A METHODOLOGY TO PRE-SCREEN COMMERCIAL BUILDINGS FOR POTENTIAL ENERGY SAVINGS USING LIMITED INFORMATION

A Dissertation

by

YIWEN ZHU

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

December 2005

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	David E. Claridge
Committee Member,	Charles Culp
	Jeff Haberl
	Warren Heffington
Head of Department,	Dennis O’Neal

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ABSTRACT

A Methodology to Pre-screen Commercial Buildings for Potential Energy Savings Using Limited Information. (December 2005)

Yiwen Zhu,

B.S., Tongji University, Shanghai, People's Republic of China;

M.S., Tsinghua University, Beijing, People's Republic of China

Chair of Advisory Committee: Dr. David. E. Claridge

Typical energy audits are sufficiently expensive and time-consuming that many owners and managers of buildings are not willing to invest the time and money required for a full audit. This dissertation provides a methodology to identify buildings with large potential energy savings using limited information, specifically, utility bills, total area and weather data. The methodology is developed based on the hypothesis: if a commercial building is properly designed, constructed, operated, and maintained, the measured energy consumption should approximately match the simulated value for a typical building of the same size with the most efficient HVAC system; otherwise, there may be potential for energy savings. There are four steps in the methodology: 1) testing to determine whether the utility bills include both weather-dependent and weather-independent loads; 2) separating weather-dependent and weather-independent loads when both are present in the same data; 3) determining the main type of HVAC system; 4) estimating potential energy savings and recommending an energy audit if appropriate.

The Flatness Index is selected to test whether the utility bills include both weather-dependent and weather-independent loads. An approach to separate the utility bills based on thermal balance is developed to separate utility bills into weather-dependent and weather-independent loads for facilities in hot and humid climates. The average relative error in estimated cooling consumption is only 1.1% for 40 buildings in Texas, whereas it is -54.8% using the traditional 3P method. An application of fuzzy logic is used to identify the main type of HVAC system in buildings from their 12-month weather-dependent energy consumption. When 40 buildings were tested, 18 systems were identified correctly, seven were incorrect and the HVAC system type cannot be identified in 15 cases. The estimated potential savings by the screening methodology in eight large commercial buildings were compared with audit estimated savings for the same buildings. The audit estimated savings are between 25% - 150% of the potential energy savings estimated by the screening procedure in seven cases. The other two cases are less accurate, indicating that further refinement of the method would be valuable. The data required are easily obtained; the procedure can be carried out automatically, so no experience is required. If the actual type of HVAC system, measured weather-dependent, and weather-independent energy consumption are known, the methodology should work better.

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CHAPTER I
INTRODUCTION

This chapter describes the motivation and objective of the work presented in this dissertation, and the contents of the following chapters will be described briefly. This section begins by reviewing the energy use in the U.S. and the potential energy savings in the building sector as the motivation for this work, and then the purpose and objective of the work will come out.

Motivation

The building sector in the U.S. accounted for about one-third of overall primary energy consumption, while commercial buildings consumed 10.6 quadrillion Btu, or about 11% of the energy used in the U.S. in 1995 (EIA, 1995, 1998).

Since the oil embargo in the early 1970s, as a response to the societal need to reduce energy use in buildings, a lot of researchers and engineers related to heating, ventilation, and air-conditioning paid more attention to thermal performance and energy conservation in buildings. New buildings can consume as little as 20% of the energy consumption in a traditional building of the same size (Goldemberg et al., 1988). Lawrence Berkeley National Laboratory (LBNL) has suggested that the annual energy bill for a home can be reduced from $1,000 to $250 if the advanced energy-efficiency building technologies, software, and standards developed by LBNL are applied (LBNL, 1995). However, these new energy-efficient building technologies, software, and standards were not available when existing buildings were constructed. So it is possible to reduce the energy consumption in existing buildings. The research in this dissertation focuses on existing commercial buildings. The median age for all commercial buildings in the U.S. in 1999 was 30.5 years, with more than 36% constructed prior to 1960 (EIA, 1999a). Some of the potential energy savings in these commercial buildings can be achieved by retrofitting and Continuous Commissioning® (CC®)[1]. Reducing energy consumption can reduce the

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

[1]Continuous Commissioning and CC are registered trademarks of the Texas Engineering Experiment Station. To improve readability, the registration symbol will not always be used.

use of nonrenewable energy sources; it can also reduce the production of pollution to the environment.

Examples of the potential for substantial savings in existing buildings are provided by the Texas LoanSTAR (Loans to Save Taxes And Resources) Program and the Continuous Commissioning® activities of the Energy Systems Laboratory (ESL). The ESL first used CC® as an attempt to achieve energy and cost savings with operations and maintenance (O&M) measures. The savings were achieved by identifying and implementing optimal operation strategies for buildings, as they were currently being used rather than implementing design intent (Claridge et al., 2001). Some case studies were presented to illustrate that energy savings can be achieved if all the O&M measures were fully implemented (Claridge et al., 1994, 1996a). Through April 2002, over $78 million measured savings from completed retrofits and $27.6 million in Continuous Commissioning® savings in 298 buildings were achieved in the Texas LoanSTAR Program (Haberl et al., 2002).

An energy conservation program for a building may include several aspects: an energy audit, retrofit installation, energy consumption metering, data analysis, retrofit/commissioning savings determination, diagnosis of faults, and optimization. The energy audit is the first step in energy conservation programs; future energy conservation opportunities are evaluated, and the potential savings are determined during the audit.

The average price for a traditional audit derived from 38 reports containing 320 buildings in the LoanSTAR Program (Heffington et al., 1992) was $0.08 per square foot. Typical energy audits are sufficiently expensive and time-consuming that many owners and managers of buildings are not willing to invest the time and money required for a full audit, so less expensive screening techniques are valuable when used to identify the best candidates for full audits. Though several methods for pre-screening have been developed to identify buildings with large potential energy savings, the data and experienced personnel required to implement them are not always readily available. There is a need to develop an automated preliminary or screening energy audit methodology that requires a minimum amount of easily obtained information.

Objective

To develop a methodology to pre-screen large commercial buildings for potential energy savings using a minimum amount of easily obtained information such as utility bills, total area, and weather data. This methodology could then be used to identify the best candidate buildings for more detailed audits.

Description of the following chapters

This dissertation is presented in seven chapters, references, appendices, and a vita. This chapter introduces the research and gives a brief synopsis of the following chapters.

Chapter II presents a detailed literature review of existing pre-screening tools for energy audits, methodologies for energy calculations in buildings, the critical elements influencing energy consumption in commercial buildings, existing methods for disaggregating energy consumption in commercial buildings, and tools for pattern recognition.

The methodology developed to pre-screen commercial buildings for potential energy savings using limited information will be explained in Chapter III. The fundamental methodology is based on the hypothesis that if a commercial building is properly designed, constructed, retrofit, operated, and maintained, the measured energy consumption should approximately match the simulated value for a typical building of the same size with the most efficient HVAC system (called the prototype building hereafter); otherwise, there may be potential for energy savings. The potential energy savings from CC® and/or retrofit can be estimated by comparing measured weather-dependent energy consumption with the simulated values in the idealized building. The potential CC® savings will be estimated as the difference between the measured consumption of the building and the simulated consumption of an idealized prototype building of the same size with the same type of HVAC system. The difference between the prototype commercial building and the idealized prototype commercial building is that the operation schedules for cold deck and hot deck of the HVAC system in the idealized commercial building are optimized. The prototype commercial building is a standard building representing a generic commercial building and is configured to avoid unique building-specific energy characteristics; the prototype commercial building used in this research is configured based on limited information.

There are usually two kinds of electricity loads in a commercial building, weather-dependent and weather-independent loads; some utility bills cover both parts. The total loads in these utility bills will be separated into two parts, after judgment is made whether there is a chiller system in the building. A 3-parameter change-point regression model can be used to separate the utility bills for commercial buildings whose chiller system needn't work at least one billing period per year; a new methodology is developed to disaggregate total electricity load in a commercial building whose chiller system works all year round. The development and testing of the approach for separating the Utility Bills based on Thermal Balance (SUBTB) in this case is presented in Chapter IV. The main type of HVAC system may be identified by comparing measured weather-dependent energy consumption with the simulated consumption in the prototype building with different types of HVAC systems if the type of HVAC system is unknown; more detail about the automatic procedure can be found in Chapter V.

It may not be definitively known whether the consumption recorded by a particular electric meter includes a chiller or not. Most buildings have their own electric chiller system to supply cooling to the building, but some get chilled water from an absorption system, a district system, or other central plant. In other cases, the electric chiller system for a building may be metered on a separate meter. Hence, a method is selected to determine whether the bills are consistent with a building that includes a chiller system or not from its 12-month utility bills; the procedure is described in Chapter III. If a commercial building gets chilled water from a central plant or other sources, and the electricity utility bill just covers the weather-independent part, the weather-independent electricity consumption can be obtained directly from the bill. If there is an electrical chiller system in a commercial building to produce chilled water for the building, and the chiller system needn't work for at least full billing period during the year, then weather-independent electricity consumption can be separated by a 3-parameter change-point regression model using 12-month utility data; otherwise the SUBTB method developed in Chapter III is used for the building whose electrical chiller system works all year round.

The measured energy consumption of a properly operating building should match simulated energy consumption in a prototype building of the same area with the exact type of HVAC system. It may be possible to identify the main type of HVAC system in a commercial building from the billing data when it is not known. An automatic procedure for identifying the HVAC system type using pattern recognition is introduced in Chapter V.

A test procedure is designed for the new prescreening method, and data from 34 facilities are used for testing the method. Test results of the new prescreening method are presented in Chapter VI. A summary of the present work, conclusions, and future direction are presented in Chapter VII, followed by references, appendices and vita.

CHAPTER II
LITERATURE REVIEW

This literature review covers the previous efforts dealing with: (i) existing pre-screening tools for energy audits, (ii) methodologies for energy calculations in buildings, (iii) the critical elements influencing energy consumption in commercial buildings, (iv) existing methods for disaggregating energy consumption in commercial buildings, (v) characteristics of weather-dependent energy consumption, and (vi) tools for pattern recognition.

Pre-screening tools available

Because typical energy audits for commercial buildings are expensive and time-consuming, other researchers have developed inexpensive audit methodologies and pre-screening tools to identify candidate buildings with potential energy savings. Publications from *ASHRAE Transactions*, *ASHRAE Handbook*s, *ASHRAE Standards*, proceedings of ACEEE (American Council for an Energy-Efficient Economy), *Energy and Buildings*, and research results from the Energy Systems Laboratory (ESL) of Texas A&M University at College Station are surveyed. The pre-screening tools available include: analysis of Energy Use Intensity (EUI) (Gardiner et al., 1984; MacDonald and Wasserman, 1989; ASHRAE, 1999a), a walk-through assessment (ASHRAE, 1999b), pre-screening indices (Liu et al., 1994), an expert system for preliminary energy audit (Gatton et al., 1995), an initial screening tool based on monthly energy consumption (Reynolds et al., 1990), energy use indices (Haberl and Komor, 1990; Doruk, 1990; Landman, 1998), building energy benchmarking and the ENERGY STAR program (Sharp, 1996; Sharp, 1998; Sartor et al., 2000; Kinney and Piette, 2002; EPA, 2003; EPA, 2004), and decision-making tools (EPIQR, TOBUS) in Europe (Jaggs and Palmer, 2000; Balaras et al, 2002; Caccavelli and Gugerli, 2002; Flourentzou et al, 2002; Wittchen and Brandt, 2002).

Chapter 34 in the *ASHRAE Application Handbook* classifies energy audits into three categories: The walk-through assessment, the energy survey and analysis, and a detailed analysis of capital-intensive modifications. The walk-through assessment can present an initial judgment of potential savings by assessment of a building's energy cost and efficiency through the analysis of energy bills and a brief survey of the building. The reliability of a walk-through assessment depends on the experience of the person performing the audit (ASHRAE, 1999b).

Lawrence Berkeley Laboratory used the sum of Energy Use Intensity (annually kBtu per total square foot of floor space) for each fuel type to calculate energy savings for energy conservation retrofits for 311 non-residential buildings (Gardiner,et al., 1984). Energy Use Intensity (EUI) is helpful for expressing the energy performance of buildings**.** MacDonald and Wasserman (1989) reviewed and evaluated techniques for analyzing metered energy consumption to determine baseline energy usage and potential energy efficiency improvements in commercial and related buildings. Comparison of annual energy use intensity for buildings of the same type allows more meaningful evaluation of potential relative improvements. *ASHRAE Standard 105-1984* provides a consistent method of measuring and expressing the energy performance of buildings. Twelve-month energy consumption data for a facility including electric energy, fuels, heating, cooling, nondepletable energy and energy delivered from the site are necessary for evaluation of energy performance (ASHRAE, 1999a).

Liu et al. (1994) used pre-screening indices based on measured hourly energy consumption data from buildings in the Texas LoanSTAR Program to identify the buildings with the potential for additional energy savings from operational improvements. High average energy consumption (either chilled water use or steam use) per unit area, a relatively large ratio of nighttime to daytime electricity consumption, a large ratio of steam to chilled water consumption, or an unexpected energy consumption pattern indicated that there were potential energy savings in these buildings.

Gatton et al. (1995) developed an expert system to find energy inefficient buildings and cost-effective energy retrofit alternatives without use of an experienced engineer. This expert system was applied in three phases. In phase one, the buildings with potential energy savings are determined based on higher values of annual energy cost per unit area and peak load; in phase two, the most likely systems or equipment for retrofit are determined; and in phase three, retrofit applications are selected based on cost/benefit analysis.

However, annual energy cost per unit area and energy usage per unit air-conditioned area has significant dependence on the building type and its use. For example, medical research centers usually have relatively high consumption, as there is more equipment and longer operating hours than in common commercial buildings.

Reynolds et al. (1990) developed a procedure to use monthly energy consumption data in the Princeton Scorekeeping Method (PRISM) as an initial screening tool to locate and define energy conservation opportunities. The PRISM CO model was applied to monthly energy consumption data first. If no suitable model could be developed with the PRISM CO model, the PRISM HO model would be tried. If neither the PRISM CO model nor the PRISM HO model could fit the data, then the PRISM HC model was used to test whether the presence of heating was interfering with the cooling analysis. If none of the PRISM models could represent the data, it was recommended to apply a flatness test to the data. If the data were not weather-dependent and no suitable PRISM model could be obtained, then further inspection was needed to find energy conservation opportunities in commercial buildings. Monthly electricity data for 34 out of 52 businesses in the Jersey Mall located in central New Jersey were used for pre-screening by this procedure. The energy consumption patterns for only two of these businesses were not easily explained.

Haberl and Komor (1990) used the annual energy cost per unit area (ECI), energy usage per unit air-conditioned area (EUI), monthly electric load factor (ELF) and monthly occupancy load factor (OLF) as pre-screening indices to help determine HVAC system problems. Analysis of monthly energy consumption by PRISM can be used to improve energy audits. Doruk (1990) studied energy use indices ELP, OLP, electrical energy power level (EEPL), electrical demand power level (EDPL), gas power level (GPL), and total energy power level (TEPL) for nine commercial building in Texas, and categorized EEPL, EDPL, GPL, and TEPL into low, medium, and high. ELF and OLF were also sorted as low, medium and high for different relations of ELF and OLF (ELF = OLF; ELF < OLF; ELF > OLF), then possible energy conservation opportunities were recommended based on some hypotheses, which were obtained from the author’s experience. Landman (1998) analyzed annual, monthly, daily, and hourly energy use indices for eleven schools in Texas, with different information about energy consumption based on weather and building occupancy scheduling present. Special attention should be paid to the different energy behavior in semester and non-semester periods for schools.

Energy Use Intensity (EUI) is the most common energy use benchmark metric in use. Building energy benchmarking is a useful starting point to target energy savings opportunities.

Sharp (1996) developed distributions of electric energy use intensities (EUI) in office buildings for the nine U.S. census divisions based on the information from the 1992 CBECS database. Building EUI was found to be related to several CBECS variables; the most significant variables after floor area were the number of occupants, number of personal computers, operating hours, and the use of an economizer or chiller. The predicted final performance models from EUI are much better benchmarks than simple census division statistics. Sharp (1998) also investigated the 1992 CBECS database as a source for energy benchmarks for local-government-owned schools. Average energy use values derived from CBECS can not evaluate energy performance of schools well. Electric use in schools was related to the total floor area, year of construction, use of walk-in coolers, electric cooling, non-electric energy use, roof construction, and HVAC operation schedule. While benchmarking based on simple distributions is a good method, the simple distributional benchmark can be improved if more building characteristics of the schools are considered.

Sartor et al. (2000) investigated strategies for benchmarking energy use in buildings with clean-rooms and laboratories; a multilevel hybrid approach utilizing statistical, modeling and a point system may be the solution. In this paper, four common strategies for benchmarking are outlined: 1) statistical analysis, 2) a point-based rating system, 3) model-based approaches, and 4) hierarchical end-use performance metrics. In statistical analysis, energy-use intensity (EUI) for a given building is compared with EUI of buildings of the same type and size from the same census region, and then the efficiency of energy use in the given building can be judged as high, low, or typical. But low energy-use intensity may not mean an energy efficient building. Simulation model-based benchmarking is based on an idealized model of building performance. For example, the

University of California Center for Environmental Research developed a model-based benchmark for laboratory benchmarking, which is based on an idealized model of equipment and system performance in the facility. Information about location, indoor air change requirements, lighting and HVAC characteristics, temperature and humidity requirements, occupancy and schedule, process equipment, etc., is necessary in this method. If only limited information about a building and HVAC system is available, then typical model-based approaches can't work. Hierarchical end-use performance metrics generate benchmarks that link energy use to climate and functional requirements. There are seven-level benchmarks in hierarchical end-use performance metrics—the idea of hierarchical measurements and metrics is to begin at the highest level and move down to the underlying system performance data; however, the data required are not always readily available. The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Rating System is a point-based rating system (Kinney and Piette, 2002), but it is a tool for evaluating new buildings so it cannot be used as a pre-screening tool for existing buildings.

The ENERGY STAR label was first introduced by the Environmental Protection Agency (EPA) in 1992 for energy-efficient computers; it has been expanded to more than 40 product categories. With the Energy Star program, Americans saved over $8 billion on their energy bills while preventing greenhouse gas emissions equivalent to the emissions from 18 million vehicles in 2003. EPA's national energy performance rating system is an evaluating tool in the program, which has been used to evaluate almost 19,000 buildings; the ENERGY STAR label has been awarded to nearly 1,400 buildings (EPA, 2004). Since Jan. 1999, EPA has provided the public the means to benchmark the energy performance of commercial buildings relative to similar buildings in the United States. Buildings with performance among the nation's top 25 percent that maintain a healthy and productive indoor environment can qualify as an ENERGY STAR building (EPA, 2003).

EPA's national energy performance rating system in ENERGY STAR Program can work as a pre-screening tool for commercial buildings such as offices and schools, but more information about the building, its occupancy, etc. are necessary, and an experienced professional Engineer (PE) is required to implement the procedure.

In order to reduce energy consumption of apartment buildings and improve living conditions, seven countries in Europe developed the Energy Performance Indoor Environmental Quality Retrofit (EPIQR) methodology to assist apartment building owners for refurbishing or retrofitting their buildings. Indoor Environmental Quality (IEQ), energy use, costs and retrofit measures are the four aspects considered when the assessment of the building condition and recommendation for refurbishment are made (Jaggs and Palmer, 2000).

A decision-making Tool for selecting Office Building Upgrading Solutions (TOBUS) has been developed by eight European institutes, which enables architects and engineers to handle the entire complex process of office refurbishment or retrofit considering deterioration, functional obsolescence of building services, energy consumption and indoor environmental quality. The TOBUS method supports building owners or managers in the initial decision-making, which might lead to a refurbishment operation (Caccavelli and Gugerli, 2002). The TOBUS software has been developed to facilitate the implementation of the TOBUS building diagnosis and decision-making method for retrofit studies (Flourentzou et al, 2002).

The TOBUS procedure includes the following main phases: (1) collecting general information about the building, such as typical floor plan, building dimensions, construction date, number of offices, utility bills, etc; (2) collecting comments about IEQ; (3) visiting the common spaces, as well as a few representative offices; and (4) analyzing the data available, try to work out some measures to solve problems with respect to one of the four categories (degradation, functional obsolescence, energy and IEQ) by the TOBUS (Wittchen and Brandt, 2002). The TOBUS methodology and tools have been implemented to study four office buildings in Greece and two office buildings in Denmark. Energy conservation in Hellenic and Danish buildings range for heating consumption from 5% to 71% and 0.5% to 6%, for cooling consumption from 1% to 38% and 4% to 20%, for lighting from 40% to 53% and 26% to 62%, for office equipment from 13% to 62% and 13% to 87% and for elevators at 35 % and 23%, respectively. TOBUS provides a first estimate of potential energy savings in office buildings (Balaras et al, 2002).

EPIQR is for residential buildings. The TOBUS has been successfully developed to evaluate condition of office buildings, and calculate a cost-efficient investment budget in the early stages of a refurbishment project. The procedure requires typically two visits to the building. Some data and information (general layout drawing, technical drawings, functional diagrams, etc.) are required before the first visit (Caccavelli and Gugerli, 2002).

Methodologies for energy calculations in buildings

A building energy calculation or simulation is an important component of the pre-screening methodology to be investigated. A number of methods have been developed to determine or predict energy consumption in buildings. These include the equivalent full-load hour method, the degree-day method, simple linear regression, multiple linear regression, change point models, ASHRAE bin method and inverse bin method, the ASHRAE TC 4.7 Simplified Energy Analysis Procedure (SEAP), detailed computer simulations (DOE-2, BLAST, etc.), as well as computer emulation (HVACSIM+, TRNSYS), Fourier series analysis and artificial neural networks (ASHRAE, 2001a; Ayres and Stamper, 1995; Dhar et al., 1998, 1999a, 1999b; Kreider et al., 2002; Thamilseran, 1999). These methodologies can be grouped as forward methods and inverse methods. Forward methods include the equivalent full-load hour method, the degree-day method, the ASHRAE bin method, SEAP, computer simulation and computer emulation. Simple linear regression, multiple linear regression, change point models, inverse bin method, Fourier series analysis and artificial neural networks are inverse methods. Measured energy consumption data are needed for inverse methods. Computer simulation models calibrated to measured data can be treated as a hybrid method. A suitable forward method for energy calculations is needed in this research, as the energy consumption by the HVAC system in a typical building and an idealized building must be calculated based on limited information.

Among the forward methods for building energy calculations, the equivalent full-load hour method and the degree-day method are extremely simple methods used to estimate yearly cooling or heating load that are not suitable for large buildings; the simple bin method doesn’t account for solar gain, internal heat gain, distribution systems, or the amount of ventilation air, so it is not suitable for commercial buildings. Simulation models and emulation models embody much of our understanding about how energy is used in buildings, but simulation models generally use less calculation time than emulation models. Simulation models range from very complex hourly models such as DOE-2, which simulate the dynamic behavior of a building's thermal mass, to simplified system models such as the ASHRAE TC 4.7 SEAP and a modified version of the SEAP (Kissock, 1993).

The ASHRAE TC 4.7 SEAP is a comprehensive modified bin method for estimating building energy usage. The procedure was originally developed for use as a complex manual calculation method or, preferably, to be programmed on a microcomputer. It can provide a reasonable level of accuracy in simulating energy consumption in a building, and it is not as complicated as DOE-2, or BLAST (Sud and Kusuda, 1982). The energy consumption values simulated for buildings by the SEAP have been compared with the results from DOE-2.1B, and were found to agree with each other within 10% for “average” values of all parameters evaluated. Larger deviations were obtained with non-“average” building characteristics, particularly for large values of glass-to-wall area ratio, internal heat gains, surface weight ratio, and night setbacks (Brotherton et al., 1987).

Building thermal mass is not considered in the original ASHRAE TC 4.7 SEAP, but incorporating a one-node thermal mass model modified it. Air temperature and mass temperature in air-conditioned space were treated as a function of gain variation (Claridge et al., 1992). The performance of the model from the modified SEAP with thermal mass and an improved solar treatment were compared with the original SEAP and DOE-2, and more reasonable results were obtained from the modified ASHRAE TC 4.7 SEAP than from the original one (Balasubramanya et al., 1992).

Detailed simulation programs such as DOE-2 and BLAST are useful for thermal analysis, but rather detailed information about the building, the building use, the HVAC system, etc., is needed. HVAC system models based on the SEAP can simulate energy consumption in a building with reasonable results, while the input data are relatively simple. In this dissertation, AirModel (Liu, 1997), based on an implementation of the ASHRAE TC 4.7 SEAP, will be used to predict the typical energy consumption and identify the critical elements influencing energy consumption in commercial buildings.

The critical elements influencing energy consumption in commercial buildings

Simulation models embody much of our understanding about how energy is used in buildings, but some detailed information about the building, the HVAC system, the schedule of occupancy and operation are needed when the model is developed, particularly for detailed simulation model such as DOE-2 and AirModel (LBL, 1981; Liu, 1997).

The needed information for an existing building is normally obtained from the blueprints of the building and a visit to the building to measure some parameters and determine some schedules. It will cost a lot of labor and time to finish the process, and there is the possibility of error or misinterpretation. Materials used actually are often different from the bulk properties reported in the literature. The operation, lighting, and occupancy schedules may vary from time to time. Some efforts have been made to estimate parameters for buildings. Rabl (1988) reviewed several methods for parameter estimation in buildings, such as thermal networks, modal analysis, differential equations, ARMA (autoregressive moving average) models, Fourier series, and calibrated computer simulations. The differential equations and ARMA model are recommended as a starting point, but the possibility of compensating errors is a big problem.

Reddy et al. (1999) proposed an inverse method to estimate building and ventilation parameters from whole-building cooling, heating and electricity use data. One-year daily energy consumption data in a large commercial building can successfully estimate overall building and ventilation parameters in a multi-step regression approach, but the method is not valid for one-year monthly data; though some parameters can be estimated from monthly data by a one-step regression approach or a two-step regression approach, but even small error or noise in the data will result in bias in the physical parameters.

Some parameters have significant influence on energy consumption, whereas others influence it rather weakly. The critical elements influencing energy consumption in commercial buildings should be identified, and the values for these parameters should be determined carefully, so that the energy simulation is successful.

Energy "signatures" of different parameters were introduced, which influence the heating and cooling energy consumption, for the purpose of speeding the process of calibrating a simulation to measured consumption data (Wei et al., 1998; Liu et al., 1998a). They examined the parametric behavior of heating and cooling use on cold deck temperature set point, supply air rate, floor area, preheat coil temperature set point, hot deck temperature set point, internal heat gain, outside air flow rate, room temperature, U-value of envelope, and use of an economizer. They examined the impact of these parameters on the energy consumption of a prototype office building with four different types of HVAC system. The parameters listed in the graphic signatures shown can be treated as potential critical elements, since only parameters that had significant influence on energy use were presented.

Sensitivity analysis helps to identify the variables in an energy simulation model that account for most variation of the energy consumption. Sensitivity analysis was performed on 25 input variables for two buildings (one was representative of small retail buildings in a relatively mild climate, and the other was an example of large office buildings in a somewhat harsher environment with greater diurnal swings) in the Pacific Northwest (Corson, 1992). These buildings used electricity as their only energy source and the analysis was carried out with the five software packages ADM-2 4.1 (R), SEA 6, TrakLoad 3.1, VCACS 10, and DOE-2.1. The results show that the heating and cooling were generally more sensitive to measures involving occupancy, weather, outside air flow rate, and the type of HVAC system, and less sensitive to measures affecting the building envelope and lighting. The results are more uniform from one modeling program to others for some measures, but changes in a few parameters fluctuate radically from one model to others. For the large office building, changes in COP of heat pump, U-value and shading coefficient of windows and the type of HVAC system, caused very different changes in the predicted results from one model to another. These differences may result from the different simplifications of procedures and algorithms that are used in the different programs. The results from DOE-2.1 are generally considered reasonable.

Special attention was paid to the effect of different types of weather on energy consumption based on a prototype building (Mahone et al., 1992). The energy consumption of a grocery and a small office building in Portland, Oregon were simulated by DOE-2, and sensitivity analysis was performed to identify the relative importance of several building and system characteristics required as inputs to the model. This study indicated that for the small office building, efforts should focus on lighting and equipment loads, and whether or not an economizer is employed (Griffiths and Anderson, 1994). Weather-independent electricity consumption in a "low-energy" office building in central New Jersey had a significant impact on total electricity consumption, and contributed 64% of the discrepancy between the simulated and actual electricity consumption in one study (Norford, 1994). PEAR (Program for Energy Analysis of Residences) Version 2.1 is a simple PC spreadsheet program developed by Lawrence Berkeley National Laboratory (LBNL) from a detailed sensitivity analysis conducted using DOE-2. It can be used to estimate annual heating and cooling energy consumption of conventional houses in over 800 locations. The required inputs are the type, location, and area of the house, area and amounts of insulation of walls and roofs, type and area of windows, amount of air leakage, perimeter length, and efficiency of air-conditioning system. These required inputs could be treated as sensitive elements to energy consumption in residential buildings (LBNL, 1996).

Sensitivity analyses have been done to identify critical elements to simulated energy consumption in commercial and residential buildings in several states. In general, measures involving weather-independent electricity consumption, occupancy, weather, outside airflow rate, and the type of HVAC system in commercial buildings are sensitive elements. Whether these results are valid for large commercial buildings in a hot and humid climate simulated by AirModel should be tested.

Non-weather dependent load schedule, occupancy schedule, etc., are necessary inputs to an energy simulation model for commercial buildings. The occupancy schedule can be represented by the non-weather dependent load schedule (lighting, equipment, and fans) in commercial buildings (Keith and Krarti, 1999).

Characteristics of weather-dependent energy consumption

Regression models of measured energy use in commercial buildings are becoming an increasingly popular method of developing baseline models used for determining retrofit savings or identifying operational and maintenance problems. A monthly regression model has higher R^2 and lower CV value than daily or hourly models, but 12 months or more data were necessary for monthly regression models (Katipamula et al., 1995). If the Air Handling Units (AHUs) are operated 24 hours per day, both daily and monthly regression models can work well; if the AHUs are shut down during unoccupied periods, neither daily nor monthly regression models can predict the energy use correctly (Wang, 1996).

As energy consumption in large commercial buildings is a complex function of climatic conditions, building characteristics, building usage, system characteristics and type of heating, ventilation and air-conditioning (HVAC) equipment used, a multiple linear regression model should work better than a single-variable model for energy consumption. Outside air dry-bulb temperature and outside air wet-bulb temperature can explain most of the variation of energy consumption for both DDCV and DDVAV systems on a monthly time scale (Katipamula et al., 1998).

Outside air dry-bulb temperature and outside air wet-bulb temperature are usually linearly related; this may result in multicollinearity in regression models. Using ambient temperature as the single independent variable can eliminate statistical problems due to multicollinearity and reduce the data-collection requirement. Two, three, four, and five parameter regression models for energy consumption vs. outside air temperature can explain most thermal behavior in commercial buildings (Kissock et al., 1998).

From the above, the profile of weather-dependent energy consumption vs. outside dry-bulb temperature for a large commercial building seems to be related to the main type of HVAC system. These characteristics may help identify the main type of HVAC system by comparing 12-month measured energy consumption with simulated consumption for different types of HVAC systems.

Existing methods for disaggregating energy consumption in commercial buildings

The pre-screening methodology to be developed requires a method that can successfully separate electricity consumption by the chiller system from normal electricity bills. Existing methods will be reviewed.

Several tools can be used to separate the utility bills if the building is located in a place where it is cold in winter, and the chiller system isn't used for at least part of the winter. The cooling only (CO) model in the Princeton Scorekeeping Method (PRISM) can be used to disaggregate the utility bills into weather-dependent electricity load and weather-independent electricity load (Reynolds et al., 1990); E-model can also be used to separate utility bills by developing a three-parameter (3-P) regression model (Kissock et al., 1994); the heating and cooling (HC) model in PRISM can also help to separate utility bills (Stram and Fels, 1986). The above methodologies can successfully separate electricity consumption in commercial buildings into weather-independent and weather-dependent parts, if the buildings are located in a place where it is cold enough in winter that the chiller system isn't used for at least one billing month. They are invalid for places where it is warm enough year round that the chiller system needs to work in the cool season, such as Texas.

Train et al. (1985) developed statistically adjusted engineering (SAE) models to estimate end-use load shapes combining engineering and statistical approaches. The SAE method may be complicated for commercial buildings, as there is much equipment in the buildings. The End-use Disaggregation Algorithm (EDA) was developed to disaggregate hourly whole-building load using the outdoor dry-bulb temperature as a single variable. The basic component of EDA is the regression of the hourly load against hourly outside dry-bulb temperature; two sets of regression equations are used, one for summer, and another for winter. To separate the load into temperature-dependent and temperature-independent loads, a regression model for winter is used to calculate the base load, when a base temperature is defined for winter. The building is simulated at the base temperature and results of the simulation are used in combination with regression results to determine the weather independent consumption (Akbari et al., 1988). The EDA approach algorithm can separate measured hourly electricity consumption successfully, but it does not appear to have been used with monthly data and it requires considerably more building information than is typically available for screening audits.

Pattern recognition was used to disaggregate the total electricity consumption for a residential building by measuring the total electricity consumption of a house. Sub-metering of the target appliance during a one-week training period is required to find the electric characteristics of individual appliances (Farinaccio and Zmeureanu, 1999). The required sub-metering prevents this approach from being used for prescreening.

A simplified method was developed to disaggregate the 24-hour profile of the whole-building electricity consumption (Bou-Saada, 1994). First, the lighting and equipment load were estimated by visiting the building during the period when no heating or cooling was required, for example, when the outside air dry-bulb temperature was between 45 °F and 75 °F, and then the HVAC electricity use in the other period was calculated by subtracting the lighting and equipment load from the total load. This method requires more data than is available for pre-screening.

Weather-independent load schedule can be displayed using Box, Whisker and Mean (BWM) statistics for each hour for all days of the week, weekdays and weekends, and the profiles of average weather-independent electrical consumption for every hour can stand for the non-weather-dependent load schedule (Haberl and Abbas, 1998a, 1998b). Hourly measured weather-independent electrical consumption of a building is necessary for some periods.

Hence, there is a need to find a way to disaggregate monthly electricity consumption in large commercial buildings located in hot and humid climates.

Tools for pattern recognition

The comparison of measured monthly energy consumption and simulated consumption in commercial buildings may help to find buildings with large potential energy savings. A portion of the process may involve pattern recognition, which can be carried out automatically instead of manually.

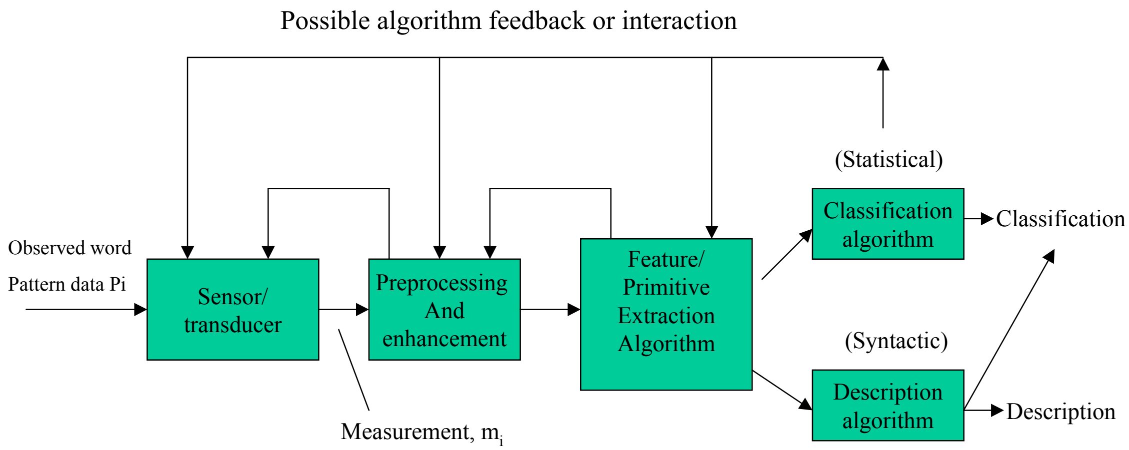

Figure 2. 1 Typical pattern recognition system structure (Source: Schalkoff, 1992).

Pattern recognition is the study of how machines learn to distinguish patterns of interest and make sound and reasonable decisions about the categories of the patterns by observing the environment. A typical pattern recognition system contains a sensor, a preprocessing mechanism, a feature extraction mechanism, and a classification algorithm. Statistical pattern recognition, syntactic pattern recognition, and neural pattern recognition are the three major approaches; typical pattern recognition system structure is shown in Figure 2.1 (Schalkoff, 1992).

Statistical pattern recognition is based on an underlying statistical model of the features, which is the most general framework to formulate solutions to pattern recognition problems. Syntactic pattern recognition is based on measures of structural similarity; speech recognition and handwriting analysis are successful applications of this approach. Neural pattern recognition is based on the response of a network of processing units to an input stimulus; this is basically a black box approach (Schalkoff, 1992). As limited valued data are available in this research, no training data are available for neural pattern recognition and no structural information is ready for syntactic pattern recognition; statistical pattern recognition may be a helpful approach.

The Bayesian classifier, the nearest neighbor classifier (1-NN), and the nearest prototype classifier (1-NP) are the common tools of statistical pattern recognition. The Bayesian classifier is an algorithm for supervised learning that stores a single probabilistic summary for each class and that assumes conditional independence of the attributes given the class, which has the lowest error rate among all classifiers. The nearest neighbor classifier assigns an input sample vector to the class of its nearest neighbors based on the labeled observations; whereas the nearest prototype classifier assigns an input sample vector to the class of its nearest prototype (Bezdek, 1981). Training data are needed when the Bayesian classifier and the nearest neighbor classifier (1-NN) are used. The nearest prototype classifier can be used for pattern recognition based on some notion of similarity or distance in feature space. However, with the nearest prototype classifier, once an input vector is assigned to a class, there is no indication of its "strength" of membership in that class. In contrast, the fuzzy memberships for samples classified by the fuzzy nearest prototype classifier can specify to what extent the input vector belongs to a particular class, just as human judgment does (Keller et al., 1985).

Fuzzy sets and membership for classes without sharp boundaries were presented in 1965 (Zadeh, 1965). Based on the fuzzy set, theories and technologies have been developed for fuzzy implications and approximate reasoning, fuzzy logic controllers, and fuzzy pattern recognition, etc. (Yen and Langari, 1999). The conventional proportional-integral-derivative (PID) control algorithm can be combined with a fuzzy logic controller for HVAC application. A PID-law-combining fuzzy controller (PFC) was developed based on the rules obtained from the operator's experience; this controller provided better performance than a conventional PID controller (Huang and Nelson, 1991). The general method for designing an FLC is using trial and observation. An FLC includes three parts: fuzzifier, fuzzy reasoning unit, and defuzzifier. Rule set, membership functions, and scale factors are three important elements that have an impact on the behavior of an FLC, and more attention should be paid to the critical elements when an FLC is developed (Huang and Nelson, 1994a). An experiment for an air-conditioning system with a chiller, an air-handling unit and an air-conditioning room was done, and the results from an FLC controller were compared with the results and a conventional PID controller. The dynamic process of the FLC has a short rise time and no overshoot (Huang and Nelson, 1994b). An FLC is usually developed based on the method of the compositional rule of inference (CRI). A new concise method of fuzzy logic reasoning—the functioning-fuzzy-subset inference (FFSI) was presented for HVAC systems, and a single-chip microcomputer has been developed to carry out the fuzzy control (Zhang et al., 2003a). The experimental result of the FFSI control for the testing room dynamic thermal system (TRDTS) is compared with the result of PID control, the indoor temperature controlled by FFSI responds rapidly with high control precision, good stability, and small stable error. Simulation results of FFSI and CRI for the indoor temperature show that the performance of FFSI is better than that of CRI (Zhang et al., 2003b). Fuzzy logic controllers have been applied in HVAC systems successfully; one method of fuzzy pattern recognition will be used to identify the main type of HVAC system in this dissertation.

As limited information is available in this research, the Bayesian classifier and the nearest neighbor classifier (1-NN) can't be developed, since there are no training data; the fuzzy nearest prototype classifier is more similar to the process of pattern recognition used by people than the nearest prototype classifier. Hence, the fuzzy nearest prototype classifier is selected as the pattern recognition tool for this research.

Summary

In this chapter, a literature review of existing pre-screening tools for energy audits has been presented; the literature review about methodologies for energy calculations in buildings, the critical elements influencing energy consumption in commercial buildings, existing methods for disaggregating energy consumption in commercial buildings, characteristics of weather-dependent energy consumption, and tools for pattern recognition, which are related to the research in this dissertation, are also summarized.

Several methods for pre-screening have been developed to identify buildings with large potential energy savings. A walk-through assessment can present an initial judgment of potential savings for a facility (ASHRAE, 1999); hourly pre-screening indices can be used to identify the buildings with potential for additional energy savings from operational improvements (Liu et al., 1994). An expert system was developed to find energy inefficient buildings and cost-effective energy retrofit alternatives (Gatton et al., 1995). The Princeton Scorekeeping Method (PRISM) can be used as a pre-screening tool to locate and define energy conservation opportunities (Reynolds et al., 1990). Annual energy cost per unit area (ECI), energy usage per unit air-conditioned area (EUI), monthly electric load factor (ELF) and monthly occupancy load factors (OLF) can be used as pre-screening indices to help determine HVAC system problems (Haberl and Komor, 1990). EPA's national energy performance rating system in ENERGY STAR Program can work as pre-screening tool for commercial buildings (EPA, 2003). The decision-making Tool of TOBUS is a prescreening tool for office buildings, whereas EPIQR is for residence building (Caccavelli and Gugerli, 2002; Jaggs and Palmer, 2000). Some experiences are important to some above pre-screening tools, such as walk-through assessment, energy use indices and the ENERGY STAR program. Daily or hourly data are necessary for pre-screening indices. The expert system for preliminary energy audit, hierarchical end-use performance metrics and statistical analysis of building energy benchmarking are not suitable for some facilities, such as medical research centers. The point-based rating system is a tool for evaluating new buildings so it cannot be used as a pre-screening tool for existing buildings. Information about location, building and HVAC characteristics, etc. is necessary in the simulation model-based benchmarking. Though PRISM can be used as an initial screening tool to locate and define energy conservation opportunities, potential energy savings are unknown from the method. The decision-making Tool of TOBUS is a prescreening tool for office buildings, whereas EPIQR is for residential buildings.

To summarize, though several pre-screening tools for energy audit are available, there is a need to develop an automated preliminary or screening energy audit methodology that requires a minimum amount of easily obtained information. A methodology will be developed to pre-screen large commercial buildings for potential energy savings using a minimum amount of easily obtained information, specifically, utility bills, total area, and weather data.

CHAPTER III
PRE-SCREENING METHODOLOGY

This chapter presents a detailed description of the pre-screening methodology for energy audits based on a minimum amount of easily obtained information such as utility bills, total area, and weather data. This method can be used to identify the best candidate buildings in the commercial sector for more detailed audits.

Introduction

Typical energy audits are sufficiently expensive and time-consuming that many owners and managers of buildings are not willing to invest the time and money required for a full audit, so less expensive screening techniques are valuable when used to identify the best candidates for full audits.

Several methods for pre-screening have been developed to identify buildings with large potential energy savings. Such as a walk-through assessment (ASHRAE, 1999), hourly pre-screening indices (Liu et al., 1994), an expert system (Gatton et al., 1995), a pre-screening tool using PRISM (Reynolds et al., 1990), Annual energy cost, consumption and occupancy index ECI, EUI, ELF and OLF (Haberl and Komor, 1990), EPA's national energy performance rating system in ENERGY STAR Program (EPA, 2003), the decision-making Tool of TOBUS and EPIQR (Caccavelli and Gugerli, 2002; Jaggs and Palmer, 2000).

A new methodology is developed based on a minimum amount of easily obtained information - specifically utility bills, total area, and weather data; the methodology can be used to identify large commercial buildings with potential energy savings. This approach implements a system and method for remotely identifying retrofit opportunities and the potential savings from implementing retrofits and CC® (Claridge, 2001). The magnitude of estimated retrofit and CC® energy savings can help make a decision about a full scale retrofit or CC® audit. The methodology may work better if information about the main type of HVAC system and weather-dependent energy consumption is also known.

Overview of the pre-screening methodology for energy audits

The pre-screening methodology for energy audits presented in this dissertation is based on the following hypothesis:

If a commercial building is properly designed, constructed, retrofit, operated, and maintained, the measured energy consumption should approximately match the simulated value for a typical building of the same size with the most efficient HVAC system (called the prototype building hereafter); otherwise, there may be potential for energy savings.

The methodology can be used to identify large commercial buildings with potential energy savings for a further detailed energy audit.

This hypothesis may be used to conceive the following methodology:

1. If the measured energy consumption of the HVAC system in a building is significantly higher than the simulated value for a typical building of the same size with the most efficient HVAC system, then there is probably potential for retrofit or CC®.
2. It may be possible to identify the main type of HVAC system by comparing weather-dependent electricity consumption and gas consumption with the consumption from multiple simulations of a typical building of the same size with a different type of HVAC system used in each simulation.
3. If the main type of HVAC system in a building can be identified, the measured consumption can be compared with the simulated energy consumption of an idealized building of the same size with the identified type of HVAC system. This should permit more explicit conclusions about the retrofit or CC® potential.
4. If the main type of HVAC system can't be identified, potential for energy savings can still be identified by comparing consumption of a building with a very efficient system, but there will be more uncertainty in the potential for retrofit or CC® improvements. Hence, a range of potential savings will be given, with this range depending on the range of HVAC systems types the building may contain.

