0.00%	-1.33%
13	Fort Worth	14	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	14	32.8	24.8	21.62	14.3	93.52	26	-14.37%	0.00%	-2.48%
14	Fort Worth	15	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	15	32.74	24.8	21.62	13.4	92.56	26	-19.76%	0.00%	-3.48%
15	Fort Worth	16	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	16	32.8	24.8	21.62	12.5	91.72	26	-25.15%	0.00%	-4.36%
16	Fort Worth	17	78	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	17	32.77	24.8	21.62	11.8	90.99	26	-29.34%	0.00%	-5.12%
17	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	10 (BASE CASE)	32.72	23.5	14.42	21.9	92.54	18.8			
18	Houston	11	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	11	32.62	23.5	14.42	20	90.54	18.8	9.29%	0.00%	1.87%
19	Houston	12	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	12	32.66	23.5	14.42	18.3	88.88	18.8	0.00%	0.00%	0.00%
20	Houston	13	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	13	32.65	23.5	14.42	16.9	87.47	18.8	-7.65%	0.00%	-1.59%
21	Houston	14	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	14	32.65	23.5	14.42	15.7	86.27	18.8	-14.21%	0.00%	-2.94%
22	Houston	15	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	15	32.7	23.5	14.42	14.6	85.22	18.8	-20.22%	0.00%	-4.12%
23	Houston	16	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	16	32.69	23.5	14.42	13.7	84.31	18.8	-25.14%	0.00%	-5.14%
24	Houston	17	78	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	17	32.68	23.5	14.42	12.9	83.5	18.8	-29.51%	0.00%	-6.05%
25	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	10 (BASE CASE)	33.04	21.5	8.02	29.2	91.76	12.4			
26	Brownsville	11	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	11	33.09	21.5	8.02	26.5	89.11	12.4	9.05%	0.00%	2.55%
27	Brownsville	12	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	12	33.07	21.5	8.02	24.3	86.89	12.4	0.00%	0.00%	0.00%
28	Brownsville	13	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	13	33	21.5	8.02	22.5	85.02	12.4	-7.41%	0.00%	-2.15%
29	Brownsville	14	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	14	33	21.5	8.02	20.9	83.42	12.4	-13.99%	0.00%	-3.99%
30	Brownsville	15	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	15	33.01	21.5	8.02	19.5	82.03	12.4	-19.75%	0.00%	-5.59%
31	Brownsville	16	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	16	33.09	21.5	8.02	18.2	80.81	12.4	-25.10%	0.00%	-7.00%
32	Brownsville	17	78	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	17	33.02	21.5	8.02	17.2	79.74	12.4	-29.22%	0.00%	-8.23%

G.4. Furnace efficiency simulation results

No	Location	SEER	AFUE(%)	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%	Duct Insulation	Duct Leakage	Ceiling R-value	Glazing U-factor	SHGC	TREE SHADING		Annual Other (mBtu/yr)	Annual DHW (mBtu/yr)	Annual Heating (mBtu/yr)	Annual Cooling (mBtu/yr)	Total (mBtu/yr)	Peak Cooling (kWh/day), 08/19	Peak Cooling (kWh/h), 08/19 16:00	Annual Cooling (kWh/yr)	Annual Heating (Therm/yr)	Annual Heating+DHW (mBtu/yr)	Cooling Differ. (%)	Heating Differ. (%)	Total Differ. (%)
		IECC 2000	IECC 2000	ASHRAE 152-2004	ASHRAE 152-2004		ASHRAE 152-2004	IECC 2000	IECC 2000	IECC 2000															
1	Amarillo	10	0.60	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	NO	0.60	33.06	29.3	66.22	15	143.58	2.192	20.351	4394	706	70.6	0.00%	41.74%	15.72%
2	Amarillo	10	0.65	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	NO	0.65	33.06	29.3	61.12	15	138.48	2.192	20.351	4394	655	65.5	0.00%	30.82%	11.61%
3	Amarillo	10	0.70	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	NO	0.70	33.09	29.3	56.72	15	134.11	2.192	20.351	4394	611	61.1	0.00%	21.40%	8.08%
4	Amarillo	10	0.75	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	NO	0.75	33.1	29.3	52.92	15	130.32	2.192	20.351	4394	573	57.3	0.00%	13.27%	5.03%
5	Amarillo	10	0.78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	NO	0.78 (BASE CASE)	33.06	29.3	50.92	15	128.28	2.192	20.351	4394	553	55.3			
6	Amarillo	10	0.80	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	NO	0.80	33.09	29.3	49.62	15	127.01	2.192	20.351	4394	540	54	0.00%	6.21%	2.36%
7	Amarillo	10	0.85	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	NO	0.85	33.06	29.3	46.72	15	124.08	2.192	20.351	4394	511	51.1	0.00%	0.00%	0.00%
8	Amarillo	10	0.90	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	NO	0.90	33.06	29.3	44.12	15	121.48	2.192	20.351	4394	485	48.5	0.00%	-5.57%	-2.10%
9	Fort Worth	10	0.60	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	NO	0.60	32.63	24.8	28.22	20.1	105.75	3.911	50.757	5876	326	32.6	0.00%	41.67%	8.51%
10	Fort Worth	10	0.65	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	NO	0.65	32.66	24.8	26.02	20.1	103.58	3.911	50.757	5876	304	30.4	0.00%	30.62%	6.28%
11	Fort Worth	10	0.70	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	NO	0.70	32.71	24.8	24.12	20.1	101.73	3.911	50.757	5876	285	28.5	0.00%	21.08%	4.38%
12	Fort Worth	10	0.75	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	NO	0.75	32.69	24.8	22.52	20.1	100.11	3.911	50.757	5876	269	26.9	0.00%	13.05%	2.72%
13	Fort Worth	10	0.78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	NO	0.78 (BASE CASE)	32.73	24.8	21.62	20.1	99.25	3.911	50.757	5876	260	26			
14	Fort Worth	10	0.80	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	NO	0.80	32.68	24.8	21.12	20.1	98.7	3.911	50.757	5876	255	25.5	0.00%	6.02%	1.27%
15	Fort Worth	10	0.85	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	NO	0.85	32.64	24.8	19.92	20.1	97.46	3.911	50.757	5876	243	24.3	0.00%	0.00%	0.00%
16	Fort Worth	10	0.90	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	NO	0.90	32.63	24.8	18.82	20.1	96.35	3.911	50.757	5876	232	23.2	0.00%	-5.52%	-1.14%
17	Houston	10	0.60	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	NO	0.60	32.75	23.5	18.72	21.9	96.87	3.41	43.162	6430	231	23.1	0.00%	41.60%	6.04%
18	Houston	10	0.65	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	NO	0.65	32.7	23.5	17.32	21.9	95.42	3.41	43.162	6430	217	21.7	0.00%	31.01%	4.46%
19	Houston	10	0.70	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	NO	0.70	32.77	23.5	16.02	21.9	94.19	3.41	43.162	6430	204	20.4	0.00%	21.18%	3.11%
20	Houston	10	0.75	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	NO	0.75	32.7	23.5	15.02	21.9	93.12	3.41	43.162	6430	194	19.4	0.00%	13.62%	1.94%
21	Houston	10	0.78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	NO	0.78 (BASE CASE)	32.72	23.5	14.42	21.9	92.54	3.41	43.162	6430	188	18.8			
22	Houston	10	0.80	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	NO	0.80	32.76	23.5	14.02	21.9	92.18	3.41	43.162	6430	184	18.4	0.00%	6.05%	0.91%
23	Houston	10	0.85	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	NO	0.85	32.73	23.5	13.22	21.9	91.35	3.41	43.162	6430	176	17.6	0.00%	0.00%	0.00%
24	Houston	10	0.90	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	NO	0.90	32.69	23.5	12.52	21.9	90.61	3.41	43.162	6430	169	16.9	0.00%	-5.30%	-0.81%
25	Brownsville	10	0.60	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	NO	0.60	33.05	21.5	10.42	29.2	94.17	4.323	54.438	8555	148	14.8	0.00%	42.35%	3.37%
26	Brownsville	10	0.65	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	NO	0.65	33.04	21.5	9.62	29.2	93.36	4.323	54.438	8555	140	14	0.00%	31.42%	2.48%
27	Brownsville	10	0.70	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	NO	0.70	33.06	21.5	8.92	29.2	92.68	4.323	54.438	8555	133	13.3	0.00%	21.86%	1.73%
28	Brownsville	10	0.75	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	NO	0.75	33.06	21.5	8.32	29.2	92.08	4.323	54.438	8555	127	12.7	0.00%	13.66%	1.08%
29	Brownsville	10	0.78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	NO	0.78 (BASE CASE)	33.04	21.5	8.02	29.2	91.76	4.323	54.438	8555	124	12.4			
30	Brownsville	10	0.80	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	NO	0.80	33.04	21.5	7.82	29.2	91.56	4.323	54.438	8555	122	12.2	0.00%	6.83%	0.50%
31	Brownsville	10	0.85	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	NO	0.85	33.08	21.5	7.32	29.2	91.1	4.323	54.438	8555	117	11.7	0.00%	0.00%	0.00%
32	Brownsville	10	0.90	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	NO	0.90	33.07	21.5	6.92	29.2	90.69	4.323	54.438	8555	113	11.3	0.00%	-5.46%	-0.45%

G.5. Heat pump efficiency simulation results

No	Location	SEER	HSPF	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%	Duct Insulation	Duct Leakage	Ceiling R-value	ROOF R-value	Glazing U-factor	SHGC	TREE SHADING		Annual Other (mBtu/yr)	Annual DHW (mBtu/yr)	Annual Heating (mBtu/yr)	Annual Cooling (mBtu/yr)	Total (mBtu/yr)	Cooling Differ. (%)	Heating Differ. (%)	Total Differ. (%)
		IECC 2000	IECC 2000	ASHRAE 152-2004	ASHRAE 152-2004		ASHRAE 152-2004	IECC 2000	IECC 2000	IECC 2000	IECC 2000										
1	Amarillo	10	5.00	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	5.0	28.85	29.3	57.7	15	130.85	0.00%	35.45%	13.06%
2	Amarillo	10	5.50	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	5.5	28.93	29.3	53.5	15	126.73	0.00%	25.59%	9.50%
3	Amarillo	10	6.00	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	6.0	28.89	29.3	50.1	15	123.29	0.00%	17.61%	6.53%
4	Amarillo	10	6.50	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	6.5	28.88	29.3	47.2	15	120.38	0.00%	10.80%	4.02%
5	Amarillo	10	6.80	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	6.8 (BASE CASE)	28.85	29.3	45.7	15	118.85			
6	Amarillo	10	7.00	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	7.0	28.89	29.3	44.7	15	117.89	0.00%	4.93%	1.87%
7	Amarillo	10	7.50	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	7.5	28.83	29.3	42.6	15	115.73	0.00%	0.00%	0.00%
8	Amarillo	10	8.00	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	8.0	28.84	29.3	40.7	15	113.84	0.00%	-4.46%	-1.63%
9	Fort Worth	10	5.00	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	5.0	28.32	24.8	25.5	20.1	98.72	0.00%	39.34%	7.82%
10	Fort Worth	10	5.50	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	5.5	28.37	24.8	23.5	20.1	96.77	0.00%	28.42%	5.69%
11	Fort Worth	10	6.00	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	6.0	28.34	24.8	21.9	20.1	95.14	0.00%	19.67%	3.91%
12	Fort Worth	10	6.50	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	6.5	28.36	24.8	20.5	20.1	93.76	0.00%	12.02%	2.40%
13	Fort Worth	10	6.80	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	6.8 (BASE CASE)	28.33	24.8	19.8	20.1	93.03			
14	Fort Worth	10	7.00	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	7.0	28.28	24.8	19.4	20.1	92.58	0.00%	6.01%	1.11%
15	Fort Worth	10	7.50	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	7.5	28.36	24.8	18.3	20.1	91.56	0.00%	0.00%	0.00%
16	Fort Worth	10	8.00	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	8.0	28.36	24.8	17.4	20.1	90.66	0.00%	-4.92%	-0.98%
17	Houston	10	5.00	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	5.0	28.33	23.5	17.6	21.9	91.33	0.00%	38.58%	5.64%
18	Houston	10	5.50	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	5.5	28.4	23.5	16.2	21.9	90	0.00%	27.56%	4.11%
19	Houston	10	6.00	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	6.0	28.39	23.5	15.1	21.9	88.89	0.00%	18.90%	2.82%
20	Houston	10	6.50	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	6.5	28.35	23.5	14.2	21.9	87.95	0.00%	11.81%	1.74%
21	Houston	10	6.80	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	6.8 (BASE CASE)	28.35	23.5	13.7	21.9	87.45			
22	Houston	10	7.00	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	7.0	28.34	23.5	13.4	21.9	87.14	0.00%	5.51%	0.80%
23	Houston	10	7.50	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	7.5	28.35	23.5	12.7	21.9	86.45	0.00%	0.00%	0.00%
24	Houston	10	8.00	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	8.0	28.33	23.5	12.1	21.9	85.83	0.00%	-4.72%	-0.72%
25	Brownsville	10	5.00	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	5.0	28.7	21.5	8.8	29.2	88.2	0.00%	46.67%	3.31%
26	Brownsville	10	5.50	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	5.5	28.63	21.5	8.1	29.2	87.43	0.00%	35.00%	2.41%
27	Brownsville	10	6.00	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	6.0	28.68	21.5	7.4	29.2	86.78	0.00%	23.33%	1.65%
28	Brownsville	10	6.50	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	6.5	28.64	21.5	6.9	29.2	86.24	0.00%	15.00%	1.02%
29	Brownsville	10	6.80	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	6.8 (BASE CASE)	28.65	21.5	6.6	29.2	85.95			
30	Brownsville	10	7.00	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	7.0	28.67	21.5	6.4	29.2	85.77	0.00%	6.67%	0.47%
31	Brownsville	10	7.50	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	7.5	28.67	21.5	6	29.2	85.37	0.00%	0.00%	0.00%
32	Brownsville	10	8.00	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	8.0	28.72	21.5	5.6	29.2	85.02	0.00%	-6.67%	-0.41%