In this section, the basic procedure of the pre-screening methodology for energy audits is described. The basic procedure is illustrated in Figure 3.1 in a flowchart format. There are four steps in the methodology, which includes: 1) a procedure for testing whether the electrical utility bills include electricity consumption by the chiller system. 2) If the utility bills include both weather-dependent and weather-independent loads, the total load in the bill should be separated into two parts by different methods for different cases (Three-parameter change-point regression model and SUBTB). More detail about the SUBTB method to separate utility bills for commercial buildings in hot and humid climates is provided in Chapter IV. 3) If the main type of HVAC system in a commercial building is unknown, the main type of HVAC system may be identified by comparing measured weather-dependent energy consumption with simulated values in a prototype building of the same size. An automated pattern recognition method is developed in Chapter V. 4) If the main type of HVAC system in a commercial building is known or identified, then the potential CC® energy saving can be estimated by comparing simulated energy consumption of the idealized building and the measured consumption. Retrofit and CC® savings can be estimated by comparing measured energy consumption with simulated values in the idealized building with the most efficient HVAC system; judgment can be made if the building deserves further detailed energy audit.

If the Air Handling Units (AHUs) are operated 24 hours per day, 12 months or more of data were necessary to develop a reliable monthly regression model (Katipamula et al., 1995; Wang, 1996), so 12 months or more of utility bills are used in this methodology.

In the pre-screening methodology for energy audits, a prototype large commercial building and an idealized large commercial building are used several times. The definition and configuration of the two buildings will be described in the following section. The critical elements for energy consumption in large commercial buildings will be identified based on the prototype large commercial building.

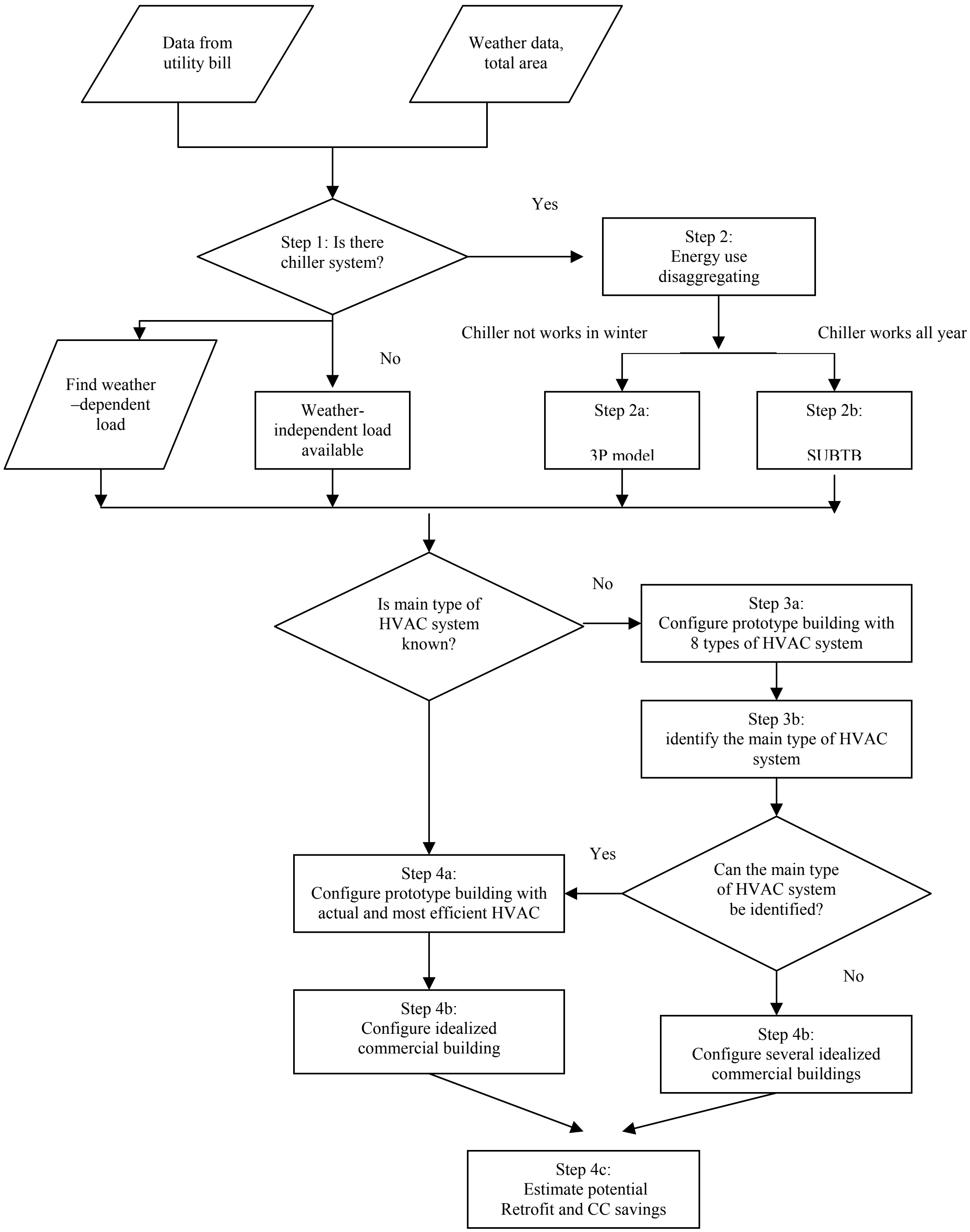

Figure 3. 1 Procedure of the pre-screening methodology for energy audit.

Prototype commercial building and idealized commercial building

To identify appropriate characteristics for the prototype and idealized commercial buildings, the results of the Commercial Building Energy Consumption Survey (CBECS) are examined. This is a national-level sample survey of commercial buildings with more than 1,000 square feet of floor space. In 1999, CBECS collected information for 4,657,000 commercial buildings in the United States, which comprised 67.338 billion square feet of floor space. The survey included 234,000 large commercial buildings (50,000 square feet or larger), with floor space of 31.866 billion square feet (EIA, 1999a).

Table 3.1 The size distribution and number of floors of large commercial buildings in the United States

(Data are from EIA, 1999a)

Floors	50,001 to 100,000 ft^2		100,001 to 200,000 ft^2		200,001 to 500,000 ft^2		Over 500,000 ft^2	
	Number of Buildings (Thousand)	Total Floor space (Million ft^2)	Number of Buildings (Thousand)	Total Floor space (Million ft^2)	Number of Buildings (Thousand)	Total Floor space (Million ft^2)	Number of Buildings (Thousand)	Total Floor space (Million ft^2)
One	48	3377	22	2930	5	1328	1	724
Two	40	2799	12	1645	4	1059	1	1081
Three	26	1776	8	1128	3	942	Q	Q
Four to Nine	28	2015	15	2112	7	2325	2	1704
Ten or More	Q	Q	3	457	4	1197	3	2638

Q: Data withheld because the Relative Standard Error (RSE) was greater than 50%, or fewer than 20 buildings were sampled.

The average size of the large commercial buildings in the United States is 136,200 square feet. Table 3.1 provides additional information on the size and number of floors of these buildings. If it is assumed that the average number of floors for those in the category “four to nine” is 6.5, the average number of floors for those with ten or more is 15, and the “data withheld” items in the table are ignored, the average number of floors is 4.8. The prototype is selected as a 128,000 ft^2 building with five floors. For simplicity, the foot-print of the prototype commercial building for this dissertation was assumed to be 160 feet * 160 feet.

The minimum requirement of outside air ventilation per person for any type of space is 15 CFM/person as specified in ASHRAE Standard 62-2001 (ASHRAE, 2001b). It is assumed that for a peak occupancy level of 200 ft^2/person, the outside airflow rate was 0.1 CFM/ft^2 in the prototype building.

For air-conditioned commercial buildings, the vertical fenestration area shouldn't exceed 50% of the gross wall area (ASHRAE, 2001c). For commercial buildings with typical fenestration and day lighting controls in Chicago or Houston, the annual electricity use can be maintained at reasonable levels when the Window-to-Wall Ratio is 0.1-0.4 (ASHRAE, 2001a). The Window-to-Wall Ratio for the 19 large buildings listed in Table 3.2 (Claridge, 1996b) ranges from 4% to 30%, with an average of 16%. These buildings may have less glazed area than typical, but a Window-to-Wall Ratio of 0.15 is assumed on every exterior wall in the prototype building.

A number of other parameters were chosen to be the same as those used by Brotherton in his prototype building (Brotherton et al., 1987). The heat lost to ground by this multi-story prototype was neglected. The windows were single-pane, double-strength glass, with a U value of 1.1 Btu/hr/ft^2/°F; the U value for the roof was 0.07 Btu/hr/ft^2/°F; the U value for the walls was 0.15 Btu/hr/ft^2/°F; the height of each floor was assumed to be 15 feet; and the thermostat set point was 75 °F. In summary, characteristics of the prototype building are listed in Table 3.3.

The Heating, Ventilating and Air-Conditioning system (HVAC) in the prototype commercial buildings is assumed to work continuously and pressurizes the building, so air infiltration is assumed to be zero. Constant volume AHU systems and variable volume AHU systems are common in commercial buildings; both will be considered in the prototype.

The total air-conditioned area can be divided into two zones: an interior zone and an exterior zone. The width of exterior zones usually is approximately 15 ft, resulting in an interior zone fraction in the prototype commercial building of 0.66.

Internal gains are the heat gains produced from lights, equipment and fans, etc. Internal gains typically range from 0 to 5 W/ft^2 (Claridge et al., 2004); they are assumed to be evenly distributed in the exterior zone and interior zone (Balasubramanya et al., 1992). The peak internal gain in the prototype building is assumed to be 2.2 W/ft^2, and the internal electricity gain schedules for weekdays and weekends are shown in Figure 3.2, which is common for large commercial buildings (Claridge et al., 2004). Internal gains will convert to cooling or heating load directly, and have a significant impact on energy consumption.

Total supply airflow rate is dependent on the cooling or heating load in the building. Based on the parameters for the prototype commercial building, 1.1 CFM/ft^2 supply airflow can remove the cooling load (the peak internal gain is 2.2 W/ft^2) if the building is in Texas. Temperature difference between return and room air temperature is assumed to be 2°F.

Table 3.2 Window-to-Wall Ratio in 19 large buildings in Texas

Building	Location	Total area (ft^2)	Ratio of window to wall area (%)
Zachry Engineering Center	College Station	324,400	12%
Education Building	Austin	251,161	30%
University Teaching Center	Austin	152,690	9%
Perry Castaneda Library	Austin	483,895	12%
Garrison Hall	Austin	54,069	19%
Gearing Hall	Austin	61,041	18%
Waggener Hall	Austin	57,598	22%
Welch Hall	Austin	439,540	20%
Winship Hall	Austin	109,064	10%
Steindam Hall	Austin	56,849	28%
Painter Building	Austin	128,409	24%
W.C. Hogg Building	Austin	48,905	12%
University Hall Building	Arlington	123,450	10%
Business Building	Arlington	149,900	4%
Fine Arts Building	Arlington	223,000	6%
Stephen F. Austin	Austin	470,000	25%
Archives Building	Austin	120,000	6%
Moody Memorial Library	Galveston	67,380	26%
John Sealy South	Galveston	373,085	10%

Table 3.3 Key characteristics of the prototype commercial building

Variable	Parameters
Air-conditioned area	128,000 ft^2
Dimensions	160x160x75 (ftxftxft)
Height of each floor	15 ft
U-value of windows	1.1 $Btu/hr/ft^2/^oF$
U-value of roof	0.07 $Btu/hr/ft^2/^oF$
U-value of walls	0.15 $Btu/hr/ft^2/^oF$
Thermostat setting	75 °F
Window-to-wall ratio	0.15
Outside air flowrate	0.1 CFM/ft^2

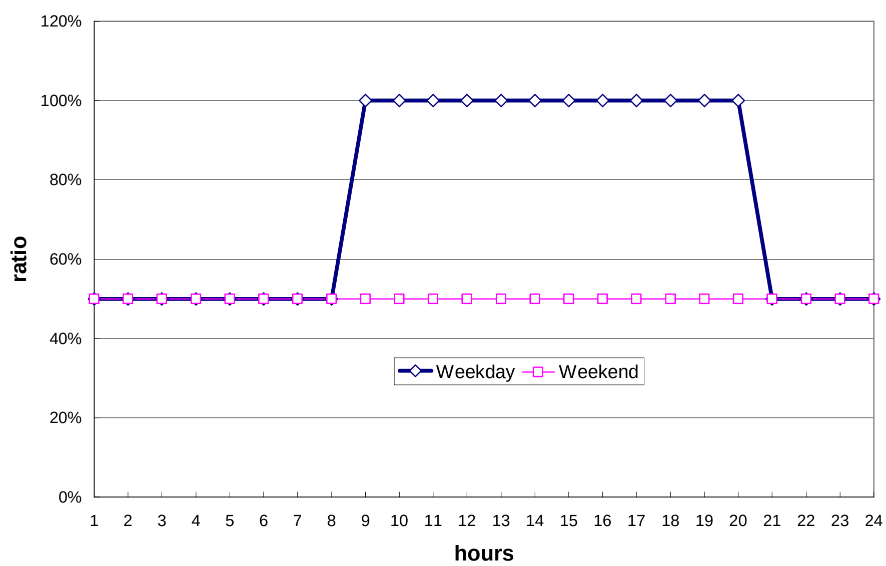

Figure 3.2 Electricity schedule during weekdays and weekends for sensitivity analysis.

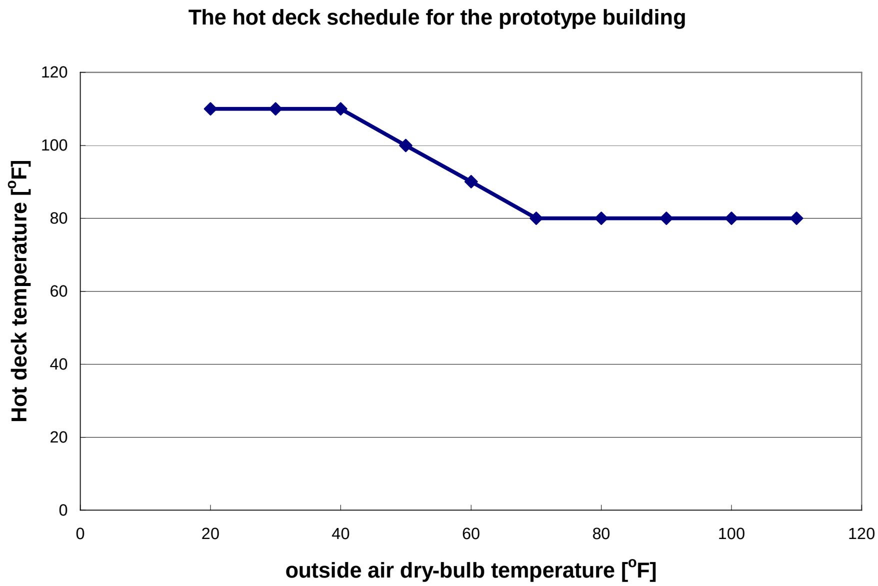

Figure 3.3 Hot deck schedule for the prototype building.

Cold deck schedule and hot deck schedule are important factors in HVAC system performance. The cold deck is assumed to be 55°F all the time; the hot deck schedule used for the prototype building is shown in Figure 3.3 (Wei et al., 1998).

In AirModel, the seasonal variation of the solar gain is approximated by a linear relationship of solar load with outside air temperature (Knebel, 1983). Solar gain can be calculated as two parts: solar gain from fenestration, and solar gain from walls and roof. The solar gain can be calculated based on the location of the building and envelope information, which can be retrieved from the prototype building. The solar gain can be calculated using the following procedure.

Solar gain from fenestration:

$Q_{solf}= M*(T-T_{ph})+Q_{solf,Jan}$ Equation 3. 1

Where $M=(Q_{solf,Jul} - Q_{solf,Jan})/(Tpc-Tph)$ Equation 3. 2

T	Outside air temperature
Tpc	Cooling Design dry-bulb temperature
Tph	Heating Design dry-bulb temperature

$$Q_{solf,Jul} = \frac{\sum_{i=1}^{N}(MSHGFi * AGi * SCi * CLFTOTi * FPS)}{t * Af} \qquad \text{Equation 3. 3}$$

Where

$Q_{solf,Jul}$ average solar contribution for July

N number of different glass exposures

MSHGFi maximum solar heat gain factor for orientation i for July at the specified latitude (Btu/hr-sf)

Agi glass area for exposure i (sf)

SCi shading coefficient of glass for exposure i

CLFTOTi 24 hour sum of CLF for orientation I

CLF Cooling load factor

FPS fraction of possible sunshine for July

t runtime of air conditioning system (hours)

Af building conditioned floor area (sf)

$$Q_{solf,Jan} = \frac{\sum_{i=1}^{N}(MSHGFi * AGi * SCi * CLFTOTi * FPS)}{24 * Af} \qquad \text{Equation 3. 4}$$

Where

MSHGFi maximum solar heat gain factor for orientation i for January at the specified latitude (Btu/hr-sf)

FPS fraction of possible sunshine for January

FPS for Austin, Texas is used for College Station, Texas. FPS for Austin, Texas (Knebel, 1983) is listed in Table 3.4. CLFTOT for different orientations are listed in Table 3.5. College Station is located at Lat. 30.58 N, Long. 96.37 W.

Table 3.4 Mean percentage of possible sunshine for Austin, Texas

Month	FPS
January	46%
July	76%

Table 3.5 The 24-hour sum of cooling load factors for glass

Orientation	CLF SUM
North	11.57
East	5.46
South	6.43
West	5.46

Maximum solar heat gain factor for orientations in Jan. and July for Lat. 32°, 24° and 40° are listed in Table 3.6, Table 3.7, and Table 3.8 (ASHRAE, 1993). The dry-bulb cooling design temperature for College Station, Texas is 96°F (1%), the dry-bulb heating design temperature for College Station, Texas is 29°F (99%) (ASHRAE, 2001a); they are treated as Tpc and Tph, respectively.

Table 3.6 Maximum solar heat gain factor for orientations in Jan. and July (Lat. 32°)

Month	North	East	South	West
January	24	175	246	25
July	40	215	72	42

Table 3.7 Maximum solar heat gain factor for orientations in Jan. and July (Lat. 24°)

Month	North	East	South	West
January	27	190	227	29
July	45	213	46	43

Table 3.8 Maximum solar heat gain factor for orientations in Jan. and July (Lat. 40°)

Month	North	East	South	West
January	20	154	254	21
July	38	216	109	41

Solar gain from walls and roof:

$$Q_{solo,Jul} = \frac{\sum_{i=1}^{N} (AiUi * CLTDSjul * K * FPSjul)}{AF} \quad \text{Equation 3.5}$$

$$Q_{solo,Jan} = \frac{\sum_{i=1}^{N} (AiUi * CLTDSjan * K * FPSjan)}{AF}$$ Equation 3.6

Table 3.9 CLTDS values for North 32° latitude

	January	July
North	0	6
East	7	15
South	26	7
West	7	15
Roof	7	23

Table 3.9 shows CLTDS for north 32° latitude. The building is assumed to be dark, K value is 1; the shading coefficient (SC) of glass for each exposure is assumed to be 0.35, the total solar gain for the prototype building is the sum of both parts.

The solar gain of the prototype building can be calculated; in July, the average solar gain is 0.121 MMBtu/hour and it is 0.065 MMBtu/hour in January. The solar gain of the building for other temperatures can be interpolated linearly.

Based on the information for the prototype commercial building, the input file of AirModel for the prototype building with a dual duct constant air volume system can be prepared. For example, the file for the prototype building with dual duct constant air volume system is listed in Appendix I.

The idealized commercial building is configured similarly to the prototype commercial building. The idealized commercial building has optimized hot-deck and cold-deck schedules. An optimized operation schedule for the HVAC system can reduce energy cost. For example, 23% of energy cost was saved when an optimized operation schedule was implemented in the Basic Science Building at UTMB (Liu et al., 1994). The optimized operation schedule of the HVAC system in a building can be obtained by a trial-and-error method. First, a hypothesized best operation schedule is chosen, and the energy consumption is simulated by AirModel; secondly, some modifications are made to the operation schedule, and the simulated energy consumption in this situation will be compared with the previous one. The process is repeated until the minimum energy consumption for the building is achieved while maintaining comfortable conditions; the last operation schedule is the optimized operation schedule (Liu et al., 1995). The optimization process for the optimized operation schedule has been automated in AirModel (Liu, 1997); both hot-deck and cold-deck temperatures of the HVAC system are adjusted during the optimization process (Liu and Claridge, 1998b).

AirModel is used to find an optimized operation schedule for the HVAC system. For example, the results of the optimization process based on 1999 data for the prototype building with a dual duct variable air volume HVAC system are shown in Figure 3.4, when chilled water is assumed to be \$3.90/MMBtu and hot water is assumed to be \$4.00/MMBtu. The minimum cold-deck temperature and maximum hot-deck temperature in each bin from Figure 3.4 form the optimized operation schedule for the HVAC system in the prototype building (Figure 3.5).

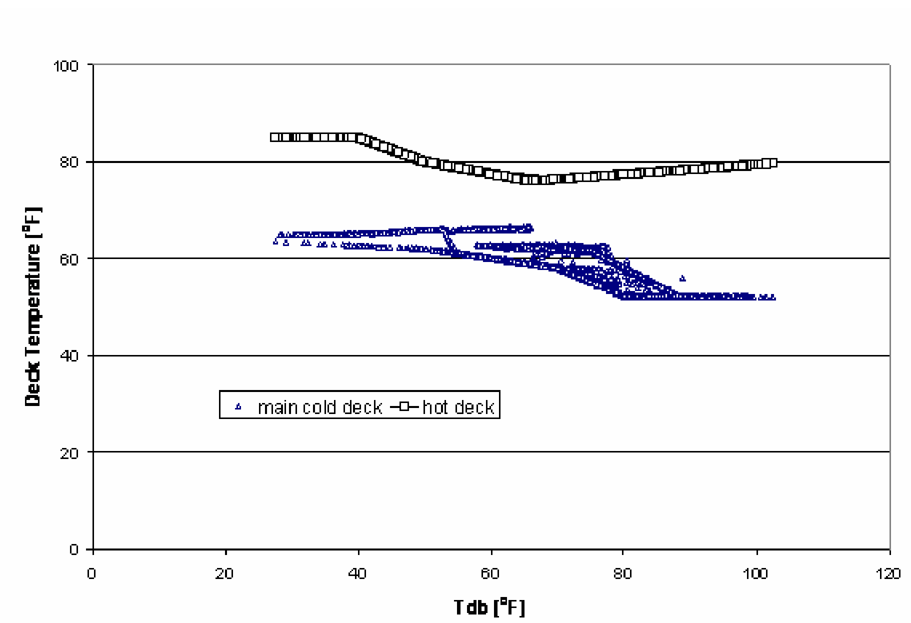

Figure 3.4 The result of the optimization process based on 1999 data for the prototype building.

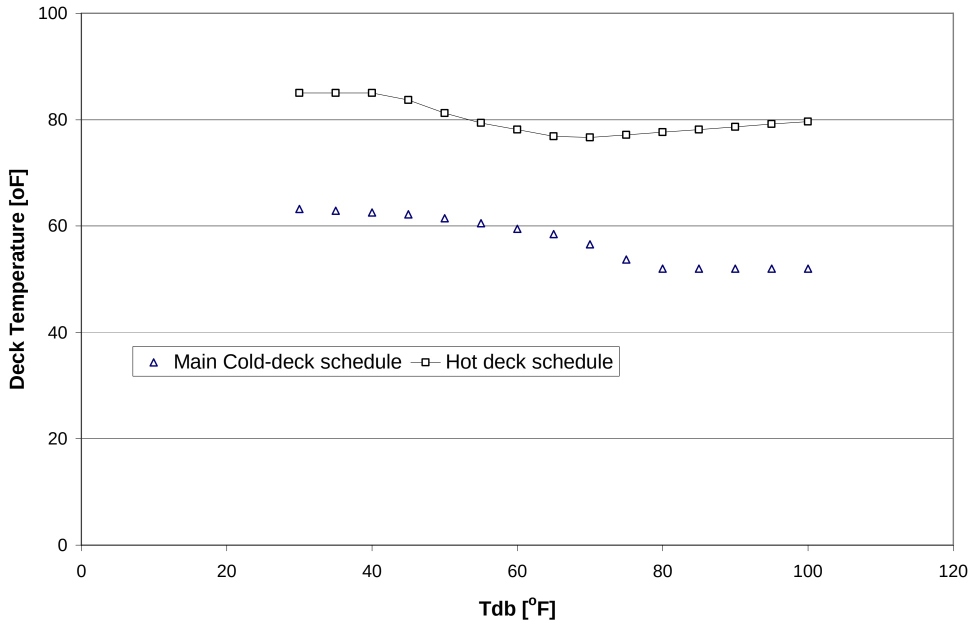

Figure 3.5 Optimized operation schedule for dual duct HVAC system in the prototype building based on 1999 data.

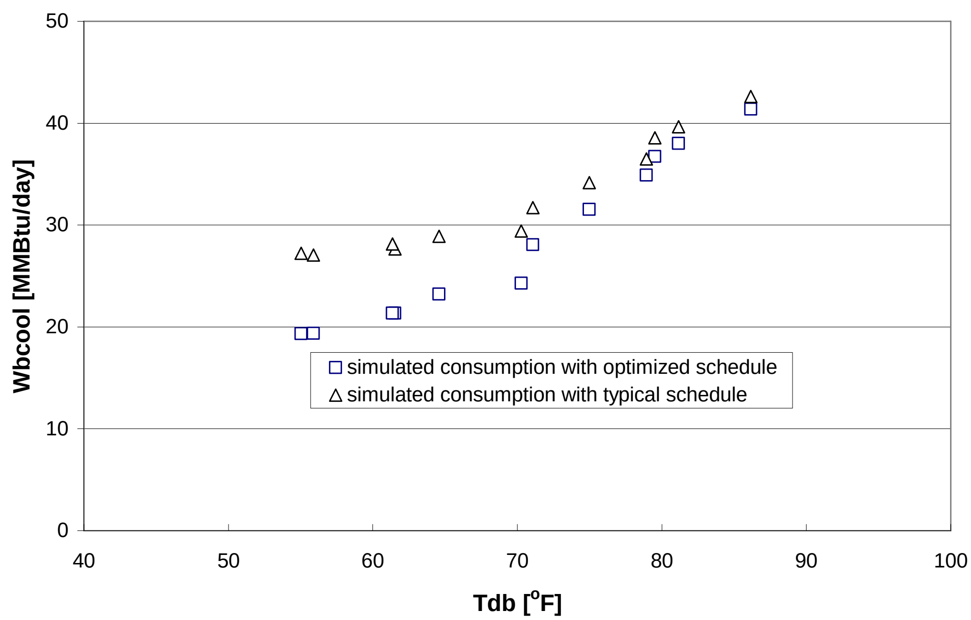

Figure 3.6 Comparison of simulated Wbcool in prototype building and idealized building.

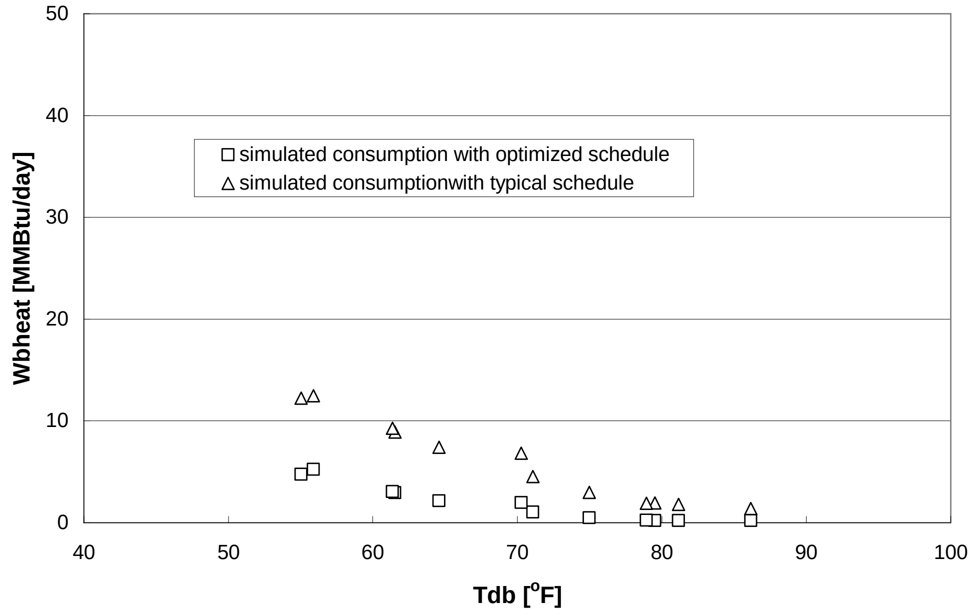

Figure 3.7 Comparison of simulated Wbheat in prototype building and idealized building.

For the prototype building with dual duct variable air volume system, the simulated monthly Wbcool and Wbheat in the idealized building are lower than those in the prototype building (Figures 3.6 and 3.7), so the impact of the optimized operation schedule is significant. Note that the optimized operation schedule for the single duct HVAC system and constant volume system in this dissertation are determined by the trial-and-error method.

Critical elements for energy consumption in large commercial buildings

Simulation models embody much of our understanding about how energy is used in buildings. Detailed simulation programs such as DOE-2 and BLAST are useful for thermal analysis, but rather detailed information about the building, building use, HVAC system, etc. is needed. AirModel (Liu, 1997) based on an implementation of the ASHRAE TC 4.7 SEAP can provide a reasonable level of accuracy in simulating energy consumption in a building, and it is not as complicated as DOE-2 or BLAST. AirModel is used as the simulation tool in this research.

Considerable information about the building and HVAC system must be input when AirModel is used, whereas only limited information is available, so numerous characteristics of the building and HVAC system must be estimated. Some parameters have a significant influence on energy consumption, whereas others influence it rather weakly. Sensitivity analysis helps to identify the variables in an energy simulation model that account for most variation of the energy consumption. In general, measures involving weather-independent electricity consumption, occupancy, weather, outside airflow rate, and the type of HVAC system in commercial buildings are sensitive elements.

The prototype building, whose main parameters are listed in Table 3.3, is used to identify the critical elements for energy consumption in large commercial buildings in a hot and humid climate using AirModel. The building is assumed to be located in College Station, Texas (Lat. 30.58 N, Long. 96.37 W), with the walls facing cardinal directions, the peak internal heat gain assumed to be 2.2 W/ft^2, and the internal electricity gain schedules for weekdays and weekends as shown in Figure 3.2.

Based on the information about the prototype commercial building, the input files of AirModel for the prototype building with a dual duct constant air volume system, a dual duct variable air volume system, a single duct constant air volume system, and a single duct variable air volume system are prepared. Weather data in College Station will be retrieved from the ESL database; the energy consumption of this building with different HVAC systems will be simulated by AirModel using 1999 weather data. The results can be treated as baseline energy consumption under "standard" conditions.

If a particular parameter changes while others remain the same for the prototype commercial building with each of the different HVAC systems, the total simulated energy consumption changes as shown in Tables 3.10 – 3.13. The parameters in the "standard" condition are listed in the first column of the tables where the simulated energy consumption in the standard condition is the baseline energy consumption. The second column lists the change of the variables studied in the sensitivity analysis. For example, when a constant air volume system whose total supply air rate is 1.1 CFM/ft^2 is converted to a variable air volume system, the supply air rate can range from 0.6 CFM/ft^2 to 1.1 CFM/ft^2. This sensitivity analysis is on the basis of yearly total energy consumption. Change of energy consumption and "Combined change" for heating and cooling are also listed as percents in the tables. Change and Combined change are defined as:

Change = 100(simulated consumption – simulated baseline consumption)/simulated baseline consumption

Combined change= 100(ΔCHW+ΔHW)/(CHW+HW)

CHW=simulated Chilled Water baseline consumption

HW=simulated Hot Water baseline consumption

ΔCHW=simulated Chilled Water consumption-CHW

ΔHW=simulated Hot Water consumption-HW

Table 3.10 Sensitivity analysis results for dual duct constant air volume system

Variable (baseline)	Variable Range	Change (%)		Combined change (%)
		wbcool	wbheat	
air-conditioned area (128000sqft)	120000sqft	-5.96%	-6.14%	-6.00%
	136000sqft	5.96%	6.15%	6.00%
cold deck schedule 55 °F	53 °F	3.09%	6.47%	3.86%
	57 °F	-0.73%	-1.62%	-0.94%
economizer (no)	20 °F~ 60 °F temperature	-19.79%	46.48%	-4.76%
total flow rate (1.1 cfm/sqft)	(1.05 cfm/sqft)	-2.76%	-5.87%	-3.47%
	(1.2 cfm/sqft)	5.54%	11.78%	6.95%
hot deck schedule	110 °F	41.92%	136.29%	63.32%
internal electrical peak gain (2.2 W/sqft)	1.5 W/sqft	-9.06%	8.44%	-5.10%
	2.9 W/sqft	11.77%	-2.58%	8.51%
outside air flow rate (0.1 cfm/sqft)	0.05 cfm/sqft	-4.63%	-3.89%	-4.46%
	0.15 cfm/sqft	3.00%	2.84%	2.96%
average floor area for each person (200 sqft/person)	150 sqft/person	2.09%	-1.47%	1.28%
room temperature (75 °F)	73 °F	12.04%	20.25%	13.91%
	77 °F	-7.89%	-13.29%	-9.12%
VAV (no)	1.1 ~ 0.6 cfm/sqft	-27.88%	-55.06%	-34.04%
exterior wall area (41739 sqft)	38000 sqft	0.04%	-0.36%	-0.05%
	48000 sqft	-0.06%	0.60%	0.09%
exterior wall U value (0.15 Btu/sqft*hr*°F)	0.1 Btu/sqft*hr*°F	0.13%	-1.32%	-0.20%
	0.2 Btu/sqft*hr*°F	-6.23%	-4.84%	-5.92%
exterior window area (6261 sqft)	2280 sqft	-0.56%	-1.97%	-0.88%
	9600 sqft	3.23%	7.54%	4.21%
	0 sqft	-6.97%	-9.30%	-7.49%
(exterior wall area is zero for this case)	48000 sqft	119.67%	259.34%	189.50%
exterior window U value (1.1 Btu/sqft*hr*°F)	0.8 Btu/sqft*hr*°F	0.12%	-1.19%	-0.18%
location (32° N)	location (24° N)	-1.61%	1.08%	-1.00%
	location (40° N)	-1.22%	1.03%	-0.09%

Table 3.11 Sensitivity analysis results for single duct constant air volume system

Variable (baseline)	Variable Range	Change (%)		Combined change (%)
		wbcool	wbheat	
air-conditioned area (128000sqft)	120000sqft	-6.17%	-6.33%	-6.23%
	136000sqft	6.17%	6.33%	6.23%
cold deck schedule 55 °F	53 °F	9.27%	13.78%	10.97%
	57 °F	-5.26%	-8.17%	-6.36%
economizer (no)	20 °F~ 60 °F temperature	-17.37%	0.18%	-10.74%
total flow rate (1.1 cfm/sqft)	(1.05 cfm/sqft)	-4.45%	-6.22%	-5.11%
	(1.2 cfm/sqft)	8.89%	12.43%	10.23%
internal electrical peak gain (2.2 W/sqft)	1.5 W/sqft	0.00%	9.67%	3.65%
	2.9 W/sqft	4.45%	-3.46%	1.46%
outside air flow rate (0.1 cfm/sqft)	0.05 cfm/sqft	-2.59%	-0.04%	-1.62%
	0.15 cfm/sqft	1.90%	0.01%	1.19%
average floor area for each person (200 sqft/person)	150 sqft/person	0.32%	-1.68%	-0.44%
room temperature (75 °F)	73 °F	1.00%	-3.37%	-0.65%
	77 °F	7.18%	14.50%	9.94%
VAV (no)	1.1 ~ 0.6 cfm/sqft	-44.78%	-61.27%	-51.00%
exterior wall area (41739 sqft)	38000 sqft	0.00%	-0.13%	-0.05%
	48000 sqft	0.00%	0.21%	0.08%
exterior wall U value (0.15 Btu/sqft*hr*°F)	0.1 Btu/sqft*hr*°F	0.00%	-0.47%	-0.18%
	0.2 Btu/sqft*hr*°F	-6.17%	-5.76%	-6.02%
exterior window area (6261 sqft)	2280 sqft	0.00%	-0.07%	-0.03%
	9600 sqft	4.45%	6.28%	5.14%
	0 sqft	0.00%	0.09%	0.03%
(exterior wall area is zero for this case)	48000 sqft	182.35%	254.23%	218.29%
exterior window U value (1.1 Btu/sqft*hr*°F)	0.8 Btu/sqft*hr*°F	0.00%	-0.42%	-0.16%
location (32° N)	location (24° N)	0.00%	1.60%	0.60%
	location (40° N)	0.00%	1.27%	0.48%

Table 3.12 Sensitivity analysis results for dual duct variable air volume system

Variable (baseline) (minimum flow rate: 0.6 cfm/sqft)	Variable Range	Change (%)		Combined change (%)
		wbcool	wbheat	
air-conditioned area (128000sqft)	120000sqft	-5.81%	-5.41%	-5.75%
	136000sqft	5.81%	5.42%	5.75%
cold deck schedule 55 °F	53 °F	2.34%	8.66%	3.32%
	57 °F	-2.36%	-8.68%	-3.34%
economizer (no)	20 °F- 60 °F temperature	-16.62%	49.48%	-6.40%
maximum flow rate (1.1 cfm/sqft)	(1.0 cfm/sqft)	0.05%	-0.13%	0.02%
	(1.2 cfm/sqft)	-0.08%	0.20%	-0.03%
hot deck schedule	110 °F	28.07%	138.32%	45.11%
internal electrical peak gain (2.2 W/sqft)	1.5 W/sqft	-12.97%	17.91%	-8.20%
	2.9 W/sqft	14.26%	-13.53%	9.96%
outside air flow rate (0.1 cfm/sqft)	0.05 cfm/sqft	-4.01%	-4.22%	-4.04%
	0.15 cfm/sqft	2.80%	3.05%	2.84%
average floor area for each person (200 sqft/person)	150 sqft/person	3.14%	-2.73%	2.23%
room temperature (75 °F)	73 °F	4.78%	1.83%	4.33%
	77 °F	-5.67%	-7.59%	-5.97%
exterior wall area (41739 sqft)	38000 sqft	0.01%	-0.83%	-0.12%
	48000 sqft	-0.01%	1.40%	0.21%
exterior wall U value (0.15 Btu/sqft*hr*°F)	0.1 Btu/sqft*hr*°F	0.03%	-3.09%	-0.45%
	0.2 Btu/sqft*hr*°F	-6.13%	-2.49%	-5.56%
exterior window area (6261 sqft)	2280 sqft	-1.23%	-3.98%	-1.66%
	19200 sqft	4.09%	8.97%	4.84%
	0 sqft	-1.89%	-6.15%	-2.55%
(exterior wall area is zero for this case)	48000 sqft	55.23%	12.00%	23.16%
exterior window U value (1.1 Btu/sqft*hr*°F)	0.8 Btu/sqft*hr*°F	0.02%	-2.78%	-0.41%
location (32° N)	location (24° N)	-2.52%	2.11%	-1.80%
	location (40° N)	-1.89%	2.09%	-1.27%

Table 3.13 Sensitivity analysis results for single duct variable air volume system

Variable (baseline) (minimum flow rate: 0.6 cfm/sqft)	Variable Range	Change (%)		Combined change (%)
		wbcool	wbheat	
air-conditioned area (128000sqft)	120000sqft	-6.01%	-6.08%	-6.03%
	136000sqft	6.02%	6.11%	6.05%
cold deck schedule 55 °F	53 °F	8.66%	18.50%	11.60%
	57 °F	-8.52%	-18.15%	-11.39%
economizer (no)	20 °F- 60 °F temperature	-17.23%	0.55%	-11.93%
maximum flow rate (1.1 cfm/sqft)	(1.0 cfm/sqft)	0.05%	0.00%	0.03%
	(1.2 cfm/sqft)	-0.07%	0.00%	-0.05%
internal electrical peak gain (2.2 W/sqft)	1.5 W/sqft	-0.85%	23.49%	6.41%
	2.9 W/sqft	1.31%	-22.56%	-5.81%
outside air flow rate (0.1 cfm/sqft)	0.05 cfm/sqft	-2.54%	-0.07%	-1.80%
	0.15 cfm/sqft	1.90%	0.03%	1.34%
average floor area for each person (200 sqft/person)	150 sqft/person	0.81%	-3.97%	-0.62%
room temperature (75 °F)	73 °F	-6.01%	-20.19%	-10.24%
	77 °F	6.35%	20.79%	10.66%
exterior wall area (41739 sqft)	38000 sqft	-0.08%	-0.46%	-0.19%
	48000 sqft	0.13%	0.78%	0.33%
exterior wall U value (0.15 Btu/sqft*hr*°F)	0.1 Btu/sqft*hr*°F	-0.28%	-1.69%	-0.70%
	0.2 Btu/sqft*hr*°F	1.90%	0.03%	1.34%
exterior window area (6261 sqft)	2280 sqft	-0.67%	-1.02%	-0.77%
	19200 sqft	2.35%	2.17%	2.29%
	0 sqft	-0.97%	-1.45%	-1.12%
(exterior wall area is zero for this case)	48000 sqft	13.59%	24.20%	16.76%
exterior window U value (1.1 Btu/sqft*hr*°F)	0.8 Btu/sqft*hr*°F	-0.26%	-1.52%	-0.63%
location (32° N)	location (24° N)	-0.49%	3.26%	0.63%
	location (40° N)	-0.34%	2.68%	0.57%

From Tables 3.10 - 3.13, it is clear that if the window area varies in a typical range, the impact on total energy consumption is significant for dual duct constant air volume systems; but for extreme situations, the impact is huge for DDCAV, SDCAV, DDVAV, and SDVAV systems. For example, if the envelope of the building is made of glass, and there is no shading for the glass, then the energy consumption in the building will double in the "standard" condition for single duct constant air volume systems.

When the HVAC system in the building is a dual duct constant air volume system, sensitivity analysis has varied 15 inputs to AirModel in a reasonable range based on the author's experience; sensitivity analysis has varied 14 inputs to AirModel for single duct constant air volume system; sensitivity analysis has been done to 14 and 13 inputs for the dual duct variable air volume system and the single duct variable air volume system, respectively. If the absolute value of combined change for a variable is greater than 5%, it is treated as a sensitive parameter. The sensitive parameters for the four basic HVAC systems are listed in Table 3.14.

Table 3.14 Sensitive parameters for four basic HVAC systems

Variable	Absolute value of Combined change (%)			
	DDCAV	SDCAV	DDVAV	SDVAV
VAV	34.04%	51%		
hot deck schedule	63.32%		45%	
cold deck schedule		10.97%		11.6%
economizer		10.74%	6.4%	11.93%
window area		5.14%		
wall U-value	5.92%	6.02%	5.56	
room temperature	13.91%	9.94%	5.97	10.66%
total flow rate	6.95%	10.23%		
internal electrical peak gain	8.51%		9.96	6.41%
air-conditioned area	6%	6.23%	5.75%	6.05%

For dual duct systems and single duct systems, variable air volume is a useful technique to save energy and can reduce cost considerably; internal electrical gain greatly influences total energy consumption for all systems except the single duct constant volume system. Room temperature in the building, economizer (except DDCAV), total airflow rate (for constant volume systems), hot deck temperature schedule (for dual duct system), and cold deck temperature schedule (for single duct system) are critical elements to energy consumption; they are related to operation of HVAC system. Since the internal electrical gain in AirModel is obtained by dividing the electricity consumption of lighting and equipment by total area, and total airflow rate is related to the area of a building simulated by AirModel, area is a sensitive parameter in AirModel as weather-dependent load and total airflow rate are sensitive parameters; wall U-value is also a sensitive parameter.

Three internal electrical gain ratio schedules are considered. In Schedule 1, the electricity consumption is assumed to be constant all day, so it is easy to find the maximum internal electricity gain from utility bills in this schedule. Schedule 2 is typical of many large commercial buildings, while schedule 3 is typical of many small commercial buildings. Schedule 2 is shown in Figure 3.2, and schedule 1 is shown in Figure 3.8, while schedule 3 is shown in Figure 3.9.

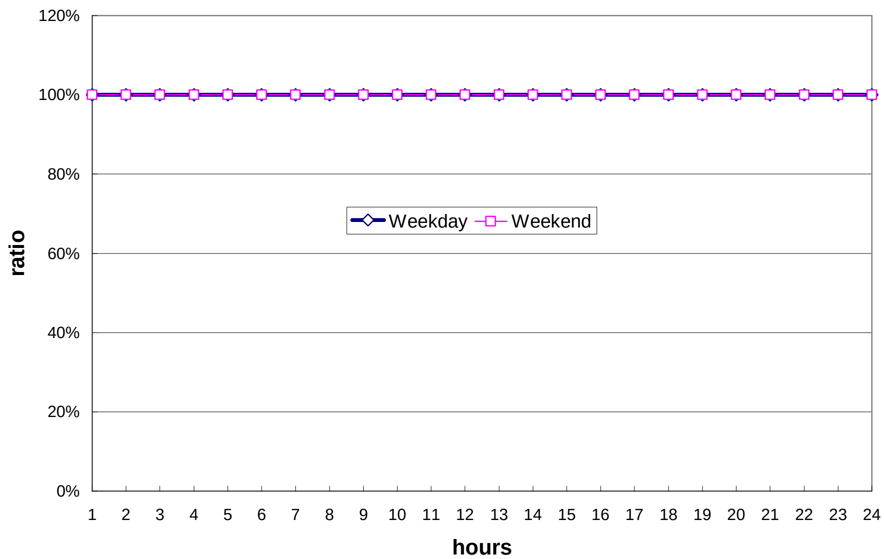

Figure 3.8 Electricity schedule 1 during weekdays and weekends.