G.6. Domestic hot water heater efficiency simulation results

No	Location	SEER	AFUE(%)	EF	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%	Duct Insulation	Duct Leakage	Ceiling R-value	ROOF R-value	Glazing U-factor	SHGC	TREE SHADING		Annual Other (mBtu/yr)	Annual DHW (mBtu/yr)	Annual Heating (mBtu/yr)	Annual Cooling (mBtu/yr)	Total (mBtu/yr)	Annual Heating+DHW (mBtu/yr)	DHW Differ. (%)	Total Differ. (%)
		IECC 2000	IECC 2000	IECC 2000	ASHRAE 152-2004	ASHRAE 152-2004		ASHRAE 152-2004	IECC 2000	IECC 2000	IECC 2000	IECC 2000										
1	Amarillo	10	0.78	0.45	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	0.45	33.07	35.8	50.92	15	134.79	55.3	44.35%	8.89%
2	Amarillo	10	0.78	0.5	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	0.50	33.09	32.2	50.92	15	131.21	55.3	29.84%	6.00%
3	Amarillo	10	0.78	0.55	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	BASE CASE (0.55)	33.06	29.3	50.92	15	128.28	55.3		
4	Amarillo	10	0.78	0.6	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	0.60	33.12	26.8	50.92	15	125.84	55.3	8.06%	1.66%
5	Amarillo	10	0.78	0.65	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	0.65	33.06	24.8	50.92	15	123.78	55.3	0.00%	0.00%
6	Amarillo	10	0.78	0.7	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	0.70	33.09	23	50.92	15	122.01	55.3	-7.26%	-1.43%
7	Amarillo	10	0.78	0.75	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	0.75	33.06	21.5	50.92	15	120.48	55.3	-13.31%	-2.67%
8	Amarillo	10	0.78	0.8	746.17	124.36	SR-8,RR-4	0.1	38	NO	0.45	0.66	NO	0.80	33.11	20.1	50.92	15	119.13	55.3	-18.95%	-3.76%
9	Fort Worth	10	0.78	0.45	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	0.45	32.74	30.3	21.62	20.1	104.76	26	44.29%	9.78%
10	Fort Worth	10	0.78	0.5	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	0.50	32.71	27.3	21.62	20.1	101.73	26	30.00%	6.60%
11	Fort Worth	10	0.78	0.55	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	BASE CASE (0.55)	32.73	24.8	21.62	20.1	99.25	26		
12	Fort Worth	10	0.78	0.6	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	0.60	32.76	22.7	21.62	20.1	97.18	26	8.10%	1.83%
13	Fort Worth	10	0.78	0.65	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	0.65	32.71	21	21.62	20.1	95.43	26	0.00%	0.00%
14	Fort Worth	10	0.78	0.7	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	0.70	32.71	19.5	21.62	20.1	93.93	26	-7.14%	-1.57%
15	Fort Worth	10	0.78	0.75	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	0.75	32.71	18.2	21.62	20.1	92.63	26	-13.33%	-2.93%
16	Fort Worth	10	0.78	0.8	746.17	124.36	SR-8,RR-4	0.1	30	NO	0.65	0.4	NO	0.80	32.67	17.1	21.62	20.1	91.49	26	-18.57%	-4.13%
17	Houston	10	0.78	0.45	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	0.45	32.73	28.7	14.42	21.9	97.75	18.8	44.22%	9.93%
18	Houston	10	0.78	0.5	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	0.50	32.77	25.8	14.42	21.9	94.89	18.8	29.65%	6.71%
19	Houston	10	0.78	0.55	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	BASE CASE (0.55)	32.72	23.5	14.42	21.9	92.54	18.8		
20	Houston	10	0.78	0.6	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	0.60	32.76	21.5	14.42	21.9	90.58	18.8	8.04%	1.87%
21	Houston	10	0.78	0.65	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	0.65	32.7	19.9	14.42	21.9	88.92	18.8	0.00%	0.00%
22	Houston	10	0.78	0.7	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	0.70	32.79	18.4	14.42	21.9	87.51	18.8	-7.54%	-1.59%
23	Houston	10	0.78	0.75	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	0.75	32.76	17.2	14.42	21.9	86.28	18.8	-13.57%	-2.97%
24	Houston	10	0.78	0.8	746.17	124.36	SR-8,RR-4	0.1	26	NO	0.75	0.4	NO	0.80	32.78	16.1	14.42	21.9	85.2	18.8	-19.10%	-4.18%
25	Brownsville	10	0.78	0.45	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	0.45	33.11	26.2	8.02	29.2	96.53	12.4	43.96%	9.12%
26	Brownsville	10	0.78	0.5	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	0.50	33.09	23.6	8.02	29.2	93.91	12.4	29.67%	6.16%
27	Brownsville	10	0.78	0.55	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	BASE CASE (0.55)	33.04	21.5	8.02	29.2	91.76	12.4		
28	Brownsville	10	0.78	0.6	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	0.60	33.05	19.7	8.02	29.2	89.97	12.4	8.24%	1.71%
29	Brownsville	10	0.78	0.65	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	0.65	33.04	18.2	8.02	29.2	88.46	12.4	0.00%	0.00%
30	Brownsville	10	0.78	0.7	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	0.70	33.04	16.9	8.02	29.2	87.16	12.4	-7.14%	-1.47%
31	Brownsville	10	0.78	0.75	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	0.75	33.12	15.7	8.02	29.2	86.04	12.4	-13.74%	-2.74%
32	Brownsville	10	0.78	0.8	746.17	124.36	SR-8,RR-4	0.1	19	NO	0.9	0.4	NO	0.80	33.03	14.8	8.02	29.2	85.05	12.4	-18.68%	-3.85%

G.7. Duct location simulation results

No	Location	SEER	AFUE(%)	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%	Duct Insulation	Duct Leakage	Ceiling R-value	DUCT LOCATION	Glazing U-factor	SHGC	TREE SHADING		Annual Other (mBtu/yr)	Annual DHW (mBtu/yr)	Annual Heating (mBtu/yr)	Annual Cooling (mBtu/yr)	Total (mBtu/yr)	Annual Heating+DHW (mBtu/yr)	Cooling Differ. (%)	Heating Differ. (%)	Total Differ. (%)
		IECC 2000	IECC 2000	ASHRAE 152-2004	ASHRAE 152-2004		ASHRAE 152-2004	IECC 2000		IECC 2000	IECC 2000											
1	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0 (Attic)	38	ATTIC	0.45	0.66	NO	0% (Attic)	33.14	29.3	42.82	13	118.26	47.2			
2	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0 (Indoor)	38	ROOM	0.45	0.66	NO	0% (Indoor)	33.04	29.3	41.42	12.8	116.56	45.8	-1.54%	-3.27%	-1.44%
3	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.05 (Attic)	38	ATTIC	0.45	0.66	NO	5% (Attic)	33.11	29.3	46.62	13.9	122.93	51			
4	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.05 (Indoor)	38	ROOM	0.45	0.66	NO	5% (Indoor)	33.04	29.3	43.62	13.4	119.36	48	-3.60%	-6.44%	-2.90%
5	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1 (Attic)	38	ATTIC	0.45	0.66	NO	10% (Attic)	33.06	29.3	50.92	15	128.28	55.3			
6	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1 (Indoor)	38	ROOM	0.45	0.66	NO	10% (Indoor)	33.06	29.3	46.02	14.1	122.48	50.4	-6.00%	-9.62%	-4.52%
7	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.15 (Attic)	38	ATTIC	0.45	0.66	NO	15% (Attic)	33.14	29.3	55.82	16.2	134.46	60.2			
8	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.15 (Indoor)	38	ROOM	0.45	0.66	NO	15% (Indoor)	33.07	29.3	48.72	14.9	125.99	53.1	-8.02%	-12.72%	-6.30%
9	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.2 (Attic)	38	ATTIC	0.45	0.66	NO	20% (Attic)	33.02	29.3	61.62	17.7	141.64	66			
10	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.20 (Indoor)	38	ROOM	0.45	0.66	NO	20% (Indoor)	33.04	29.3	51.82	15.8	129.96	56.2	-10.73%	-15.90%	-8.25%
11	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0 (Attic)	30	ATTIC	0.65	0.4	NO	0% (Attic)	32.72	24.8	18.42	15.9	91.84	22.8			
12	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0 (Indoor)	30	ROOM	0.65	0.4	NO	0% (Indoor)	32.73	24.8	17.92	15.5	90.95	22.3	-2.52%	-2.71%	-0.97%
13	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.05 (Attic)	30	ATTIC	0.65	0.4	NO	5% (Attic)	32.7	24.8	19.92	17.8	95.22	24.3			
14	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.05 (Indoor)	30	ROOM	0.65	0.4	NO	5% (Indoor)	32.74	24.8	18.92	16.7	93.16	23.3	-6.18%	-5.02%	-2.16%
15	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1 (Attic)	30	ATTIC	0.65	0.4	NO	10% (Attic)	32.73	24.8	21.62	20.1	99.25	26			
16	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1 (Indoor)	30	ROOM	0.65	0.4	NO	10% (Indoor)	32.76	24.8	19.92	18.2	95.68	24.3	-9.45%	-7.86%	-3.60%
17	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.15 (Attic)	30	ATTIC	0.65	0.4	NO	15% (Attic)	32.71	24.8	23.62	23	104.13	28			
18	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.15 (Indoor)	30	ROOM	0.65	0.4	NO	15% (Indoor)	32.73	24.8	21.12	19.9	98.55	25.5	-13.48%	-10.58%	-5.36%
19	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.2 (Attic)	30	ATTIC	0.65	0.4	NO	20% (Attic)	32.73	24.8	25.92	26.9	110.35	30.3			
20	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.20 (Indoor)	30	ROOM	0.65	0.4	NO	20% (Indoor)	32.75	24.8	22.42	21.9	101.87	26.8	-18.59%	-13.50%	-7.68%
21	Houston	10	78	746.17	124.36	SR-8,RR-4	0 (Attic)	26	ATTIC	0.75	0.4	NO	0% (Attic)	32.67	23.5	12.22	16.8	85.19	16.6			
22	Houston	10	78	746.17	124.36	SR-8,RR-4	0 (Indoor)	26	ROOM	0.75	0.4	NO	0% (Indoor)	32.67	23.5	11.92	16.4	84.49	16.3	-2.38%	-2.45%	-0.82%
23	Houston	10	78	746.17	124.36	SR-8,RR-4	0.05 (Attic)	26	ATTIC	0.75	0.4	NO	5% (Attic)	32.68	23.5	13.22	19.1	88.5	17.6			
24	Houston	10	78	746.17	124.36	SR-8,RR-4	0.05 (Indoor)	26	ROOM	0.75	0.4	NO	5% (Indoor)	32.69	23.5	12.52	18.1	86.81	16.9	-5.24%	-5.30%	-1.91%
25	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1 (Attic)	26	ATTIC	0.75	0.4	NO	10% (Attic)	32.72	23.5	14.42	21.9	92.54	18.8			
26	Houston	10	78	746.17	124.36	SR-8,RR-4	0.1 (Indoor)	26	ROOM	0.75	0.4	NO	10% (Indoor)	32.69	23.5	13.22	20.1	89.51	17.6	-8.22%	-8.32%	-3.27%
27	Houston	10	78	746.17	124.36	SR-8,RR-4	0.15 (Attic)	26	ATTIC	0.75	0.4	NO	15% (Attic)	32.69	23.5	15.72	25.7	97.61	20.1			
28	Houston	10	78	746.17	124.36	SR-8,RR-4	0.15 (Indoor)	26	ROOM	0.75	0.4	NO	15% (Indoor)	32.67	23.5	14.02	22.5	92.69	18.4	-12.45%	-10.81%	-5.04%
29	Houston	10	78	746.17	124.36	SR-8,RR-4	0.2 (Attic)	26	ATTIC	0.75	0.4	NO	20% (Attic)	32.66	23.5	17.32	30.8	104.28	21.7			
30	Houston	10	78	746.17	124.36	SR-8,RR-4	0.20 (Indoor)	26	ROOM	0.75	0.4	NO	20% (Indoor)	32.67	23.5	14.92	25.4	96.49	19.3	-17.53%	-13.86%	-7.47%
31	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0 (Attic)	19	ATTIC	0.9	0.4	NO	0% (Attic)	33.02	21.5	6.92	22.4	83.84	11.3			
32	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0 (Indoor)	19	ROOM	0.9	0.4	NO	0% (Indoor)	32.99	21.5	6.82	22	83.31	11.2	-1.79%	-1.45%	-0.63%
33	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.05 (Attic)	19	ATTIC	0.9	0.4	NO	5% (Attic)	33.07	21.5	7.42	25.4	87.39	11.8			
34	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.05 (Indoor)	19	ROOM	0.9	0.4	NO	5% (Indoor)	33.06	21.5	7.12	24.4	86.08	11.5	-3.94%	-4.04%	-1.50%
35	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1 (Attic)	19	ATTIC	0.9	0.4	NO	10% (Attic)	33.04	21.5	8.02	29.2	91.76	12.4			
36	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.1 (Indoor)	19	ROOM	0.9	0.4	NO	10% (Indoor)	33.12	21.5	7.52	27.2	89.34	11.9	-6.85%	-6.23%	-2.64%
37	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.15 (Attic)	19	ATTIC	0.9	0.4	NO	15% (Attic)	33.13	21.5	8.62	34	97.25	13			
38	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.15 (Indoor)	19	ROOM	0.9	0.4	NO	15% (Indoor)	33.01	21.5	8.02	30.7	93.23	12.4	-9.71%	-6.96%	-4.13%
39	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.2 (Attic)	19	ATTIC	0.9	0.4	NO	20% (Attic)	33.06	21.5	9.42	40.4	104.38	13.8			
40	Brownsville	10	78	746.17	124.36	SR-8,RR-4	0.20 (Indoor)	19	ROOM	0.9	0.4	NO	20% (Indoor)	33.02	21.5	8.52	34.9	97.94	12.9	-13.61%	-9.55%	-6.17%