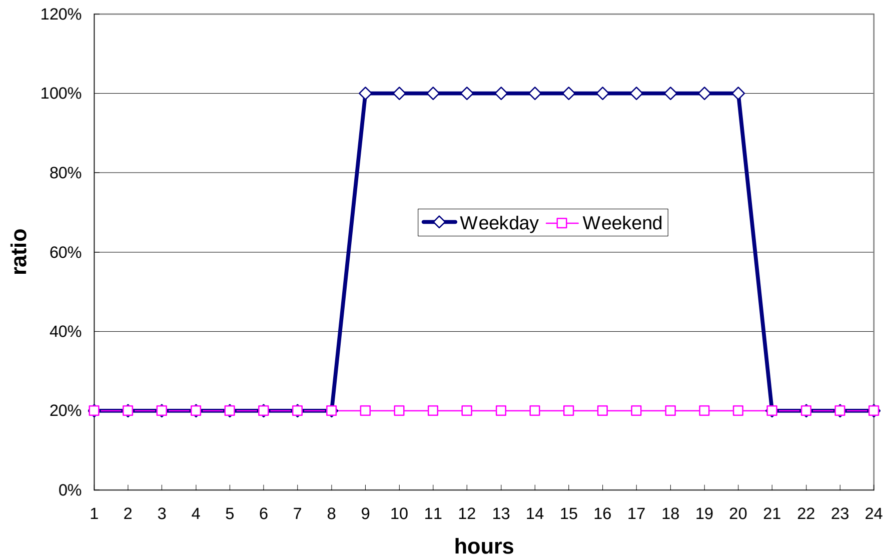

Figure 3.9 The electricity schedule 3 during weekdays and weekends.

No matter which internal electrical gain ratio is used, the total electricity consumption is the same. The maximum internal electrical gains for the three schedules are listed in Table 3.15.

The weather data of 1999 for College Station, Texas in the ESL database is used, and the HVAC system in the building is assumed to be DDCAV, DDVAV, SDCAV and SDVAV respectively.

Table 3.15 the maximum internal electrical gains in three schedules

Schedule	Maximal internal electrical gain (W/sq-ft)
Schedule 1	1.5
Schedule 2	2.2
Schedule 3	3.0

Table 3.16 shows the simulated energy consumption of constant volume systems for the different cases. If the simulated consumption values under schedule 2 are treated as the reference, the relative differences and combined differences are shown in Table 3.17

for other schedules. Tables 3.18 and 3.19 are for variable volume systems. Relative difference and Combined difference are defined as:

Relative Difference = (simulated consumption – reference consumption)/reference consumption

Combined Difference= (Relative Difference$_{wbcool}$ +Relative Difference$_{wbheat}$)/2

Table 3.16 The total simulated energy consumption under different schedules for constant volume systems

Schedule	Wbcool (MMBtu) (DDCAV)	Wbheat (MMBtu) (DDCAV)	Wbcool (MMBtu) (SDCAV)	Wbheat (MMBtu) (SDCAV)
1	16,945	4,660	31,115	18,335
2	16,527	4,846	30,977	18,786
3	16,662	5,308	32,273	20,333

Table 3.17 The relative difference of simulated energy consumption for different cases for constant volume systems

Schedule	Wbcool (DDCAV)	Wbheat (DDCAV)	Combined difference	Wbcool (SDCAV)	Wbheat (SDCAV)	Combined difference
1	2.53%	-3.84%	-0.66%	0.45%	-2.4%	-0.98%
2	0	0	0	0	0	0
3	0.82%	9.54%	5.18%	4.19%	8.23%	6.21%

Table 3.18 The total simulated energy consumption under different schedules for variable volume systems

Schedule	Wbcool (MMBtu) (DDVAV)	Wbheat (MMBtu) (DDVAV)	Wbcool (MMBtu) (SDVAV)	Wbheat (MMBtu) (SDVAV)
1	12,290	1,964	17,145	6,745
2	11,920	2,179	17,107	7,276
3	11,883	2501	17,269	7,841

Table 3.19 The relative difference of simulated energy consumption for different cases for variable volume systems

Schedule	Wbcool (DDVAV)	Wbheat (DDVAV)	Combined difference	Wbcool (SDVAV)	Wbheat (SDVAV)	Combined difference
1	3.11%	-9.82%	-6.47%	0.22%	-7.29%	-3.54%
2	0	0	0	0	0	0
3	-0.3%	14.84%	7.27%	0.95%	7.78%	4.37%

The energy consumption for the prototype building in College Station, Texas is simulated under the three different internal electrical gain ratio schedules using 1999 weather data. The results are shown in Tables 3.17 and 3.19, indicating that there are sometimes significant differences between simulated consumption as a function of gain schedule for the extreme differences tested. However, the real schedules for in large buildings won't vary as much as tested with these three schedules, so only a single electrical gain ratio schedule will be used. Schedule 2 is used in the remainder of this dissertation.

In mild weather, the cooling load from heat conduction through the envelope and from ventilation with fresh air can be neglected; cooling load from reheating some times can be neglected for variable air volume system (VAV); cooling load from occupancy is much smaller than that from lighting and equipment in commercial buildings. Solar gain usually has an influence on the exterior zone; the exterior zone of the prototype building is 43500 sqft. Solar gain will be compared with cooling load from lighting and equipment in the exterior zone.

The hourly average electricity consumption for lighting and equipment is 1.5 W/sqft, which is assumed to change to cooling load; then cooling load from lighting and equipment in the exterior zone is 0.2226 MMBtu/hr and cooling load from lighting and equipment in the whole building is 0.655 MMBtu/hr. The solar gains in different situations will be compared with the internal load from lighting and equipment, which helps to explain the influence of window area on the total energy consumption. Five cases are studied in Table 3.20: case 1 is the baseline case, cases 2 and 3 account for the situations when window area varies in a reasonable range, while cases 4 and 5 are extreme cases. Case number is listed in the first column of the table, the window area is shown in the second column, SC in column 3 stands for shading coefficient of the window, and total solar gains of the prototype building in January and July are listed in the last two columns. The solar gains of the prototype building for different cases include solar gain from windows, walls, and roof. Equations 3.3 – 3.6 are used to calculate the values. For example, though window area is 0 in case 5, solar gain from walls and roof is listed in the table.

From Table 3.21, the average solar gain in the baseline case is 0.093 MMBtu/hr. This corresponds to 41% of the cooling load from lighting and equipment in the exterior zone, and to 14.2% of the cooling load from lighting and equipment in the whole building. Differences between case 1 and case 2 are relatively small compared with the cooling load from lighting and equipment in the exterior zone and the whole building, when window area varies in a small range; however, for case 3, case 4, and case 5, the relative difference can't be neglected when window area changes a lot.

The simulated energy consumption in a prototype building with dual duct constant volume system or single duct constant volume system are studied in different solar gain situations. The impact of solar gain on energy consumption in a commercial building can not be neglected when the area and shading efficient of windows change, particularly to some extreme situation (case 4). Comparing average solar gain change in different cases with the average cooling load from lighting and equipment supports this conclusion.

Table 3.20 The window and solar gain information for the prototype building

Case	Location	window area (ft^2)	SC	Qsol,Jan. (MMBtu)	Qsol,July (MMBtu)
1	32° N	6261	0.35	0.065	0.121
2	32° N	2280	0.35	0.048	0.100
3	32° N	19200	0.35	0.120	0.189
4	32° N	48000	1	0.684	0.914
5	32° N	0	1	0.039	0.088

Table 3.21 The solar gains for the five cases in MMBtu/hr and Relative Difference or change from case 1 as a percentage of cooling load from lighting and equipment in the exterior zone or the whole building.

Case	Qsol,average (MMBtu/hr)	Change from case 1 (MMBtu/hr)	Relative difference (in exterior zone)	Relative difference (in whole building)
1	0.093			
2	0.074	-0.019	-8.48%	-2.88%
3	0.154	0.061	27.57%	9.37%
4	0.799	0.706	317.27%	107.82%
5	0.063	-0.030	-13.34%	-4.53%

Sensitivity analysis has examined the impact of several factors on the performance of a prototype building located in College Station, Texas. The results show that four kinds of elements will significantly affect the energy consumption. These elements are:

1. Special system characteristics, such as economizer and VAV.
2. The total air-conditioned area, wall U value, and window area of a commercial building.
3. Some HVAC system operation parameters, such as room set temperature, total flow rate, hot deck temperature schedule, and cold deck temperature schedule.
4. The internal electrical gain.

Most critical elements for a large commercial building in a hot and humid climate determined by AirModel are also treated as critical elements by other researchers except for total air-conditioned area (Wei et al., 1998; Corson, 1992; Norford et al., 1994; LBNL, 1996); the reason why total air-conditioned area is treated as a critical element by AirModel is that weather-independent electricity load in a building is input as a function of area in AirModel. These critical elements will be carefully considered in the research. The internal electrical gain will be determined from electricity bills; the type of HVAC system will be identified; total area is known; typical values of other parameters of the building and HVAC system will be used in this research.

Description of the pre-screening procedure

The prototype building configuration and the idealized building configuration will be used together to identify large commercial buildings with significant potential energy savings. The following is a detailed description of the four steps involved in the pre-screening methodology.

Identifying the types of loads covered by utility bills (Step 1)

It may not be definitively known whether the consumption recorded by a particular electric meter includes a chiller or not. Most buildings have their own electric chiller system to supply cooling to the building, but some get chilled water from an absorption system, a district system, or other central plant. In other cases, the electric chiller system for a building may be metered on a separate meter. Hence, it can be valuable to determine whether the bills are consistent with a building that includes a chiller system or not. Haberl and Komor (1989) used PRISM to determine heating, cooling and base-level electricity consumption in buildings. Five types of electricity consumption models are considered: (1) base-level plus cooling, (2) base-level plus heating, (3) base-level plus heating and cooling, (4) base-level only and (5) erratic consumption (does not fit any of the above). A base-level only model indicates that there is no weather-dependent electricity consumption covered by the bills. Reynolds et al. (1990) present the Flatness Index (FI), which is defined as the ratio of the standard deviation of daily average consumption in each month divided by the mean value of the monthly consumption. FI can be used to identify whether the load is weather dependent or weather independent if no suitable cooling only (CO), heating only (HO), or heating and cooling (HC) models can be obtained; usually FI less than 0.11 indicates that the load has little or no weather dependence.

The Administration Office is a facility of the Port Arthur Independent School District, where chilled water for HVAC is produced by chiller systems attached to the facility; CO model and FI tests based on monthly electricity consumption from electrical utility bills are shown in Figures 3.10 and 3.11, while the parameters for the two models are listed in Table 3.22 and Table 3.23. The monthly electricity consumption values for Harrington Tower on the main campus of Texas A&M University are formed from monitored hourly consumption. Figures 3.12 and 3.13 show the CO model and the FI test result for Harrington Tower while Table 3.24 and 3.25 list the two models. FI is greater than 0.11 for the Administration Office, and the CO model is quite good (R^2=0.811); whereas FI is less than 0.11 for Harrington Tower, and the CO model is poor (R^2=0.2661). This illustrates how the FI test based on the monthly electricity consumption can identify whether there is chiller consumption in a set of electricity bills.

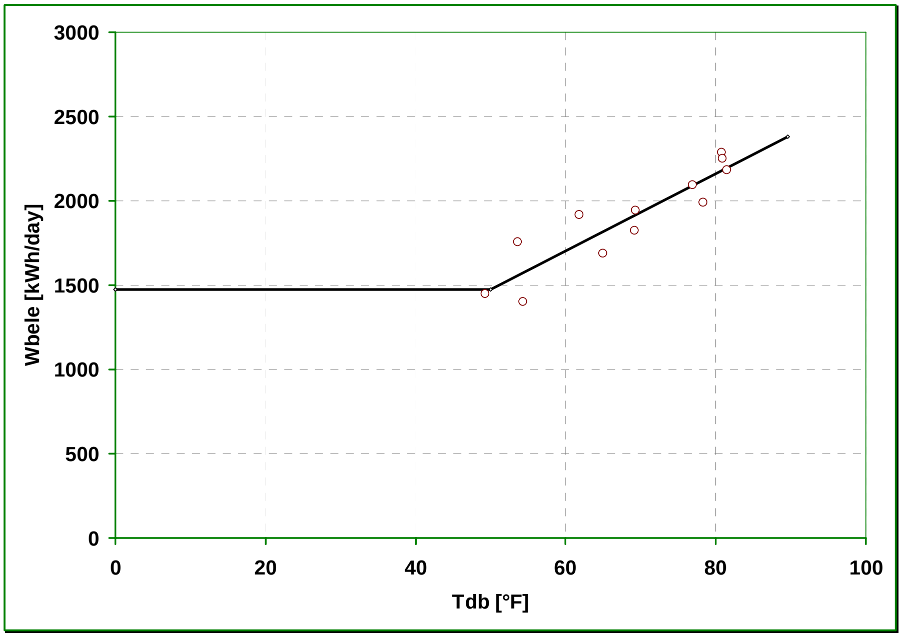

Figure 3.10 Three-parameter change point regression model for the Administration Office based on the 2003 data.

Table 3.22 Model parameters for the three-parameter change point regression model for the Administration Office based on the 2003 data

Ycp	1474.4164
Left Slope	0.0000
Right Slope	22.8986
Change Point	49.9656
R2	0.8282
AdjR2	0.8110
RMSE	126.1833
CV-RMSE	6.6%
NL	1
NR	11
Ntotal	12
Model	3P_CP Cooling

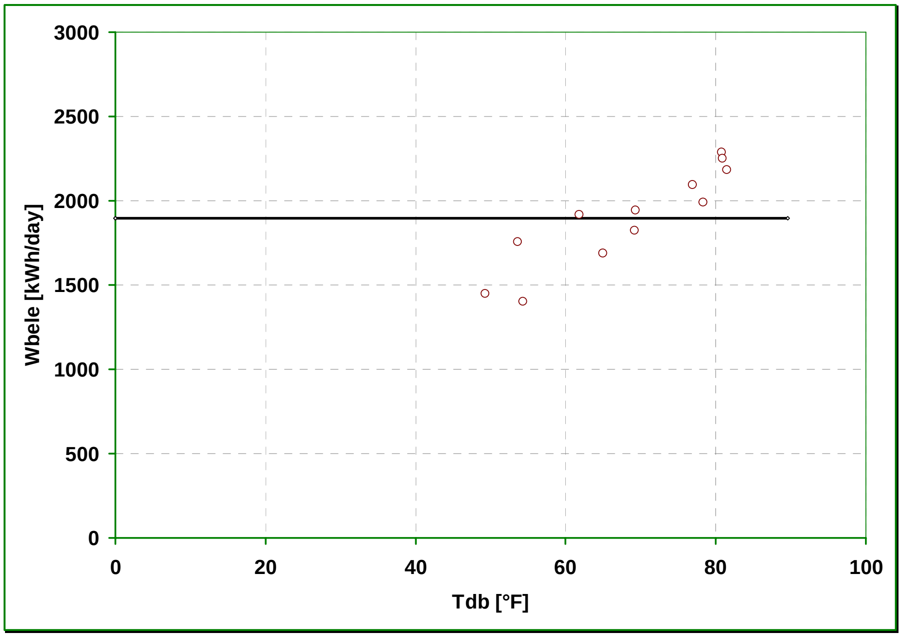

Figure 3.11 FI test for Administration Office based on 2003 data.

Table 3.23 Model parameters for one-parameter regression model for the Administration Office based on the 2003 data

Ntotal	12
Mean Y	1897.9973
StdDev	290.2687
CV-StdDev	15.3%
Model	Mean

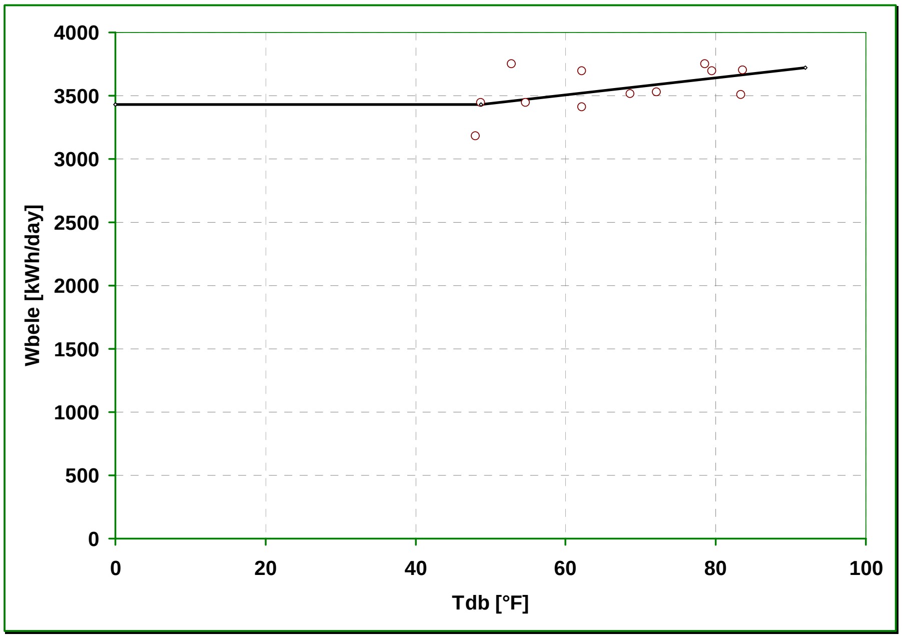

Figure 3.12 Three-parameter change point regression model for Harrington Tower based on 1997 data.

Table 3.24 Model parameters for three-parameter change point regression model for Harrington Tower based on the 1997 data

Ycp	3433.4333
Left Slope	0.0000
Right Slope	6.7499
Change Point	48.7448
R2	0.2661
AdjR2	0.1927
RMSE	155.5166
CV-RMSE	4.4%
NL	2
NR	10
Ntotal	12
Model	3P_CP Cooling

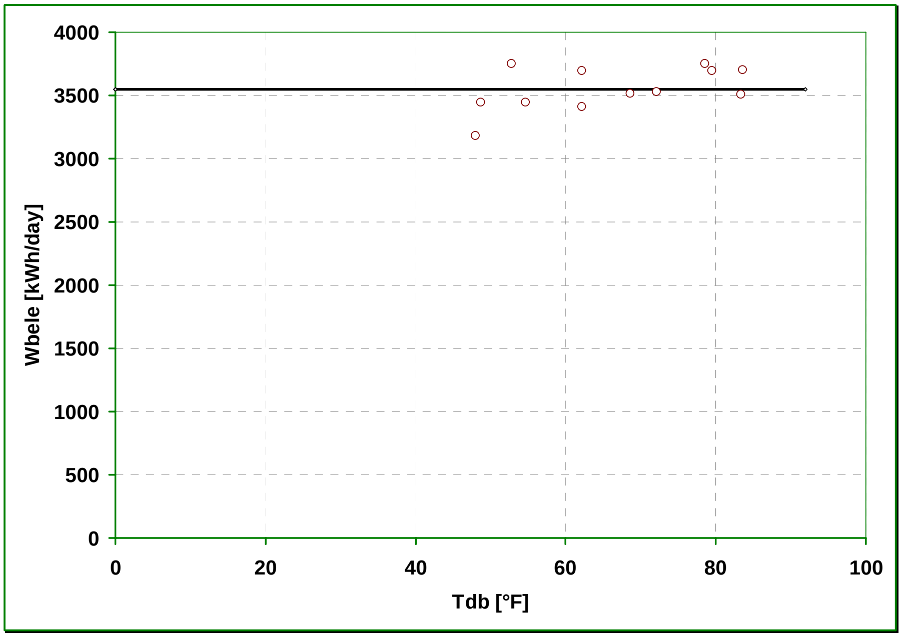

Figure 3.13 FI test for Harrington Tower based on the 1997 data.

Table 3.25 Model parameters for one-parameter regression model for Harrington Tower based on the 1997 data

Ntotal	12
Mean Y	3551.6356
StdDev	173.0817
CV-StdDev	4.9%
Model	Mean

Separating electricity consumption in utility bills (Step 2)

Utility bills are the most widely available source of measured information about energy consumption of individual buildings. Electricity consumption in commercial buildings typically includes weather-independent and weather-dependent loads. The first is consumed by lighting, plug loads, fans, pumps, etc., and this portion typically does not vary substantially with outside weather conditions. It is eventually converted to heat, most of which contributes to building cooling load. The weather-dependent load varies strongly with outside weather conditions (e.g., temperature, humidity, sunlight.) since it is consumed by the chiller(s) and ancillary equipment (some buildings also use electricity for heating, but they are not considered in this dissertation). It is important for energy auditors to know how much energy is used for cooling in a building, both when screening a building prior to conducting an audit, and as part of the audit process.

The heating and cooling model in the Princeton Scorekeeping Method (PRISM) can be used to disaggregate the utility bills (Reynolds et al., 1990) into weather-dependent and weather-independent components for facilities located in the northern U.S., where cold winters result in chiller systems being turned off for several months. This approach is available in a variety of commercial software packages and has been tested and made available by ASHRAE RP-1050 (Kissock et al., 2003). When monthly average outside air temperature is lower than 40 °F, it is assumed that the chiller system in the facility is not working during these months, and the daily average electricity consumption should be almost constant for these months. The electricity use due to lighting, equipment, and fans should be almost constant for the whole year. In other months, the chiller system works to supply chilled water for the facility. The three-parameter (3P) change-point regression model can successfully separate electricity consumption into weather-independent and weather-dependent portions if the building chiller system is turned off for at least one month during the winter.

Fairview Medical Center – Riverside is located in Minneapolis, MN. There are two chillers in this facility, which are 1100 tons and 1280 tons, respectively. Either could supply enough chilled water for the building in the summer. It is usually cold there in the winter, so the chiller system needn't work in the winter. The whole building electricity consumption values (Wbele) for the facility are recorded in the ESL database at 15-minute intervals since July 2000. More than 96.5% of 15-minute measured Wbele during August 2000 and July 2001 were valid; these data were converted to monthly data. Monthly weather data is available on the National Oceanic and Atmospheric Administration (NOAA) (http://www.ncdc.noaa.gov/pdfs/lcd/lcd.html) web page and is used as needed (Figure 3.14). A three-parameter change-point regression model is developed for Fairview Medical Center – Riverside based on the data from August 2000 through July 2001 (Figure 3.15); the estimated weather-independent electricity consumption is 34,266 kWh/day (Table 3.26). Fifteen-minute electricity consumption by the chiller system in Fairview Medical Center – Riverside is also recorded in the database; the difference between Wbele and electricity consumption by the chiller system is the weather-independent load. The measured yearly average weather-independent load is 33,070 kWh/day giving a 3.6% difference between the estimated and actual values.

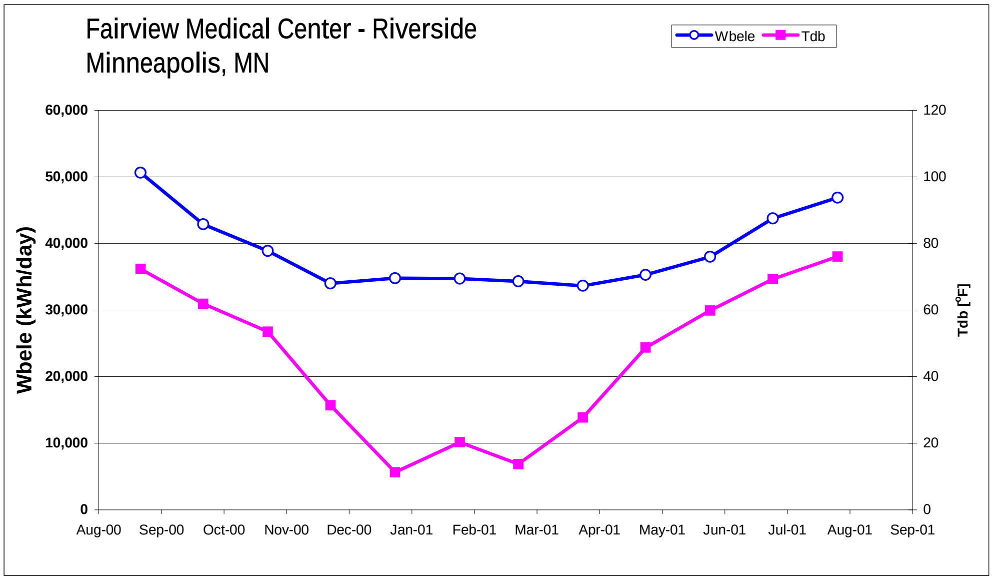

Figure 3.14 Monthly average Wbele and Tdb for Fairview Medical Center – Riverside.

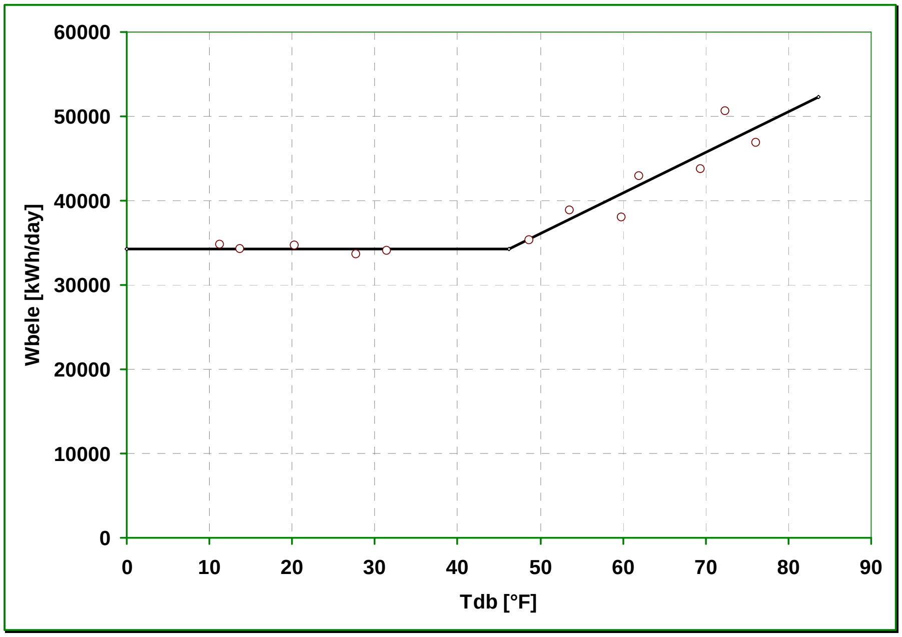

Figure 3.15 3-P regression model for Fairview Medical Center – Riverside based on the data for August 2000 through July 2001.

Table 3.26 Model parameters for three-parameter change point regression model for Fairview Medical Center - Riverside based on the data for August 2000 through July 2001

Ycp	34266.3919
Left Slope	0.0000
Right Slope	480.6696
Change Point	46.2690
R2	0.9128
AdjR2	0.9040
RMSE	1776.5802
CV-RMSE	4.6%
NL	5
NR	7
Ntotal	12
Model	3P_CP Cooling

This method can be expected to introduce a systematic bias in the values of cooling consumption estimated for buildings where the chiller system operates in the winter, as is often the case in Texas. The Junior High School is located in College Station, Texas. The hourly whole building electricity consumption (Wbele) and outside air dry-bulb temperature from May 2001 through April 2002 for the facility are recorded in the ESL database. Daily whole building electricity consumption and electricity consumption by the chillers are displayed in Appendix Figure III1; these data were converted to monthly data, and monthly average electricity consumption and monthly electric demand for the period of May 2001 – April 2002 are shown in Figure 3.16. The electricity consumption for the Junior High School for this summer is uncommon, since it does not show the usual summer decrease due to summer vacation, so the school may have been occupied throughout the summer. A 3-P regression model is developed based on these data (Figure 3.17), and indicates that the weather-independent electricity consumption in the facility is 3,641 kWh/day (Table 3.27). Hourly electricity consumption by the chiller system in the Junior High School is also recorded in the database; the difference between Wbele and electricity consumption by the chiller system is the weather-independent load (Figure 3.18). The measured yearly average weather-independent load is 3,307 kWh/day. There is a significant difference between the weather-independent load estimated using the 3-P regression model and the actual load; in fact the chiller system in the Junior High School works every month of the year in College Station (Figure 3.19). There is a 10.1% difference between the annual value of weather independent load estimated with the 3-P model and the actual value.

The estimated monthly weather-dependent electricity consumption values estimated from the 3-P model are compared with the actual values in Figure 3.20; the 3-P model over-estimates annual weather-dependent electricity consumption by 17.5%.

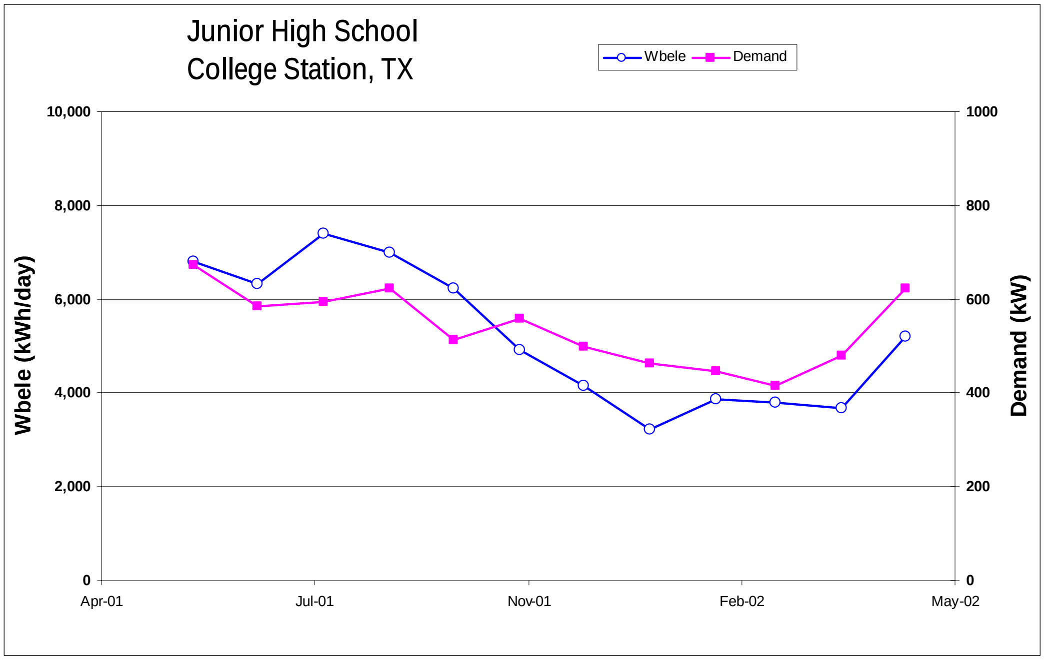

Figure 3.16 Monthly average Wbele and peak demand for the Junior High School.

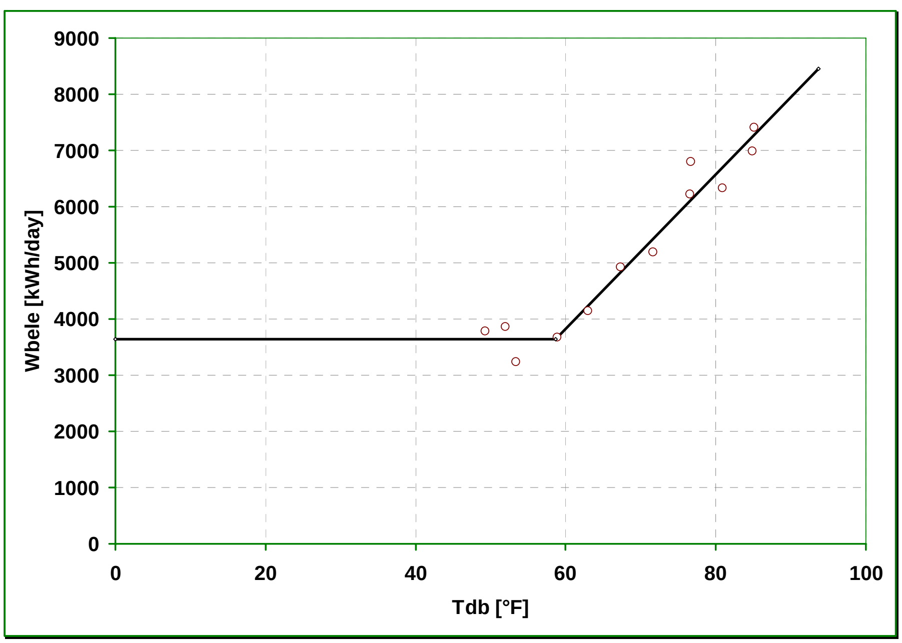

Figure 3.17 3-P regression model for the Junior High School based on the data for May 2001 through April 2002.

Table 3.27 Model parameters for three-parameter change point regression model for the Junior High School based on the data for May 2001 through April 2002

Ycp	3641.2688
Left Slope	0.0000
Right Slope	137.2964
Change Point	58.6461
R2	0.9583
AdjR2	0.9541
RMSE	317.2729
CV-RMSE	6.1%
NL	3
NR	9
Ntotal	12
Model	3P_CP Cooling

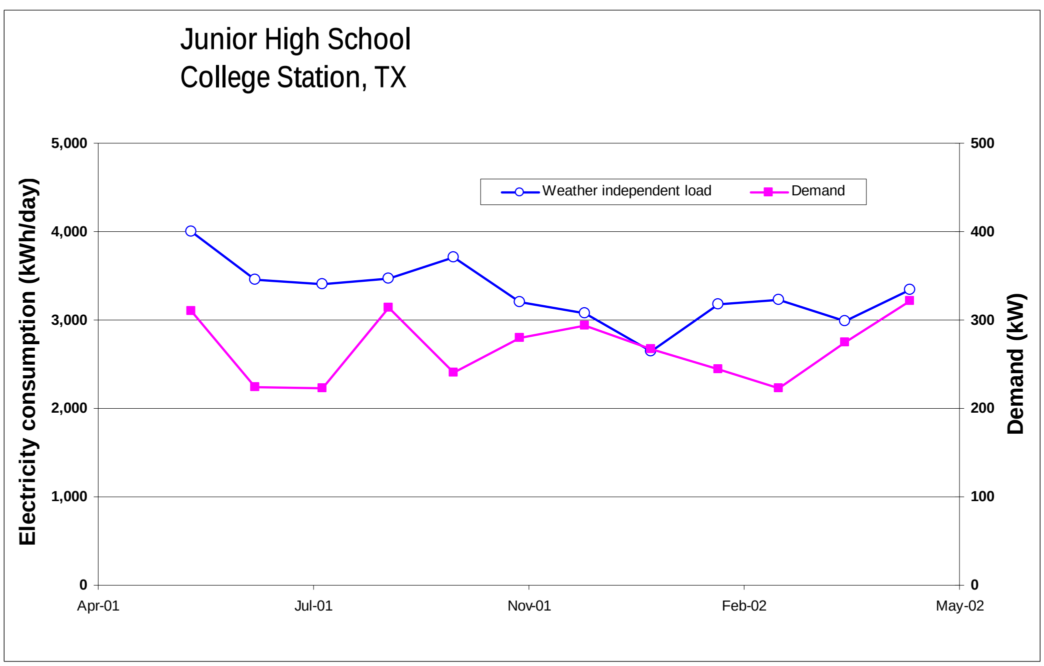

Figure 3.18 Monthly average weather-independent loads and peak demand at the Junior High School.

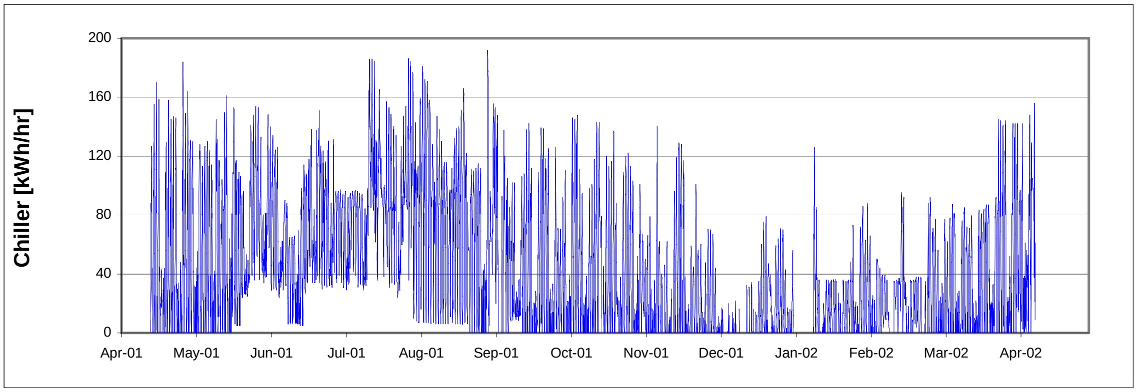

Figure 3.19 Monitored chiller system electricity consumption in the Junior High School.

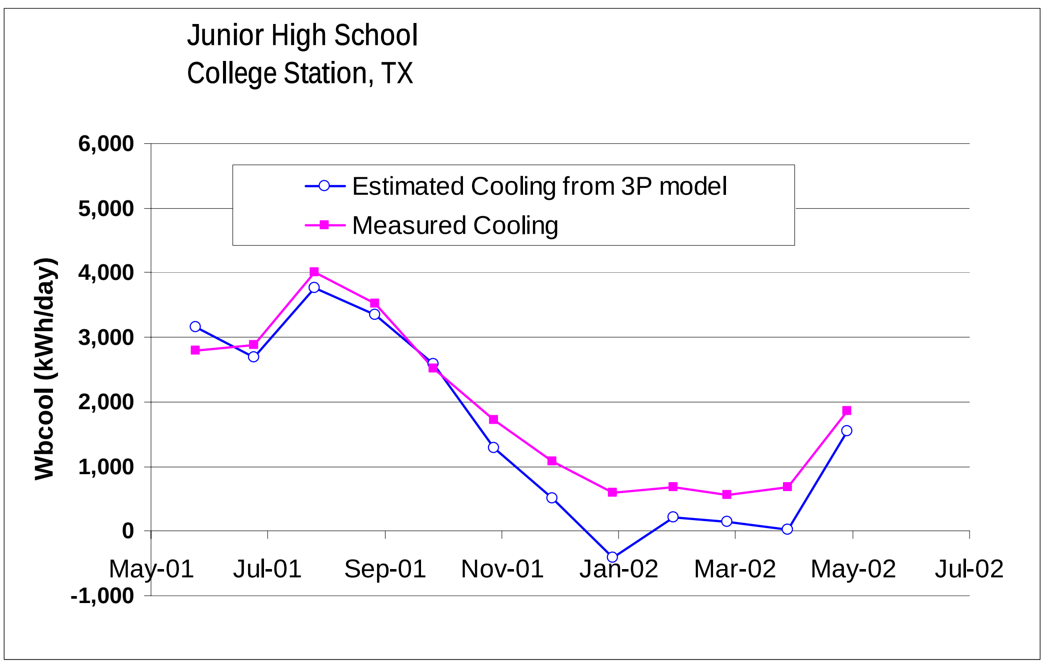

Figure 3.20 Comparison of monthly average weather-dependent loads and values from the 3-P model for the Junior High School.

The estimated yearly average weather-independent electricity consumption in Fairview Medical Center – Riverside and the Junior High School estimated by three-parameter change point regression models are compared with the actual values in Table

3.28. There is a systematic bias for the Junior High School where the chiller system operates in the winter. The difference in the table is defined as:

$$\text{Difference}=\frac{(Estimated - Actual)}{Actual}$$

Table 3.28 Comparison of estimated and actual yearly average weather-independent electricity consumption

Facility	Estimated (kWh/day)	Actual (kWh/day)	Difference
Fairview Medical Center – Riverside	34,266	33,070	3.6%
Junior High School	3,641	3,307	10.1%

A methodology to Separate the Utility Bills based on Thermal Balance (SUBTB) for the purpose of disaggregating monthly electricity consumption into weather-dependent and weather-independent consumption is developed, which is applicable to large commercial buildings in climates where chillers operate year-round. The methodology uses as inputs the monthly electric bills, monthly heating consumption (typically gas bills), monthly average temperature, and building area. More detail about the SUBTB methodology will be provided in Chapter IV.

In summary, when weather-independent and weather-dependent electricity consumption are combined in one utility bill, a 3-P change-point regression model or the SUBTB methodology will be used to disaggregate monthly electricity consumption for facilities in different locations.

Identifying the main type of HVAC system in a building (Step 3)

Eight HVAC systems common in large commercial buildings are Single Duct Constant Air Volume systems (SDCAV), Single Duct Constant Air Volume systems with a temperature economizer (SDCAVECO), Single Duct Variable Air Volume systems (SDVAV), Single Duct Variable Air Volume systems with a temperature economizer (SDVAVECO), Dual Duct Constant Air Volume systems (DDCAV), Dual Duct Constant Air Volume systems with a temperature economizer (DDCAVECO), Dual Duct Variable Air Volume systems (DDVAV) and Dual Duct Variable Air Volume systems with a temperature economizer (DDVAVECO). If a commercial building is properly designed, constructed, operated, and maintained, the measured energy consumption should approximately match the simulated consumption for a typical building of the same size with the actual type of HVAC system used in the building. This characteristic can help identify the main type of HVAC system in a building.

The prototype building in this study is a typical building, which can be configured based on the total area and weather-independent electricity consumption as described in the section "Prototype Commercial Building and Idealized Commercial Building". For example, the total area of Zachry Engineering Center is 324,400 ft^2. The Zachry prototype building is configured as a 13-floor building with a 158-foot square footprint to match the total area. The yearly average electricity consumption rate for Lighting and Equipment (L&E) in Zachry Engineering Center in 1999 was 2.5 W/ft^2. Total airflow rate is set to be 1.1 CFM/ft^2 in the beginning when energy consumption in the Zachry prototype in 1999 was simulated by AirModel. The cooling load can't be removed at times as the total airflow rate is too low; the airflow was increased in steps of 0.05 CFM/ft^2 until the cooling load can always be met; the flow rate required to meet the cooling load is 1.35 CFM/ft^2. Weather data recorded in the ESL database for College Station, Texas in 1999 are used for simulation, and the simulated hourly energy consumption values are converted to monthly data. Monthly simulated and measured 1999 energy consumption values for Zachry Engineering Center are shown in Figures 3.20 and 3.21.

Prototype buildings based on the area of six other buildings on the main campus of Texas A&M University are configured, and the results are shown in Table 3.29. The yearly average electricity consumption rates by Lighting and Equipment (L&E) in the seven buildings are listed in Table 3.30. Comparison of monthly simulated energy consumption by different HVAC systems for Zachry Engineering Center, Harrington Tower, Blocker Building, Oceanography and Meteorology, Wehner Building, Koldus Student Services, and G. Rollie White are shown in Appendix II (Figure II1 – Figure II14). Simulated Whole Building Cooling water consumption (Wbcool) for the buildings with different HVAC systems is generally separable, but some are similar. The same was true of simulated Whole Building Heating consumption (Wbheat). If both simulated

Wbcool and Wbheat are considered for a building with different HVAC systems, simulated energy consumption of different HVAC systems are not similar. Systems with similar Wbcool or Wbheat characteristics for the seven buildings are summarized in Table 3.31. For example, simulated Wbcool consumption in Zachry Engineering Center with SDVAVECO is similar to consumption with a DDCAVECO or DDVAVECO system, while simulated Wbcool consumption for the SDVAV system is similar to that for the DDVAV system. This characteristic can be achieved from the plot that shows the relationship between simulated energy consumption and outside air temperature for different HVAC systems. Neither measured Wbcool nor measured Wbheat can identify the main type of HVAC system in a building by itself. If 12 months of measured Wbcool and measured Wbheat are available, the main type of HVAC system in the building can be identified.

Table 3.29 Dimensions of prototype buildings used to approximate seven buildings on the TAMU campus

site #	facility	area (ft^2)	# of floors	height (ft)	width (ft)	length (ft)	roof (ft^2)	wall (ft^2)	window (ft^2)
1	Zachry Engineering Center	324,400	13	195	158	158	24,954	107,143	16,072
509	Harrington Tower	130,844	5	75	162	162	26,169	42,200	6,330
510	Blocker Building	257,953	10	150	161	161	25,795	83,796	12,569
511	Oceanography and Meteorology	180,316	7	105	160	160	25,759	58,616	8,792
528	Wehner Building	192,001	8	120	155	155	24,000	64,662	9,699
576	Koldus Student Services	111,022	4	60	167	167	27,756	34,769	5,215
580	G. Rollie White	177,838	7	105	159	159	25,405	58,212	8,732

Table 3.30 Yearly average L&E for seven buildings at Texas A&M University

Building	Site	Period	Yearly average L&E consumption (W/SQFT)
Zachry Engineering Center	1	1/99 - 12/99	2.50
Harrington Tower	509	1/ 97 - 12/97	1.10
Blocker Building	510	5/97 - 4/98	1.70
Oceanography and Meteorology	511	4/97 - 3/98	2.20
Wehner Building	528	1/00 - 12/00	1.54
Koldus Student Services	576	1/99 - 12/99	2.65
G.R. White Coliseum	580	8/97 - 7/98	0.86

Table 3.31 Similarity of simulated energy consumption with different HVAC systems

Building	Site	In Wbcool vs. Tdb plot	In Wbheat vs. Tdb plot	Considering Wbcool and Wbheat plots
Zachry Engineering Center	1	(SDVAVECO, DDCAVECO, DDVAVECO) (SDVAV, DDVAV)	(SDVAVECO, SDVAV) (SDCAV, SDCAVECO)	No two systems are similar
Harrington Tower	509	(SDVAVECO, DDCAVECO, DDVAVECO) (DDCAV, SDVAV)	(SDVAVECO, SDVAV) (SDCAV, SDCAVECO)	No two systems are similar
Blocker Building	510	(SDVAVECO, DDCAVECO, DDVAVECO) (DDCAV, SDVAV)	(SDVAVECO, SDVAV) (SDCAV, SDCAVECO)	No two systems are similar
Oceanography and Meterology	511	(SDVAVECO, DDCAVECO, DDVAVECO)	(SDVAVECO, SDVAV) (SDCAV, SDCAVECO)	No two systems are similar
Wehner Building	528	(SDVAVECO, DDCAVECO, DDVAVECO)	(SDVAVECO, SDVAV) (SDCAV, SDCAVECO)	No two systems are similar
Koldus Student Services	576	(SDVAVECO, DDCAVECO, DDVAVECO) (DDVAV, SDVAV)	(SDVAVECO, SDVAV) (SDCAV, SDCAVECO)	No two systems are similar
G.R. White Coliseum	580	(SDVAVECO, DDCAVECO, DDVAVECO) (DDCAV, SDVAV)	(SDVAVECO, SDVAV) (SDCAV, SDCAVECO)	No two systems are similar

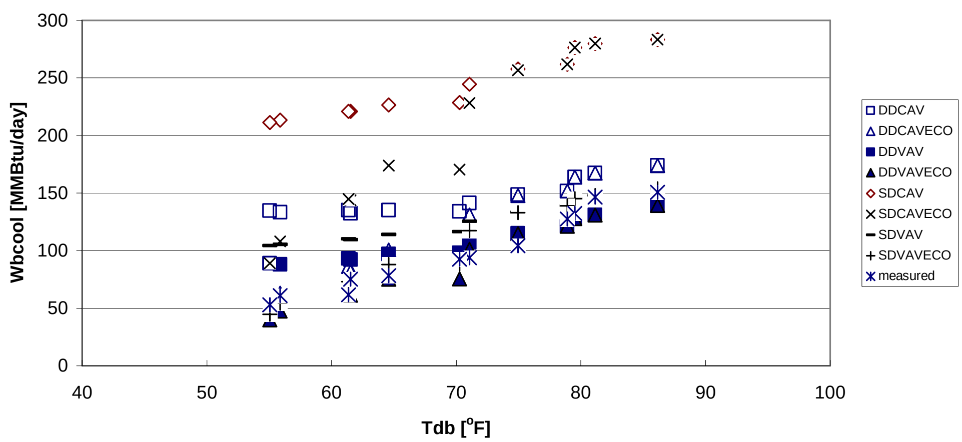

Figure 3.21 Comparison of measured Wbcool and simulated consumption by eight systems for Zachry Engineering Center.