G.8. Tree shading simulation results

No	Location	SEER	AFUE(%)	Supply Duct Area (sq.ft), 30%	Return Duct Area (sq.ft), 5%	Duct Insulation	Duct Leakage	Ceiling R-value	Glazing U-factor	SHGC	TREE SHADING	TREE SHADING	Annual Other (mBtu/yr)	Annual DHW (mBtu/yr)	Annual Heating (mBtu/yr)	Annual Cooling (mBtu/yr)	Total (mBtu/yr)	Annual Heating+DHW (mBtu/yr)	Cooling Differ. (%)	Heating Differ. (%)	Total Differ. (%)
		IECC 2000	IECC 2000	ASHRAE 152-2004	ASHRAE 152-2004		ASHRAE 152-2004	IECC 2000	IECC 2000	IECC 2000											
1	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	NO	BASE CASE	33.06	29.3	50.92	15	128.28	55.3			
2	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	E	LIVEOAK (E)	32.95	29.3	52.52	13.5	128.27	56.9	-7.53%	2.54%	0.13%
3	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	W	LIVEOAK (W)	32.98	29.3	51.22	14.6	128.1	55.6	0.00%	0.00%	0.00%
4	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	EW	LIVEOAK (EW)	32.88	29.3	52.82	13.1	128.1	57.2	-10.27%	3.12%	0.00%
5	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	E	DECIDUOUS (E)	32.95	29.3	51.72	13.5	127.47	56.1	-7.53%	0.98%	-0.49%
6	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	W	DECIDUOUS (W)	33.01	29.3	51.02	14.6	127.93	55.4	0.00%	-0.39%	-0.13%
7	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	EW	DECIDUOUS (EW)	32.96	29.3	51.82	13.1	127.18	56.2	-10.27%	1.17%	-0.72%
8	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	E	EVERGREEN (E)	32.94	29.3	52.62	13.5	128.36	57	-7.53%	2.73%	0.20%
9	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	W	EVERGREEN (W)	33.08	29.3	51.22	14.5	128.1	55.6	-0.68%	0.00%	0.00%
10	Amarillo	10	78	746.17	124.36	SR-8,RR-4	0.1	38	0.45	0.66	EW	EVERGREEN (EW)	32.98	29.3	52.92	13	128.2	57.3	-10.96%	3.32%	0.08%
11	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	NO	BASE CASE	32.73	24.8	21.62	20.1	99.25	26			
12	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	E	LIVEOAK (E)	32.59	24.8	22.32	18.9	98.61	26.7	-3.08%	2.29%	-0.24%
13	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	W	LIVEOAK (W)	32.73	24.8	21.82	19.5	98.85	26.2	0.00%	0.00%	0.00%
14	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	EW	LIVEOAK (EW)	32.54	24.8	22.52	18.4	98.26	26.9	-5.64%	3.21%	-0.60%
15	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	E	DECIDUOUS (E)	32.59	24.8	21.92	18.9	98.21	26.3	-3.08%	0.46%	-0.65%
16	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	W	DECIDUOUS (W)	32.73	24.8	21.72	19.5	98.75	26.1	0.00%	-0.46%	-0.10%
17	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	EW	DECIDUOUS (EW)	32.53	24.8	22.02	18.4	97.75	26.4	-5.64%	0.92%	-1.11%
18	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	E	EVERGREEN (E)	32.64	24.8	22.32	18.8	98.56	26.7	-3.59%	2.29%	-0.29%
19	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	W	EVERGREEN (W)	32.72	24.8	21.82	19.5	98.84	26.2	0.00%	0.00%	-0.01%
20	Fort Worth	10	78	746.17	124.36	SR-8,RR-4	0.1	30	0.65	0.4	EW	EVERGREEN (EW)	32.57	24.8	22.52	18.3	98.19	26.9	-6.15%	3.21%	-0.67%
21	Hoston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	NO	BASE CASE	32.72	23.5	14.42	21.9	92.54	18.8			
22	Hoston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	E	LIVEOAK (E)	32.68	23.5	14.82	20.9	91.9	19.2	-2.79%	2.07%	-0.31%
23	Hoston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	W	LIVEOAK (W)	32.67	23.5	14.52	21.5	92.19	18.9	0.00%	0.00%	0.00%
24	Hoston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	EW	LIVEOAK (EW)	32.6	23.5	14.92	20.5	91.52	19.3	-4.65%	2.75%	-0.73%
25	Hoston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	E	DECIDUOUS (E)	32.55	23.5	14.62	21	91.67	19	-2.33%	0.69%	-0.56%
26	Hoston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	W	DECIDUOUS (W)	32.69	23.5	14.42	21.5	92.11	18.8	0.00%	-0.69%	-0.09%
27	Hoston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	EW	DECIDUOUS (EW)	32.62	23.5	14.62	20.5	91.24	19	-4.65%	0.69%	-1.03%
28	Hoston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	E	EVERGREEN (E)	32.65	23.5	14.82	20.9	91.87	19.2	-2.79%	2.07%	-0.35%
29	Hoston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	W	EVERGREEN (W)	32.64	23.5	14.52	21.5	92.16	18.9	0.00%	0.00%	-0.03%
30	Hoston	10	78	746.17	124.36	SR-8,RR-4	0.1	26	0.75	0.4	EW	EVERGREEN (EW)	32.55	23.5	15.02	20.4	91.47	19.4	-5.12%	3.44%	-0.78%
31	Brownville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	NO	BASE CASE	33.04	21.5	8.02	29.2	91.76	12.4			
32	Brownville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	E	LIVEOAK (E)	33	21.5	8.12	28	90.62	12.5	-2.44%	1.25%	-0.74%
33	Brownville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	W	LIVEOAK (W)	33.08	21.5	8.02	28.7	91.3	12.4	0.00%	0.00%	0.00%
34	Brownville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	EW	LIVEOAK (EW)	32.94	21.5	8.22	27.5	90.16	12.6	-4.18%	2.49%	-1.25%
35	Brownville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	E	DECIDUOUS (E)	32.98	21.5	8.02	28.1	90.6	12.4	-2.09%	0.00%	-0.77%
36	Brownville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	W	DECIDUOUS (W)	33.07	21.5	8.02	28.7	91.29	12.4	0.00%	0.00%	-0.01%
37	Brownville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	EW	DECIDUOUS (EW)	33.02	21.5	8.02	27.6	90.14	12.4	-3.83%	0.00%	-1.27%
38	Brownville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	E	EVERGREEN (E)	32.94	21.5	8.12	28	90.56	12.5	-2.44%	1.25%	-0.81%
39	Brownville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	W	EVERGREEN (W)	33.05	21.5	8.02	28.7	91.27	12.4	0.00%	0.00%	-0.03%
40	Brownville	10	78	746.17	124.36	SR-8,RR-4	0.1	19	0.9	0.4	EW	EVERGREEN (EW)	32.86	21.5	8.22	27.5	90.08	12.6	-4.18%	2.49%	-1.34%

APPENDIX H

COMPARISON OF WINDOW INPUT METHOD

Since Mukhopadhyay (2005) discussed two window input methods to test the accuracy of using the Window-5 option against the Shading Coefficient (SC) option, the comparison between results from this study and results from Mukhopadhyay (2005) was performed.

The version of the model used for her study was 'IECC1105.INP' which has been developed by the Energy Systems Laboratory, Texas A&M University on the basis of specifications provided by the 2000/2001 IECC.

However, since IECC1105.INP (Figure H.1, left) was the initial simulation input model for analyzing the IECC-compliant residential house, IECC1105.INP had different characteristics from SNGFAM2ST.INP (Figure H.1, right) which was used for this dissertation. IECC1105.INP did not consider the duct model in the attic space, the attic space and NREL DHW heater performance curve.

Because the simulation house of Mukhopadhyay (2005) was 1,500 ft^2 and 25% window-to-wall ratio, the size of the house (SNGFAM2ST.INP) was modified to the same size to compare the saving differences by changing window types. Figure H.2 shows the simulation results using SNGFAM2ST.INP, Figure H.3 shows the simulation results from Mukhopadhyay (2005) which used IECC1105.INP, and Figure H.4 shows the saving differences between this study and Mukhopadhyay (2005).

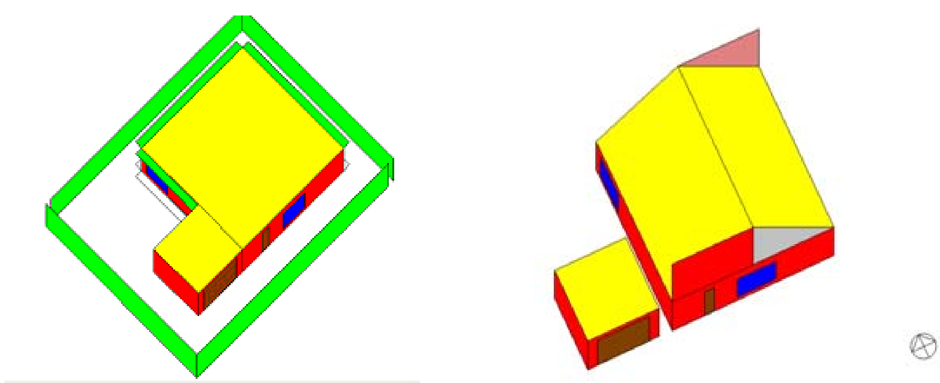
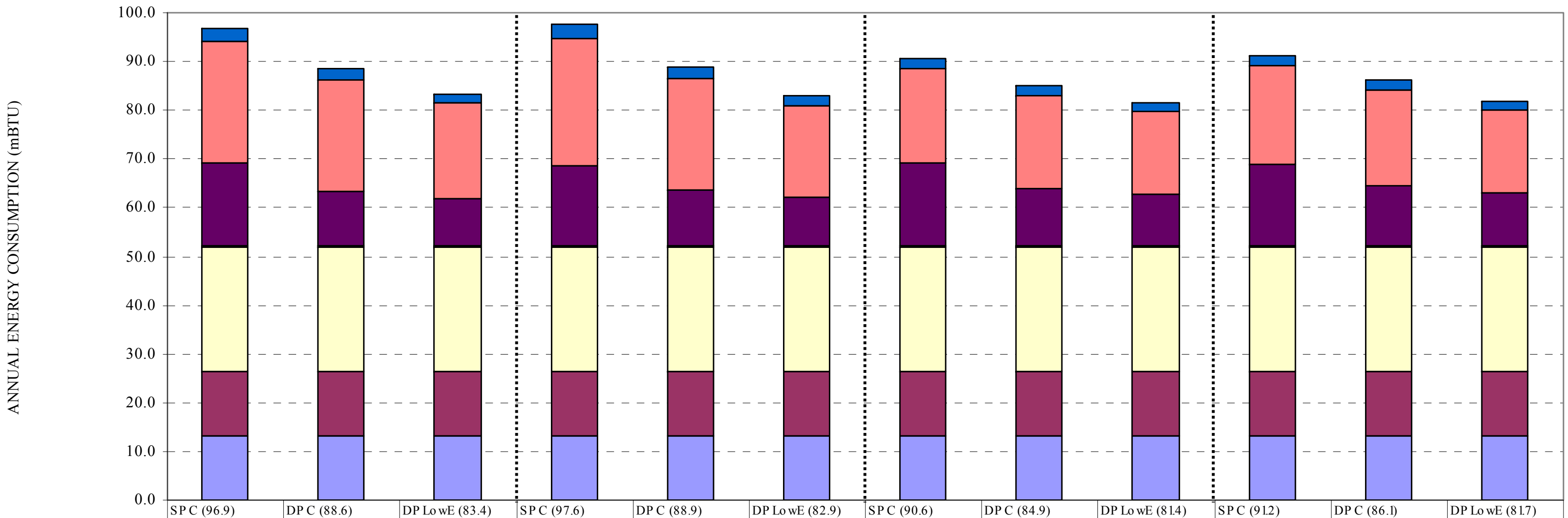
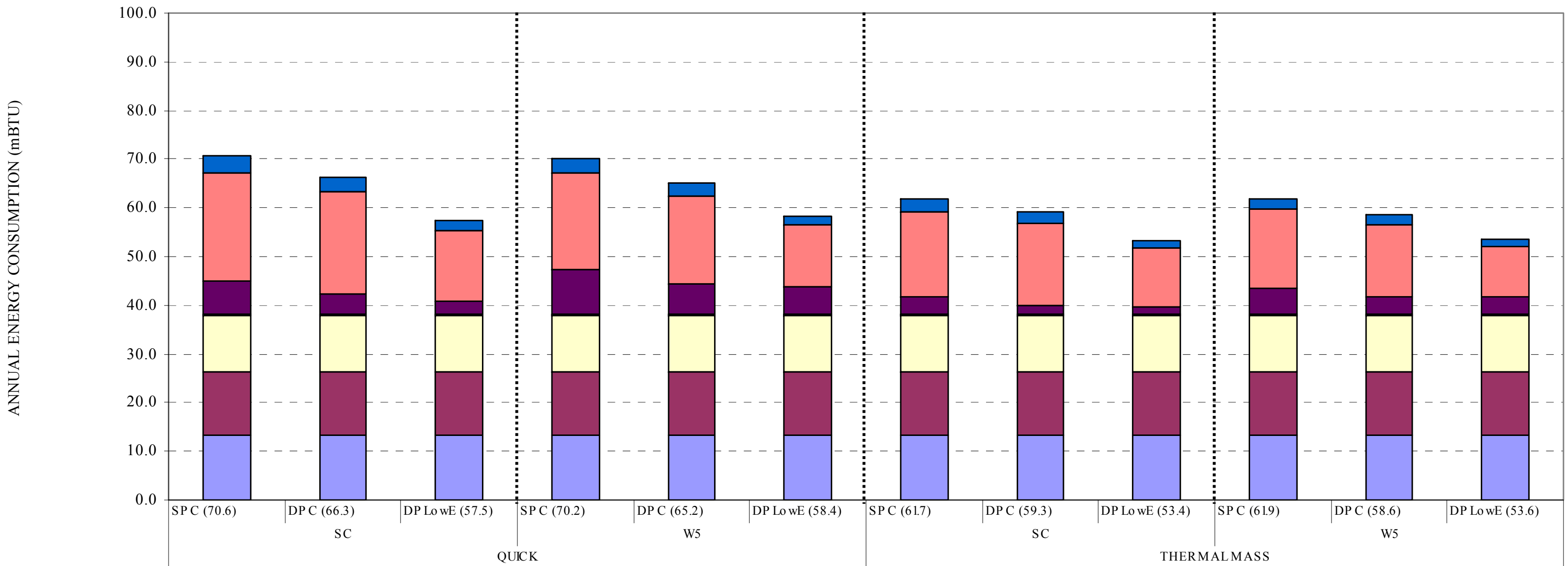