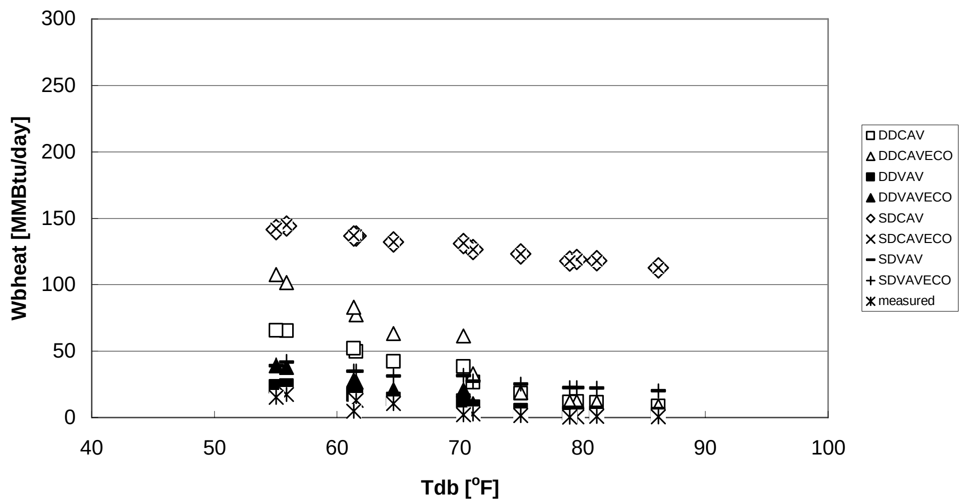

Figure 3. 22 Comparison of measured Wbheat and simulated consumption by eight systems for Zachry Engineering Center.

From Figure 3.21, the measured Wbcool values for Zachry Engineering Center were close to simulated Wbcool values for the prototype building with the DDVAV, DDVAVECO, and SDVAVECO systems. From Figure 3.22, simulated Wbheat values for the DDVAV system were closer to measured Wbheat than those for any other system by eye. The main HVAC system in the building would be inferred to be the DDVAV system. There were 12 DDVAV AHUs and three SDCAV AHUs and the capacity of the three SDCAV AHUs are very small, so the judgment was correct.

Two rules were followed when measured energy consumption was compared with simulated values to identify the main type of HVAC system:

1. Two “lines” (measured energy consumption vs. Tdb and simulated vs. Tdb) should be “close”.
2. The two “lines” should be “approximately parallel”.

The concepts of “close” and “approximately parallel” are fuzzy, by the nature of language. The four plots in Figure 3.23 can help to explain the concepts of “close” and “approximately parallel”; the two lines in the upper-left plot are close and parallel, whereas the two lines in the bottom-left plot are not close but parallel; the two plots in the right side help to understand what is approximately parallel. This process can be carried out automatically by the fuzzy nearest prototype classifier. More detail about fuzzy nearest prototype classifiers will be given in Chapter V.

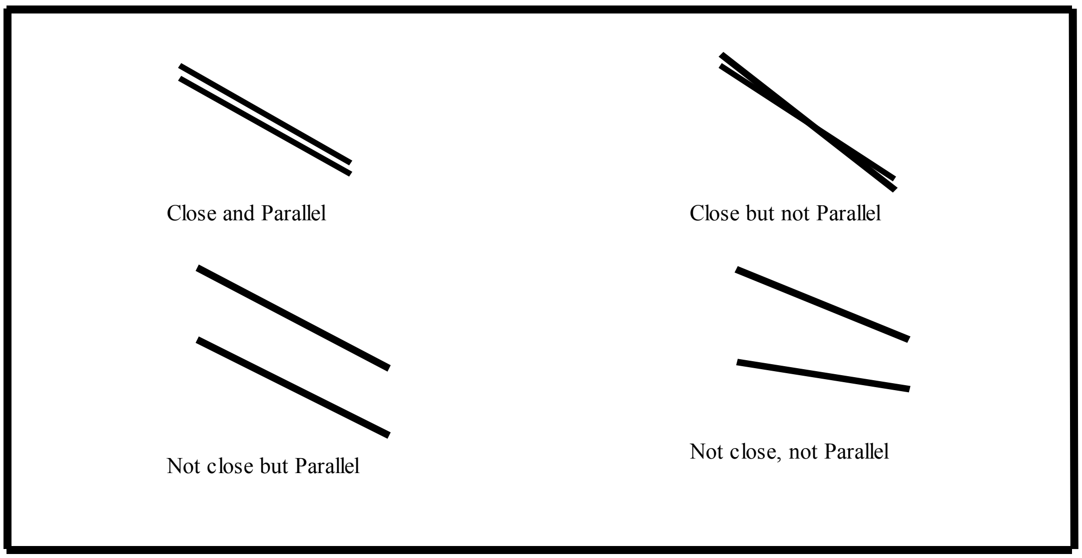

Figure 3. 23 Definition of close and parallel for two lines.

Estimation of potential energy savings (Step 4)

In order to estimate potential energy savings in commercial buildings, an idealized commercial building is configured that is similar to the prototype commercial building, but the idealized commercial building has optimized hot-deck and cold-deck schedules.

AirModel is used to find optimized operation schedules for the HVAC system. For example, the results of the optimization process based on 1999 data for Zachry Engineering Center are shown in Figure 3.24 when chilled water is assumed to cost \$3.90/MMBtu and hot water is assumed to cost \$4.00/MMBtu, and the identified HVAC system in Zachry Engineering Center is DDVAV. The minimum cold-deck temperature and maximum hot-deck temperature in each bin from Figure 3.24 form the optimized operation schedules for the HVAC system in Figure 3.25.

After the optimized operation schedules of the HVAC system in Zachry Engineering Center are determined, the simulated Wbcool and Wbheat in the idealized building of the same size are compared with the simulated consumption in the prototype building of the same size in Figures 3.26 and 3.27. Simulated Wbcool and Wbheat values in the idealized building are lower than those in the prototype building; simulated Wbheat values in the idealized building are generally lower than measured consumption, but measured Wbcool consumption values at low temperatures are lower than the idealized values. The total weather-dependent energy cost in 1999 for Zachry Engineering Center is $148,173; the difference between the actual cost and the simulated cost for the idealized building is -$4,166. It appears that there are no potential savings in the building based on the 1999 data. This might be expected since retrofits in Zachry Engineering Center were finished in 1991, and CC® was finished in 1997. Figure 3.28, the weather–dependent energy consumption for years 1998, 1999, 2000, and 2001 are quite similar, so it appears there are no large potential savings in 1999 for the building.

Summary

A detailed description of the pre-screening methodology has been presented in this chapter. After the prototype commercial building and idealized commercial building are configured, a four-step procedure for the pre-screening methodology is described. More details about steps 2 and 3 will be described in Chapter IV and Chapter V; the methodology will be tested in Chapter VI.

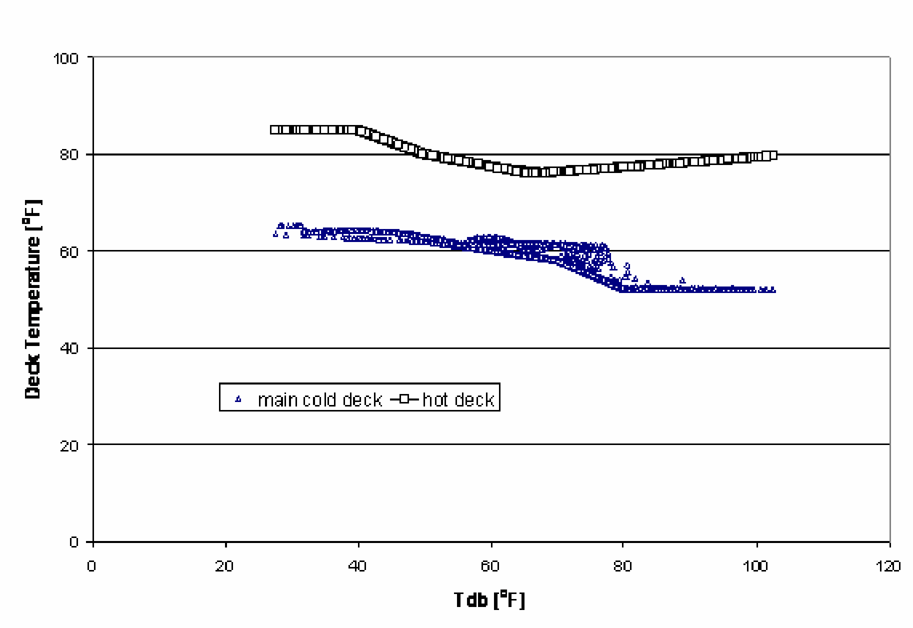

Figure 3.24 The results of the optimization process based on 1999 data for Zachry Engineering Center (DDVAV).

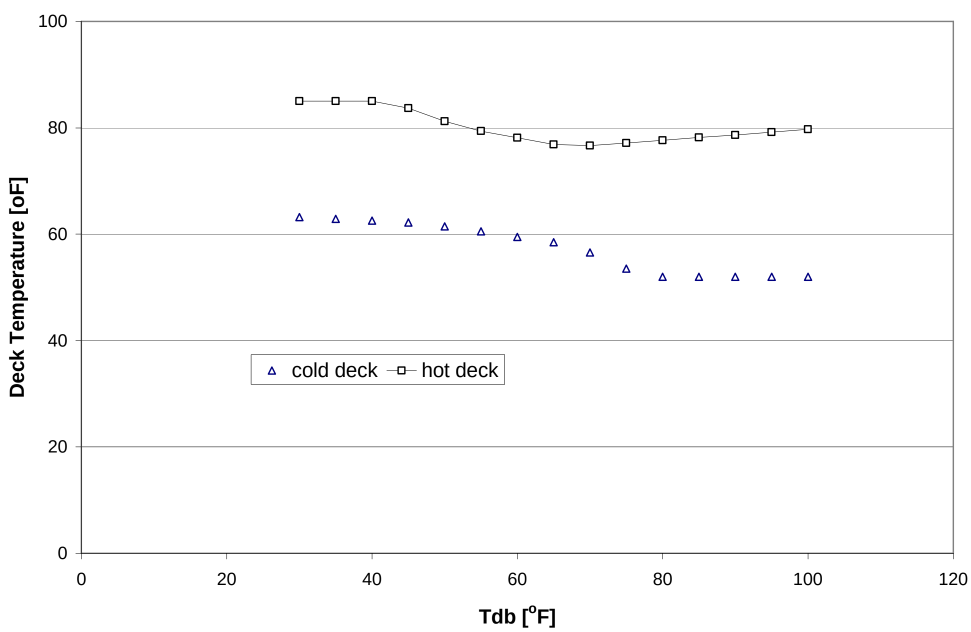

Figure 3.25 Optimized operation schedules for HVAC system in Zachry Engineering Center based on 1999 data.

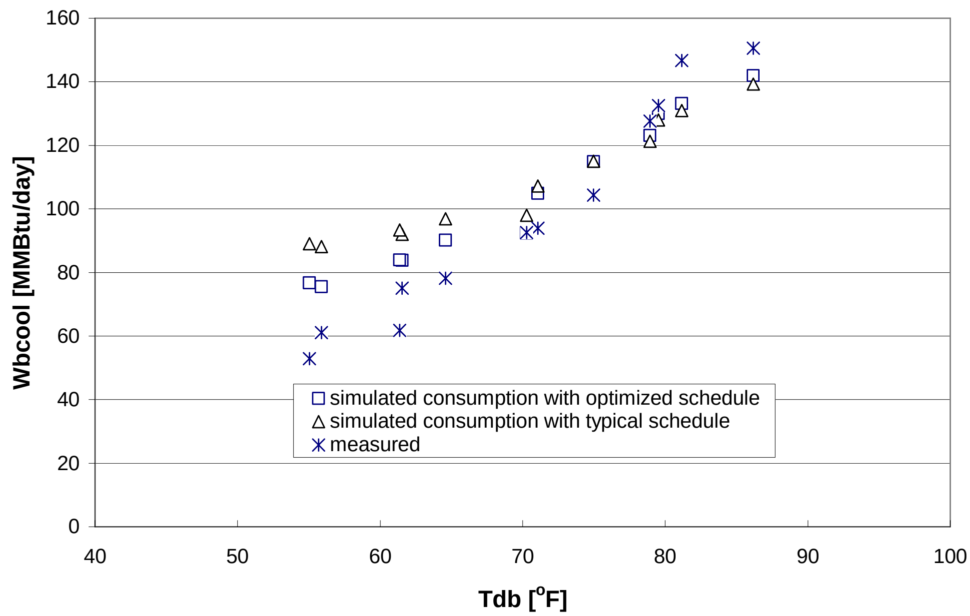

Figure 3.26 Comparison of 1999 measured Wbcool in Zachry Engineering Center with the simulated Wbcool in prototype building and idealized building.

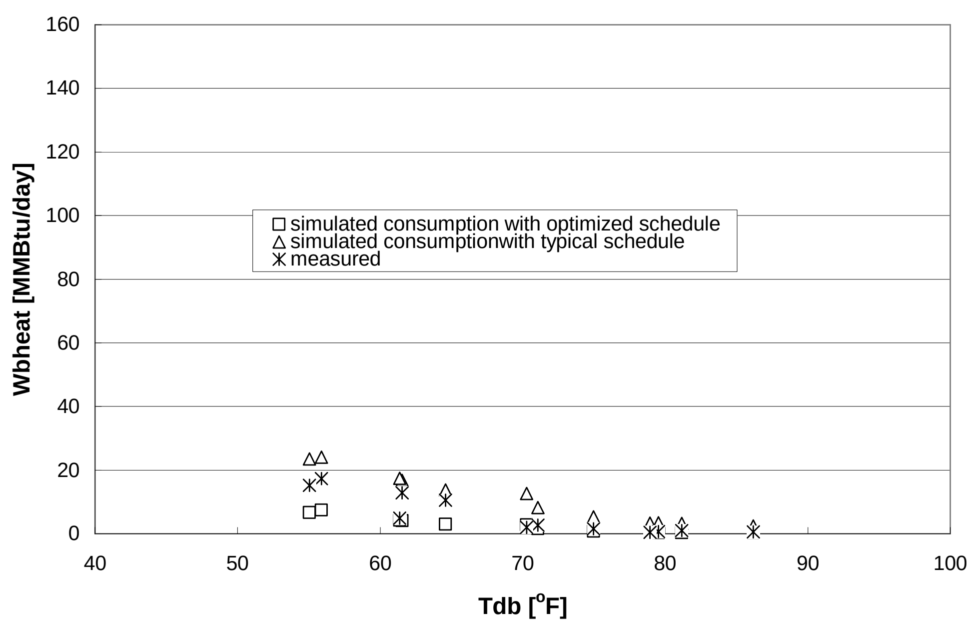

Figure 3.27 Comparison of 1999 measured Wbheat in Zachry Engineering Center with the simulated Wbheat in prototype building and idealized building.

Zachry Engineering Center (1)

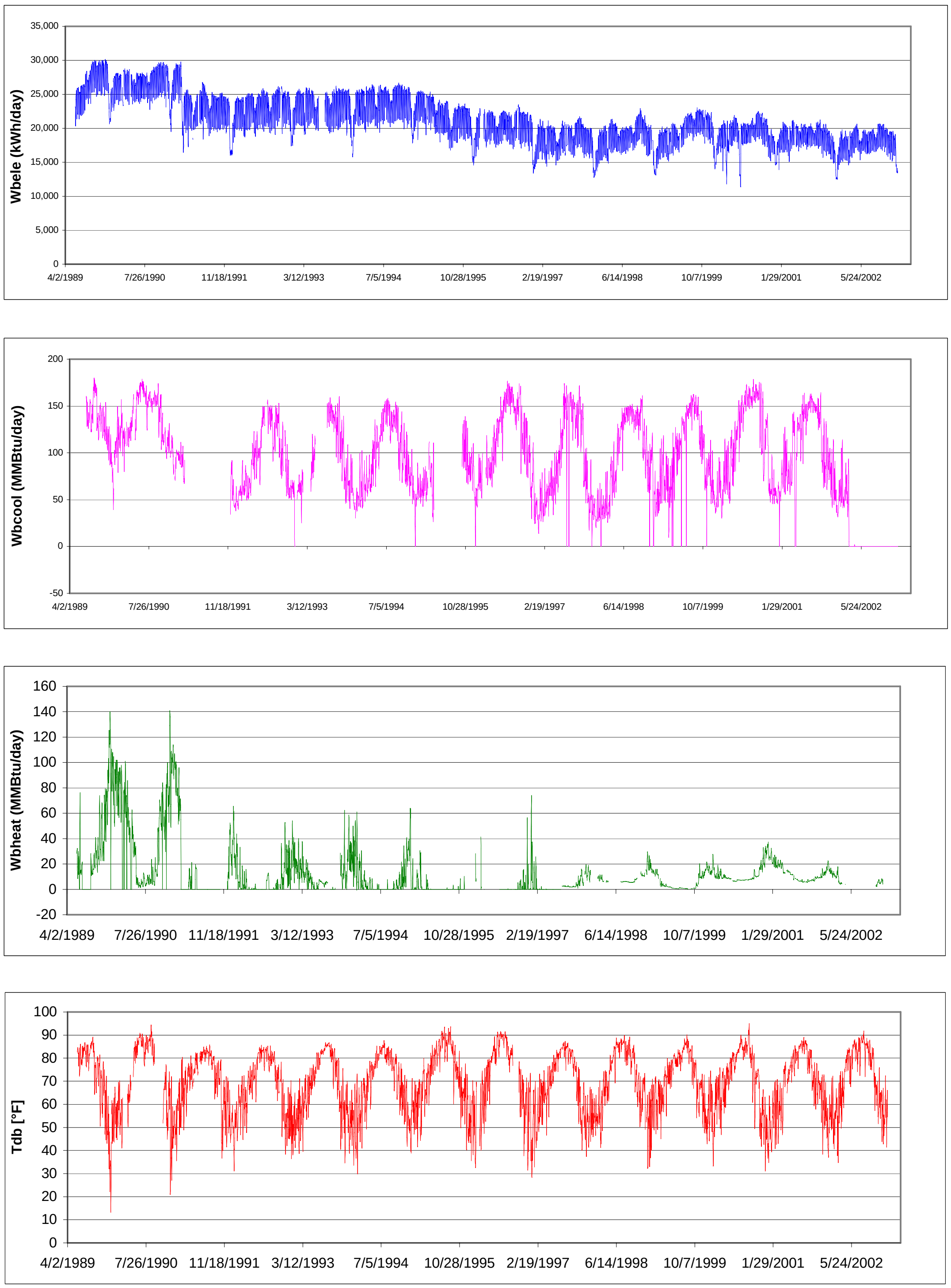

Figure 3.28 Daily energy consumption and Tdb time series for Zachry Engineering Center.

CHAPTER IV
DISAGGREGATING ENERGY CONSUMPTION IN COMMERCIAL BUILDINGS

Introduction

Utility bills are the most widely available source of measured energy consumption data for individual buildings. Electricity consumption in commercial buildings can be separated into weather-independent and weather-dependent consumption (Train et al., 1985; Akbari et al., 1988). The electricity consumed by lighting, plug loads, fans, pumps, etc. typically varies little with outside weather conditions (is weather-independent) and is eventually converted to heat, most of which contributes to building cooling load. By contrast, the consumption of chillers and ancillary equipment varies strongly with outside weather conditions (e.g., temperature, humidity, sunlight) – hence is weather-dependent. Some buildings also use electricity for heating, but they are not considered in this dissertation. Weather-independent electricity consumption in a commercial building has a significant impact on total electricity consumption, and contributed about 64% of the discrepancy between the simulated and actual electricity consumption in one study (Norford, 1994).

It is important to know how much energy is used for cooling in a building, both when screening a building prior to conducting an audit, and as part of the audit process. Since utility bills combine the weather-independent and weather-dependent consumption in a single bill, it is important to have a reliable method for separating these consumption components.

Several methods have been developed to separate utility bills into weather-dependent and weather-independent components. The cooling only (CO) or cooling and heating (CH) model in the Princeton Scorekeeping Method (PRISM) can be used to disaggregate utility bills (Reynolds et al., 1990). Three-parameter change-point (3P) regression models (Kissock et al., 1998) also can successfully separate electricity consumption into weather-independent and weather-dependent portions in buildings without electric heating if the chiller system is turned off for at least one full billing period during the year. It may be possible to separate the weather-dependent electricity consumption from the weather-independent part using 4P models, but a suitable methodology for accomplishing this has not been reported in the literature. The 3P model can be expected to introduce a systematic bias in the values of cooling consumption estimated for buildings where the chiller system operates throughout the winter, as is often the case in the South.

This chapter is devoted to describing a method to disaggregate monthly electricity consumption into weather-dependent and weather-independent consumption for large buildings in which chillers operate throughout the year. This implementation of a system and method to remotely determine whether an energy consuming chiller is metered by a particular set of utility bills has been named “Separate the Utility Bills based on Thermal Balance” (SUBTB). It requires as inputs only the monthly electric bills, monthly heating consumption (typically gas bills), monthly average temperature, and building area, and hence is readily carried out remotely. It is not applicable to buildings with electric heating or absorption cooling (Zhu and Claridge, 2004).

Methodology

The prototype commercial building represents a generic commercial building and is configured to avoid unique building-specific energy characteristics; the prototype commercial building used in this dissertation is configured based on only the building area. After the cooling loads in internal gain-dominated commercial buildings in hot climates are analyzed, an algorithm to Separate the Utility Bills based on Thermal Balance (SUBTB) is presented. The SUBTB methodology requires an estimate of the overall building thermal loss coefficient UA (Btu/hr/°F). This can be calculated from the building thermal characteristics, but the SUBTB method is not highly sensitive to this input as shown in Chapter III; hence, it is easier to use a typical UA value based on that of a prototype building of the same area as the building being analyzed. The estimated UA values from prototype commercial buildings are not far away from the empirical values. Typical modified balance temperature is defined in this chapter and determined based on several buildings; this quantity is needed for application of SUBTB methodology.

Thermal balance in a gain-dominated building

Most commercial buildings in hot climates can be characterized as internal gain-dominated buildings; the combination of electrical gains, solar gains and occupant gains is generally substantially larger than the gains or losses from envelope heat transfer, ventilation air and infiltration. Cooling is generally more important than heating. The major thermal gains in such buildings are from:

(1) Heat transfer through the envelope (negative values mean heating load)

$$\dot{Q}_1 = \dot{Q}_{env}$$

(2) Ventilation and infiltration air (negative values mean heating load)

$$\dot{Q}_2 = \dot{Q}_{vent}$$

(3) Solar gain $\dot{Q}_3 = \dot{Q}_{sol}$

(4) Occupants $\dot{Q}_4 = \dot{Q}_{occ}$

(5) Lighting, equipment, fans, etc. $\dot{Q}_5 = \dot{Q}_{L\&E}$

(6) Heat supplied for reheat or heating (all values are negative) $\dot{Q}_6 = \dot{Q}_{heat}$

The algebraic sum of these terms corresponds to the cooling that must be supplied to the building. If there is no cooling requirement in the building, these terms will sum to zero with $\dot{Q}_{heat}$ providing the heat required in a pure heating situation. The algebraic sum of all six terms is referred to as the "chiller load" ($\dot{Q}_{CH}$), though the cooling may come from another source such as a district cooling system.

$$\dot{Q}_{CH} = \sum_{1}^{6} \dot{Q}_i \qquad \text{Equation 4.1}$$

The first four terms are difficult to measure and are rarely measured individually. $\dot{Q}_{env}$ and $\dot{Q}_{vent}$ are proportional to the difference between the room temperature and the outside air temperature with $\dot{Q}_{vent}$ also having humidity dependence. $\dot{Q}_{sol}$ depends on the weather and the building characteristics, while $\dot{Q}_{occ}$ depends on the number of occupants, the time they spend in the building, their activity levels, etc.

The terms $\dot{Q}_5 = \dot{Q}_{L\&E}$ and $\dot{Q}_6 = \dot{Q}_{heat}$ are different. A good measure of $\dot{Q}_{heat}$ is generally available if the gas or oil consumption of the building is measured and the building does not have significant process loads. $\dot{Q}_{L\&E}$ is measured less frequently, but is contained within the building electricity consumption that is normally metered by the utility. The electricity bills from the utility normally include the weather-independent electricity consumption (for lighting, plug loads, equipment, fans, etc.) that is typically somewhat larger than $\dot{Q}_{L\&E}$ due to outdoor lighting and other uses of electricity that are not converted to heat in the space, and the weather-dependent consumption, or "chiller electricity" is denoted as $\dot{E}_{CH}$. The weather-independent electric consumption is denoted as $\dot{E}_{L\&E}$ and a fraction, f, of this consumption is assumed to become $\dot{Q}_{L\&E}$ so

$$\dot{Q}_{L\&E} = f\dot{E}_{L\&E} \qquad \text{Equation 4.2}$$

The methods described in the introduction, such as using the 3P regression model, may be used to separate the electricity bills into $\dot{E}_{L\&E}$ and $\dot{E}_{CH}$ for buildings where chillers are off for at least one billing period each year. A new method is presented for separating the billed consumption into $\dot{E}_{L\&E}$ and $\dot{E}_{CH}$ for buildings where the chillers are operated every month of the year.

Algorithm to separate the utility bills based on thermal balance

A new algorithm is presented to Separate the Utility Bills based on Thermal Balance (SUBTB). This algorithm is an integral part of the implementation of a system and method to remotely identify the presence of chillers and determine potential savings and retrofits. This algorithm is applicable to large commercial buildings with electric chiller systems, such that the whole building electricity consumption ($\dot{E}_{tot}$) can be disaggregated into a weather independent component ($\dot{E}_{L\&E}$) and a weather dependent component or chiller electric consumption ($\dot{E}_{CH}$) so

$$\dot{E}_{tot} = \dot{E}_{L\&E} + \dot{E}_{CH} \qquad \text{Equation 4.3}$$

From thermal balance on the building, the chilled water or cooling supplied by the chiller system ($\dot{Q}_{CH}$) removes the cooling load as given by Equation 4.1. It is assumed that gas usage data ($\dot{Q}_{gas}$) is available from gas bills and that the boiler system has an efficiency η_b. Equation 4.1 can be changed to the form:

$$\dot{Q}_{CH} = \dot{Q}_{MCH} + \dot{Q}_{L\&E} + \eta_b \dot{Q}_{gas} \qquad \text{Equation 4.4}$$

where

$$\dot{Q}_{MCH} \equiv \sum_{1}^{4} \dot{Q}_i = \dot{Q}_{env} + \dot{Q}_{vent} + \dot{Q}_{sol} + \dot{Q}_{occ} \qquad \text{Equation 4.5}$$

If the chiller COP is defined to include the electricity consumption of the chiller, cooling tower, pumps, etc., then

$$\dot{Q}_{CH} = COP \cdot \dot{E}_{CH} \qquad \text{Equation 4.6}$$

Equations 4.2 – 4.6 may be solved to obtain $\dot{E}_{L\&E}$ as:

$$\dot{E}_{L\&E} = \frac{COP \times \dot{E}_{tot} - \dot{Q}_{MCH} - \eta_b \dot{Q}_{gas}}{f + COP} \qquad \text{Equation 4.7}$$

This is the key equation in the SUBTB method. From this equation, $\dot{E}_{tot}$ and $\dot{Q}_{gas}$ are measured quantities. In general, the quantities COP, η_b, f and $\dot{Q}_{MCH}$ will have to be estimated before $\dot{E}_{L\&E}$ is estimated by using Equation 4.7. The quantities COP, η_b, and f are all known physical quantities for which it is relatively easy to make reasonable estimates. $\dot{Q}_{MCH}$ is more complex, so more detail will be presented before attempting to estimate parameter values and test the use of this approach for estimating $\dot{E}_{L\&E}$.

Modified chiller load

If all lights, equipment, fans, etc. in a building were turned off, and the heating/reheat units were also turned off, then the remaining cooling load would correspond to $\dot{Q}_{MCH}$ as defined in equation 4.5. Hence $\dot{Q}_{MCH}$ is called the modified chiller load. Using standard notation, the first two terms in Equation 4.5 can be expressed as:

$$\dot{Q}_{env} = UA_{env}(T_{OA} - T_{rm}) \qquad \text{Equation 4.8}$$

$$\dot{Q}_{vent} = 1.08 \dot{V}_{vent}(T_{OA} - T_{rm}) \qquad \text{Equation 4.9}$$

where

T_{OA} is the outside air dry bulb temperature in °F,

T_{rm} is the inside air dry bulb temperature in °F,

UA_{env} is the overall thermal loss coefficient of the building envelope in Btu/(hr·°F), and

$\dot{V}_{vent}$ is the rate at which ventilation and infiltration air enters the building in CFM.

The last two terms, $\dot{Q}_{sol}$ and $\dot{Q}_{occ}$ will be treated as constants in this analysis. For a building whose only sources of heat are the gains from occupants and solar gains, the average outside temperature at which the inside or room temperature will correspond to the room thermostat set temperature, T_{set}, will be a balance temperature, T_{Mbal}, that can be expressed as

$$T_{Mbal} = T_{set} - \frac{\dot{Q}_{sol} + \dot{Q}_{occ}}{UA_{equiv}} \qquad \text{Equation 4.10}$$

where

$$UA_{equiv} = UA_{env} + 1.08\dot{V}_{vent} \qquad \text{Equation 4.11}$$

Using these definitions, $\dot{Q}_{MCH}$ can be expressed as

$$\dot{Q}_{MCH} = UA_{equiv}(T_{OA} - T_{Mbal}) \qquad \text{Equation 4.12}$$

The problem has now been transformed to one where T_{Mbal} and UA_{equiv} need to be determined to obtain $\dot{Q}_{MCH}$. Hence estimation of COP, η_b, f, T_{Mbal} and UA_{equiv} are necessary before equation 4.7 is used to estimate $\dot{E}_{L\&E}$. In this dissertation, f is assumed to be 1.

Determining typical values of the modified balance temperature

Values of T_{Mbal} for several buildings will be calculated to determine whether an average value may be used in equation 4.7 for evaluating $\dot{Q}_{MCH}$. Rearranging equation 4.4, and using equation 4.12, $\dot{Q}_{MCH}$ can be expressed as:

$$\dot{Q}_{MCH} = \dot{Q}_{CH} - \dot{Q}_{L\&E} - \eta_b \dot{Q}_{gas} = UA_{equiv}(T_{OA} - T_{Mbal}) \qquad \text{Equation 4.13}$$

This expresses $\dot{Q}_{MCH}$ in terms of Electricity consumption for lighting, plug loads, fans, etc. ($\dot{E}_{L\&E}$), chiller load ($\dot{Q}_{CH}$) and heating consumption data ($\dot{Q}_{heat}/\eta_b$). Hourly measured values of these three quantities are available in the ESL database for several dozen buildings. Yearly sets of this data for three buildings were converted to monthly data by summing to get monthly totals. Chilled water and heating water data (Btu/hr) were converted to kWh/day to compute $\dot{Q}_{MCH}$. Figures 4.1 – 4.3 show the relationship between monthly average modified chiller load and monthly average outside air dry-bulb temperature for the three buildings. These figures show that the measured average daily modified chiller load for each month has a highly linear correlation with the outside air temperature for these sites.

The modified chiller load would be zero when the outside temperature is equal to the room temperature in the building if solar gain were zero; there were no occupants and no latent load. The temperatures in these buildings are typically 72 - 75°F, so it is clear that solar gain, occupants and latent loads serve to lower the temperature at which the modified chiller load is zero. This temperature was defined in equations 4.10 and 4.12 as the modified balance temperature, T_{Mbal}, of the building[2]. From Figures 4.1 – 4.3, the modified balance temperature T_{Mbal} is between 60°F and 70°F in these three buildings, and the slope of these plots corresponds to UA_{equiv}.

Linear two-parameter regression is used to determine the modified balance temperatures for six buildings on the Texas A&M campus in College Station with the results shown in Table 4.1. The average value of T_{Mbal} was 67.8°F; the table also shows the data period used to develop the model and the slope or equivalent UA value for each of these buildings.

[2] This temperature is related to, but different from the balance temperature used in variable base degree-day calculations since it does not include internal gains from lights, plug loads, etc.

Table 4.1 Modified balance temperatures and empirical equivalent UA values for six buildings at Texas A&M University

Buildings at Texas A&M University	Period	Empirical UA_{equiv} [kWh/(day·°F)]	T_{Mbal} [°F]
Harrington	Jan. 97-Dec. 97	409	66.41
Blocker	Jan. 97-Dec. 97	572	66.81
Oceanography and Meteorology	Jan. 97-Dec. 97	637	62.94
Wehner	Jan. 98-Dec. 98	456	75.12
Koldus Student Services	Jan. 99-Dec. 99	351	62.74
G. Rollie White	Jan. 97-Dec. 97	442	72.83

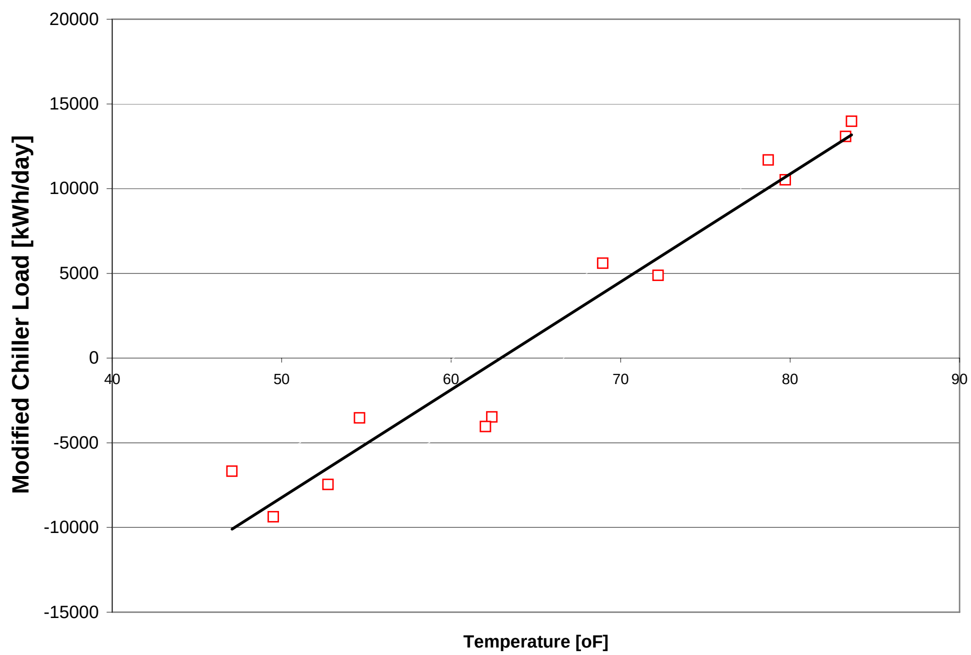

Figure 4.1 The modified chiller load vs. monthly average outside air temperature for the Oceanography and Meteorology Building at Texas A&M University.

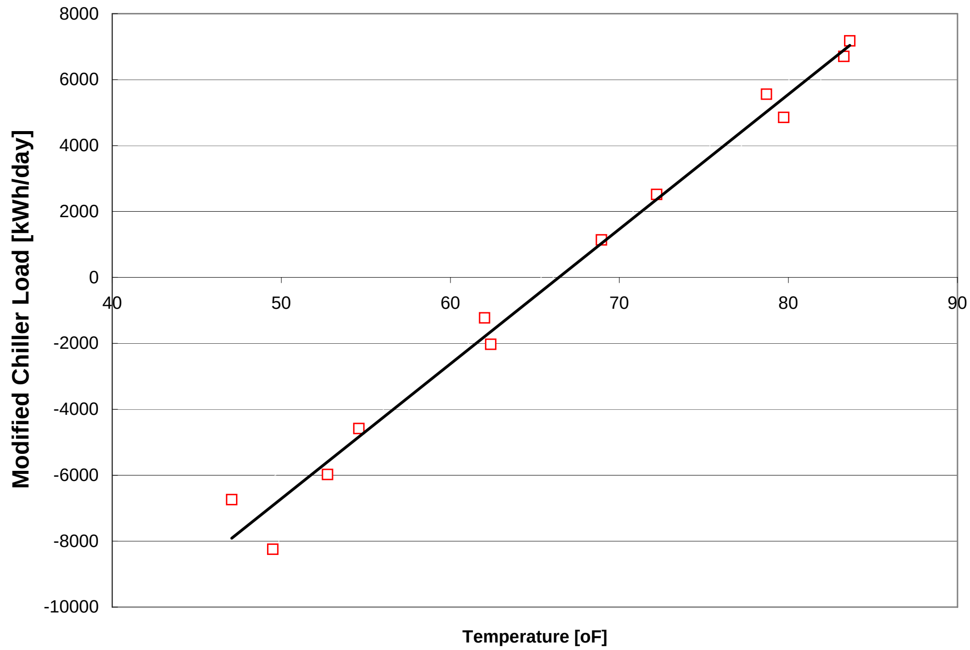

Figure 4.2 The modified chiller load vs. monthly average outside air temperature for Harrington Tower at Texas A&M University.

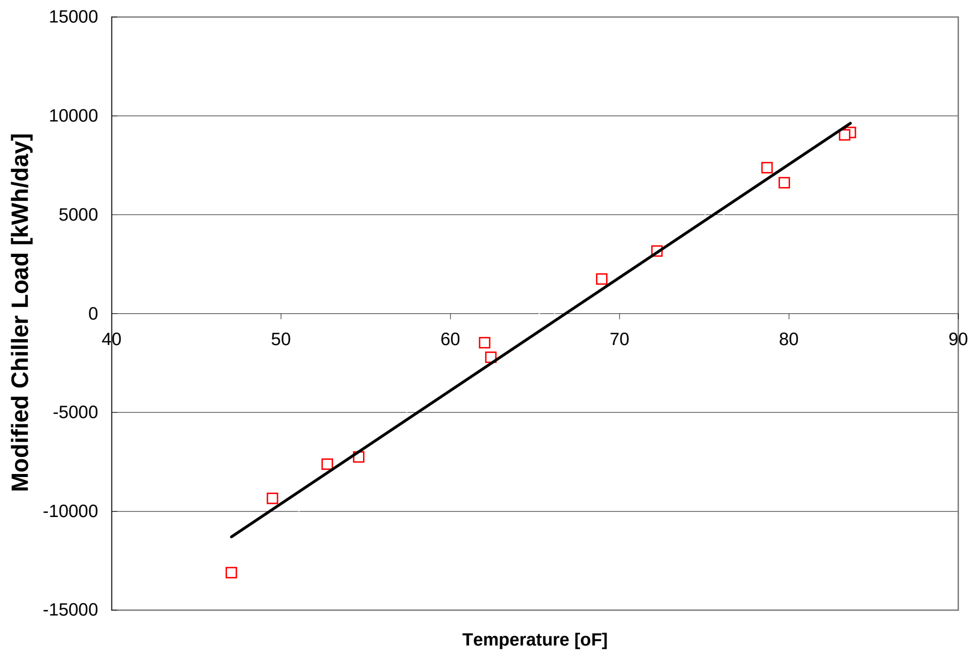

Figure 4.3 The modified chiller load vs. monthly average outside air temperature for the Blocker Building at Texas A&M University.

The prototype building is used to generate values of $(UA)_{equiv}$ based on the total area of several buildings for comparison with the empirical values determined from measured consumption data. For each building, a prototype of the same area was configured by choosing the layout of each floor to be approximately 160 feet by 160 feet. The dimensions were adjusted as needed to give an integer number of floors for each building. Six prototype buildings were configured, based on the areas of the six buildings for which values of T_{Mbal} were determined in Table 4.1; equivalent UA values shown in Table 4.2 were estimated for each building. The empirical values of $(UA)_{equiv}$ determined from the slope of Modified Chiller Loads for the individual buildings are 1.45 to 2.28 times the estimated equivalent UA values for the prototype buildings, with an average value of 1.8.

Table 4.2 Comparison of empirical values of $(UA)_{equiv}$ determined from the slope of modified chiller load and those estimated for prototype buildings of the same area

Building	Total area (ft^2)	Empirical UA_{equiv}		Estimated $(UA)_{equiv}$ (Btu/hour/°F)
		(kWh/day/°F)	(Btu/hour/°F)	
Harrington	130844	409	58,130	29,256
Blocker	257953	572	81,344	56, 060
Oceanography and Meteorology	180316	637	90,507	39,741
Wehner	192001	456	64,761	42,785
Koldus Student Services	111022	351	49,833	24,885
G. Rollie White	177838	442	62,888	39,322

If more information about envelope and fresh air rate are known, the values of $(UA)_{actual}$ for envelope and fresh air rate will get closer to the slope of Modified Chiller Loads for a particular building. Based on actual exterior wall area, window area, U value for walls and windows, outside air flow rate in year 2000 for Harrington, Oceanography and Meteorology, and Wehner (Cho, 2002), $(UA)_{actual}$ can be calculated if heat loss from roof and ground are neglected. The comparison of $(UA)_{actual}$ and $(UA)_{equiv}$ are in Table 4.3, if $(UA)_{actual}$ is assumed constant in recent years. It is seen that the actual UA_values are much closer to the empirical $(UA)_{equiv}$ values. More precise UA-values can be achieved when UA for roof and ground are included.

Table 4.3 Comparison of empirical values of $(UA)_{equiv}$ determined from the slope of Modified Chiller Load with those estimated for prototype buildings of the same area and actual one

Building	Harrington	Oceanography and Meteorology	Wehner
Total area (ft^2)	130,844	180,316	192,001
Exterior walls (ft^2)	41,200	63,248	45,000
Windows (ft^2)	19,017	26,208	30,000
U for walls (Btu/hour/°F/ft^2)	0.20	0.20	0.20
U for windows (Btu/hour/°F/ft^2)	0.80	0.98	0.92
Fresh air rate (CFM/ft^2)	0.15	0.19	0.10
(UA)actual (Btu/hour/°F/ft^2)	44,650	75,334	57,336
Empirical $(UA)_{equiv}$ (Btu/hour/°F)	58,130	90,507	64,761
Estimated $(UA)_{equiv}$ (Btu/hour/°F)	29,256	39,741	42,785

Thus the value of $\dot{E}_{L\&E,est}$ is derived from measured values of $\dot{E}_{tot}$, $\dot{Q}_{gas}$, estimated values of $\dot{Q}_{MCH}$, f, η_b, and COP. Monthly values of $\dot{E}_{L\&E,est}$ are used to obtain annual values. Estimated values of $\dot{E}_{CH}$ are then obtained as $\dot{E}_{CH,est} = \dot{E}_{tot} - \dot{E}_{L\&E,est}$ (annual average value).

Investigation of COP and η_b in hot and humid climates

In this research, COP and η_b in hot and humid climates are assumed constant all year; the typical COP and typical η_b will be investigated in this section.

The Robert E. Johnson Building (215) is located in Austin, Texas, the hourly electricity consumption [kWh] by two chillers ($\dot{E}_{CH}$) and the chilled water output [MMBtu] ($\dot{Q}_{CH}$) from the two chillers are monitored by the Energy Systems Laboratory (ESL). The COP of each chiller is defined as:

$$COP = \dot{Q}_{CH} * 293.1 / \dot{E}_{CH}$$

The hourly $\dot{E}_{CH}$ and $\dot{Q}_{CH}$ during Jan. 2001 – Dec. 2003 are retrieved from the ESL database, and COP is calculated if both data types are available. From Figures 4.4 and 4.5, COP values for the two chillers show substantial variation, but don't appear to change a lot with the seasons. From Figures 4.6 and 4.7, it is clearer that COP of the two chillers is not always independent of outside weather. The three data “columns” in the two figures results from the accuracy of measured outside dry-bulb temperature data; there are temperature gaps between 93.49 °F and 95.28 °F, 95.51 °F and 96.07 °F, 96.65 °F and 100 °F during Jan. 2001 – Dec. 2003. COP values for the two chillers are higher than usual, as they are determined from electricity consumption by the chiller(s) instead of the chiller(s) and ancillary equipment (such as pumps, fans, and cooling towers).

If there are over 80% of valid hourly data in one month, then the hourly data are converted to monthly total CHW and CHE. Note that while this does not give true monthly totals, it is assumed that the monthly COP for such months will not differ substantially from the actual monthly COP. A monthly COP is not calculated for months where less than 80% of the data are valid. Monthly COP is calculated in the same way as COP. Calculated monthly COP values for chiller 1 and chiller 2 in the Robert E. Johnson building (215) are shown in Figure 4.8 where it may be observed that monthly COP variation does not appear to depend on the season. The monthly COP values for the two chillers are listed in Table 4.4 where the -99 for January 2001 indicates insufficient valid data; COP for chiller 2 in Feb. 2001 is very low and is deemed unreliable.

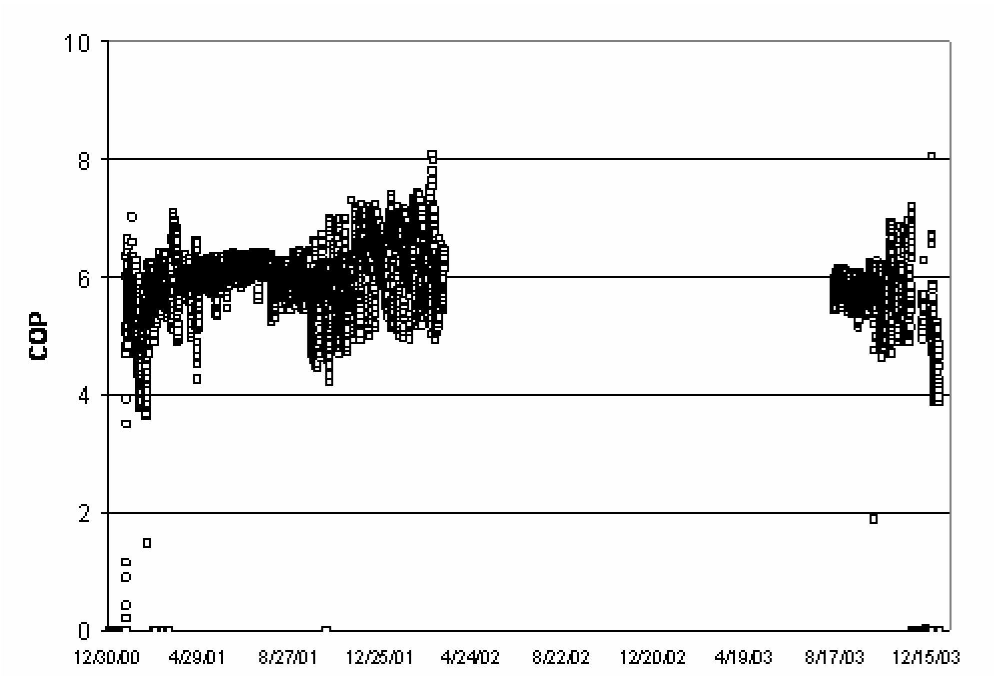

Figure 4.4 Hourly COP of chiller 1 in Robert E. Johnson Building in 2001 – 2003.

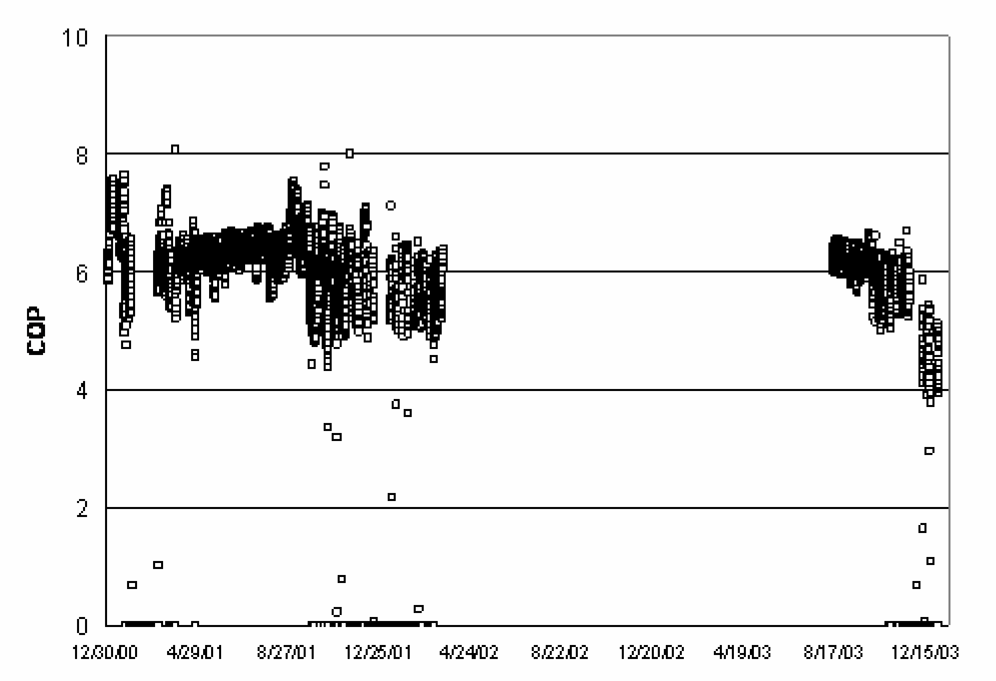

Figure 4.5 Hourly COP of chiller 2 in Robert E. Johnson Building for 2001 – 2003.

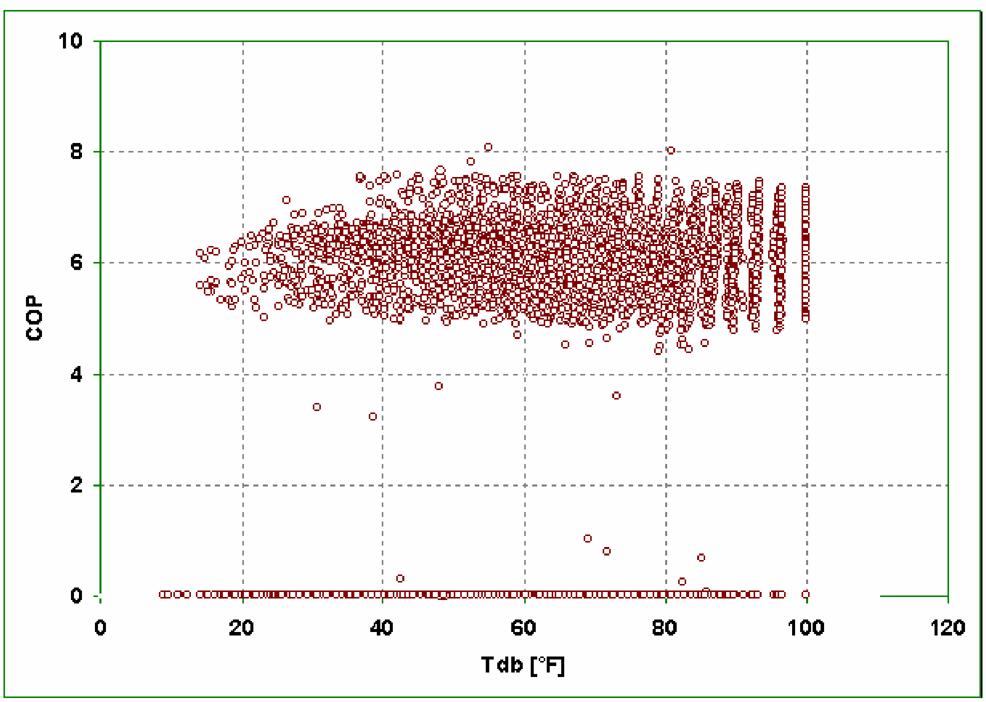

Figure 4.6 Relationships between COP of chiller 1 in the Robert E. Johnson Building and Tdb.

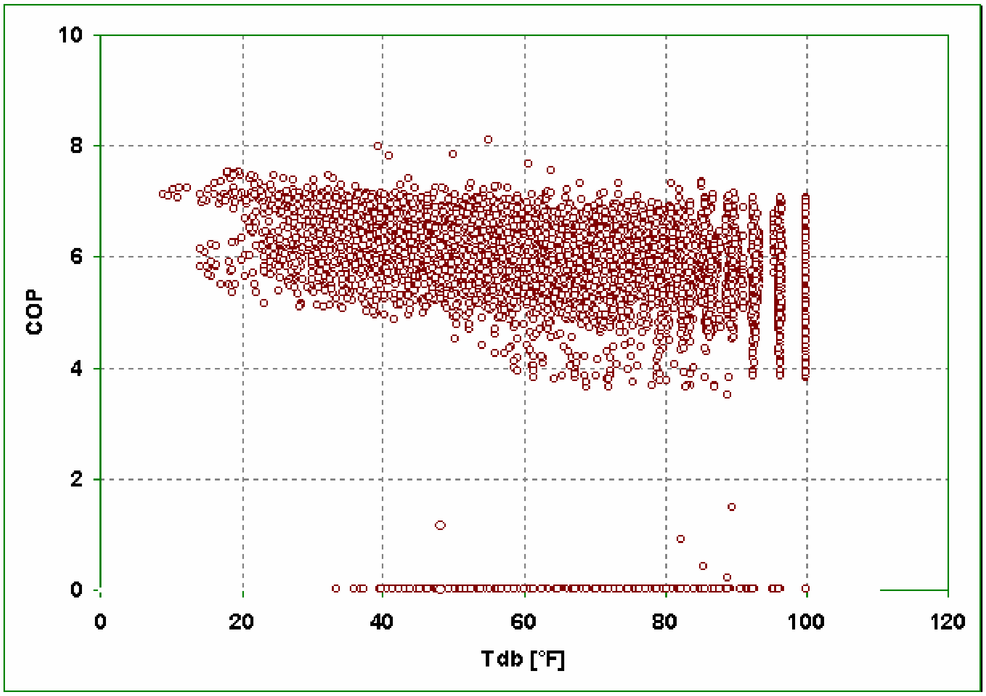

Figure 4.7 Relationships between COP of chiller 2 in the Robert E. Johnson Building and Tdb.

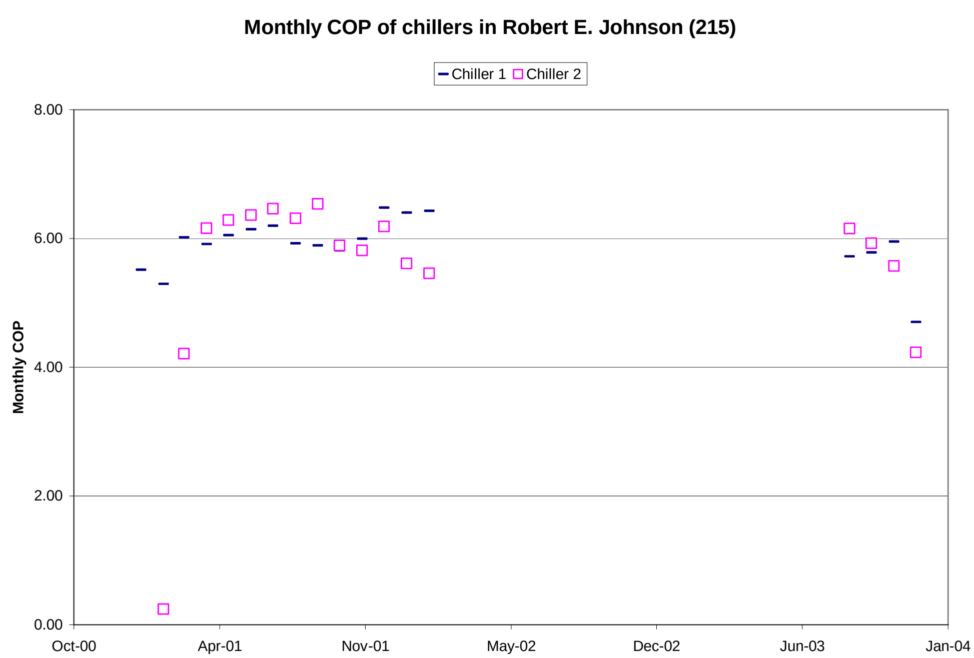

Figure 4.8 Monthly COP time series in the Robert E. Johnson Building.

Table 4.4 Monthly COP for chillers in the Robert Johnson E. Building

month	COP for chiller 1	COP for chiller 2
Jan-01	5.51	-99.00
Feb-01	5.29	-99.00*
Mar-01	6.02	4.21
Apr-01	5.91	6.16
May-01	6.05	6.28
Jun-01	6.14	6.36
Jul-01	6.20	6.46
Aug-01	5.93	6.31
Sep-01	5.89	6.54
Oct-01	5.82	5.89
Nov-01	6.00	5.82
Dec-01	6.48	6.19
Jan-02	6.40	5.61
Feb-02	6.43	5.46
Sep-03	5.72	6.15
Oct-03	5.78	5.92
Nov-03	5.95	5.57
Dec-03	4.70	4.23

* The COP of chiller 2 in 2/2001 is only 0.24, it is unreliable.

From Figures 4.9 and 4.10, there is significant variation in COP for different months at the same temperature for the two chillers; the slopes of COP vs. monthly average temperature are 0.0051 (1/°F) and 0.0414 (1/°F) for chiller 1 (18 months) and chiller 2 (16 months), respectively. COP values for chiller 2 in March 2001 and December 2003 are significantly lower than comparable months; the slope of COP vs. monthly average temperature for chiller 2 is 0.0234 if COP values in these two months are treated as unreliable (Figure 4.11). Though the slope of COP vs. monthly average temperature is not zero for the two chillers, the slope is so small that COP will not be treated as sensitive to outside temperature.

Hourly and monthly COP values of two chillers are studied based on the data from the Robert E. Johnson Building; based on this investigation, it appears that both hourly and monthly COP can be treated as approximately constant all year for the purposes of this study. In order to find a typical COP-value for chiller systems in hot and humid climates, a survey was made based on the monitored chiller system electricity consumption and chilled water output data available for this study.

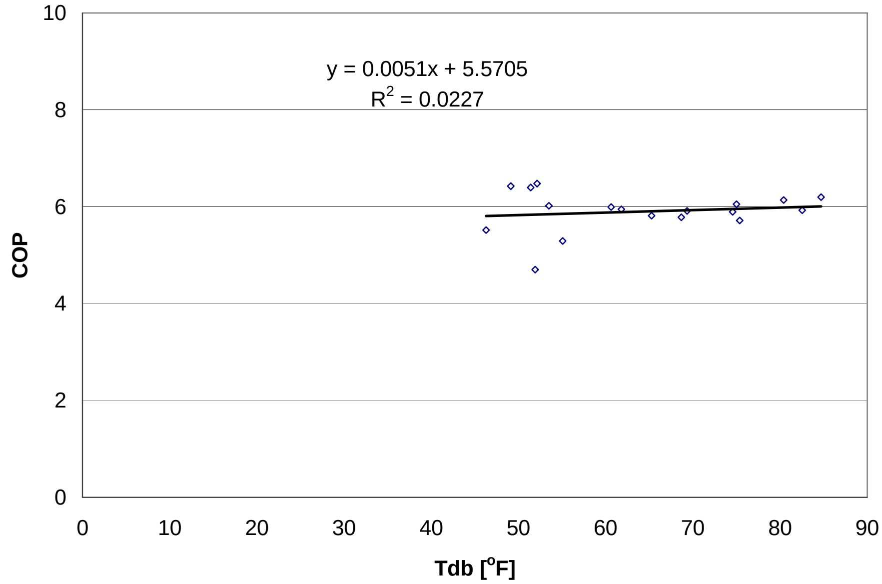

Figure 4.9 Monthly COP for chiller 1 in the Robert E. Johnson Building during 2001 – 2003.

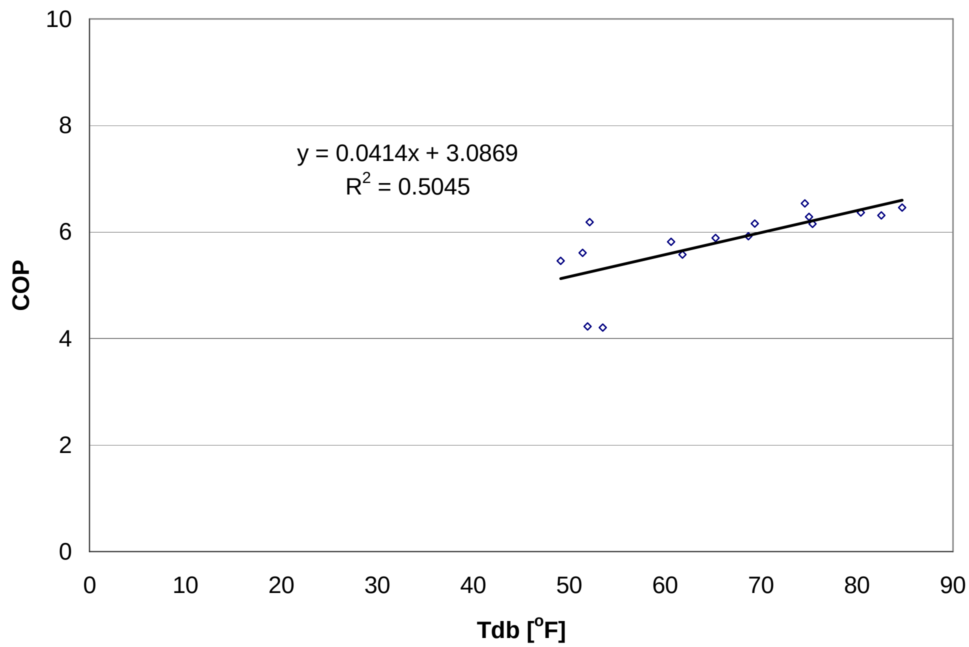

Figure 4.10 Monthly COP for chiller 2 in the Robert E. Johnson Building during 2001 – 2003 (16 months).

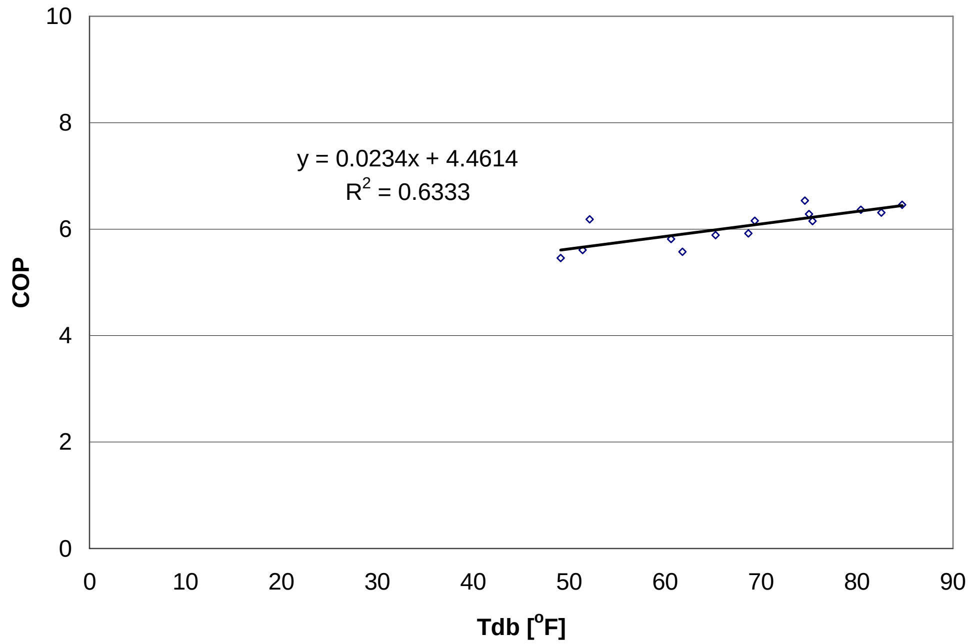

Figure 4.11 Monthly COP for chiller 2 in the Robert E. Johnson Building during 2001 – 2003 (14 months).

Qualified monitored data for several facilities are available during periods of 1994 – 2003 in the ESL database. These facilities, listed in Table 4.5, are in Texas except for the Neil Kirkman Building A-Wing (922), which is in Florida. Among the 16 facilities, electricity consumption by chiller(s) and by auxiliary device are monitored separately for seven facilities (Government Center (146), UTA Thermal Energy Plant (173), Main CUP (310), College of the Mainland (320), Valle Verde Campus (325), Rio Grande Campus (326) and Neil Kirkman Building A-Wing (922)). For other facilities, the total electricity consumption by the chiller system is monitored, and the channels used to achieve electricity consumption by chiller and auxiliary equipment are listed in Table III1 of Appendix III, the channels for chilled water supplied are also listed in the table; the description of the channels are listed in Table III2.

The monitored daily time series data for the 16 facilities are listed in Appendix III. COP values shown in Figures III2 – III17 are for the chiller system including chiller and auxiliary devices, such as chilled water pumps, cooling towers, etc. From these plots, suitable periods are selected for the survey. Where both chilled water consumption and electricity consumption by the chiller system are available, daily COP values of the chiller system derived from chilled water production and electricity consumption by chiller system are in a reasonable range.

From Figure III2, electricity consumption by the chillers at the University of Texas Pan Am is sometimes negative before September 1, 1996, and the monitored data is wrong; no data are recorded in the database after October 6, 1997; so the period during 9/1/1996 – 10/6/1997 is selected to determine weighted average COP (COP_{wa}) for this facility. From Figure III4, though electricity consumption and chilled water production by the chillers at Delmar College are known before and after the period 7/19/1994 – 3/30/1998, COP outside of this period may be unreliable; weighted average COP (COP_{wa}) for this facility is calculated based on the data during 7/19/1994 – 3/30/1998. From Figure III5, though data for the Government Center (George Allen Building) are available before December 1, 1994, the COP sometimes is over 10, and the data are unreliable; the data during 12/1/1994 – 4/7/2000 are used for evaluating the performance of the chiller system. From Figure III15, COP for the chiller system at Valle Verde Campus after June 19, 1996 varied over a large range, and data during 10/25/1994 – 6/19/1996 seem valid to calculate efficiency of the chiller system. For the other 12 facilities, all data available are used in this survey. In one day, if both the monitored electricity consumption by the chiller system and output of chilled water are qualified, and COP is in a reasonable range, then this day is treated as a valid day. The number of valid days is also listed in Table 4.5.

From Figures III2 – III17, most COP_{wa} of chiller systems in the 16 facilities don't change with season, whereas for chiller systems in J.H. Winters (211), Central Services Building (226), Austin Convention Center (230), Main CUP (310), and Rio Grande Campus (326), COP_{wa} in summer is higher than in the cool season, particularly for the chiller system in J.H. Winters (211). The reason is probably that the chiller system works near full capacity in summer, whereas the cooling load is low and the chiller system works much below design condition in other seasons. The variation of COP for the chiller system in the four facilities is in a small range except for that in J.H. Winters (211). Some improvement should be made to the chiller system in J.H. Winters (211). From Figures

III2 – III17, it is concluded that COP for the chiller system in hot and humid climates can be treated as independent of weather for purposes of this study.

Table 4.5 COP values and other information for the chiller systems surveyed

Facility	COP_{wa}	Period		Total # of days	# of valid days
		Beginning	Ending		
University of Texas Pan Am	2.58	9/1/1996	10/6/1997	400	392
Stroman High School	2.32	1/24/1994	9/8/1997	1323	720
Delmar College	4.0	7/19/1994	3/30/1998	1351	1261
Government Center (George Allen Bldg.)	3.48	12/1/1994	4/7/2000	1954	1579
TSTC Harlingen	3.97	10/25/1994	7/25/1997	1004	283
UTA Thermal Energy Plant	2.60	1/1/1994	3/12/1998	1531	1076
TAMUK- Central Plant-1	4.10	11/22/1998	3/13/2000	477	387
TAMUK- Central Plant-2	3.60	8/18/2000	4/9/2003	964	598
J.H. Winters	2.46	8/8/1995	9/9/2002	2589	2059
Central Services Building	2.59	12/22/1995	1/11/2001	1847	1711
Austin Convention Center	3.64	1/3/1994	12/15/1997	1442	1206
Main CUP	4.56	11/8/1994	7/18/1996	618	583
College of the Mainland	3.4	10/11/1994	5/25/1997	957	813
Valle Verde Campus	3.99	10/25/1994	6/19/1996	603	317
Rio Grande Campus	2.53	12/6/1994	12/2/1999	1822	1242
Neil Kirkman Building A-Wing	3.29	10/10/1995	6/24/1996	258	169

Based on the data in selected periods, weighted average COPs (COP_{wa}) are calculated for these sites (Table 4.5). The average COP_{wa} for the 16 sites is 3.32, which will be treated as the typical COP for the chiller system in hot and humid climates. A test of normality by SPSS (SPSS, 2001) shows that the sixteen COP_{wa} values are normally distributed (Figure 4.12) with a significance level of 0.041, and standard deviation of 0.7144. The significance level indicates the error rate of people judging whether this sample is normally distributed. The square points in Figure 4.12 indicate the measured COP_{wa} values for the 16 sites; if all the measured data are on the straight line in the plot, then they constitute a perfect normal distribution; the y value of the straight line in the plot indicates the normalized difference between the COP and the average COP; the standard deviation of the 16 COP_{wa} values is used in the normalization process. Y values for the 16 points shown are those for 16 normally distributed data points generated by SPSS based on a standard deviation of 0.7144 and an average value of 0. These Y-values are then assigned to the measured values for the 16 systems that are plotted along the COP-axis.

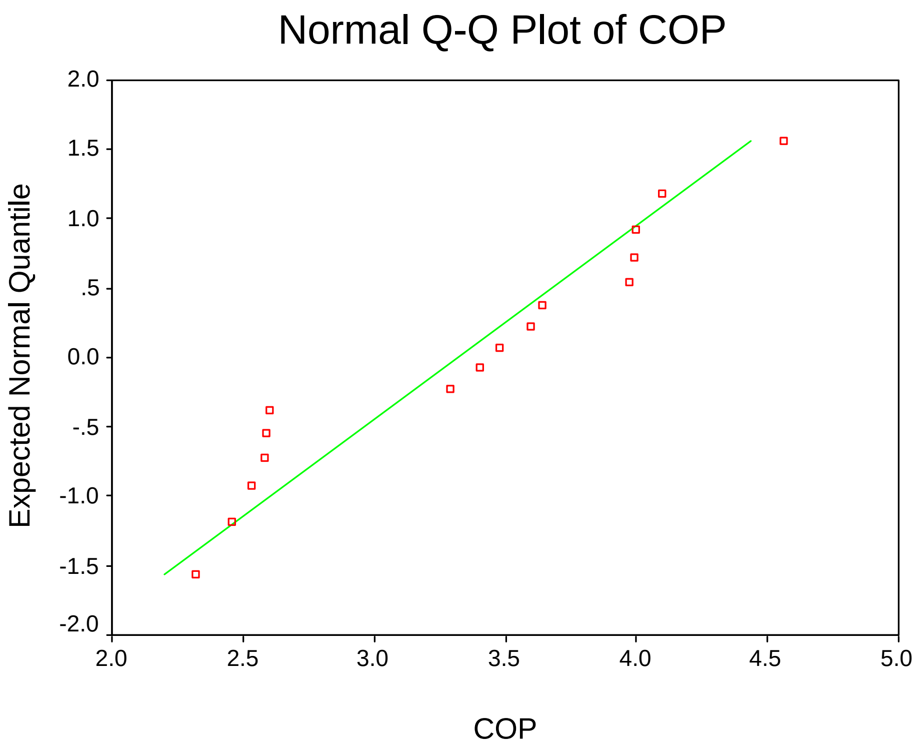

Figure 4.12 Normal Q-Q plot of the sixteen COP_{wa}.

Boilers are necessary for the heating system in many commercial buildings. Boilers are classified as hot water or steam systems. Water systems are typically used when the building is also serviced by chillers. If the heat is used for both comfort heating and process heat, the heating medium must travel a great distance, or the heat is used by an absorption cooling system, then steam systems are a better option. A hot water boiler in a commercial building usually uses natural gas as fuel. The minimum required thermal efficiency for a large gas boiler (over 300 kBtu/h) is 80%, which can be treated as the typical efficiency for boilers (NBI, 1998).

From the above investigation, the COP of chiller system in hot and humid climates won't vary a lot and can be treated as constant; the typical COP of chiller system will be assumed to be 3.32, and typical boiler efficiency is about 80%.

Results

Test of the SUBTB methodology

Measured consumption data from 34 buildings in Texas were selected to test the SUBTB methodology. Each of these buildings had heating, cooling, and L&E data measured separately, so the “utility bills” used to test the SUBTB methodology were assembled from the measured data (use of “utility bill” or “bills” in quotation marks henceforth will indicate such “bills”). Five of the buildings selected had undergone retrofits and/or major operational changes that reduced the cooling consumption by 20% - 50%, so additional data from these buildings was used to give a total of 40 building-years of data. Henceforth this test data is referred as “40 buildings” even though the data came from only 34 buildings. The overall chiller system COP was created randomly by SPSS with an average value of 3.32 and standard deviation of 0.7144 (SPSS, 2001). This was done so the “bills” would include the typical variation in chiller COP. The created COP values for the 40 buildings are listed in Table 4.6 and are normally distributed (Figure 4.13). The average and standard deviation of the created COPs are compared with expected values in Table 4.7. Efficiency of the boilers was assumed to be 80% in the entire annual “utility bills” presented in this section. Table 4.8 shows the 12-month data set used for each building, the size, and the predominant HVAC system type used in each building, along with the average daily values of $\dot{E}_{L\&E}$, $\dot{E}_{CH}$, and $\dot{E}_{tot}$ consumption for the period analyzed.

The buildings included in the sample range in size from about 50,000 ft^2 to almost 900,000 ft^2. Three-fourths of them have predominantly VAV AHUs, and only half a dozen have predominantly single duct systems. The proportion of dual-duct systems is higher than typical, but these systems are much more common in buildings in hot and humid climates where the SUBTB method is intended to apply.

Existing methods used to disaggregate electricity consumption into weather-dependent cooling consumption and weather-independent consumption were reviewed in the introduction. Of these methods, only the method based on the use of Three-Parameter change-point (3P) or Five-Parameter change-point (5P) regression models is simple enough that it can be readily used as part of the energy audit screening process. This method assumes that there is no cooling consumption during the winter months or the period when the lowest or "baseline" consumption is used. This method will be used as the basis for comparison for the SUBTB method developed and will subsequently be referred to as the "3P method."

Both the 3P and the SUBTB methods were used to split the electric "utility bills" summarized in Table 4.8 into cooling consumption ($\dot{E}_{CH,est}$) and the weather-independent consumption ($\dot{E}_{L\&E,est}$). These derived values are then compared with the measured values in terms of the relative errors for each case as defined below.

$$RE_{\dot{E}_{CH}} = \frac{\dot{E}_{CH,est,yr} - \dot{E}_{CH,meas,yr}}{\dot{E}_{CH,meas,yr}} \quad \text{Equation 4.14}$$

$$RE_{\dot{E}_{CH}/\dot{E}_{tot}} = \frac{\dot{E}_{CH,est,yr} - \dot{E}_{CH,meas,yr}}{\dot{E}_{tot,meas,yr}} \quad \text{Equation 4.15}$$

$$RE_{\dot{E}_{L\&E}} = \frac{\dot{E}_{L\&E,est,yr} - \dot{E}_{L\&E,meas,yr}}{\dot{E}_{L\&E,meas,yr}} \quad \text{Equation 4.16}$$

The subscripts "yr" indicate an annual average in each case, while "meas" indicates a measured value.

$RE_{\dot{E}_{CH}}$ is probably the most valuable measure of error. Most energy audits are performed to find ways to reduce heating and cooling consumption. Hence, the error in the cooling consumption determined from a methodology that disaggregates $\dot{E}_{tot}$ consumption will be expected to have the most impact on an energy audit. $RE_{\dot{E}_{CH}/\dot{E}_{tot}}$ compares the error in the derived cooling values with the whole building electric consumption. The fluctuations that occur in the consumption of non-weather-dependent consumption of buildings will be expected to limit the accuracy of any simple disaggregation method. Consequently, if $RE_{\dot{E}_{CH}}$ is large in a particular case and $RE_{\dot{E}_{CH}/\dot{E}_{tot}}$ is small, this suggests the error may be largely due to fluctuations in the non-weather-dependent consumption. The absolute error in the derived $\dot{E}_{L\&E,est}$ value is simply the negative of the absolute error in the derived $\dot{E}_{CH,est}$ value. The $RE_{\dot{E}_{L\&E}}$ provides a measure of this error relative to the $\dot{E}_{L\&E}$ consumption in the building. A comparison is made between disaggregation results from the SUBTB method and the 3P method in Table 4.9.

In Table 4.9, Column 1 shows the site ID number for each line, columns 2-6 show the $\dot{E}_{CH,est}$ and $\dot{E}_{L\&E,est}$ values derived using the 3P method and the three corresponding error terms. The notation for $RE_{\dot{E}_{CH}/\dot{E}_{tot}}$ has been shortened to $RE_{\dot{E}_{tot}}$ to fit better in the table. Columns 7-11 show the $\dot{E}_{CH,est}$ and $\dot{E}_{L\&E,est}$ values derived using the SUBTB method and the three corresponding error terms. Column 12 shows the ratio of the measured value of $\dot{E}_{CH,meas}$ to $\dot{E}_{tot}$ to provide a direct measure of the size of the cooling consumption relative to $\dot{E}_{tot}$ in each building.

The bottom line of Table 4.9 shows the algebraic average of the relative error columns. As expected, the 3P method shows a large systematic bias for these buildings, with an average relative error in the cooling determination of –54.8%. None of the buildings have derived cooling values within 10% of the measured value and 17 are low by over 60%. By contrast, the SUBTB method shows an average relative error in the cooling consumption that is only 1.1%. The SUBTB method underestimates the cooling consumption of 25 of the buildings and overestimates the cooling consumption of 15 buildings.

Table 4.6 Random COP values used to form accumulated utility electric bills for 40 buildings

building name	site	data period	COP
Zachry Engineering Center	1a	1/90 - 1/91 (w/o 10/90)	4.26
Zachry Engineering Center	1b	94	4.21
Zachry Engineering Center	1c	97	3.63
Education Building	100	95	2.42
University Teaching Center	101	93	3.79
Perry Castaneda Library	102	94	3.95
Garrison Hall	103	93	2.96
Gearing Hall	104	92	3.95
Waggener Hall	105	93	3.79
Welch Hall	106	9/92 - 8/93	3.25
Burdine Hall	107	92	3.53
Nursing Building	108	95	2.08
University Hall	111	96	3.12
Business Building	112a	7/93 - 6/94	1.62
Business Building	112b	97	2.04
Fine Arts Building	113	97	3.5
R.A. Steindam Hall	115	93	2.5
Painter Hall	116	9/92-10/93 (w/o 6,7/93)	2.44
W.C. Hogg Building	117	93	4.24
Medical School Building	124a	5/92 - 4/93	2.08
Medical School Building	124b	95	1.99
College of Business Administration	165	96	3.76
Graduate School of Business	166	96	1.84
Biology Building	187	2001	2.45
Science Building	188	10/00 - 9/01	2.35
Chemistry North	189	2001	4.95
Chemistry South	195	2001	3.4
Law School	197	2001	2.18
John H. Reagan	203	97	2
Brown Heatly Building	236	98	3.97
School of Public Health	300a	3/91 - 3/92 (w/o 10/91)	4.61
School of Public Health	300b	94	2.9
John Sealy North	400	95	3.31
Moody Library	403	94	3.04
John Sealy South Towers	404	95	3.93
Evans Library (old)	491	12/00 -12/01 (w/o 6/01)	3.69
E. Langford Architecture Center	494	2000	2.62
Biological Sciences West Building	496	9/97 - 8/98	3.03
Teague	497a	1/96 - 1/97 (w/o 3/96)	3.93
Teague	497b	99	3.06

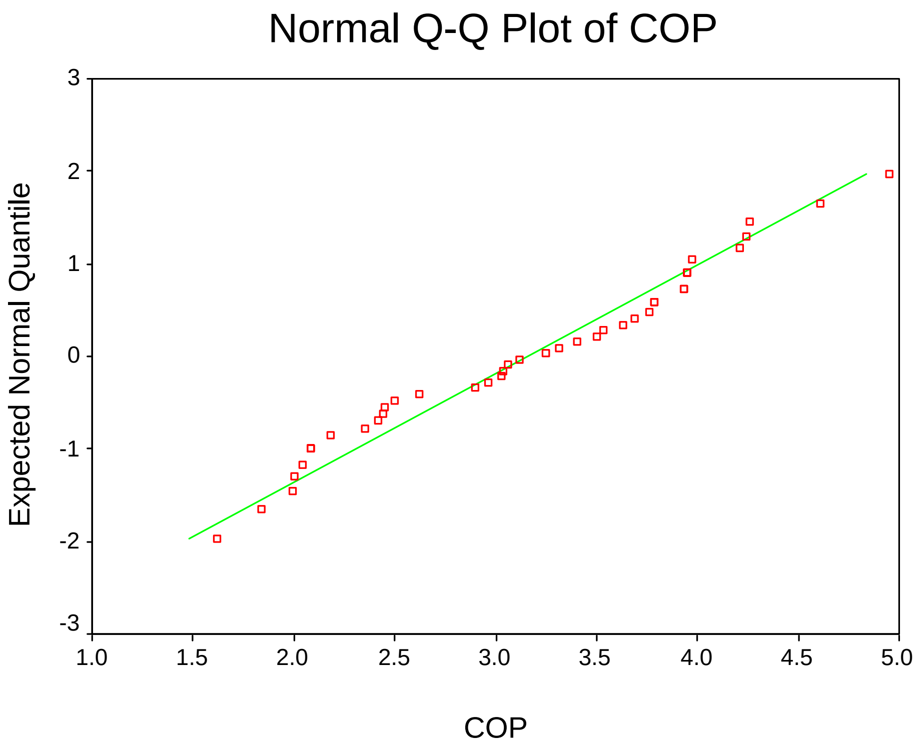

Figure 4.13 Normal Q-Q plot of the 40 COP values created by SPSS.

Table 4.7 Comparison of average and standard deviation between the created and measured COP values

Source	Number	Mean	Std. Deviation
Created COP	40	3.16	0.852
Measured COP	16	3.32	0.714

Table 4.8 Building characteristics and daily average values of annual "utility bills" for the 40 building-years of consumption data used to test the SUBTB method

Bldg. ID	Area (ft^2)	Data Period	Main HVAC System	Avg. Meas. Consumption (kWh/day)		
				$\dot{E}_{L\&E}$	$\dot{E}_{CH}$	$\dot{E}_{tot}$
1a	324400	1/90 - 1/91 (w/o 10/90)	DDCAV	26461	8656	35117
1b	324400	94	DDVAV	23638	6719	30357
1c	324400	97	DDVAV	18422	7229	25651
100	251161	95	DDVAV	5493	5317	10810
101	152690	93	DDVAV	4029	1469	5498
102	483895	94	SDVAV, DDVAV (60:40)	21210	7063	28273
103	54069	93	DDVAV	840	733	1573
104	61041	92	DDVAV	1562	957	2519
105	57598	93	DDVAV	2864	854	3718
106	439540	9/92 - 8/93	DDCAV, DDVAV(4:2)	24604	18600	43204
107	103441	92	DDVAV	2574	1493	4067
108	94815	95	DDVAV + economizer	2476	2800	5276
111	123450	96	DDVAV	3990	1207	5197
112a	149900	7/93 - 6/94	DDVAV	6829	7928	14757
112b	149900	97	DDVAV	4813	2594	7407
113	223000	97	DDVAV + economizer	8874	6980	15854
115	56849	93	DDVAV + economizer	993	1192	2185
116	128409	9/92-10/93 (w/o 6,7/93)	DDVAV + economizer	6514	5893	12407
117	48905	93	DDVAV + economizer	1169	708	1877
124a	887187	5/92 - 4/93	DDCAV	90274	119811	210085
124b	887187	95	DDCAV	78193	99647	177840
165	242857	96	DDVAV	9527	4425	13952
166	146763	96	DDVAV	6396	3764	10160
187	156219	2001	SDVAV	10364	6154	16518
188	118544	10/00 - 9/01	DDVAV	3624	2028	5652
189	64360	2001	DDVAV	5192	716	5908
195	128600	2001	DDVAV	3700	3891	7591
197	129043	2001	DDVAV	7496	2992	10488
203	169746	97	DDVAV + economizer	12733	4686	17419
236	262905	98	DDVAV	23973	6206	30179
300a	233738	3/91 - 3/92 (w/o 10/91)	DDCAV	11923	10059	21982
300b	233738	94	DDCAV	11473	8584	20057
400	68512	95	CAV	10869	6470	17339
403	67380	94	CAV	4214	3937	8151
404	373085	95	CAV	23926	17001	40927
491	812289	12/00 -12/01 (w/o 6/01)	DDCAV	20373	7182	27555
494	102105	2000	SDVAV	5624	3731	9355
496	96038	9/97 - 8/98	DDVAV	7308	4746	12054
497a	63515	1/96 - 1/97 (w/o 3/96)	DDCAV	6219	2844	9063
497b	63515	99	DDVAV	3823	2050	5873

Table 4.9 Comparison of derived values ChE$_{est}$, L&E$_{est}$, and errors using the 3P and SUBTB methods for 40 years of data from 34 buildings

Site	$\dot{E}_{CH,est}$, $\dot{E}_{L\&E,est}$ and errors using 3P method					$\dot{E}_{CH,est}$, $\dot{E}_{L\&E,est}$ and errors using SUBTB method					CHW/ WBE
	$\dot{E}_{CH,est}$	$RE_{\dot{E}_{CH}}$	$RE_{\dot{E}_{tot}}$	$\dot{E}_{L\&E,est}$	$RE_{\dot{E}_{L\&E}}$	$\dot{E}_{CH,est}$	$RE_{\dot{E}_{CH}}$	$RE_{\dot{E}_{tot}}$	$\dot{E}_{L\&E,est}$	$RE_{\dot{E}_{L\&E}}$	
	(kWh/day)	(%)	(%)	(kWh/day)	(%)	(kWh/day)	(%)	(%)	(kWh/day)	(%)	
1a	2320	-74.4%	-19.0%	33200	25.5%	11684	29.0%	7.4%	23830	-9.9%	0.25
1b	3870	-43.0%	-9.5%	26530	12.2%	7568	12.6%	2.8%	22790	-3.6%	0.22
1c	5400	-25.3%	-7.1%	20250	9.9%	6179	-14.5%	-4.1%	19470	5.7%	0.28
100	2410	-54.7%	-26.9%	8400	52.9%	3958	-25.6%	-12.6%	6850	24.7%	0.49
101	680	-53.6%	-14.3%	4820	19.5%	2027	38.0%	10.1%	3470	-13.9%	0.27
102	2970	-58.4%	-14.6%	25330	19.4%	10334	46.3%	11.6%	17940	-15.4%	0.25
103	470	-34.6%	-16.1%	1100	30.2%	622	-15.1%	-7.0%	950	13.2%	0.47
104	420	-56.4%	-21.4%	2100	34.5%	860	-10.1%	-3.8%	1660	6.2%	0.38
105	420	-51.0%	-11.7%	3300	15.2%	1062	24.4%	5.6%	2660	-7.3%	0.23
106	7170	-61.4%	-26.4%	36030	46.4%	16297	-12.4%	-5.3%	26910	9.4%	0.43
107	410	-72.9%	-26.7%	3660	42.2%	1705	14.2%	5.2%	2360	-8.2%	0.37
108	1100	-61.8%	-32.8%	4200	69.8%	2351	-16.0%	-8.5%	2930	18.1%	0.53
111	1000	-17.4%	-4.0%	4200	5.3%	1662	37.7%	8.8%	3535	-11.4%	0.23
112a	1520	-80.9%	-43.5%	13240	93.9%	4423	-44.2%	-23.7%	10330	51.3%	0.54
112b	1050	-59.2%	-20.7%	6350	31.9%	2661	2.5%	0.9%	4750	-1.4%	0.35
113	3280	-52.9%	-23.3%	12570	41.6%	5606	-19.7%	-8.7%	10250	15.5%	0.44
115	890	-24.7%	-13.5%	1290	29.6%	803	-32.7%	-17.8%	1380	39.2%	0.55
116	1200	-79.8%	-37.9%	11200	72.2%	4038	-31.5%	-14.9%	8370	28.5%	0.47
117	440	-38.4%	-14.5%	1440	23.3%	986	39.2%	14.8%	890	-23.7%	0.38
124a	43500	-63.7%	-36.3%	166600	84.6%	90336	-24.6%	-14.0%	119750	32.7%	0.57
124b	66340	-33.4%	-18.7%	111500	42.6%	52497	-47.3%	-26.5%	125340	60.3%	0.56
165	1310	-70.3%	-22.3%	12640	32.7%	3634	-17.9%	-5.7%	10320	8.3%	0.32
166	1810	-52.0%	-19.3%	8350	30.6%	2788	-25.9%	-9.6%	7370	15.3%	0.37
187	2760	-55.1%	-20.5%	13760	32.7%	6435	4.6%	1.7%	10080	-2.7%	0.37
188	750	-62.7%	-22.5%	4900	35.1%	1903	-6.2%	-2.2%	3750	3.5%	0.36
189	460	-35.4%	-4.3%	5450	4.9%	2081	190.6%	23.1%	3830	-26.3%	0.12
295	1050	-73.1%	-37.5%	6540	76.9%	3430	-11.8%	-6.1%	4160	12.5%	0.51
197	1100	-63.5%	-18.1%	9400	25.3%	2912	-2.7%	-0.8%	7575	1.1%	0.29
203	1820	-61.0%	-16.4%	15600	22.5%	5260	12.3%	3.3%	12160	-4.5%	0.27
236	2780	-55.3%	-11.4%	27400	14.3%	9029	45.5%	9.4%	21150	-11.8%	0.21
300a	1860	-81.5%	-37.3%	20120	68.8%	10652	5.9%	2.7%	11330	-5.0%	0.46
300b	3530	-58.9%	-25.2%	16530	44.1%	5701	-33.6%	-14.4%	14360	25.1%	0.43
400	4540	-29.9%	-11.2%	12800	17.8%	6298	-2.7%	-1.0%	11040	1.6%	0.37
403	430	-89.0%	-43.0%	7720	83.2%	3634	-7.7%	-3.7%	4520	7.2%	0.48
404	6210	-63.5%	-26.4%	34720	45.1%	13050	-23.2%	-9.7%	27880	16.5%	0.42
491	4630	-35.6%	-9.3%	22930	12.6%	7010	-2.4%	-0.6%	20540	0.8%	0.26
494	2670	-28.4%	-11.3%	6690	18.9%	3039	-18.5%	-7.4%	6320	12.3%	0.40
496	1680	-64.5%	-25.4%	10370	41.9%	3543	-25.4%	-10.0%	8510	16.5%	0.39
497a	1130	-60.3%	-18.9%	7930	27.6%	3587	26.1%	8.2%	5480	-11.9%	0.31
497b	960	-53.1%	-18.5%	4910	28.5%	1794	-12.5%	-4.4%	4080	6.7%	0.35
Avgs.		-54.8%	-20.9%		36.7%		1.1%	-2.7%		6.9%	0.37

The same data were used to test the predicted monthly electricity consumption by the chiller system. 480-months of electricity consumption by the chiller systems were derived for the 40 buildings. The results are shown in Figure 4.14. The average monthly relative error for the derived $\dot{E}_{CH,est}$ is 1.22%, the standard deviation of the relative error is 41.45%, and most values are between ±40% (82.7%). From Figure 4.15, the bias in the monthly values of $RE_{\dot{E}_{CH},mon}$ from the 3P results can be seen, with 90% of the monthly values negative.