Figure H.1 DrawBDL view of IECC1105.INP (left) and SNGFAM2ST.INP (right)



	QUICK						THERMAL MASS					
	SC			W5			SC			W5		
	SP C (96.9)	DP C (88.6)	DP LowE (83.4)	SP C (97.6)	DP C (88.9)	DP LowE (82.9)	SP C (90.6)	DP C (84.9)	DP LowE (81.4)	SP C (91.2)	DP C (86.1)	DP LowE (81.7)
VENT FANS	2.7	2.4	2.0	2.8	2.4	1.9	2.0	1.9	1.7	2.1	2.0	1.7
SPACE COOL	25.1	23.0	19.4	26.1	22.8	18.7	19.3	19.1	17.0	20.2	19.6	17.0
SPACE HEAT	17.0	11.1	9.9	16.6	11.6	10.2	17.2	11.8	10.6	16.8	12.4	10.9
PUMPS & MISC	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
DOM HOT WATER	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5	25.5
MISC EQUIPMT	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
AREA LIGHTS	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2

Figure H.2 Annual building energy performance (BEPS) report from this study



VENT FANS	3.3	3.1	2.1	3.0	2.7	1.9	2.4	2.4	1.6	2.2	2.0	1.4
SPACE COOL	22.4	21.0	14.5	19.9	18.0	12.7	17.6	16.9	12.2	16.1	14.9	10.4
SPACE HEAT	6.7	4.0	2.7	9.1	6.3	5.6	3.5	1.8	1.4	5.4	3.5	3.6
PUMPS & MISC	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
DOM HOT WATER	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6
MISC EQUIPMT	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2
AREA LIGHTS	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2	13.2

Figure H.3 Annual building energy performance (BEPS) report from Mukhopadhyay (2005)

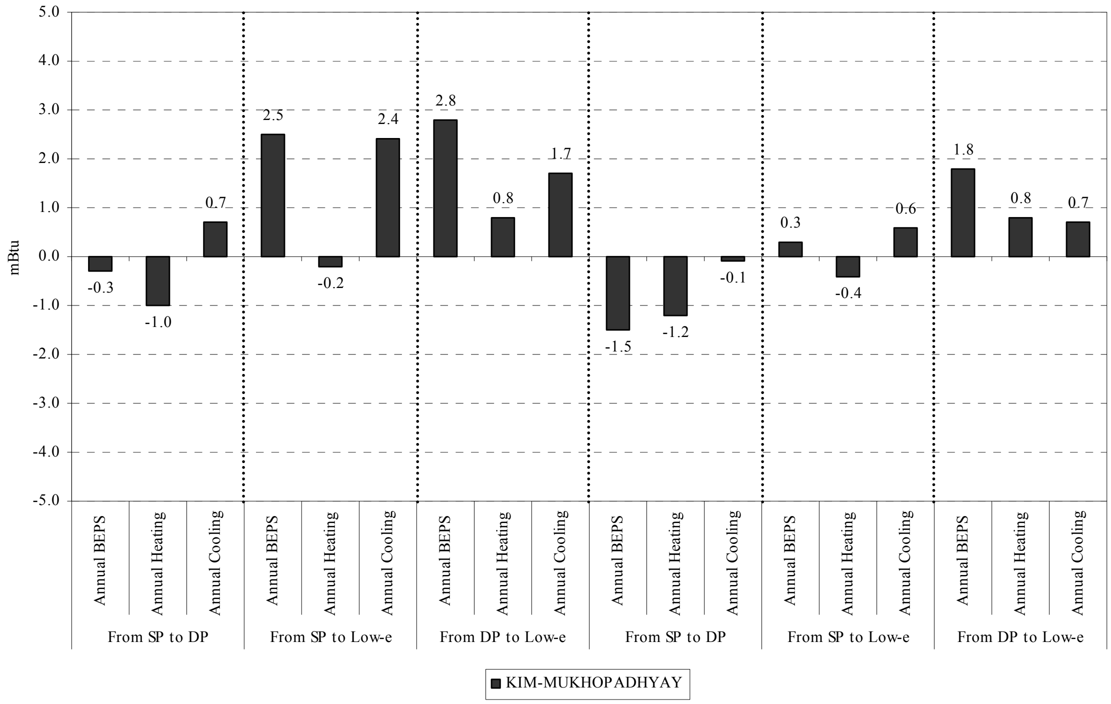


Figure H.4 Saving differences between this study and Mukhopadhyay (2005)

APPENDIX I

VERIFICATION TEST OF DUCT MODEL

In order to verify the duct model, the model was compared with the manual calculation based on ASHRAE 152-2004 and EnergyGuage version 2.42 from the Florida Solar Energy Center (FSEC), which can consider the duct loss/gain from the attic space. Three results were used for comparison including: 1) simulation with duct model based on ASHRAE 152, 2) manual calculation of ASHRAE 152 directly entered into the DOE-2 input file without duct model, and 3) simulation using EnergyGuage. A house with a size similar to the case-study house was developed with EnergyGuage version 2.42, and then several parameters were changed to compare with results from each simulation. The Houston TMY2 data was used for all simulations.

A Sensitivity analysis was performed by changing parameters including supply duct area (ft^2), return duct area (ft^2), supply duct R-value, return duct R-value, and supply duct leakage rate (%).

The results showed the acceptable difference between the simulation with the duct model based on ASHRAE 152 and simulation using the EnergyGuage. The largest difference between two results was 4% when changing supply duct R-value from R-6 to R-2.

Table I.1 Simulation variables

	Original	1	2	3	4	5	6	7	8	9
Supply duct area (ft^2)	340	425	408	391	374	306	289	272	255	
Return duct area (ft^2)	60	75	72	69	66	54	51	48	45	
Supply duct R-value	6	2	4	8	10					
Return duct R-value	6	2	4	8	10					
Supply duct leakage (%)	10	2	4	6	8	12	14	16	18	20

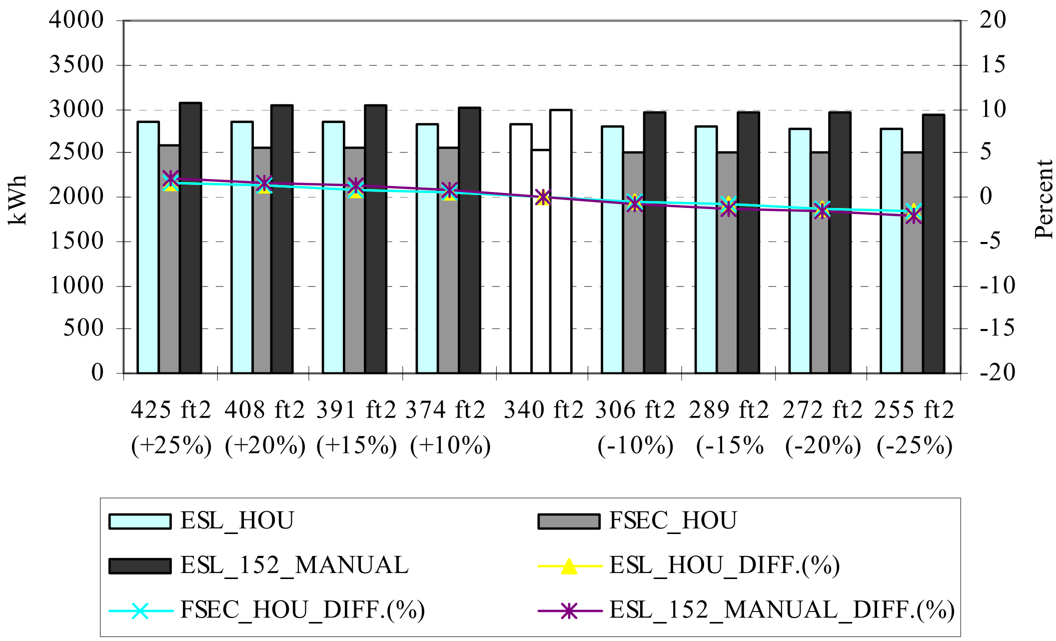


Figure I.1 The variation of supply duct area and results

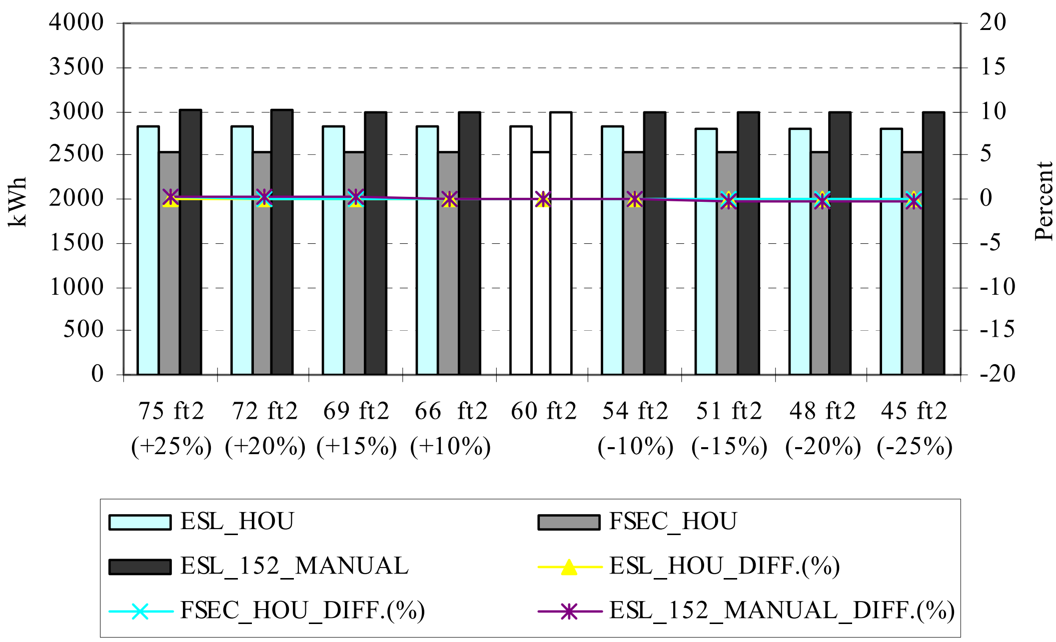


Figure I.2 The variation of return duct area and results

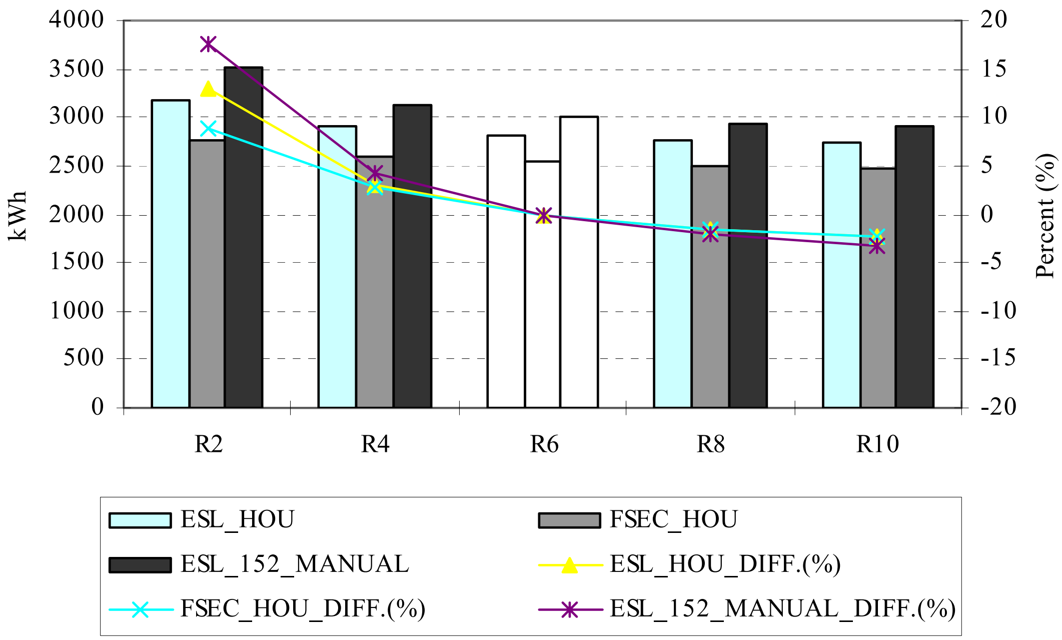


Figure I.3 The variation of supply duct R-value and results

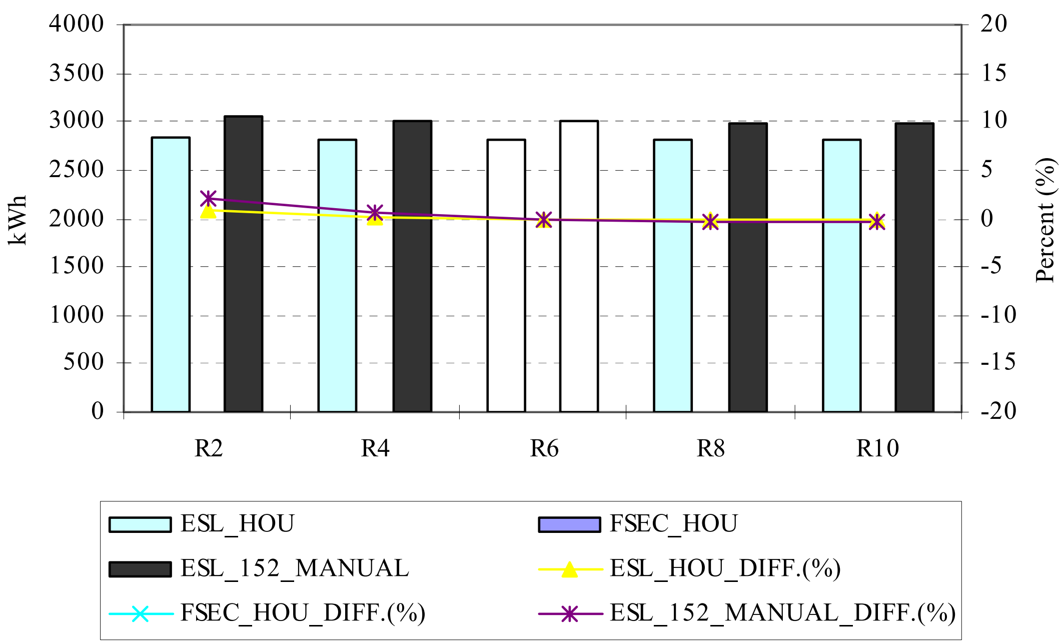


Figure I.4 The variation of return duct R-value and results

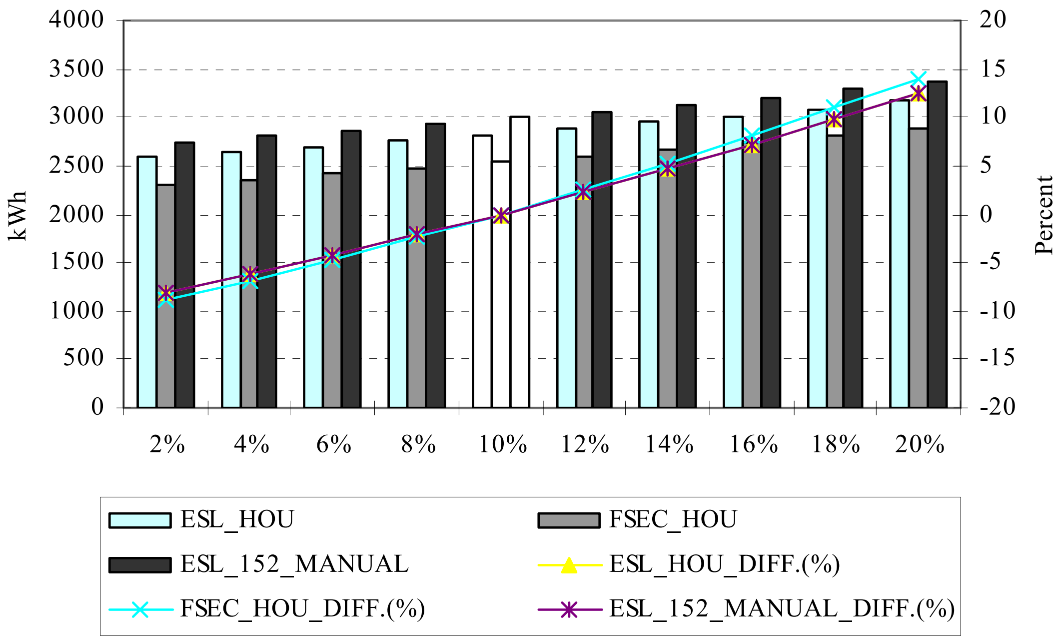


Figure I.5 The variation of supply duct leakage and results

APPENDIX J

COMPARISON OF WITH AND WITHOUT GARAGE CONSTRUCTION OF IECC-CODE COMPLIANT SIMULATION MODEL

This study compared energy consumption of the case-study house and IECC-code compliant model. Since the case-study house does not have a garage space while the IECC-code complaint house includes the garage space, the comparison of with and without garage space of the IECC-code compliant model was performed.