Monthly $RE_{\dot{E}_{CH},mon}$ is defined as:

$$RE_{\dot{E}_{CH},mon} = \frac{\dot{E}_{CH,est,mon} - \dot{E}_{CH,meas,mon}}{\dot{E}_{CH,meas,yr}} \qquad \text{Equation 4.17}$$

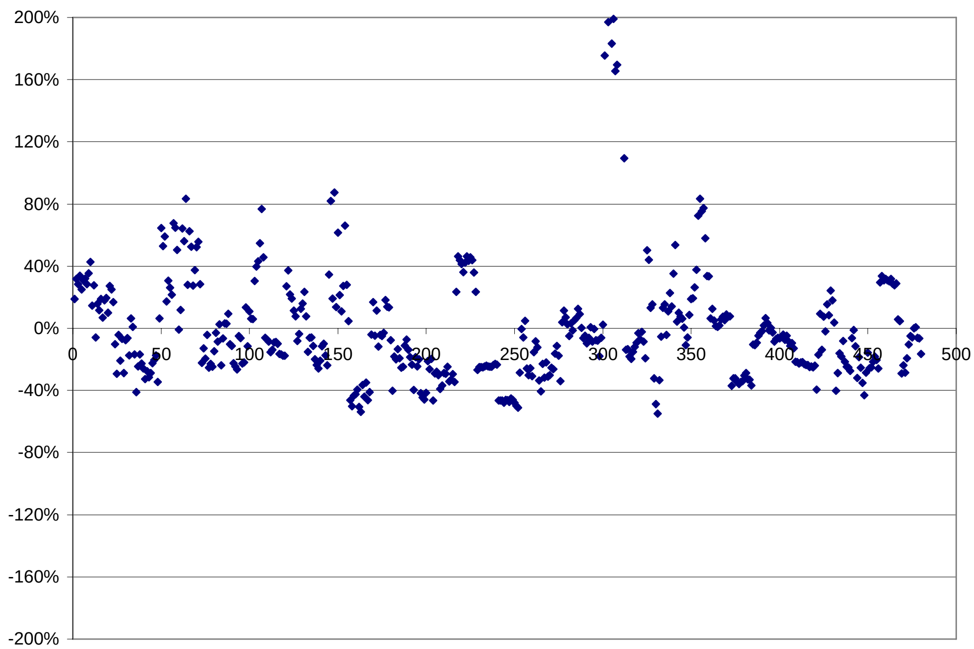

Figure 4.14 Monthly relative error of weather-dependent electricity consumption ($\dot{E}_{CH,est}$) derived using the SUBTB method for 480 months of data in 40 buildings.

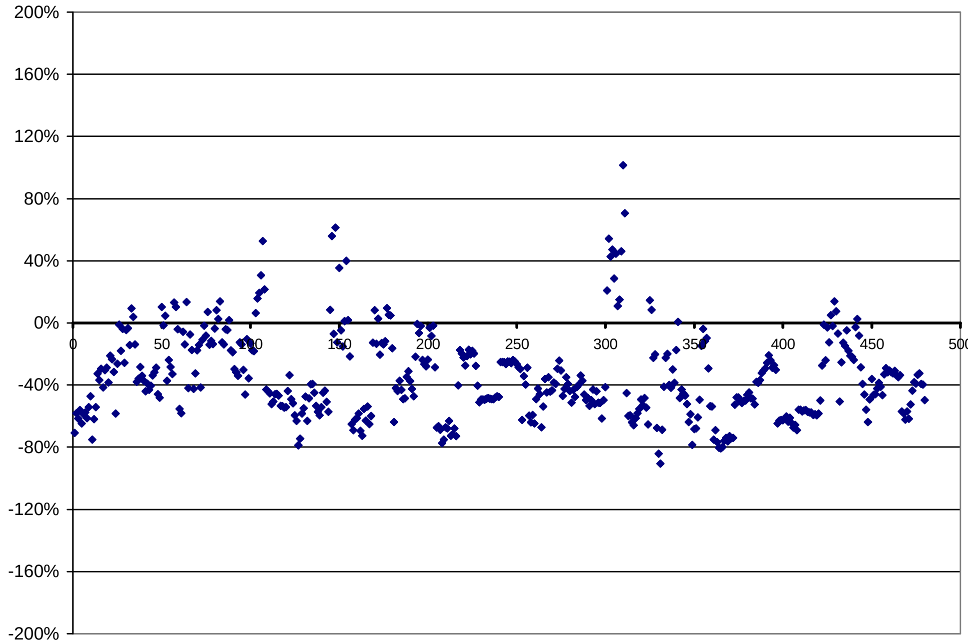

Figure 4.15 Monthly relative error of weather-dependent electricity consumption ($\dot{E}_{CH,est}$) derived using the 3P method for 480 months of data in 40 buildings.

Sensitivity analysis

The SUBTB methodology requires information such as estimated values of $\dot{Q}_{MCH}$, η_b, f and COP, when it is used. Determining $\dot{Q}_{MCH}$ additionally requires that estimated values for UA_{env} and $\dot{V}_{vent}$ be used to determine UA_{equiv} and use of an estimated value of T_{Mbal}. UA_{env} is estimated from the prototype building with the same area and typical values of $\dot{V}_{vent}$ and T_{Mbal} are used. While η_b and COP will vary from building to building, there is basis for an estimated value, so in this case, single estimated values were used.

Analysis is presented here that explores the sensitivity of the SUBTB method to changes in $(UA)_{equiv}$, T_{Mbal}, f, η_b and COP. The Koldus Student Services Building, located on the main campus of Texas A&M University at College Station, is used as a case study building for this sensitivity analysis. As has been done for the other campus buildings used in this study, hourly data were retrieved from the database, and converted to monthly data. The electric "utility bills" were assembled assuming a COP for the complete chiller and distribution system of 3.0 and gas utility bills made assuming η_b is 0.8. With these assumptions, 1995 "utility bills" were constructed for the Koldus Student Services Building as:

$$\dot{E}_{tot} = \dot{E}_{L\&E} + \dot{Q}_{CH} /3$$

$$\dot{Q}_{gas} = \dot{Q}_{heat} /0.8$$

The "utility bills" as constructed are listed in Table 4.10, along with the monthly average outside air dry-bulb temperatures. Both bills are shown in terms of kWh/day. This unit is unconventional for gas, but is shown for direct comparison with the electric bills.

In the prototype of the Koldus Student Services Building, T_{Mbal} was assumed to be 67.8°F, and $\dot{V}_{vent}$/Area was assumed to be 0.1 CFM/ft^2. This resulted in a UA_{env} value of 12,894 Btu/hr/°F and UA_{equiv} of 24,885 Btu/hr/°F from the prototype building.

If COP is assumed to be 3, all electricity consumption by lighting and equipment is assumed to convert to internal load, efficiency of boiler is 80%, the yearly average $\dot{E}_{L\&E,est}$ consumption derived for the Koldus Student Services Building for 1999 with the SUBTB method is 7,740 kWh/day; the measured average $\dot{E}_{L\&E}$ consumption in 1999 was 7,197 kWh/day. The difference between derived $\dot{E}_{L\&E,est}$ and the actual value was 7.5%, so the methodology works quite well in this case. The derived average $\dot{E}_{L\&E,est}$ consumption for this case was treated as the baseline $\dot{E}_{L\&E}$ consumption for the sensitivity study.

The five major parameters that must be assumed in the SUBTB methodology were varied over a wide range to explore the impact on derived $\dot{E}_{L\&E,est}$ values. These are compared with the baseline derived $\dot{E}_{L\&E}$ in Table 4.11. It is clear that $\dot{E}_{L\&E,est}$ has very little dependence on UA_{equiv}, so use of the prototype building as the source of this parameter appears justified. Likewise, the dependence on f and η_b is quite weak. The largest difference is 12.36% when COP changed from 3 to 5; this suggests that any information that can be used to improve the estimate for COP should be used when using the SUBTB methodology. The methodology shows moderate sensitivity to T_{Mbal}, but there does not appear to be a simple basis for improving this estimate short of more detailed solar and occupancy estimates.

The error in Table 4.11 is defined as:

Error = ($\dot{E}_{L\&E,est}$ - baseline $\dot{E}_{L\&E,est,base}$)/ $\dot{E}_{L\&E,est,base}$ $\times 100\%$

Table 4.10 "Utility bills" for the Koldus Student Services Building

Month	Temp [°F]	Eletricity bill (kWh/day)	Gas bill (kWh/day)
Jan-99	55.87	8192	601
Feb-99	61.54	9651	1442
Mar-99	61.36	9182	1025
Apr-99	71.10	10910	352
May-99	74.99	10999	72
Jun-99	79.52	11777	0
Jul-99	81.16	11857	12
Aug-99	86.17	12268	11
Sep-99	78.92	12020	296
Oct-99	70.30	11099	756
Nov-99	64.57	10417	1115
Dec-99	55.04	8929	1430

Table 4.11 Sensitivity Analysis Results for the Koldus Student Services Building (T_{Mbal} =67.8°F)

Variable (baseline)	Variable Range	$\dot{E}_{L\&E,est}$ (kWh/day)	Error
UA_{equiv} (24885 Btu/hr/°F)	15000 (Btu/hr/°F)	7779	0.50%
	50000 (Btu/hr/°F)	7640	-1.28%
EFF_{boiler} (80%)	60%	7769	0.38%
	90%	7725	-0.19%
COP (3)	2.5	7330	-5.30%
	2.75	7548	-2.47%
	3.5	8058	4.12%
	5	8696	12.36%
T_{Mbal} (67.8°F)	62°F	7486	-3.28%
	73°F	7967	2.94%
f (1)	0.9	7938	2.56%
	0.8	8147	5.26%
The yearly average $\dot{E}_{L\&E,est,base}$		7740	

Conclusions

The SUBTB methodology has been developed and used to disaggregate monthly electricity consumption for 40 building-years of data collected from 34 buildings that use cooling on a 12-month basis into cooling and non-cooling components. These buildings had electric “utility bills” that were constructed from separately measured electricity consumption and cooling consumption. The average error of estimated cooling consumption by the SUBTB methodology is 1.1%, which is substantially better than the average error of –54.8% obtained with the 3P method. The SUBTB methodology appears to remove the systematic bias that is present when the minimum consumption month is assumed to have no cooling and appears to offer a methodology more suitable than the 3P method for disaggregating monthly electricity consumption for large commercial buildings in hot and humid climates.

CHAPTER V
IDENTIFYING THE TYPE OF HVAC SYSTEM

Introduction

The comparison of measured monthly energy consumption and simulated consumption in commercial buildings will be used to identify the main type of HVAC system in buildings. This is an important part of the implementation of a system and method to remotely identify air handler systems and components and retrofit and CC® opportunities. The main type of HVAC system in the Zachry Engineering Center is identified as a dual duct variable air volume system based on the 1999 data in Chapter III. A portion of the process may involve pattern recognition, which can be carried out automatically instead of manually.

Pattern recognition is the study of how machines learn to distinguish patterns of interest and make sound and reasonable decisions about the categories of the patterns by observing the environment. Statistical pattern recognition, syntactic pattern recognition, and neural pattern recognition are the three major approaches (Schalkoff, 1992). As limited valued data are available in this research, no training data are available for neural pattern recognition and no structural information is ready for syntactic pattern recognition; statistical pattern recognition may be a helpful approach.

The Bayesian classifier, the nearest neighbor classifier (1-NN), and the nearest prototype classifier (1-NP) are the common tools of statistical pattern recognition (Bezdek, 1981). Training data are needed when the Bayesian classifier and the nearest neighbor classifier (1-NN) are used. The nearest prototype classifier can be used for pattern recognition based on some notion of similarity or distance in feature space. However, with the nearest prototype classifier, once an input vector is assigned to a class there is no indication of its "strength" of membership in that class. In contrast, the fuzzy memberships for samples classified by the fuzzy nearest prototype classifier can specify to what extent the input vector belongs to a particular class, just as human judgment does (Keller et al., 1985).

Fuzzy sets and membership for classes without sharp boundaries were presented in 1965 (Zadeh, 1965). Based on the fuzzy set, theories and technologies have been developed for fuzzy implications and approximate reasoning, fuzzy logic controllers, fuzzy pattern recognition, etc. (Yen and Langari, 1999). As limited information is available in this research, the Bayesian classifier and the nearest neighbor classifier (1-NN) can't be developed since there are no training data; the fuzzy nearest prototype classifier is more similar to the process of pattern recognition used by people than the nearest prototype classifier. Hence, the fuzzy nearest prototype classifier is selected as the pattern recognition tool for this research.

Methodology

Two rules are followed when measured energy consumption values in a commercial building are compared with simulated values in the prototype building of the same size to identify the main type of HVAC system:

1. Two "lines" (measured energy consumption vs. Tdb and simulated vs. Tdb) should be "close".
2. The two "lines" should be "approximately parallel".

What distance between two lines can be called "close"? If two lines are parallel, the angle between the two lines would be 0°, and the two lines never cross each other. If the angle between two lines is 2°, are they "approximately parallel"? The concepts of "close" and "approximately parallel" are fuzzy, by the nature of language.

This process can be finished automatically by the fuzzy nearest prototype classifier. The energy consumption values in a building with different HVAC systems are assumed to be compact, well-separated clusters. Informally, a compact cluster has a "ball-like" shape. The center of the ball is called the center or the prototype of the cluster. The simulated energy consumption values in a building with different types of HVAC system are assumed to be the prototype of energy consumption in the building with the corresponding type of HVAC system. The membership, $U_i(X)$, for each HVAC system in the fuzzy nearest prototype algorithm (Keller et al., 1985) can be calculated from:

$$Ui(X) = \frac{\frac{1}{\|X - Zi\|^{\frac{2}{(m-1)}}}}{\sum_{j=1}^{c} \left(\frac{1}{\|X - Zj\|^{\frac{2}{(m-1)}}} \right)} \qquad \text{Equation 5.1}$$

m determines how heavily the distance is weighted when calculating each prototype's contribution to the membership value. m is usually 2.

c number of prototypes (8 types of HVAC system are considered).

$Z_1, Z_2, \ldots, Z_c$ prototype vectors (12 months of consumption for HVAC system i will constitute prototype "i")

X vector to be classified (corresponds to the 12 months of measured consumption

$\left\| X - Z \right\|^{\frac{2}{(m-1)}}$ the distance between the two vectors, defined as the Euclidean Distance

$\sum_i |d_i|^{\frac{2}{(m-1)}}$, where d_i is the difference between components *i* of X and Z

This algorithm just follows Rule 1 that "two 'lines' (measured energy consumption vs. Tdb and simulated consumption vs. Tdb) should be close," and membership is assigned to each type of HVAC system. The smaller the distance between measured consumption data vector "X" and simulated consumption vector Z_i of HVAC system "*i*", the larger $U_i(X)$ will be, with a maximum value of unity. This algorithm is modified to account for Rule 2.

If measured energy consumption is far away from simulated consumption for a certain type of HVAC system, the actual system is definitely not the type simulated, and it is not necessary to check if the two "lines" are almost parallel (in fact, the membership is very small in this case, and Rule 1 is enough). On the other hand, if measured consumption is close to simulated consumption and the lines are not parallel, the two "lines" must cross each other.

Monthly values of simulated energy consumption in a prototype building (SECPB) are assumed to be centered on the actual monthly energy consumption in a typical building (AECTB); it is expected that SECPB will fluctuate around AECTB resulting from the differences between the configuration of the prototype building and the real building, a less than perfect simulation model and measurement errors. If the absolute value of the difference between individual pairs of SECPB and AECTB is less than an amount δ, the simulated energy consumption in a prototype building may be considered to represent the exact energy consumption in the building. In this case, the two "lines" are not treated as crossing each other.

δ may depend on the building, location, weather, schedule, etc.; "Relative Difference (RD)" (Equation 5.2) is used to judge whether the measured consumption values are not far away from simulated values, which is a function of monthly average measured consumption (MAMC), monthly average simulated consumption (MASC), and annual peak daily average consumption (APDC) for one month.

If the "Relative Difference" is defined for Wbcool and Wbheat as

$$\mathrm{RD} = \frac{(MAMC - MASC)}{APDC} \qquad \text{Equation 5.2}$$

and the value of RD is between -δ/ APDC and +δ/ APDC, no crossover is considered to occur no matter whether the measured and simulated consumption lines intersect or not. The energy consumption values simulated for buildings by the SEAP agree with the results from DOE-2.1B within about 10% for "average" values of all parameters evaluated. (Brotherton et al., 1987). On this basis, if Relative Difference is greater than 0.1 or less than -0.1, "crossover" will be assumed to occur within this study.

For example, measured Wbcool consumption in the Zachry Engineering Center (site 1) in Jan. 1999 is 30.56 MMBtu/day, maximum monthly Wbcool consumption in 1999 is 75.28 MMBtu/day. The simulated Wbcool consumption with the DDCAV system in Jan. 1999 is 89.467MMBtu/day, and the relative difference is –0.783 [(30.56-89.467)/75.28], so crossover is assumed to occur.

The "Out-range number" (ORN) may be used to determine the "total crossover number" (NC_i). ORN is determined by counting the number of times (N^+) that relative consumption is above δ/ APDC and the number of times (N^+) when relative consumption is below –δ/ APDC. The smaller of N^+ and N^- is treated as the initial crossover number (NC_i). Then ORN = N^++N^-, so ORN≤12. It may be observed that if the two lines are approximately perpendicular, then it may be possible for N^+ and N^- to both be as large as six when twelve-months of data are used for pattern recognition. Hence if the total crossover number for different out-range numbers is modified; the modified total crossover number will become a measure of the angle between the lines. Equation 5.3 can be used to determine the crossover number (NC). NC can then indicate how close the "two lines" are to being approximately parallel. Lines that are parallel will have a crossover number (NC) of zero, so if NC is greater than zero, the membership should be reduced.

$$NC=\frac{12 * NCi}{ORN} \qquad \text{Equation 5.3}$$

After NC is determined from Equation 5.3, membership from Equation 5.1 can be modified as shown in Equation 5.4. ModM is the same as original membership if NC is zero0; and ModM will be just 5% of the original value if NC is 6. The sum of modified membership (ModM) for Wbcool and Wbheat should be the same. Equation 5.5 is used to adjust the membership so that the sum of membership of all systems is 1. The contributions of the two adjusted memberships (AdjM) for Wbcool and Wbheat are then weighted equally; last membership (LastM) from Equation 5.6 represents the combination of the two.

$$\text{ModM} = \text{membership} * (1\text{-}0.015(2^{NC}\text{-}1)) \qquad \text{Equation 5.4}$$

$$\text{AdjM}=\frac{\text{modified membership for each system}}{\text{Sum of modified membership}} \qquad \text{Equation 5.5}$$

$$\text{LastM}=\frac{(\text{AdjM}_{\text{Wbcool}}+\text{AdjM}_{\text{Wbheat}})}{2} \qquad \text{Equation 5.6}$$

Data in Figures 3.20 and 3.21 for the Zachry Engineering Center in 1999 are used to calculate last membership for different HVAC systems. The last memberships for each system for the Zachry Engineer Center are listed in Table 5.1.

Table 5.1 Last membership for eight HVAC systems in the Zachry Engineering Center

	DDCAV	DDCAVECO	DDVAV	DDVAVECO	SDCAV	SDCAVECO	SDVAV	SDVAVECOE
LastM	0.023	0.048	0.419	0.282	0.002	0.003	0.050	0.172

Analysis

In Table 5.1, last membership for each system is listed. For example, the membership for DDVAV in the Zachry Engineering Building (site 1) is 0.419. What information can be inferred from this number? In other words, how can membership for a fuzzy set be explained? The membership functions of an input variable's fuzzy sets should usually be designed to satisfy two conditions (Yen and Langari, 1999):

1. Each membership function overlaps only with the closest neighboring membership functions;
2. For any possible input data, its membership values in all relevant fuzzy sets should sum to 1 (or nearly so).

Figure 5.1 shows a common membership function with 3 classes (10, 20, 30). If x is 15, the class of x is fuzziest (Membership of 15 for class 1 is 0.5; membership of 15 for class 2 is 0.5; membership of 15 for class 3 is 0). The membership function in Equation 5.1 doesn't satisfy the two conditions mentioned above. If X and Zj are scalars, Zj are assumed to be 10, 20, and 30 (3 prototypes). Figure 5.2 shows the memberships which result from Equation 5.1.

If x is 15, its class should be fuzziest (half is 10, half is 20). Membership of 15 to class 1 is 0.473684; membership of 15 to class 2 is 0.473684; membership of 15 to class 3 is 0.052632. In other words, if membership to one class is greater than 0.473684, it has a higher probability of belonging to this class than to either of the others.

In fact, people don't make judgments based only on two options. For example, Ruspini tried to assign 95 training vectors into four partitions (Bezdek, 1981). If more than two options are considered, it is not fuzziest when membership is 0.5 (Langari, 2002).

What is the criterion for judgment when it is fuzziest? In the case examined, X is a vector with 12 elements and the total number of prototypes is 8. One criterion often used is to add 0.2 to the fuzziest option (Keller et al., 1985). For the case above, the fuzziest option will be 0.125, so the criterion might be 0.125 + 0.2 = 0.325. This criterion has been relaxed slightly to 0.3 for the systems tested in this dissertation. For four options, 0.45 (0.25 + 0.2) will be used in this research as the criterion. Hence it will be assumed that the type of HVAC system in the building is the corresponding system type when these criteria are met.

Conclusions

From Table 5.1, the largest membership for the type of HVAC system in the Zachry Engineering Center is 0.419 for the DDVAV system based on the data in 1999. The main HVAC system in the building would be inferred to be the DDVAV system since this membership is greater than 0.30; there were 12 DDVAV AHUs and 3 SDCAV AHUs, and the capacity of the three SDCAV AHUs are very small, so the judgment is correct.

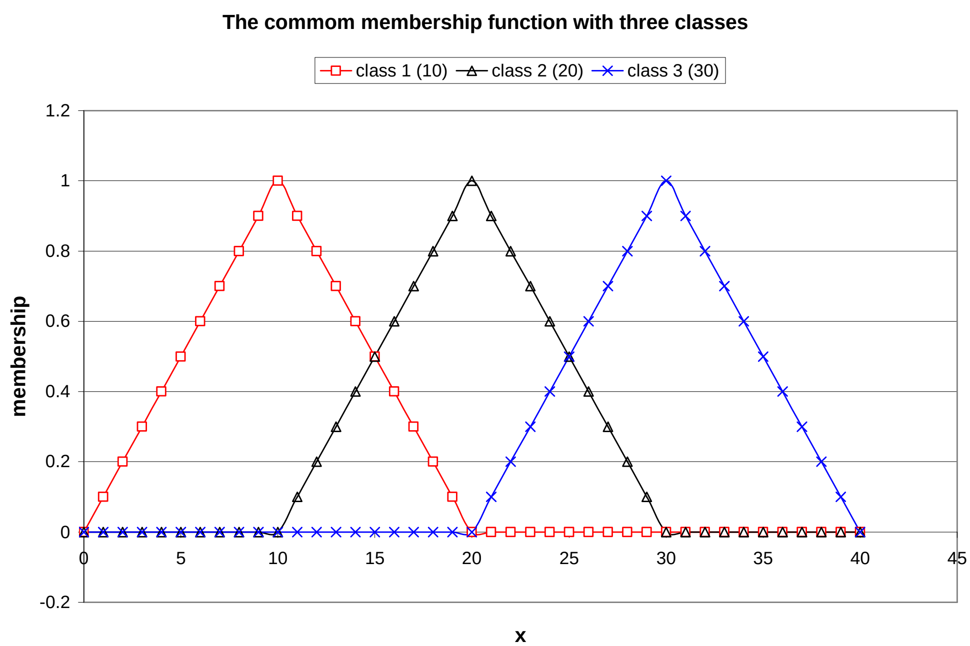

Figure 5.1 Example of common membership function with 3 classes.

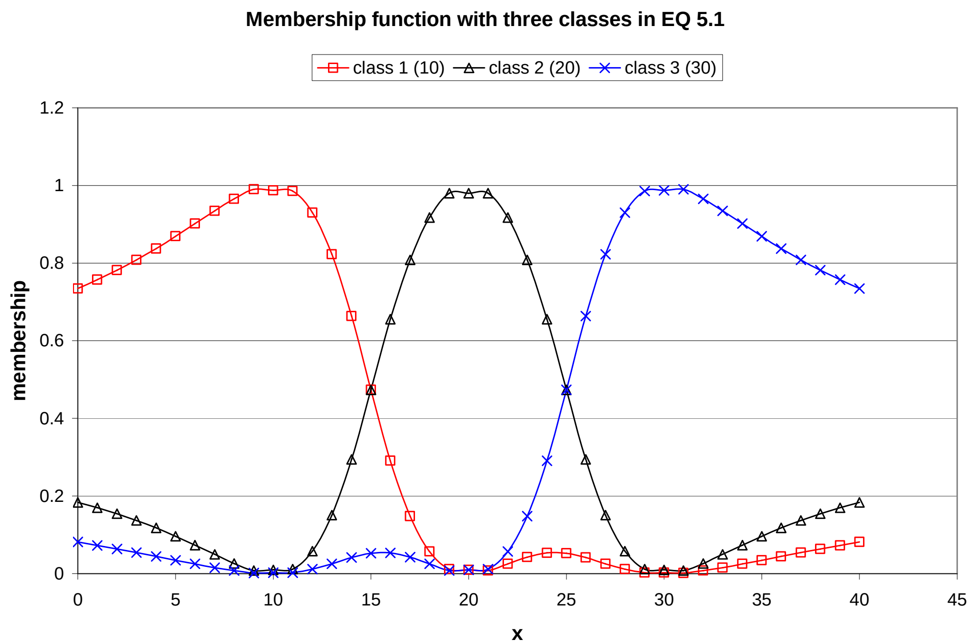

Figure 5.2 Membership function from EQ 5.1 with 3 prototypes.

CHAPTER VI
TEST REPORT FOR THE PRE-SCREENING METHODOLOGY

Introduction

A new methodology is developed based on a minimum amount of easily obtained information – specifically utility bills, total area, and weather data. This methodology can be used to identify large commercial buildings with potential energy savings, and estimate potential retrofit and CC® energy savings, which can help decide whether the building merits further audit for retrofit or CC®.

There are four steps in the methodology, which are: 1) a procedure for testing whether the electrical utility bill includes electricity consumption by the chiller system. 2) If the utility bill includes both weather-dependent and weather-independent loads, the total load in the bill will be separated into two parts by different methods for different cases. 3) If the main type of HVAC system in a commercial building is unknown, the main type of HVAC system maybe identified by comparing measured weather-dependent energy consumption with simulated values in a prototype building of the same size. An automated pattern recognition method is developed to carry out the procedure. 4) If the main type of HVAC system in a commercial building is known or identified, an idealized building of the same size with actual type of HVAC system can be configured; then the potential CC® energy saving can be estimated by comparing simulated energy consumption of the idealized building and the measured consumption. Retrofit and CC® savings can be estimated by comparing measured energy consumption with simulated values in the idealized building with the most efficient HVAC system; judgment can then be made whether the building is deserving of a further detailed energy audit.

A test of the methodology is carried out based on accumulated utility bills for 40 building-years of data from 34 buildings; this chapter presents the test results.

Buildings selected and accumulated utility bills

In order to test the pre-screening methodology, 34 buildings are selected, whose hourly energy consumption values are recorded in the database managed by the Energy Systems Laboratory (ESL) at Texas A&M University. Some information about these buildings is listed in Table 6.1. Column 1 lists the site number of the building, the main types of HVAC system in these buildings are listed in Column 2, more detailed information about HVAC systems can be found in Column 3, the source of the information about the building is stated in Column 4, Columns 5 and 6 show the retrofit dates and CC® dates, and the main retrofits implemented in these buildings are listed in the last column.

As the consumption data available for the 34 buildings is hourly, monthly electricity and gas bills are aggregated from the measured hourly energy consumption values. "Gas bills" are assembled from measured whole building heating consumption (Wbheat) while electricity bills are formed by combining measured electricity consumption by lighting & equipment $\dot{E}_{L\&E}$ with "electricity consumption" by the chiller system as determined from the measured chilled water data. It is assumed that COP kWh of chilled water are produced by one kWh of electricity, where the COP value for each of the 40 buildings is created as described in Chapter IV.

Hourly energy consumption and outside dry-bulb air temperature (Tdb) are retrieved from the database for selected periods during 1990 - 2002; the program "Todaily" (Ahmad et al., 1994) is used to convert the hourly data to daily data if there are more than 22 valid hourly data points in one day. The daily energy consumption and outside air dry-bulb temperature (Tdb) time series for the 34 buildings are in Appendix IV. The data were validated and corrected in one case as detailed in Appendix IV. The monthly average daily energy consumption is derived from the daily energy consumption values in each month.

Table 6.1 Selected information about the buildings used to test the pre-screening methodology

Site #	Main type of HVAC	Detailed information	Reference	Retrofit date	CC date	Main retrofit
1	DDVAV	12 DDVAV (12-40hp), 3 CV multizone AHU(1-1hp, 1-7hp,1-10hp), 4CV single zone AHU (4-3hp)	1995 AECR	91	96-97	DDCAV—DDVAV
100	DDVAV	8 DDVAV AHU (8-50hp), 3 DDCAV (2-7.5hp, 1-5hp)	1997 AECR	May-91		DDCAV—DDVAV
101	DDVAV	8 DDVAV AHU (2-30hp,2-20hp,3-25hp,1-15hp)	1995 AECR	Dec-90		DDCAV—DDVAV
102	SDVAV, DDVAV (60:40)	8 SDVAV (8-75hp), 4 DDVAV(4-100hp)	1995 AECR	Dec-90		CAV—VAV
103	DDVAV	2 DDVAV (1-30hp,1-25hp), 1VAV multizone AHU (5hp), 1 CV single zone AHU (3hp)	1995 AECR	May-91		CAV—VAV
104	DDVAV	4 DDVAV (2-30hp, 2-25hp), 2 single zone CAV (1-5hp, 1-2)	1995 AECR	May-91		CAV—VAV
105	DDVAV	2 DDVAV (2-40hp)	1995 AECR	May-91		CAV—VAV
106	DDCAV, DDVAV(4:2)	4 DDCAV(4-100hp), 2 DDVAV (2-hp)	1995 AECR	Feb-92		CAV—VAV
107	DDVAV	2 DDVAV (1-100hp, 1-70hp), 2 CV single zone AHU (1-15hp,1-0.5hp)	1995 AECR	May-91		CAV—VAV
108	SDVAV +economizer	2 VAV AHUs (2-100hp)	1995 AECR	Apr-91		CAV—VAV +economizer
111	DDVAV	2 DDVAV (2-125hp)	1995 AECR	Aug-91		CAV—VAV
112	DDVAV	3 DDVAV (1-100hp, 1-50hp, 1-40hp)	1995 AECR	Jul-91		CAV—VAV
113	DDVAV + economizer	4 DDVAV (1-100hp, 1-50hp, 2-75hp), 8 single zone CV (3-15hp, 1-10hp, 1-5hp, 1-3hp, 1-2hp, 1-1hp)	1995 AECR	Aug-91		CAV--VAV + economizer
115	DDVAV + economizer	2 DDVAV (1-50 hp, 1-40hp)	1996 AECR	Feb-93		CAV—VAV + economizer
116	DDVAV +economizer	2 DDVAV (2-80hp), 3 CV single zone (1-1.5hp,2-3hp), 1 VAV single zone (50 hp), 2 multizone AHU (1-7.5hp, 1-30hp)	1997 AECR	Feb-92		CAV—VAV +economizer (not work)
117	DDVAV + economizer	2 DDVAV (2-40hp), 2 SDCAV (2-5hp)	1998 AECR	Jun-91		CAV—VAV +economizer (not work)
124	DDCAV	24 combination of DDCAV, multiple & single zone units (8-125hp, 4-100hp, 8-75hp, 1-60 hp, 2-10hp)	1995 AECR	91-93		
165	DDVAV	4 DDVAV (2-440hp, 1-50hp, 1-145hp)	1995 AECR	Dec-93		CAV—VAV
166	DDVAV	2 DDVAV (1-190hp, 1-165hp)	1995 AECR	Dec-93		CAV—VAV
187	SDVAV	3 SDVAV for main building	2000 AECR		Aug-00	
188	DDVAV	4 DDVAV, 2 single-zone CAV, 2 multi-zone CAV	2000 AECR		Aug-00	
189	DDVAV	5 DDVAV, 1 single-zone CAV, 1 makeup AHU	2000 AECR		Aug-00	
195	DDVAV	9 DDVAV, 5 single-zone CAV, 1 makeup AHU	2000 AECR		Aug-00	
197	DDVAV	4 DDVAV, 1 single-zone CAV, 1 SDVAV	2000 AECR		Aug-00	
203	DDVAV + economizer	2 DDVAV	1995 AECR	4/93-9/94		lighting & upgrade economizer
236	DDVAV	DDVAV	2000 AECR			
300	DDCAV	20 DDCAV (10-25hp, 7-20hp, 1-15hp, 1-8hp, 1-2hp), 3 VAV (3-50hp)	1997 AECR	3/92-6/94		EMCS
400	CAV	5CAV	1996 AECR			EMCS
403	CAV	2 CAV (2-50hp)	1996 AECR			EMCS
404	CAV	9 CAV with 25% fresh air	1996 AECR			EMCS
491	DDCV	2 DDCAV	2001 AECR			
494	SDVAV	10 SDVAV	2000 AECR	Jan-97		photocell project
496	DDVAV	3 DDVAV	1998 AECR	Jan-97		CAV-VAV
497	DDVAV	11 DDVAV	1998 AECR	Jan-97		CAV-VAV

Test results

The whole building electricity consumption data $\dot{E}_{tot}$ (Wbele) used for testing are accumulated utility bills, which cover both weather-dependent and weather-independent loads; gas bills $\dot{Q}_{gas}$ (Wbheat) used for testing are assembled from measured whole building heating consumption. The electricity consumption data are first separated into weather-dependent and weather-independent parts. The separated weather-independent electricity loads, $\dot{E}_{L\&E,est}$, determined by SUBTB for the 40 buildings are shown in the third column of Table 6.2. $RE_{L\&E}$ values for the separated results are in the next column, and the average $RE_{\dot{E}_{L\&E}}$ is 6.88%. The first column lists the site number of the building, total area of the building is in the fourth column, and the last column gives the predicted peak electricity use. The predicted peak electricity use for Lighting and Equipment ($\dot{E}_{L\&E,est}$) per unit area is from the weather-dependent part based on the assumption that these buildings are fully occupied 12 hours of each weekday, whereas they are half occupied the rest of the time.

An automated pattern recognition method is developed to identify the main type of HVAC system in each building. To implement the process, prototype buildings based on the total area and peak electricity use per unit area are configured. The estimated UA value for wall and roof and the UA value for windows from the total area are in columns 3 and 4 of Table 6.3; fan power for each building in the last column of the table is determined by Equation 6.1. It is assumed that the airflow rate in the air-conditioned space is 1.1 CFM/FT^2, the pressure rise of the fan is three inches of water; the efficiency of the motor is 90% and the efficiency of the fan is 80% (ASHRAE, 2000).

$$Power_{fan}=1.1*Area*3/(6346*0.9*0.8) \qquad \text{Equation 6.1}$$

After prototype buildings are configured, energy consumption in these prototype buildings with different types of HVAC system can be simulated by AirModel, and hourly simulated energy consumption values are converted into monthly consumption. For example, Figures 6.1 and 6.2 show the monthly simulated and measured weather-dependent energy consumption for the Education Building.

The monthly-simulated weather-dependent energy consumption values with different HVAC systems are compared with “measured values”, which are determined from the “utility bills” using the SUBTB methodology; then membership for each type of HVAC system is obtained. The same routine is followed for all cases in Table 6.2. Memberships for eight types of HVAC systems are obtained in the 40 cases shown in columns 3 – 10 of Table 6.4, and the inferred HVAC system is listed in column 2 based on these memberships. It is assumed that if the maximum membership value among the eight memberships for a case is larger than 0.3, then the main type of HVAC system can be identified. If no economizer systems are considered, memberships for only four types of HVAC systems (DDCAV, DDVAV, SDCAV, and SDVAV) are considered for the 40 cases shown in Table 6.5. In these cases, it is assumed that if the maximum membership value among the four memberships for a case is larger than 0.45, then the main type of HVAC system can be identified. The final identified results in the two situations are compared with the actual HVAC system in Table 6.6.

Using pattern recognition with eight options, the type of HVAC system is correctly identified in 12 cases, 13 cases are identified incorrectly, and the method did not produce a result in 15 cases. 10 of the 13 incorrect judgments identified the presence of an economizer where there was no economizer based on the information from the Energy Consumption Report (Claridge, 1996b, 1999; Haberl and Claridge, 2001); among these ten cases, six system types are correctly identified if the economizer is neglected. These errors may largely result from the relatively small impact of economizers on HVAC systems in Texas. Using pattern recognition with only four options, the type of HVAC system is correctly identified in 17 cases, incorrectly identified in 7 cases, and can’t be identified for 16 cases. It appears that use of pattern recognition with four options is better than with eight options. However, if the judgments with or without economizer are treated as the same result with eight options, then only seven judgments are wrong, and the HVAC system type can’t be identified for 15 cases. For case 106, the failure in pattern recognition may result from the mixed HVAC systems. The following test is based on the results of pattern recognition with eight options with the assumption that the judgment with or without economizer is treated the same.

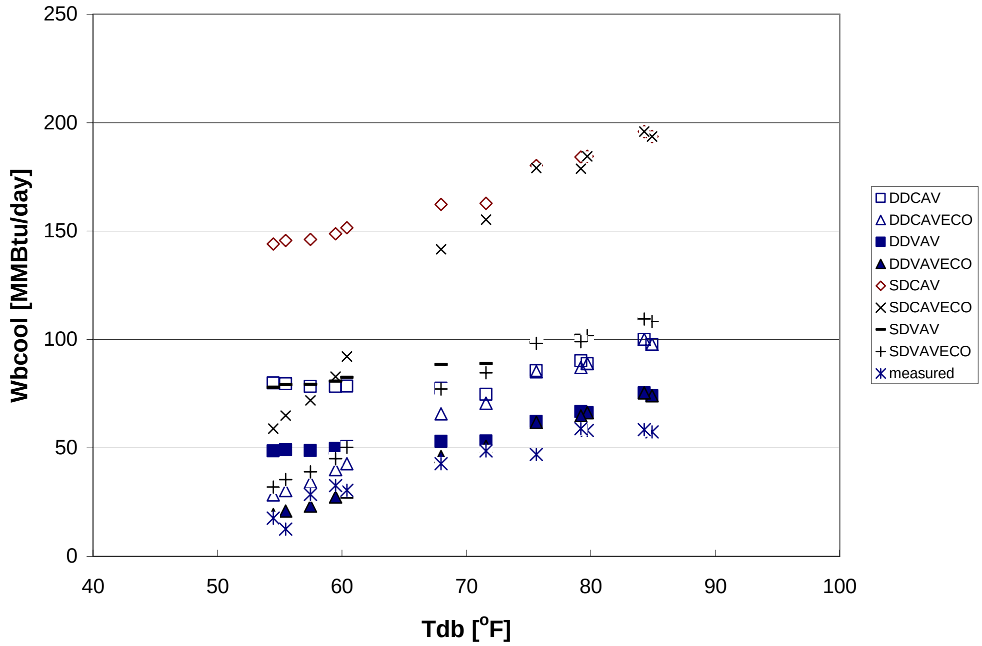

Figure 6.1 Simulated and measured Wbcool for the Education Building in 1995.

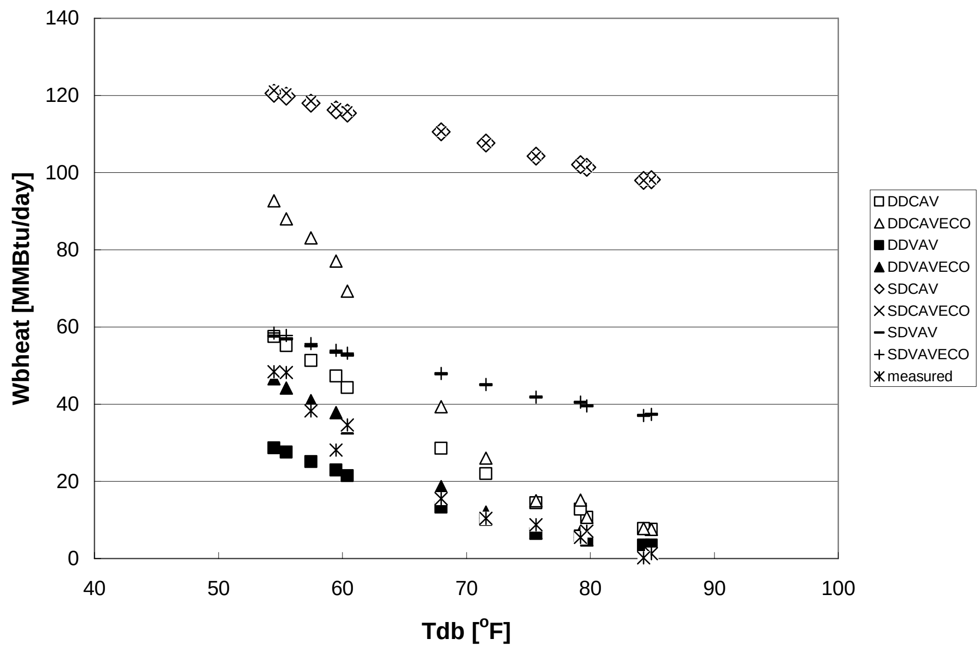

Figure 6.2 Simulated and measured Wbheat for the Education Building in 1995.

Table 6.2 Estimated weather-independent electric load by SUBTB method for 40 years of data from 34 buildings

Site	Period	$\dot{E}_{L\&E,est}$ (kWh/day)	$RE_{\dot{E}_{L\&E}}$	Total area (ft^2)	Predicted peak use (W/ ft^2)
1a	1/1990 - 1/1991 (w/o 10/1990)	23,830	-9.9%	324,400	4.51
1b	1994	22,790	-3.6%	324,400	4.31
1c	1997	19,470	5.7%	324,400	3.69
100	1995	6,850	24.7%	251,161	1.68
101	1993	3,470	-13.9%	152,690	1.40
102	1994	17,940	-15.4%	483,895	2.28
103	1993	950	13.2%	54,069	1.08
104	1992	1,660	6.2%	61,041	1.67
105	1993	2,660	-7.3%	57,598	2.83
106	9/1992 - 8/1993	26,910	9.4%	439,540	3.76
107	1992	2,360	-8.2%	103,441	1.40
108	1995	2,930	18.1%	94,815	1.89
111	1996	3,535	-11.4%	123,450	1.76
112a	7/1993 - 6/1994	10,330	51.3%	149,900	4.23
112b	1997	4,750	-1.4%	149,900	1.94
113	1997	10,250	15.5%	223,000	2.82
115	1993	1,380	39.2%	56,849	1.49
116	9/1992-10/1993 (w/o 6,7/1993)	8,370	28.5%	128,409	4.00
117	1993	890	-23.7%	48,905	1.12
124a	5/1992 - 4/1993	119,750	32.7%	887,187	8.29
124b	1995	125,340	60.3%	887,187	8.68
165	1996	10,320	8.3%	242,857	2.61
166	1996	7,370	15.3%	146,763	3.08
187	2001	10,080	-2.7%	156,219	3.96
188	10/2000 - 9/2001	3,750	3.5%	118,544	1.94
189	2001	3,830	-26.3%	64360	3.65
195	2001	4,160	12.5%	128,600	1.99
197	2001	7,575	1.1%	129,043	3.60
203	1997	12,160	-4.5%	169,746	4.40
236	1998	21,150	-11.8%	262,905	4.94
300a	3/1991 - 3/1992 (w/o 10/1991)	11,330	-5.0%	233,738	2.98
300b	1994	14,360	25.1%	233,738	3.77
400	1995	11,040	1.6%	68,512	9.90
403	1994	4,520	7.2%	67,380	4.12
404	1995	27,880	16.5%	373,085	4.59
491	12/2000 -12/2001 (w/o 6/2001)	20,540	0.8%	812,289	1.55
494	2000	6,320	12.3%	102,105	3.80
496	9/1997 - 8/1998	8,510	16.5%	96,038	5.44
497a	1/1996 - 1/1997 (w/o 3/1996)	5,480	-11.9%	63,515	5.29
497b	1999	4,080	6.7%	63,515	3.94

Table 6.3 Estimated UA values and fan power for the "prototype" of the buildings based on total area

Site #	Facility	Area (ft^2)	UA for wall and roof (Btu/°F/hr)	UA for window (Btu/°F/hr)	Fan power (hp)
1	Zachry Engineering Center	324,400	17,818	17,679	234
100	Education Building	251,161	14,161	13,643	181
101	University Teaching Center	152,690	9,272	8,240	110
102	Perry Castaneda Library	483,895	25,513	26,103	349
103	Garrison Hall	54,069	4,466	2,831	39
104	Gearing Hall	61,041	4,871	3,008	44
105	Waggener Hall	57,598	4,672	2,922	42
106	Welch Hall	439,540	23,203	23,532	317
107	Burdine Hall	103,441	6,844	5,537	75
108	Nursing Building	94,815	6,479	5,302	68
111	University Hall	123,450	7,877	6,763	89
112	Business Building	149,900	9,171	8,164	108
113	Fine Arts Building	223,000	12,822	12,196	161
115	R.A. Steindam Hall	56,849	4,629	2,903	41
116	Painter Hall	128,409	8,069	6,898	93
117	W.C. Hogg Building	48,905	4,159	2,692	35
124	Medical School Building	887,187	45,384	47,971	641
165	College of Business Administration	242,857	13,459	12,727	175
166	Graduate School of Business	146,763	9,056	8,078	106
187	Biology Building	156,219	9,399	8,335	113
188	Science Building	118,544	7,685	6,628	86
189	Chemistry North	64,360	4,941	3,783	46
195	Chemistry South	128,600	8,076	6,903	93
197	Law School	129,043	8,093	6,915	93
203	John H. Reagan	169,746	10,228	9,384	123
236	Brown Heatly Building	262,905	14,530	13,958	190
300	School of Public Health	233,738	13,169	12,486	169
400	John Sealy North	68,512	5,147	3,903	49
403	Moody Library	67,380	5,091	3,870	49
404	John Sealy South Towers	373,085	20,753	21,033	269
491	Evans Library (old)	812,289	41,677	43,890	587
494	E. Langford Architecture Center	102,105	6,788	5,502	74
496	Biological Sciences West Building	96,038	6,531	5,336	69
497	Teague	63,515	4,898	3,758	46

Table 6.4 Memberships of HVAC systems for 40 cases tested (eight options)

Building ID	Identified system (>0.3)	Membership							
		DDCAV	DDCAVECO	DDVAV	DDVAVECO	SDCAV	SDCAVECO	SDVAV	SDVAVECO
1a	DDCAV	0.399	0.036	0.201	0.063	0.010	0.012	0.217	0.062
1b	DDVAV	0.020	0.043	0.430	0.279	0.004	0.006	0.068	0.149
1c	DDVAV	0.032	0.060	0.329	0.305	0.006	0.009	0.087	0.171
100	DDVAVECO	0.217	0.059	0.185	0.446	0.004	0.005	0.036	0.048
101	DDVAV	0.058	0.073	0.548	0.220	0.005	0.008	0.036	0.053
102	-	0.078	0.070	0.240	0.158	0.006	0.008	0.216	0.224
103	DDVAVECO	0.097	0.077	0.255	0.452	0.007	0.009	0.044	0.059
104	DDVAVECO	0.118	0.087	0.246	0.389	0.008	0.011	0.061	0.079
105	DDVAVECO	0.061	0.065	0.109	0.536	0.006	0.008	0.086	0.129
106	DDCAVECO	0.138	0.345	0.090	0.110	0.048	0.079	0.050	0.141
107	DDVAV	0.099	0.073	0.457	0.214	0.006	0.008	0.067	0.076
108	DDCAVECO	0.104	0.395	0.133	0.121	0.009	0.013	0.070	0.156
111	DDVAV	0.037	0.064	0.464	0.347	0.004	0.006	0.028	0.050
112a	-	0.128	0.019	0.218	0.235	0.009	0.015	0.203	0.174
112b	DDVAV	0.049	0.107	0.627	0.005	0.011	0.037	0.114	0.050
113	-	0.282	0.028	0.036	0.192	0.008	0.016	0.143	0.294
115	DDVAVECO	0.061	0.087	0.328	0.425	0.005	0.007	0.030	0.059
116	-	0.174	0.095	0.137	0.132	0.009	0.012	0.251	0.190
117	-	0.146	0.165	0.050	0.193	0.007	0.010	0.193	0.236
124a	-	0.100	0.122	0.096	0.091	0.160	0.254	0.091	0.086
124b	-	0.127	0.084	0.124	0.185	0.064	0.204	0.076	0.137
165	DDVAV	0.058	0.070	0.435	0.266	0.008	0.011	0.063	0.089
166	DDVAV	0.027	0.048	0.442	0.313	0.004	0.006	0.055	0.107
187	DDCAV	0.304	0.114	0.122	0.085	0.055	0.052	0.174	0.093
188	DDVAV	0.056	0.015	0.428	0.359	0.006	0.011	0.063	0.064
189	SDVAV	0.300	0.040	0.164	0.087	0.009	0.009	0.312	0.080
195	-	0.158	0.249	0.135	0.119	0.032	0.040	0.176	0.091
197	-	0.072	0.059	0.253	0.240	0.010	0.014	0.197	0.155
203	-	0.063	0.054	0.186	0.228	0.004	0.006	0.225	0.234
236	-	0.073	0.050	0.219	0.200	0.005	0.007	0.227	0.221
300a	DDCAV	0.341	0.141	0.064	0.051	0.114	0.116	0.106	0.066
300b	DDVAVECO	0.081	0.065	0.124	0.370	0.004	0.006	0.128	0.221
400	-	0.059	0.242	0.082	0.095	0.156	0.206	0.076	0.085
403	-	0.214	0.069	0.052	0.036	0.257	0.259	0.070	0.042
404	SDVAVECO	0.279	0.088	0.106	0.061	0.007	0.008	0.117	0.333
491	DDVAV	0.075	0.091	0.344	0.312	0.012	0.016	0.063	0.087
494	SDVAVECO	0.146	0.128	0.065	0.175	0.004	0.005	0.136	0.341
496	-	0.140	0.153	0.110	0.239	0.007	0.011	0.129	0.211
497a	-	0.230	0.244	0.098	0.076	0.076	0.091	0.108	0.078
497b	SDVAVECO	0.018	0.046	0.089	0.198	0.002	0.004	0.259	0.385

Table 6.5 Memberships of HVAC systems in 40 cases tested (four options)

Building ID	DDCAV	DDVAV	SDCAV	SDVAV
1a	0.49	0.24	0.01	0.26
1b	0.07	0.72	0.01	0.20
1c	0.10	0.64	0.02	0.24
100	0.35	0.53	0.01	0.10
101	0.11	0.81	0.01	0.07
102	0.14	0.46	0.01	0.39
103	0.22	0.65	0.02	0.12
104	0.26	0.58	0.02	0.14
105	0.25	0.38	0.02	0.35
106	0.42	0.30	0.15	0.14
107	0.17	0.70	0.01	0.12
108	0.42	0.34	0.04	0.21
111	0.10	0.80	0.01	0.09
112a	0.24	0.38	0.02	0.36
112b	0.06	0.76	0.02	0.16
113	0.50	0.07	0.02	0.40
115	0.16	0.71	0.02	0.11
116	0.30	0.24	0.02	0.44
117	0.40	0.15	0.02	0.43
124a	0.22	0.22	0.36	0.21
124b	0.32	0.29	0.23	0.15
165	0.12	0.72	0.02	0.14
166	0.08	0.75	0.01	0.16
187	0.45	0.19	0.08	0.27
188	0.10	0.77	0.01	0.12
189	0.42	0.20	0.01	0.37
195	0.35	0.26	0.08	0.31
197	0.14	0.47	0.02	0.37
203	0.13	0.39	0.01	0.47
236	0.14	0.41	0.01	0.43
300a	0.49	0.11	0.24	0.17
300b	0.21	0.41	0.02	0.36
400	0.13	0.26	0.37	0.24
403	0.32	0.08	0.50	0.11
404	0.42	0.29	0.01	0.28
491	0.16	0.67	0.03	0.14
494	0.31	0.26	0.02	0.41
496	0.29	0.31	0.02	0.38
497a	0.45	0.19	0.16	0.21
497b	0.06	0.31	0.01	0.63

Table 6.6 Comparison of HVAC system identified and actual system in 40 cases tested

Building ID	Period	System identified (4 options)	System identified (8 options)	Actual HVAC system
1a	1/90-1/91 (no 10/91)	DDCAV	DDCAV	DDCAV
1b	94	DDVAV	DDVAV	DDVAV
1c	97	DDVAV	DDVAV	DDVAV
100	95	DDVAV	DDVAVECO	DDVAV
101	93	DDVAV	DDVAV	DDVAV
102	94	DDVAV	-	SDVAV:DDVAV (6:4)
103	93	DDVAV	DDVAVECO	DDVAV
104	92	DDVAV	DDVAVECO	DDVAV
105	93	-	DDVAVECO	DDVAV
106	9/92 - 8/93	-	DDCAVECO	DDCAV: DDVAV (4:2)
107	92	DDVAV	DDVAV	DDVAV
108	95	-	DDCAVECO	SDVAV+economizer
111	96	DDVAV	DDVAV	DDVAV
112a	7/93 - 6/94	-	-	DDVAV
112b	97	DDVAV	DDVAV	DDVAV
113	97	DDCAV	-	DDVAV+economizer
115	93	DDVAV	DDVAVECO	DDVAV+economizer
116	9/92 - 10/93 (no 6,7/93)	-	-	DDVAV+economizer
117	93	-	-	DDVAV+economizer
124a	5/92 - 4/93	-	-	DDCAV
124b	95	-	-	DDCAV
165	96	DDVAV	DDVAV	DDVAV
166	96	DDVAV	DDVAV	DDVAV
187	1	DDCAV	DDCAV	SDVAV
188	10/00 - 9/01	DDVAV	DDVAV	DDVAV
189	1	-	SDVAV	DDVAV
195	1	-	-	DDVAV
197	1	DDVAV	-	DDVAV
203	97	SDVAV	-	DDVAV+economizer
236	98	-	-	DDVAV
300a	3/91 - 3/92 (no 10/91)	DDCAV	DDCAV	DDCAV
300b	94	-	DDVAVECO	DDCAV
400	95	-	-	CAV
403	94	SDCAV	-	CAV
404	95	-	SDVAVECO	CAV
491	12/00 - 12/01 (no 6/01)	DDVAV	DDVAV	DDCAV
494	0	-	SDVAVECO	SDVAV
496	9/97 - 8/98	-	-	DDVAV
497a	1/96 - 1/97 (no 3/96)	DDCAV	-	DDCAV
497b	99	SDVAV	SDVAVECO	DDVAV

In order to identify the buildings with potential energy savings, the idealized commercial building is configured similarly to the prototype commercial building; the idealized commercial building has optimized hot-deck and cold-deck schedules. AirModel is used to find the optimized operation schedules for the HVAC system. For example, the results of the optimization process based on 1995 data for the Education Building are shown in Figure 6.3 when chilled water is assumed to cost \$3.90/MMBtu, hot water is assumed to cost \$4.00/MMBtu and the HVAC system in the Education Building is DDVAV. The minimum cold-deck temperature and maximum hot-deck temperature in each bin from Figure 6.3 form the optimized operation schedules for the HVAC system in the Education Building (Figure 6.4).

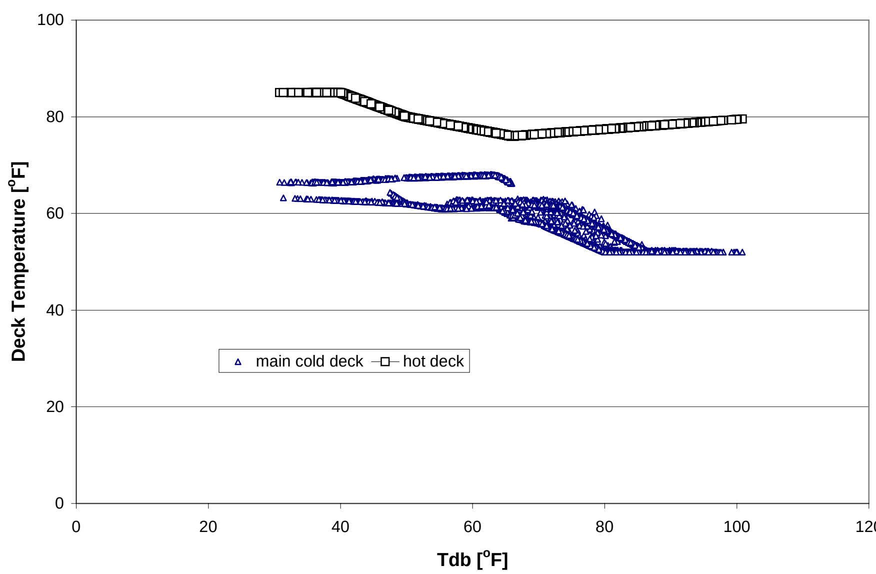

Figure 6.3 The result of the optimization process based on the 1995 data for the Education Building (DDVAV).

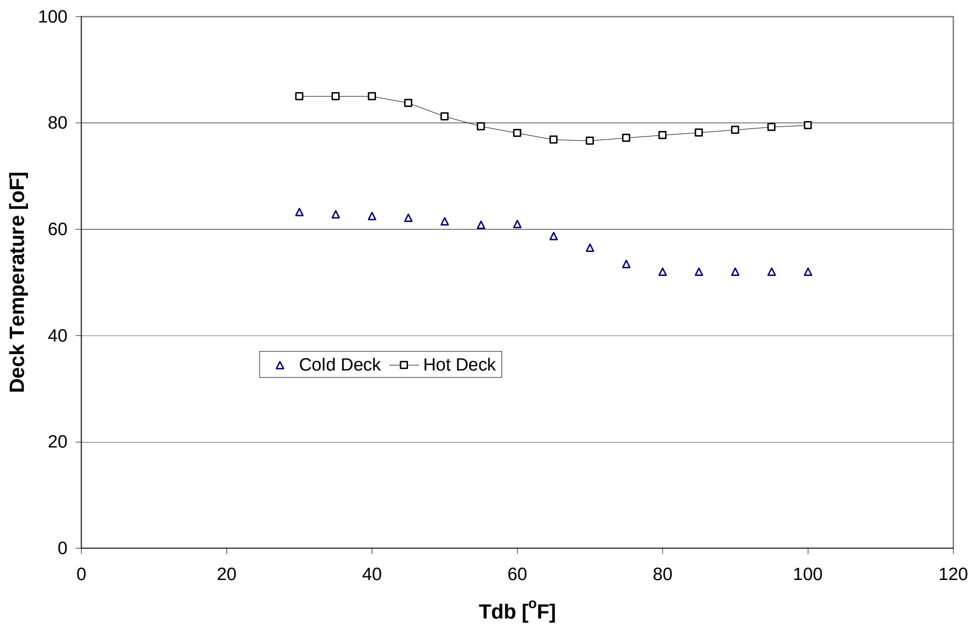

Figure 6.4 Optimized operation schedule for HVAC system in the Education Building based on the 1995 data.

After the optimized operation schedules of the HVAC system in the Education Building are determined, the simulated Wbcool and Wbheat in the idealized building of the same size are compared with measured consumption and simulated consumption in the prototype building of the same size in Figures 6.5 and 6.6. Simulated Wbcool and Wbheat values in the idealized building are lower than those in the prototype building; while measured consumption is lower at low ambient temperatures. The total weather-dependent energy cost in 1995 for the Education Building is $93,683; the difference between the actual cost and the simulated cost for the idealized building is $14,124. This indicates 15.08% potential savings in Education Building based on the 1995 data, but the idealized building is an imaginary building, which may be considerably different from the actual situation. The Education Building would not be recommended for a full audit if the criterion requires potential saving of 20%, 30%, or 40% before an audit is recommended. The retrofits in the Education Building were finished in May 1991; from

Figure III2 (Appendix III), the weather–dependent energy consumption in 1992, 1993, 1994, and 1995 are similar each year in the Education Building.

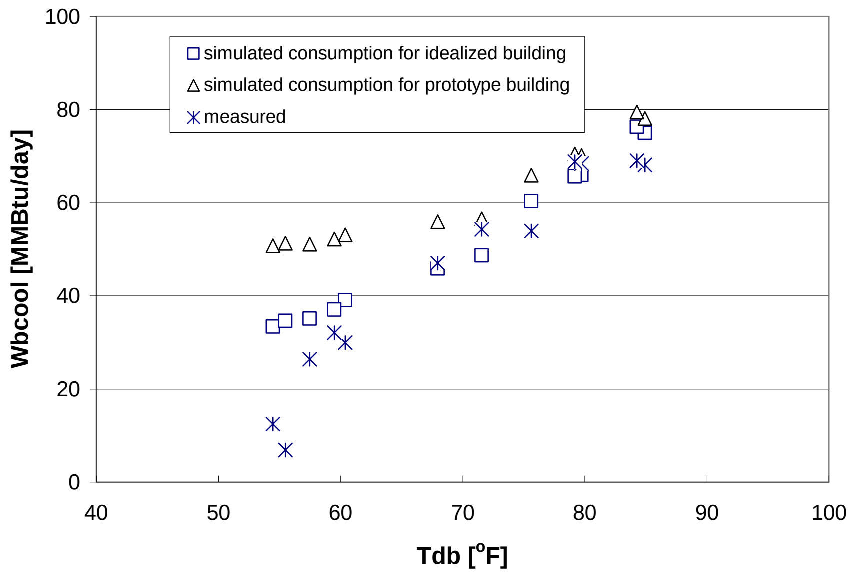

Figure 6.5 Comparison of measured 1995 Wbcool in the Education Building with the simulated Wbcool in the prototype and idealized buildings of the same size.

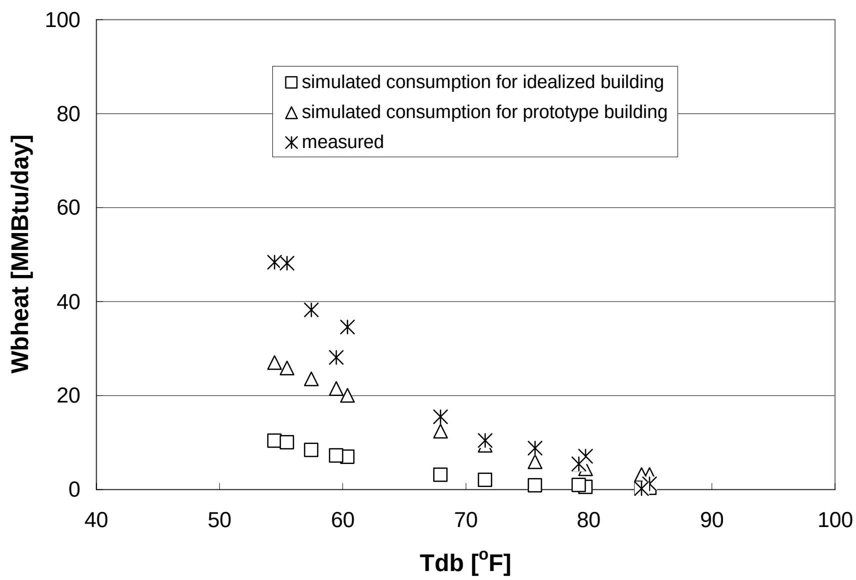

Figure 6.6 Comparison of measured 1995 Wbheat in the Education Building with the simulated Wbheat in the prototype and idealized buildings of the same size.

The same procedures are implemented for the 40 cases tested. If the identified HVAC system is a dual duct system, the most efficient system is the dual duct variable air volume system (DDVAV) as an economizer is not common in Texas, but if the actual HVAC system is a dual duct system with economizer, the most efficient system is the dual duct variable air volume system with economizer (DDVAVECO); it is the same for single-duct systems. If the main type of HVAC system is unknown, then there is more uncertainty; the most efficient system is treated as being either a DDVAV or SDVAV system, respectively. Potential savings in the two cases are estimated in all cases, but the final recommendation is based on the DDVAV system if the main type of HVAC system is unknown. The results are summarized in Table 6.7, and the potential energy savings based on the actual HVAC system are also listed in the table for comparison. From the table, the impact of the economizer on the percentage of total CC® and retrofit savings is generally not large, the difference is less than 15% in cases 113, 115, 116, 117, and 203, which have economizers. However, there is a large difference in the predicted potential energy savings if the identified HVAC system is different from the actual system. For example, the identified HVAC system in case 108 is DDCAV with potential savings of 48% while the actual system is SDVAVECO with potential savings of only 10%. The savings identified in case 497b is -11%, while the actual DDVAV system has projected savings of 17%. In this dissertation, if the savings' percentage for a case is less than 30%, it is treated as if there is not much savings potential. The evaluation of energy efficiency for 40 cases is listed in Table 6.8. For other thresholds, the evaluations are listed in Tables 6.9 and 6.10.

Table 6.7 Potential CC® savings and potential total savings (CC® & Retrofit)

Building ID	Period	Identified HVAC	Actual HVAC	CC savings	% of CC savings	most efficient system	CC & Retrofit savings	% of CC & Retrofit savings
1a	1/1990-1/1991 (no 10/1991)	DDCAV	DDCAV	($5,873)	-2.24%	DDVAV	$62,099	23.71%
1b	1994	DDVAV	DDVAV	($34,272)	-25.70%	DDVAV	($34,272)	-25.70%
1c	1997	DDVAV	DDVAV	($41,575)	-39.32%	DDVAV	($41,575)	-39.32%
100	1995	DDVAV	DDVAV	$14,124	15.08%	DDVAV	$14,124	15.08%
101	1993	DDVAV	DDVAV	$4,649	9.49%	DDVAV	$4,649	9.49%
102	1994	-				DDVAV	$73,360	29.84%
102	1994	-				SDVAV	($79,333)	-32.27%

Table 6.7 (Continued)

Building ID	period	Identified HVAC	Actual HVAC	CC savings	% of CC savings	most efficient system	CC & Retrofit savings	% of CC & Retrofit savings
102	1994		SDVAV: DDVAV(6:4)					
103	1993	DDVAV	DDVAV	$742	4.72%	DDVAV	$742	4.72%
104	1992	DDVAV	DDVAV	($585)	-3.07%	DDVAV	($585)	-3.07%
105	1993	DDVAV	DDVAV	($1,393)	-6.49%	DDVAV	($1,393)	-6.49%
106	9/1992 - 8/1993	DDCAV	DDCAV	$136,348	34.41%	DDVAV	$190,307	48.03%
107	1992	DDVAV	DDVAV	$12,057	28.21%	DDVAV	$12,057	28.21%
108	1995	DDCAV		$19,628	31.86%	DDVAV	$29,538	47.95%
108	1995		SDVAVECO	$6,212	10.08%	SDVAVECO	$6,212	10.08%
111	1996	DDVAV	DDVAV	($2,220)	-6.04%	DDVAV	($2,220)	-6.04%
112a	7/1993 - 6/1994	-				DDVAV	$19,980	21.32%
		-				SDVAV	($1,790)	-1.91%
			DDVAV	$19,980	21.32%	DDVAV	$19,980	21.32%
112b	1997	DDVAV	DDVAV	$16,269	25.24%	DDVAV	$16,269	25.24%
113	1997	-				DDVAV	$49,835	37.24%
113	1997	-				SDVAV	($10,425)	-7.79%
113	1997		DDVAVECO	$58,606	43.80%	DDVAVECO	$58,606	43.80%
115	1993	DDVAV		$317	1.79%	DDVAV	$317	1.79%
115	1993		DDVAVECO	($394)	-2.22%	DDVAVECO	($394)	-2.22%
116	9/1992 - 10/1993 (no 6,7/1993)	-				DDVAV	$29,097	32.27%
116	9/1992 - 10/1993 (no 6,7/1993)	-				SDVAV	$7,983	8.85%
116	9/1992 - 10/1993 (no 6,7/1993)		DDVAVECO	$37,254	41.32%	DDVAVECO	$37,254	41.32%
117	1993	-				DDVAV	$13,955	50.25%
117	1993	-				SDVAV	($4,364)	-15.71%
117	1993		DDVAVECO	$12,390	44.61%	DDVAVECO	$12,390	44.61%
124a	5/1992 - 4/1993	-				DDVAV	$1,651,159	70.05%
124a	5/1992 - 4/1993	-				SDVAV	$1,665,943	70.68%
124a	5/1992 - 4/1993		DDCAV	$1,435,060	60.89%	DDVAV	$1,651,159	70.05%
124b	1995	-				DDVAV	$403,787	34.49%
124b	1995	-				SDVAV	$418,383	35.73%
124b	1995		DDCAV	$178,364	15.23%	DDVAV	$403,787	34.49%
165	1996	DDVAV	DDVAV	($29,754)	-45.53%	DDVAV	($29,754)	-45.53%
166	1996	DDVAV	DDVAV	($10,178)	-19.17%	DDVAV	($10,178)	-19.17%
187	2001	DDCAV		$73,028	44.47%	DDVAV	$97,850	59.59%
187	2001		SDVAV	$73,940	45.03%	SDVAV	$73,940	45.03%
188	10/2000 - 9/2001	DDVAV	DDVAV	$11,194	23.55%	DDVAV	$11,194	23.55%

Table 6.7 (Continued)

Building ID	Period	Identified HVAC	Actual HVAC	CC savings	% of CC savings	most efficient system	CC & Retrofit savings	% of CC & Retrofit savings
189	2001	-				DDVAV	$24,494	48.05%
189	2001	-				SDVAV	$13,011	25.52%
189	2001		DDVAV	$24,494	48.05%	DDVAV	$24,494	48.05%
195	2001	-				DDVAV	$55,883	58.92%
195	2001	-				SDVAV	$22,065	23.26%
195	2001		DDVAV	$55,883	58.92%	DDVAV	$55,883	58.92%
197	2001	-				DDVAV	$9,255	15.19%
197	2001	-				SDVAV	($13,761)	-22.59%
197	2001		DDVAV	$9,255	15.19%	DDVAV	$9,255	15.19%
203	1997	-				DDVAV	$19,388	17.59%
203	1997	-				SDVAV	($3,173)	-2.88%
203	1997		DDVAVECO	$31,118	28.24%	DDVAVECO	$31,118	28.24%
236	1998	-				DDVAV	$33,057	17.72%
236	1998	-				SDVAV	$6,760	3.62%
236	1998		DDVAV	$33,057	17.72%	DDVAV	$33,057	17.72%
300a	3/1991 - 3/1992 (no 10/1991)	DDCAV	DDCAV	$131,412	45.76%	DDVAV	$170,261	59.29%
300b	1994	DDVAV		$1,929	1.71%	DDVAV	$1,929	1.71%
300b	1994		DDCAV	($24,596)	-21.84%	DDVAV	$1,929	1.71%
400	1995	-				DDVAV	$70,765	47.51%
400	1995	-				SDVAV	$71,555	48.04%
400	1995		CAV			VAV		
403	1994	-				DDVAV	$58,796	61.72%
403	1994	-				SDVAV	$48,400	50.80%
403	1994		CAV			VAV		
404	1995	SDVAV		$5,212	1.87%	SDVAV	$5,212	1.87%
404	1995		CAV			VAV		
491	12/2000 - 12/2001 (no 6/2001)	DDVAV		($104,488)	-77.31%	DDVAV	($104,488)	-77.31%
491	12/2000 - 12/2001 (no 6/2001)		DDCAV	($196,978)	-145.73%	DDVAV	($104,488)	-77.31%
494	2000	SDVAV	SDVAV	$951	1.41%	SDVAV	$951	1.41%
496	9/1997 - 8/1998	-				DDVAV	$14,551	19.81%
496	9/1997 - 8/1999	-				SDVAV	$7,916	10.78%
496	9/1997 - 8/2000		DDVAV	$14,551	19.81%	DDVAV	$14,551	19.81%
497a	1/1996 - 1/1997 (no 3/1996)	-				DDVAV	$49,729	55.36%
497a	1/1996 - 1/1997 (no 3/1996)	-				SDVAV	$43,632	48.57%
497a	1/1996 - 1/1997 (no 3/1996)		DDCAV	$35,635	39.67%	DDVAV	$49,729	55.36%
497b	1999	SDVAV		($4,147)	-10.94%	SDVAV	($4,147)	-10.94%
497b	1999		DDVAV	$6,413	16.91%	DDVAV	$6,413	16.91%

Table 6.8 Recommendation for future detailed energy audit (30%)

Building ID	CC Savings	CC & Retrofit Savings
1a	N	Y not much
1b	N	N
1c	N	N
100	Y not much	Y not much
101	Y not much	Y not much
102		Y not much
103	Y not much	Y not much
104	N	N
105	N	N
106	Y	Y
107	Y not much	Y not much
108	Y	Y
111	N	N
112a		Y not much
112b	Y not much	Y not much
113		Y
115	Y not much	Y not much
116		Y
117		Y
124a		Y
124b		Y
165	N	N
166	N	N
187	Y	Y
188	Y not much	Y not much
189		Y
195		Y
197		Y not much
203		Y not much
236		Y not much
300a	Y	Y
300b	Y not much	Y not much
400		Y
403		Y
404	Y not much	Y not much
491	N	N
494	Y not much	Y not much
496		Y not much
497a		Y
497b	N	N

Table 6.9 Recommendation for future detailed energy audit (20%)

Building ID	CC Savings	CC & Retrofit Savings
1a	N	Y
1b	N	N
1c	N	N
100	Y not much	Y not much
101	Y not much	Y not much
102		Y
103	Y not much	Y not much
104	N	N
105	N	N
106	Y	Y
107	Y	Y
108	Y	Y
111	N	N
112a		Y
112b	Y	Y
113		Y
115	Y not much	Y not much
116		Y
117		Y
124a		Y
124b		Y
165	N	N
166	N	N
187	Y	Y
188	Y	Y
189		Y
195		Y
197		Y not much
203		Y not much
236		Y not much
300a	Y	Y
300b	Y not much	Y not much
400		Y
403		Y
404	Y not much	Y not much
491	N	N
494	Y not much	Y not much
496		Y not much
497a		Y
497b	N	N

Table 6.10 Recommendation for future detailed energy audit (40%)

Building ID	CC Savings	CC & Retrofit Savings
1a	N	Y not much
1b	N	N
1c	N	N
100	Y not much	Y not much
101	Y not much	Y not much
102		Y not much
103	Y not much	Y not much
104	N	N
105	N	N
106	Y not much	Y
107	Y not much	Y not much
108	Y not much	Y
111	N	N
112a		Y not much
112b	Y not much	Y not much
113		Y not much
115	Y not much	Y not much
116		Y not much
117		Y
124a		Y
124b		Y not much
165	N	N
166	N	N
187	Y	Y
188	Y not much	Y not much
189		Y
195		Y
197		Y not much
203		Y not much
236		Y not much
300a	Y	Y
300b	Y not much	Y not much
400		Y
403		Y
404	Y not much	Y not much
491	N	N
494	Y not much	Y not much
496		Y not much
497a		Y
497b	N	N

Analysis of test results

From Tables 6.8, 6.9, and 6.10, different “cut-off” criteria are used to judge energy savings for the 40 cases tested; the results are listed in Table 6.11. Fourteen cases are recommended for a more detailed energy audit, if the 30% of criterion is used; however, 20 cases are recommended for further energy audits, if the criterion is changed to 20%; if 40% is used as the “cut-off” criterion, only 11 cases are recommended for a more detailed energy audit. It may also be noted that in the four cases where constant volume systems were identified as being present, the system and method implemented identified potential retrofit savings of 14 – 25% from retrofitting to variable volume systems. The benefit of this screening methodology is that fewer buildings with higher savings potential will be audited instead of auditing all buildings. When the savings criterion for judgment is higher, fewer cases are recommended for further energy audits; when the criterion is lower, more cases are recommended. If the actual type of HVAC system is known and measured weather-dependent and weather-independent energy consumption are known, the methodology should work better.

Table 6.11 Summary of buildings recommended for audits with different “cut-off” criteria

iterm	20%	30%	40%
recommended case	1a, 102, 106, 107, 108, 112a, 112b, 113, 116, 117, 124a, 124b, 187, 188, 189, 195, 300a, 400, 403, 497a	106, 108, 113, 116, 117, 124a, 124b, 187, 189, 195, 300a, 400, 403, 497a	106, 108, 117, 124a, 187, 189, 195, 300a, 400, 403, 497a
# of recommended cases	20	14	11

Figure V1 – Figure V80 in the appendix show the relationship between the monthly average Wbele, Wbheat and Tdb for the 40 test buildings shown in Table 6.7. The sum of Energy Use Intensity (annual kBtu per total square foot of floor space) for each fuel type can be used to determine potential energy efficiency improvements in commercial and related buildings (Gardiner,et al., 1984; MacDonald and Wasserman, 1989). The 40 test buildings are institutional buildings in Texas; they are in the West South Central census region as shown in Figure 6.7 (EIA, 1999b). EUI for these buildings considering electricity consumption (including electricity consumption by chiller system) and gas consumption are compared in Figure 6.8

Buildings with a EUI higher than the 50th percentile of the 40 building data set (123.77 kBtu/year/FT^2) or 75th percentile (170.51 kBtu/year/FT^2) might be assumed to merit audits. If so, the twenty and ten buildings selected based on these criteria are listed in columns 2 and 4 respectively of Table 6.12.

The buildings recommended for energy audits with 20% and 40% "cut-off" criteria based on the prescreening tool are listed in columns 3 and 5 for comparison. From Table 6.12, if the buildings recommended for an audit based on an EUI of 170.51 kBtu/year/FT^2 (the line in Figure 6.8 indicates this value) are compared with those based on the 40% "cut-off", seven of the ten buildings recommended by the EUI criterion are also recommended for an energy audit by the prescreening tool, whereas cases 1a, 124b, 496 are not recommended. When the criterion is changed to 123.77 kBtu/year/FT^2, while the number (20) of buildings recommended by the EUI criterion is the same as that by the prescreening tool with 20% "cut off", only 14 cases (1a, 106, 112a, 113, 116, 124a, 124b, 187, 189, 195, 300a, 400, 403 and 497a) are recommended for audits by both methods.

The buildings recommended for audits by the EUI criterion and the prescreening tool for the 40 test buildings are the same for about 2/3 of the buildings recommended for audits, but about 1/3 differ, so further testing of the prescreening methodology will be done.

Table 6.12 Comparison of buildings recommended for audits by the EUI criteria and the prescreening tool.

Item	50th percentile	20%	75th percentile	40%
Cases recommended for audit	1a, 106, 112a, 113, 116, 124a, 124b, 187, 189, 195, **203**, **236**, 300a, 400, 403, **404**, **494**, **496**, 497a, **497b**	1a, **102**, 106, **107**, **108**, 112a, **112b**, 113, 116, **117**, 124a, 124b, 187, **188**, 189, 195, 300a, 400, 403, 497a	**1a**, 106, 124a, **124b**, 187, 300a, 400, 403, **496**, 497a	106, **108**, **117**, 124a, 187, **189**, **195**, 300a, 400, 403, 497a
# of recommended cases	20	20	10	11

(Buildings shown in bold are not recommended by both criteria)

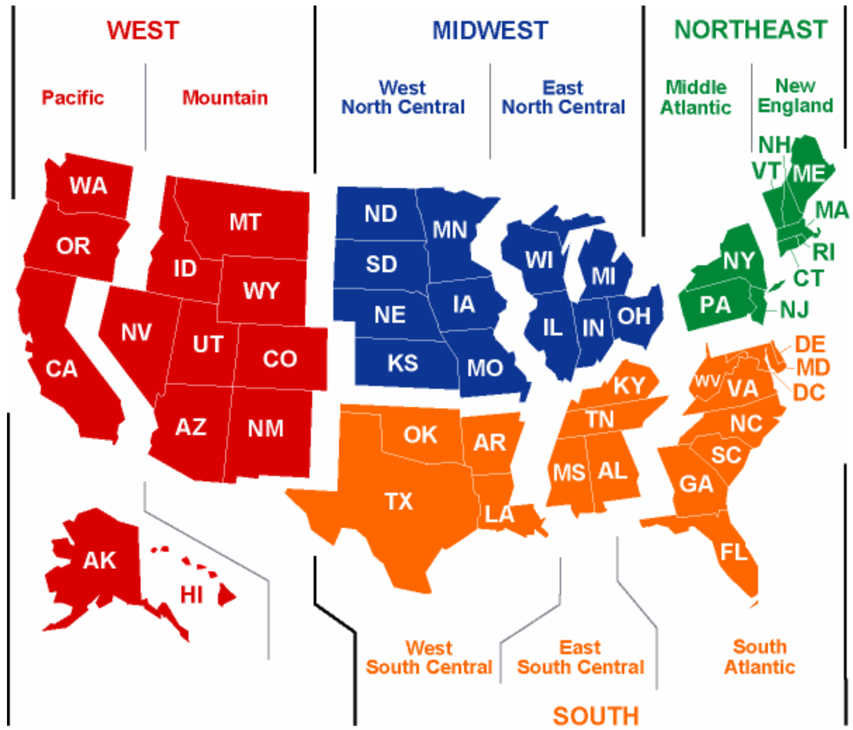

Figure 6.7 U.S Census Regions and Divisions (Source: EIA, 1999b)

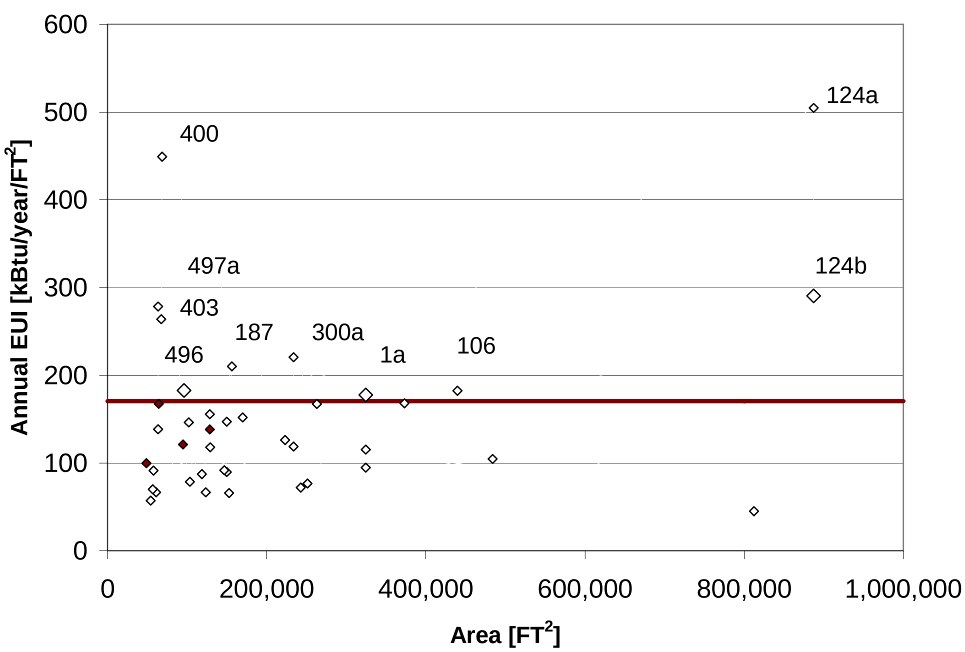

Figure 6.8 Comparison of annual EUI for 40 institutional test buildings in Texas

Further testing of the methodology

When the pre-screening methodology is used on large commercial buildings, potential CC® and total retrofit and CC® savings are estimated based on the idealized commercial building. The estimated potential energy savings from the screening procedure will be compared with the potential retrofit or CC® savings identified in field audits. This will provide a check to determine if the savings estimated by the pre-screening methodology are reasonable. Ten buildings are selected for further testing; the main measures and date of retrofits or CC® are listed in Table 6.13. The test periods before retrofits or CC® for the ten buildings can be found in Table 6.17. For some buildings, 12-month data before retrofit and CC® are not available; six-month data are used for the test in those cases. For example, for Building 107, the data from 12/90 – 5/91 is the only available data before retrofit; savings from this period are doubled when potential savings are determined for the building.

For buildings 107, 108, 116, and 117, there are no monitored weather data for some months before CC® or retrofit. The four buildings are all in Austin, Texas, and weather data for College Station, Texas are used to make up the missing gap. Table 6.14 summarizes the periods for which substitute weather data is used.

The monitored electricity consumption is not complete for some buildings. Since weather independent electricity consumption in a commercial building is normally relatively constant throughout the year, the average value is used for the missing periods. Some missing energy consumption is estimated in other ways (Table 6.15). The COP values used to form accumulated electricity utility bills are selected from the random COP values for each site given in Table 4.6. The average COP is 3.29 with a standard deviation of 0.75 (Table 6.16).

After weather data before retrofit and CC® are prepared and utility bills are formed, the weather-independent electricity consumption is separated from the total electricity bills using the SUBTB methodology. The weather-independent electricity consumption values in the 10 buildings determined by SUBTB are compared with the measured values in Table 6.17. The difference between the actual weather-independent electricity consumption and predicted results are less than 15% except for site 494 so the disaggregation is deemed successful for 9 of the 10 buildings. As the estimated potential savings from the screening procedure just includes chilled water and hot water savings using a particular energy price, the audit estimated savings also include only savings from chilled water and hot water at the same prices; the price for chilled water is assumed to be \$3.90/MMBtu and it is \$4.00/MMBtu for hot water. With the same prices for chilled water and hot water, the audit estimated savings for chilled water and hot water from retrofit or CC® are calculated. The audit estimated chilled water, hot water, and cost savings for the 10 selected buildings are listed in Table 6.18, and electricity savings are not included. The audit estimated savings from chilled water and hot water vary from \$6,000 to \$150,000.

Table 6.13 The main measures and date of retrofits or CC® for 10 buildings

Building ID	Facility	main retrofits or CC	Date for Retrofits or CC
1-pre	Zachry Engineering Center	Systems are converted to VAV system	Mar-91
106-pre	Welch Hall	lighting and variable speed pumping	Feb-92
107-pre	Burdine Hall	Systems are converted to VAV system	May-91
108-pre	Nursing Building	Systems are converted to VAV system	Apr-91
113-pre	Fine Arts Building	lighting and variable speed pumping	May-94
116-pre	Painter Hall	Systems are converted to VAV system	Feb-92
117-pre	W.C. Hogg Building	Systems are converted to VAV system	June-91
494-pre	E. Langford Architecture Center	Continuous Commissioning® and variable speed pumping	Jan-97
496-pre	Biological Sciences West Building	lighting and VAV system	Jan-97
497-pre	Teague	Systems are converted to VAV system	Jan-97

Table 6.14 The periods when substitute weather data was used for five buildings

Building	Period	Data
107	12/90 – 2/91	College Station data used
108	11/90 – 2/91	College Station data used
116	1/91 – 2/91	College Station data used
117	1/91 – 2/91	College Station data used

Table 6.15 The process used for filling missing data

Building	Energy	Missing period	Filling Process
107	Electricity	12/90	Average consumption in 1/91 – 5/91
113	Wbheat	2/91	Estimated from model based on data during 3/91 – 7/91
116	Electricity	1,2/91	Average consumption in 3/91 – 6/91
496	Electricity	1/96 – 3/96	Average consumption in 4/96 – 12/96
496	Wbheat	5/96 - 6/96	Estimated from model based on data during other months of 1996

Table 6.16 COP selected for further testing

Building	Selected COP from 40 cases
1-pre	4.26
106-pre	3.25
107-pre	3.53
108-pre	2.08
113-pre	3.5
116-pre	2.44
117-pre	4.24
494-pre	2.62
496-pre	3.03
497-pre	3.93

The potential savings estimated by the screening procedure from retrofits and CC® in these building are listed in column 3 of Table 6.19. The screening estimates are compared with audit estimated energy savings in column 5; the audit estimated energy savings are abstracted from the Energy Consumption Report (Claridge, 1996b, 1999). For Teague (497), only audit retrofit savings are listed in the report, the savings from M&O are not included (Goebel, 1994); the total savings from retrofit and M&O for Teague are listed in Table 6.19. The audit estimated energy savings should match or be a little lower than the screening procedure estimated potential energy savings, as audit estimated energy savings are not based on idealized operation. The table shows that on average, the screening procedure gave results quite close to the audits, with the audits estimating 87% of the total savings for the 10 buildings estimated by the screening procedure. The average value of the ratio of audit estimate to screening estimate with each building weighted equally is 0.94. However, the RMS deviation of the ratio from the average is 0.69.

Table 6.17 Comparison of SUBTB determined and actual weather-independent electricity consumption

Site # of site	Period	Actual yearly average L&E use (kWh/day)	SUBTB Determined Yearly Average L&E (kWh/day)	Difference
1	1/90 -1/91 (no 10/90)	26461	23833	-9.9%
106	3/91 - 2/92	27991	31982	14.3%
107	12/90-5/91	4421	3946	-10.7%
108	11/90-4/91	4589	4563	-0.6%
113	2/91 - 7/91	10734	11737	9.3%
116	1/91-6/91	8696	9833	13.1%
117	1/91-6/91	1752	1998	14.0%
494	7/96 - 12/96	7736	9731	25.8%
496	1/96 - 12/96	7537	8546	13.4%
497	1/96 - 1/97 (no 3/96)	6219	5476	-11.9%

Table 6.18 Audit estimated savings from chilled water and hot water

Building ID	Facility	Audit Savings		
		Chilled Water (MMBtu/month)	Hot Water (MMBtu/month)	Cost Savings ($/year)
1-pre	Zachry Engineering Center	2,215	956	$149,550
106-pre	Welch Hall	395	525	$43,686
107-pre	Burdine Hall	212	130	$16,162
108-pre	Nursing Building	253	177	$20,336
113-pre	Fine Arts Building	475	505	$46,470
116-pre	Painter Hall	551	547	$52,043
117-pre	W.C. Hogg Building	93	43	$6,416
494-pre	E. Langford Architecture Center	227	-23	$9,520
496-pre	Biological Sciences West Building	218	114	$15,674
497-pre	Teague	459	290	$35,434

Table 6.19 Comparison of screening procedure estimated and audit estimated heating and cooling savings

Building ID	Period	CC & Retrofit Savings	Screening Procedure CC & Retrofit Savings	Audited Estimated Savings	Audit Estimate /Screening Est.
1-pre	1/1990-1/1991 (no 10/1991)	$62,099	24%	$149,550	2.41
106-pre	3/1991 - 2/1992	$122,671	36%	$43,686	0.36
107-pre	12/1990 - 5/1991	$35,904	52%	$16,162	0.45
108-pre	11/1990 - 4/1991	$50,865	61%	$20,336	0.40
113-pre	2/1991 - 7/1991	$26,624	22%	$46,470	1.75
116-pre	1/1991 - 6/1991	$43,952	40%	$52,043	1.18
117-pre	1/1991 - 6/1992	$22,481	63%	$6,416	0.29
494-pre	1996	$6,731	8%	$9,520	1.41
496-pre	1996	$33,241	35%	$15,674	0.47
497-pre	1/1996-1/1997 (no 3/1996)	$49,729	55%	$35,434	0.71
	total	$454,297		$395,291	0.87

Figure 6.9 shows the ratio of audit savings to the screening estimated potential savings in the ten facilities. The audit estimated savings are between 25% - 250% of potential energy savings estimated by the screening procedure in ten cases. The ratio for Zachry Engineering Center (site 1) and Fine Art Building (site 113) are over 150%. The measured savings in Zachry Engineering Center and Fine Art Building are compared with the audit savings from the Energy Consumption Report (Claridge, 1996b) and the estimated savings from the prescreening methodology in Table 6.20; the actual savings in the two facilities are much lower than the audit estimated savings, the audit estimated savings appear to be high. The separation failure of electricity consumption in the E. Langford Architecture Center (site 494) may explain why estimated potential energy savings are much lower than audit estimated energy savings.