Figure J.1 showed the DrawBDL views of with garage and without garage space which were used for the comparisons.

From the simulations, it was found that the garage space plays a part as a significant shading device to the residential house. After removing the garage space from the simulation input file, annual cooling energy use increased by 9.4%, annual heating energy use decreased by 5.4%. The total annual energy use increased slightly by 0.9%. This means that the garage space could provide the benefit to save the annual energy use consumptions because of the shading effects.

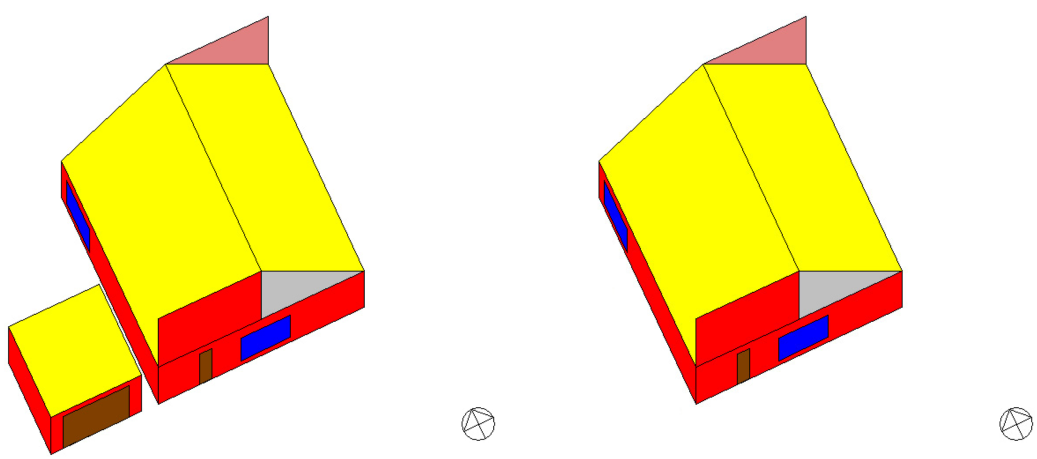
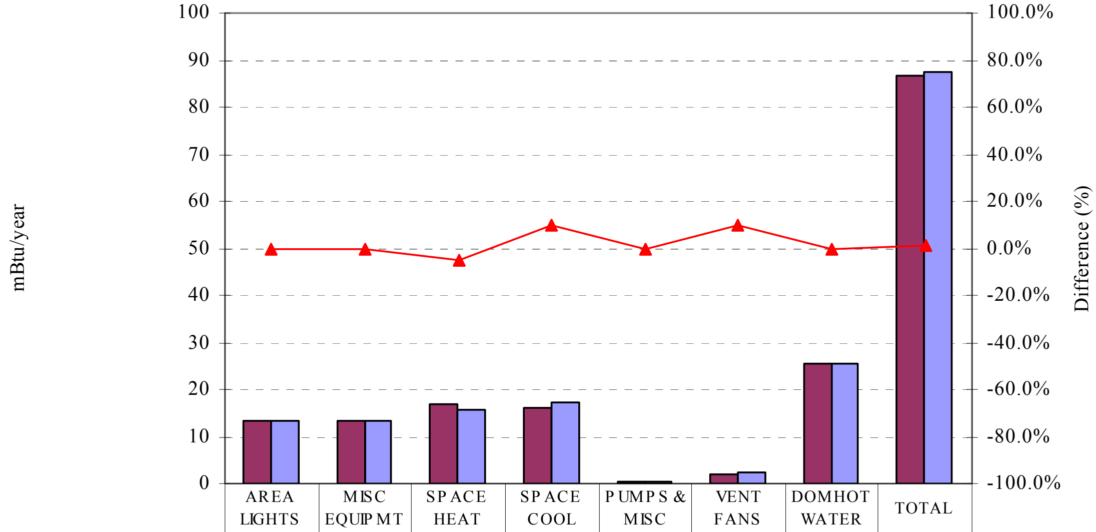


Figure J.1 DrawBDL views of with (left) and without (right) garage space



	AREA LIGHTS	MISC EQUIPMT	SPACE HEAT	SPACE COOL	PUMPS & MISC	VENT FANS	DOMHOT WATER	TOTAL
WITH GARAGE	13.2	13.2	16.7	15.9	0.2	2	25.5	86.7
WITHOUT GARAGE	13.2	13.2	15.8	17.4	0.2	2.2	25.5	87.5
DIFFERENCE (%)	0.0%	0.0%	-5.4%	9.4%	0.0%	10.0%	0.0%	0.9%

Figure J.2   Comparison results with and without garage space

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