Note that the actual prices for hot water and chilled water in these buildings are not the prices used in the pre-screening methodology; Table 6.21 lists the actual prices (Liu, 2004). For the 10 buildings in Table 6.21, the average price for HW/steam is $5.54/MMBtu; the average price for CHW is $6.11/MMBtu. Today, the prices would be much higher, but this is expected to have little impact on the comparison of the screening results with the audit results.

Table 6.20 Comparison of actual savings with audit estimated savings and estimated potential savings in Zachry Engineering Center and Fine Arts Building

Facility	Wbcool savings (MMBtu/month)	Wbheat savings (MMBtu/month)	Actual Savings	Estimated Savings by Prescreening tool	Audit Savings from Energy Consumption Report
Zachry Engineering Center	348	414	$36,158	$62,099	$149,550
Fine Arts Building	283	61	$16,172	$26,624	$46,470

Table 6.21 Actual HW and CHW prices in 10 buildings

Building ID	Location	HW/steam ($/MMBtu)	CHW($/MMBtu)
1	Texas A&M University	4.75	4.67
106	UT, Houston	8.00 (steam)	8.30
107	UT, Austin	6.20	7.43
108	UT, Austin	6.20	7.43
113	UT, Arlington	3.64	4.42
116	UT, Austin	6.20	7.43
117	UT, Austin	6.20	7.43
494	Texas A&M University	4.75	4.67
496	Texas A&M University	4.75	4.67
497	Texas A&M University	4.75	4.67

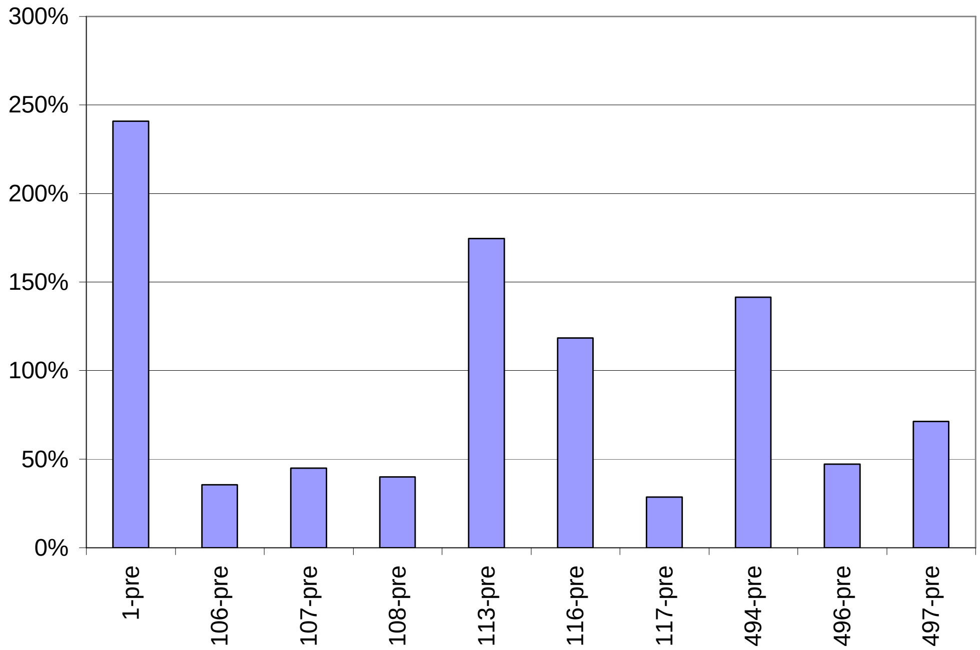

Figure 6.9 Ratio of audit savings to the estimated potential savings in 10 facilities

Conclusions

The pre-screening methodology is tested for 40 cases based on the accumulated utility bills. 14 cases are recommended for a more detailed energy audit if a 30% savings criterion is used; however, 20 cases are recommended for further energy audit, if the criterion is changed to 20%; if 40% is used as the "cut-off" criterion, only 11 cases are recommended for a more detailed energy audit. The audit estimated savings were between 25% - 150% of potential energy savings estimated by the screening procedure for eight cases where regular audit estimates of energy savings are available, but the other cases show even wider discrepancies; so further study of the method is needed.

The pre-screening methodology can identify commercial buildings with significant potential energy savings using only total area, monthly utility bills, and weather data. The benefit of the methodology is only buildings with significant potential savings may be selected for further energy audit instead of all buildings. The total number of buildings recommended for an audit depends on the savings criterion used for identifying buildings to be recommended for an audit. When the savings criterion is raised, fewer cases are recommended for further energy audits; when the criterion is lowered, more cases are recommended. If the actual types of HVAC systems in the buildings and measured weather-dependent and weather-independent energy consumption are known, the methodology should work better.

CHAPTER VII
CONCLUSIONS AND FUTURE DIRECTIONS

General

A pre-screening methodology has been developed to identify large commercial buildings with potential energy savings based on limited information, specifically utility bills, total area, and weather data. There are four steps in the methodology: 1) checking whether the utility bills cover both weather-dependent and weather-independent loads; 2) determining weather-dependent and weather-independent loads; 3) determining the main type HVAC system; and 4) estimating potential energy savings and recommendation an energy audit when appropriate. The method has been tested using consumption data for 40 cases, and 11-20 buildings are recommended for an energy audit, when the savings criterion required recommending an audit varies from 40% down to 20%. The estimated potential savings determined by the screening method have been compared with field audit estimated savings for seven large buildings; the audit estimated potential savings are within 25% to 150% of the savings estimated by the screening procedure for eight cases whose audit energy savings are known. If the actual types of HVAC system, measured weather-dependent and weather-independent energy consumption are known, the methodology should work better.

Bill checking

It may not be definitively known whether the consumption recorded by a particular electric meter includes a chiller or not. Flatness index (FI), which is defined as the ratio of standard deviation of daily average consumption in each month divided by the mean daily consumption, can be used to identify whether the load is weather dependent or weather independent if no suitable cooling only (CO), heating only (HO), or heating and cooling (HC) models can be obtained; usually if FI is less than 0.11, this indicates that the load has little or no weather dependence.

Disaggregating utility bills

If electricity consumption in commercial buildings covers weather-independent and weather-dependent parts; the first part is consumed by lighting, plug loads, fans, pumps, etc. This portion typically does not vary substantially with outside weather conditions and is eventually converted to heat, most of which contributes to building cooling load. The second part varies strongly with outside weather conditions (e.g., temperature, humidity, sunlight) since it is consumed by the chiller(s) and ancillary equipment (some buildings also use electricity for heating, but they are not considered in this dissertation). It is important for energy auditors to know how much energy is used for cooling in a building, both when screening a building prior to conducting an audit, and as part of the audit process.

Several methods have been developed to separate utility bills into weather-dependent and weather-independent components for facilities located in the northern United States, where they always have cold winters, and keep their chiller system turned off for a significant period each year. The three-parameter (3P) change-point regression model can successfully separate electricity consumption into weather-independent and weather-dependent portions if the building chiller system is turned off for at least one billing month during the winter. This method can be expected to introduce a systematic bias in the values of cooling consumption estimated for buildings where the chiller system operates throughout the winter, as is often the case in Texas. A methodology to Separate the Utility Bills based on Thermal Balance (SUBTB) for the purpose of disaggregating monthly electricity consumption into weather-dependent and weather-independent consumption was developed, which is applicable to large commercial buildings in climates where chillers operate year-round, such as Texas. The methodology uses as inputs the monthly electric bills, monthly heating consumption (typically gas bills), monthly average temperature, and building area.

In other words, when weather-independent and weather-dependent electricity consumptions are covered in one utility bill, a 3-P change-point regression model or the SUBTB approach will be used to disaggregate monthly electricity consumption for facilities in different locations. The average relative error in estimated cooling consumption is only 1.1% for 40 buildings in Texas, whereas it is -54.8% from 3-P change-point regression models.

Pattern recognition of the main type of HVAC system

If the main type of HVAC system in a commercial building is unknown, the main type of HVAC system may be identified by comparing measured weather-dependent energy consumption with simulated values in a prototype building of the same size. If a commercial building is properly designed, constructed, operated, and maintained, the measured energy consumption should approximately match the simulated consumption for a typical building of the same size with the actual type of HVAC system. This characteristic can help identify the main type of HVAC system in a building. Two rules were followed when measured energy consumption was compared with simulated values to identify the main type of HVAC system: 1) Two “lines” (measured energy consumption vs. Tdb and simulated vs. Tdb) should be close; 2) The two “lines” should be approximately parallel. This process can be finished automatically by the fuzzy nearest prototype classifier. The classifier is used to identify the main type of HVAC system in 40 tested buildings in Texas from their 12-month weather-dependent consumption. 18 systems were correctly identified, seven judgments are wrong and the HVAC system type can’t be identified for 15 cases.

Estimation of potential energy savings

An idealized commercial building is similar to a prototype commercial building; the difference is that an idealized commercial building has optimized hot-deck and cold-deck schedules. If the main type of HVAC system in a commercial building is known or identified, an idealized building of the same size with actual type of HVAC system can be configured. Then, the potential CC® energy savings can be estimated by comparing simulated energy consumption of the idealized building and the measured consumption; Retrofit and CC® savings can be estimated by comparing measured energy consumption with simulated values in the idealized building with the most efficient HVAC system; judgment can be made if the building is deserving of further detailed energy audits.

Test results of the pre-screening methodology

The accumulated utility bills for 40 buildings are used to test the methodology, and 14 cases are recommended for a more detailed energy audit, if 30% potential savings are required to recommend an audit. However, 20 cases are recommended for further energy audit, if the criterion is changed to 20%; if 40% is used as the "cut-off" criterion, only 11 cases are recommended for a more detailed energy audit. The benefit of the methodology is that fewer buildings will be checked instead of all buildings. When the criterion for judgment is higher, fewer cases are recommended for further energy audit. When the criterion is lower, more cases are recommended.

Conclusions

A pre-screening methodology is developed to identify large commercial buildings with large potential energy savings using limited information, specifically utility bills, total area, and weather data. After four steps are carried out, several results can be obtained: (1) judgment can be made if weather-dependent and weather-independent electricity consumption is included in the utility bills of a commercial building; (2) the weather-independent electricity consumption can be separated from utility bills if it is unknown; (3) the main type of HVAC system can be identified if no information is available; and (4) potential energy savings from retrofit and CC® can be estimated in the commercial building; then, judgment can be made whether a further energy audit is necessary.

This methodology can be used to identify the best candidates for full audits based on limited information. 14 of 40 tested cases are recommended for a more detailed energy audit, if a 30% savings criterion is used. The data required are easily obtained; the procedure can be carried out automatically, so no experience is required. If the actual types of HVAC system, measured weather-dependent and weather-independent energy consumption are known, the methodology should work better.

Future directions

A pre-screening methodology is developed and tested for identifying large commercial buildings with potential energy savings; not all buildings are recommended for further energy audit.

The methodology is tested with “accumulated” utility bills, but more confidence can be obtained from a test with actual utility bills of several large commercial buildings; if the buildings tested are all over the United States instead of just Texas, then the validity of the methodology can be confirmed.

Three of the “cut-off” criteria are used when recommendation is made whether there is some potential energy savings in a large commercial building based on the estimated potential energy savings. Which criterion should be used deserves further study.

The latent load from fresh air should be considered when SUBTB is used to separate electricity utility bills for large commercial buildings in hot and humid climates.

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APPENDIX I

INPUT FILE OF PROTOTYPE BUILDING FOR SENSITIVITY ANALYSIS

```
Section     1:00  General     Information

1.1   Relative    humdity     -1    or    dew   point 0

      1
1.2   Dry   bulb  temperature (F)   range (low  and   high)

      -25   110
1.3   Do    you   have  decimal     date  in    the   input file  (1=y
      or    0=n)
      1
1.4   Job   for   each  subsystem:  0-Not exist 1     simulation  and
      3     optimization
      1     0     0     0     0     0     0
1.5   The   key   system      in    this  investigation     (1    to
      7)
      1
1.6   The   first Vacation    period:month      day   to    month day

      1     1     1     2
1.7   The   second      vacation    period:month      day   to    month
      day
      1     1     1     2
1.8   The   third vacation    period:month      day   to    month day

      1     1     1     2

1.9   Energy      price $/kWh $/MMBtu-CHW $/MMBtu-HW

      0.05  3.9   4

Section     2:00  Inputs      for   sub-system  1

1     System      type  (1-DDPOA    2     DDPMA 3     SDRHOA      4
      SDRHMA      5     SDHC  and   6     SDHCH)
      2

2     Conditioned floor area  (sq-ft)     and   fraction    of
      interior    area
      128000      0.66

3     Occupied    period:     Start and   end   for   Weekday
      Saturday    Sunday      Vacation
      0     23    0     23    0     23    0     23

4     Room  temperature for   occupied    and   unoccupied  (heating
      and   cooling)
      75    75    75    75

5     Total flow  rate  and   outside     air   flow  rate  (cfm/sq-
ft)to interior    and   exterior    zones
```

```
      1.1   1.1   0.1   0.1

6     Minimum     air   flow  for   occupied    and   unoccupied

      1.1   1.1

7     Maximum     room  relative    humidity
      0.6
8     Minimum     air   flow  through     each  duct  (for  DD
      system)
      0
9     Excessive   Air   Leakage     CFM/sq-ft
      1.00E-01
10    O.A.  CO2   -350  Zone  CO2   -1000 ppm
      380   840
11    O.A.  control     1:bet=c     2:CFMoa=c   3:CFMoa>=CFMoamin 4:IAQ
      5:IAQ+Occupancy
      1
12    Economizer  Type  1-Enth.     2-Temp.     3-None

      3
13    Economizer  Range Tmin  Tmax
      20    60
14    Minimum     and   maximum     outside     air   intake
      fraction
      0.1   1
15    Internal    Heat  Gain  W/sq-ft
      2.2   2.2
16    Average     Floor Area  For   Each  Person      sq-ft/person
      200
17    Clock Internal    Electrical  gain  Ratio for   Weekdays
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      1     1     1     1
      1     1     1     1
      1     1     1     1
      0.5   0.5   0.5   0.5
18    Clock Internal    Electrical  Gain  Ratio for   Saturday
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
19    Clock Internal    Electrical  Gain  Ratio for   Sunday
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
20    Clock Internal    Electrical  Gain  Ratio for   Vacation
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
      0.5   0.5   0.5   0.5
```

```
      0.5   0.5   0.5   0.5
21    Nighttime   Base  Electrical  Gain  Ratio

      0.5
22    Exterior    Wall  Area  (sq-ft)     and   U     value (Btu/sq-ft
      hr    F)
      67339 0.119586718

23    Exterior    Window      Area  (sq-ft)     and   U     value
      (Btu/sq-ft  hr    F)
      6260.869565 1.1

24    Air   infiltration      for   interior    and   exterior    zones
      (ACH)
      0     0
25    Solar Gains (Solarmin   Toa   Solarmax    Toa)

      0.06519993  28.58 0.120920444 96.08

26    Supply      air   fan   HP    and   control     model(1-VFD 2-IGV
      3-VSD 4-DAD 5-BFIGV     6-BFDAD
      68    1
27    Return      air   fan   HP    and   control     model(1-VFD 2-IGV
      3-VSD 4-DAD 5-BFIGV     6-BFDAD
      0     1
28    Temp. Diff. Between     Return      and   Room  Air   Temp  F

      2
29    Clock HVAC  Operation   Model for   Weekdays
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
30    Clock HVAC  Operation   Model for   Saturday
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
31    Clock HVAC  Operation   Model for   Sunday
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
32    Clock HVAC  Operation   Model for   Vacation
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
      1     1     1     1
33    Cold  Deck  Schedule:   Tc1   Ta1   ..... Tc5   Ta5
```

	55	20	55	50	55	70	55	80	55	100
34	Hot	Deck	Schedule:		Th1	Ta1	.....	Th5	Ta5	
	110	20	110	40	100	50	80	70	80	110
35	Pre-heat		deck	schedule:		Tph1	Ta1	.....	Tph5	Ta5
	53	10	53	30	53	50	55	85	55	110
36	Pre-cooling		Deck	Schedule		Tpc1	Ta1	.....	Tpc5	Ta5
	60	160	60	260	57	360	57	460	57	560

APPENDIX II

CHARACTER OF ENERGY CONSUMPTION FOR DIFFERENT HVAC SYSTEMS

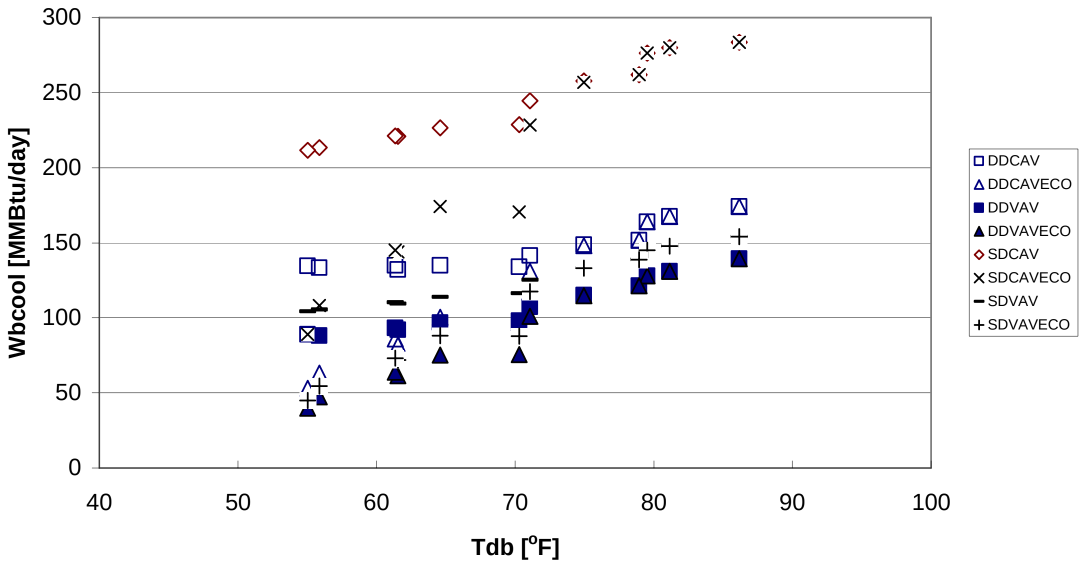


Figure II1 Comparison of simulated Wbcool consumption by eight systems for Zachry Engineering Center.

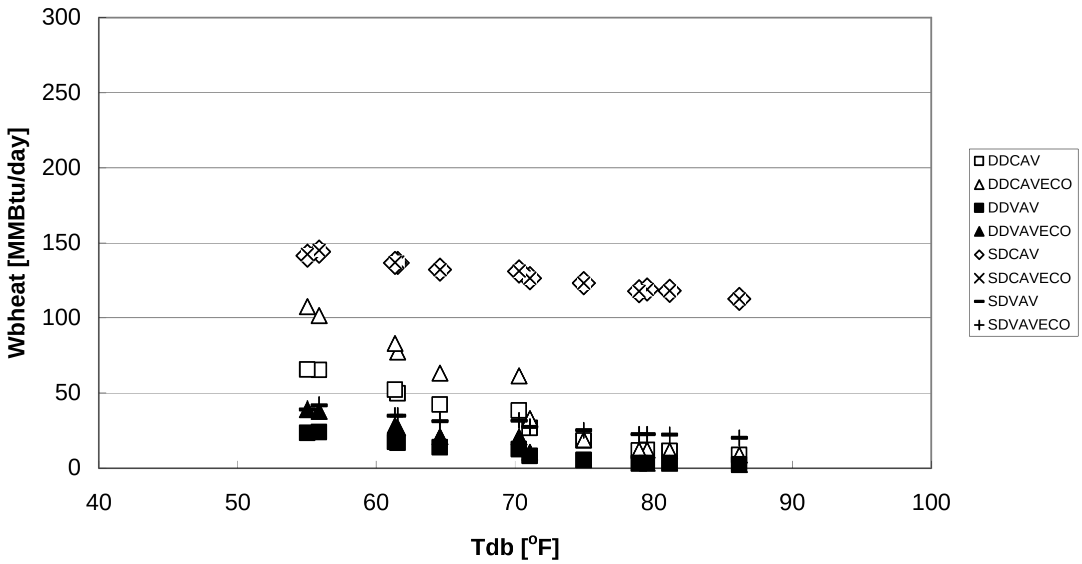


Figure II2 Comparison of simulated Wbheat consumption by eight systems for Zachry Engineering Center.

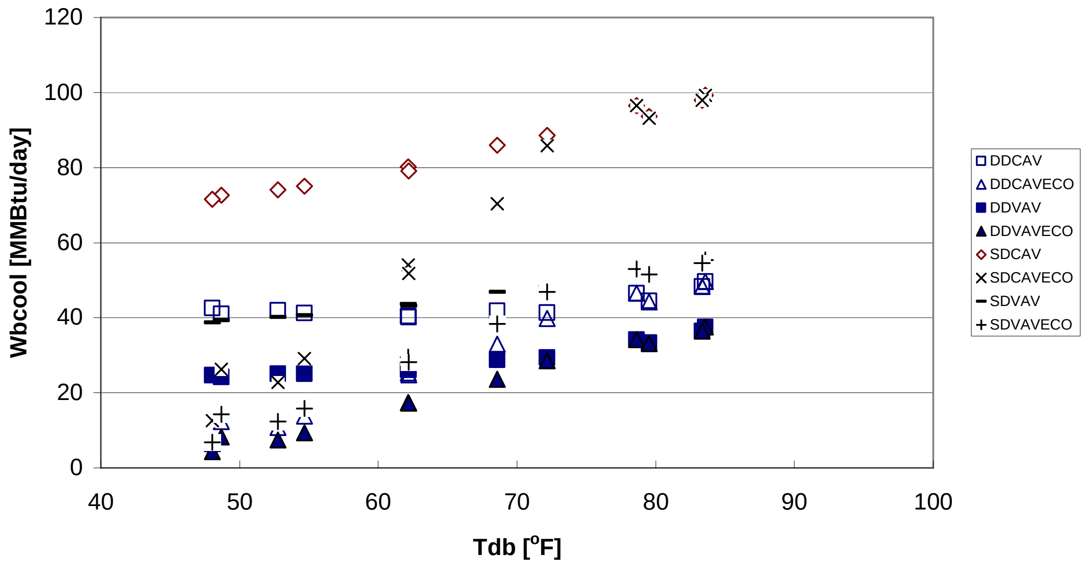


Figure 113 Comparison of simulated Wbcool consumption by eight systems for Harrington Tower.

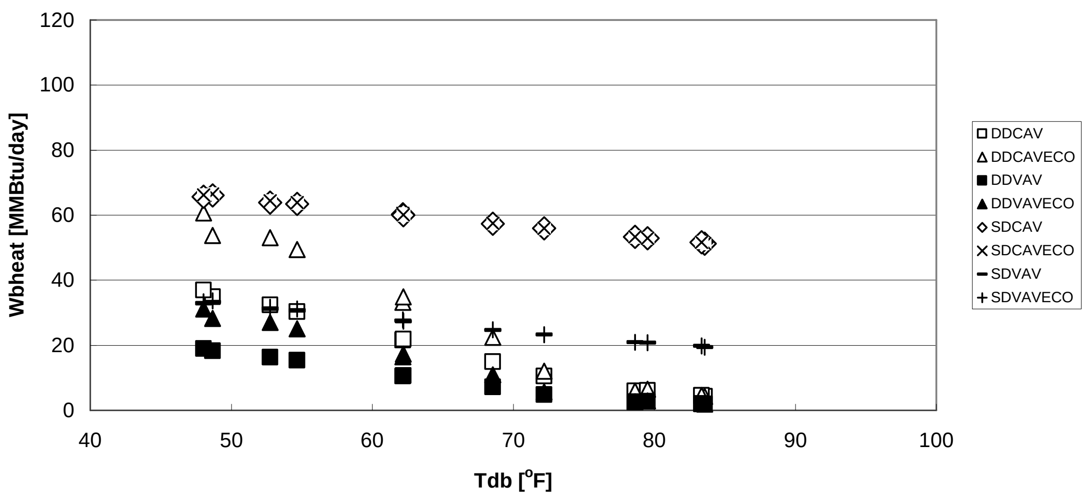


Figure 114 Comparison of simulated Wbheat consumption by eight systems for Harrington Tower.

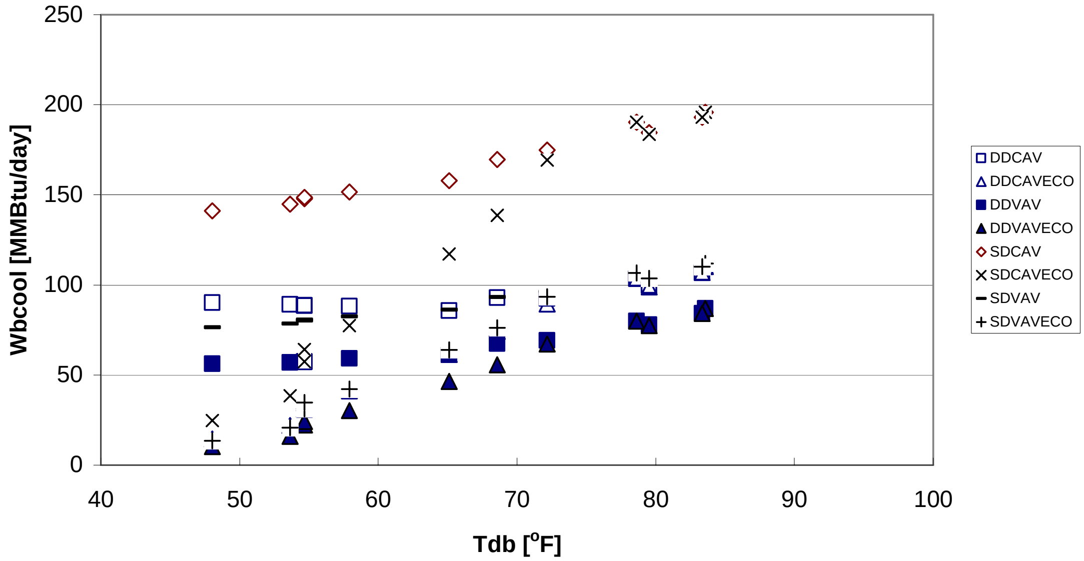


Figure 115 Comparison of simulated Wbcool consumption by eight systems for Blocker Building.

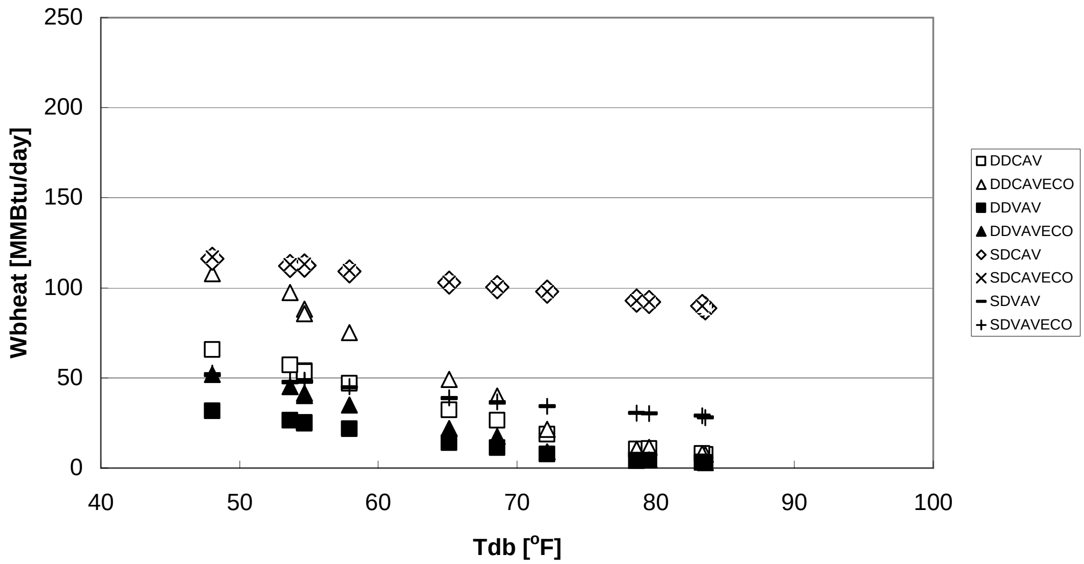


Figure 116 Comparison of simulated Wbheat consumption by eight systems for Blocker Building.

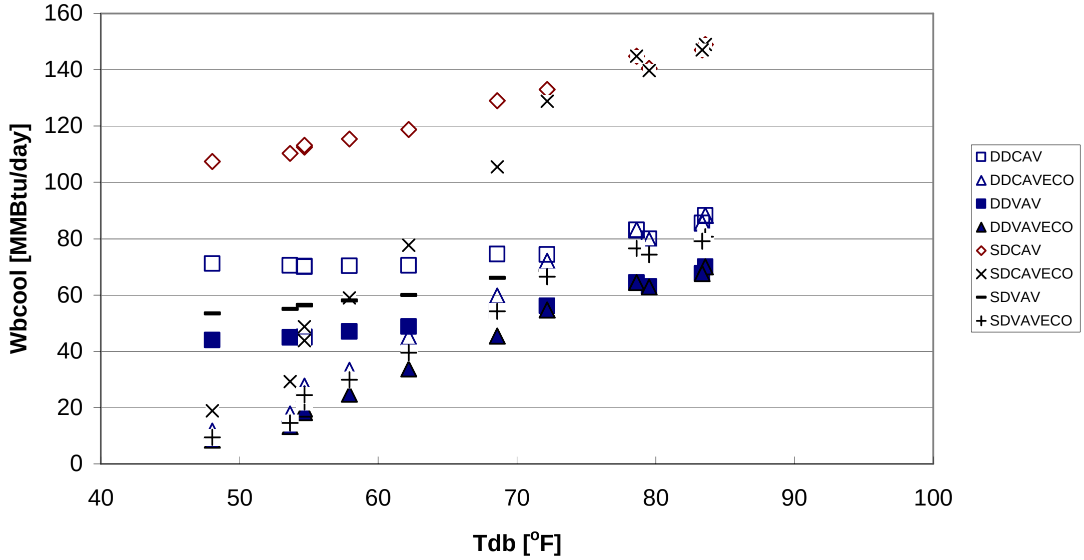


Figure 117 Comparison of simulated Wbcool consumption by eight systems for Oceanography and Meteorology.

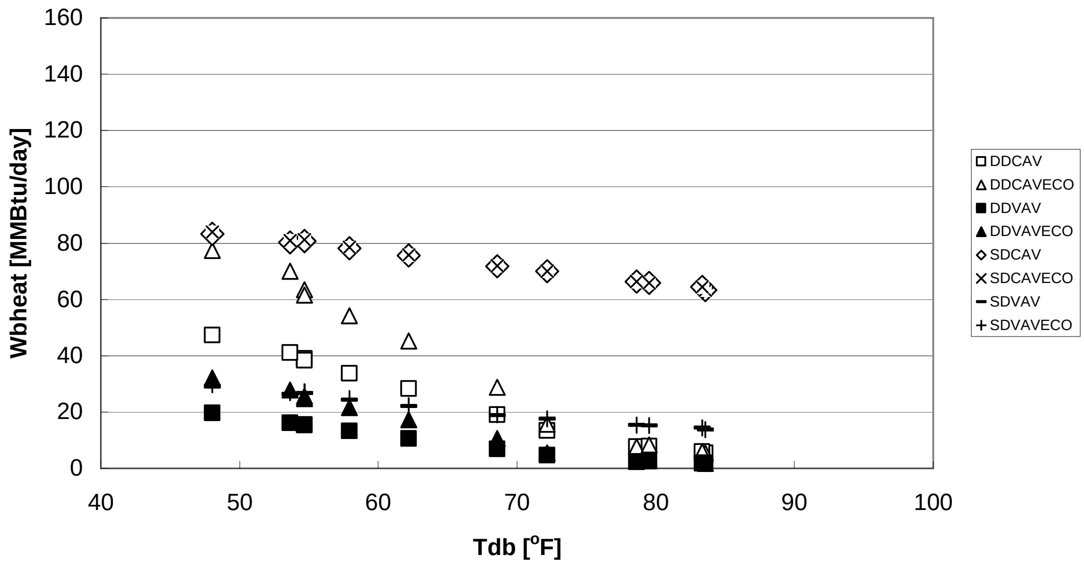


Figure 118 Comparison of simulated Wbheat consumption by eight systems for Oceanography and Meteorology.

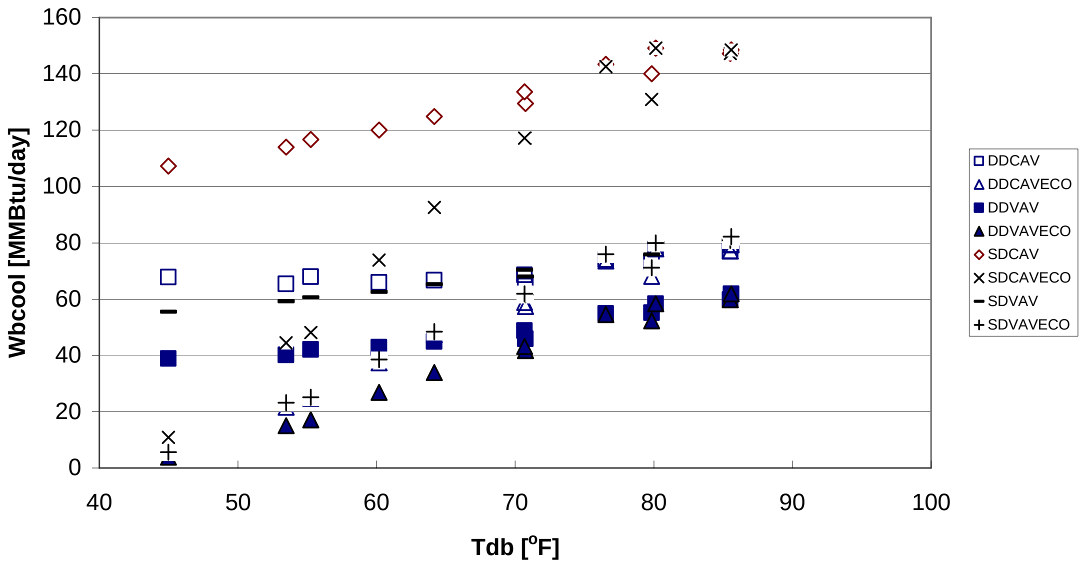


Figure I19 Comparison of simulated Wbcool consumption by eight systems for Wehner Building.

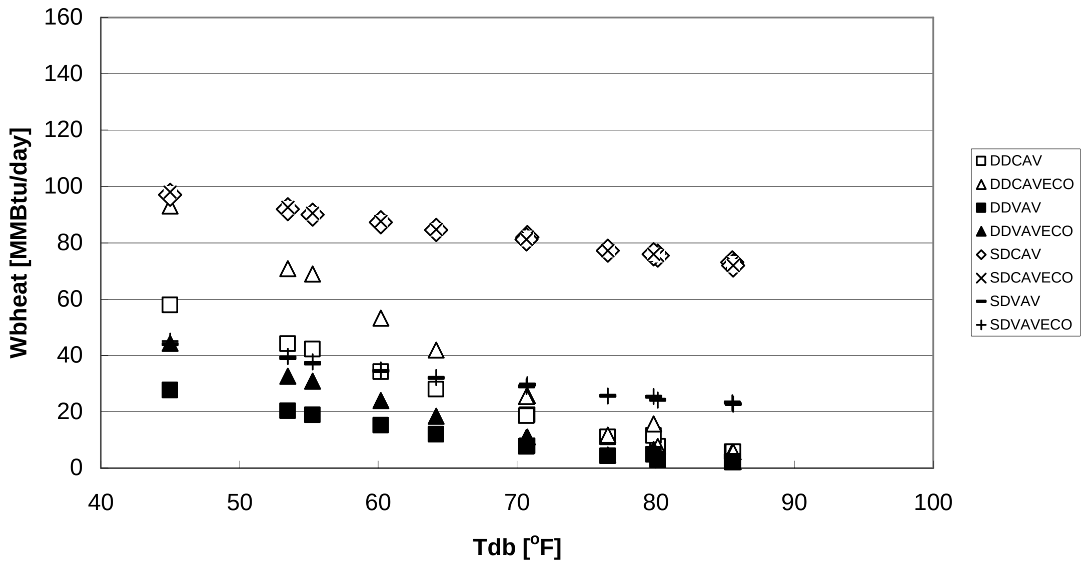


Figure I110 Comparison of simulated Wbheat consumption by eight systems for Wehner Building.

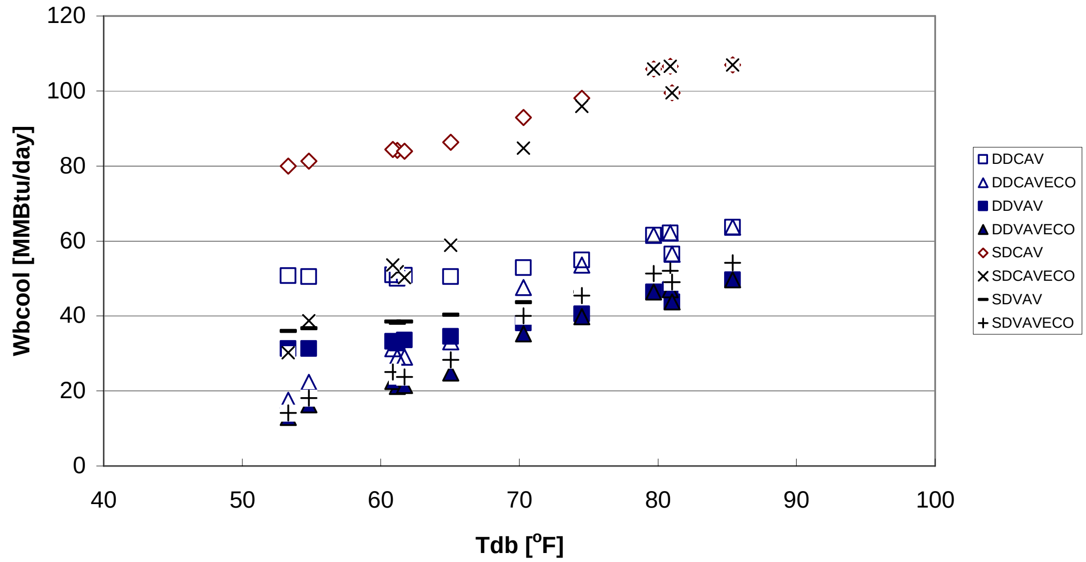


Figure I11 Comparison of simulated Wbcool consumption by eight systems for Koldus Student Services.

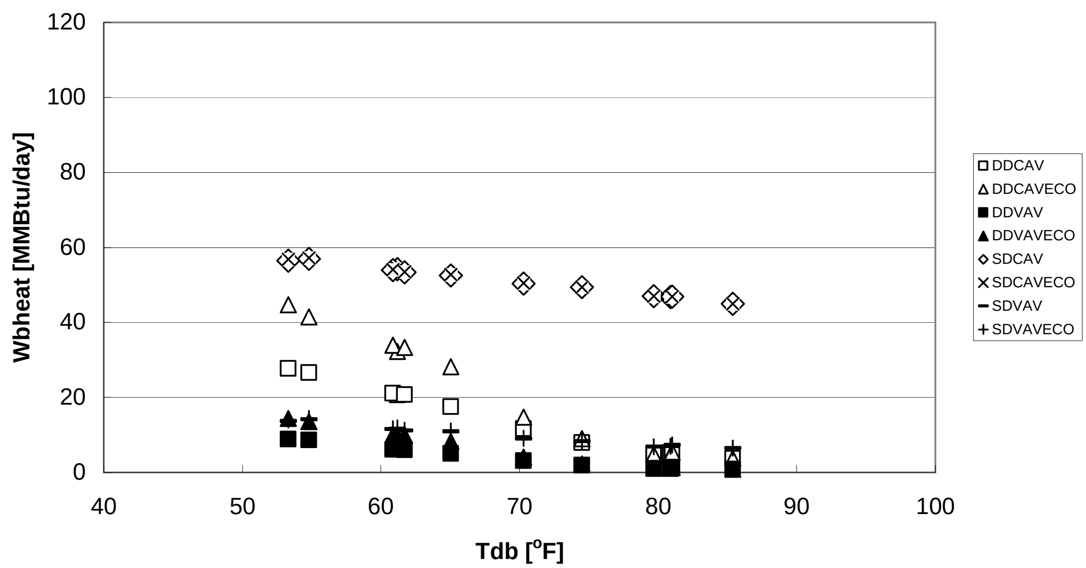


Figure I12 Comparison of simulated Wbheat consumption by eight systems for Koldus Student Services.

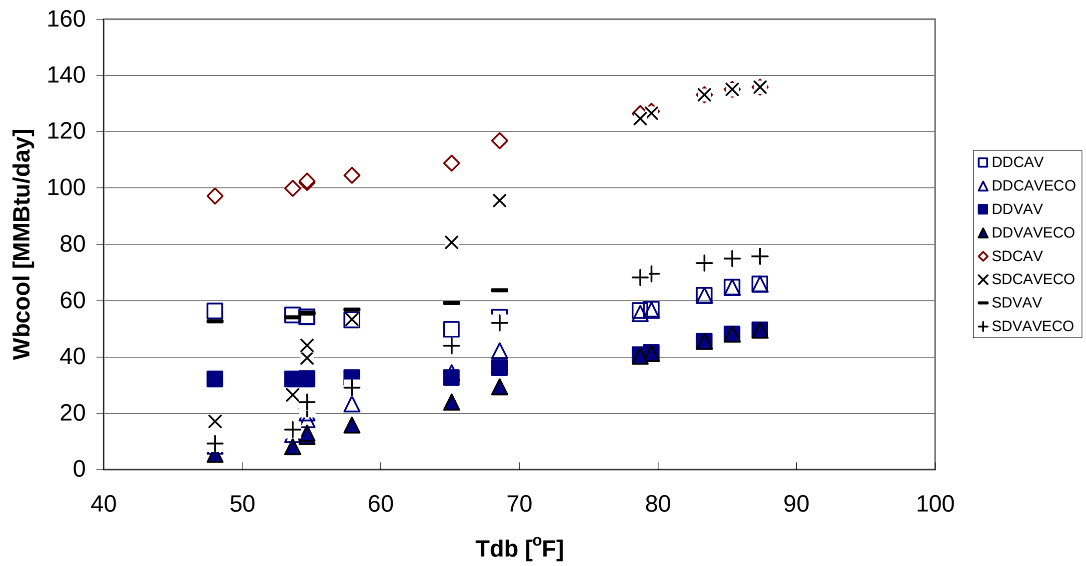


Figure I113 Comparison of simulated Wbcool consumption by eight systems for G. Rollie White.

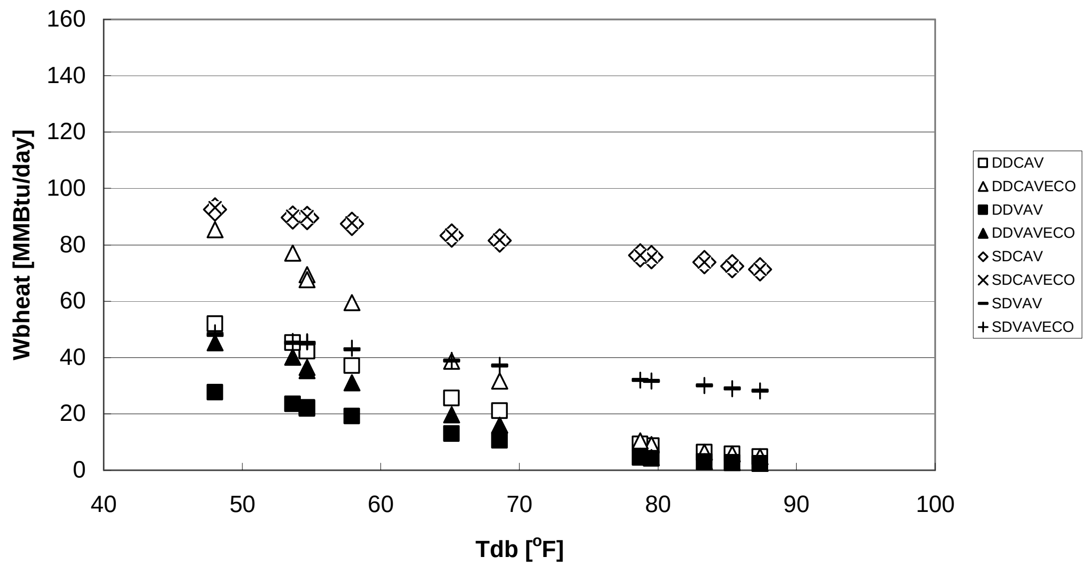


Figure I114 Comparison of simulated Wbheat consumption by eight systems for G. Rollie White.

APPENDIX III

INVESTIGATION OF COP FOR CHILLER SYSTEM

Table III1 Channels for electricity consumption by chiller system and supplied chilled water.

Facility	site number	Channels for cooling	Channels for chiller system	Note
Junior High School	998		4380+ 4381+ 4382+ 4383	
University of Texas Pan Am	125	322	320-321+1518	
Stroman High School	126	324	325	
Delmar College	143	165+167	155+156+157+158	
Government Center (George Allen Bldg.)	146	1019	1010+1011+1012+1013+1526+1000+1001+1002+1003+1004+1005+1006+1007+1008+1009+1014+1015	Before 11/17/94 11:00, there is no ch1526
TSTC Harlingen	150	3011=>1106	3001+3002+3003=>1107	8/30/96 23:59
UTA Thermal Energy Plant	173	1249	1228+1229+1234+1235+1240+1241+1255+1256+1261+1262+1224+1225+1226+1227+1230+1231+1232+1233+1236+1237+1238+1239+1251+1252+1253+1254+1257+1258+1259+1260+1263+1264+1265+1266	
TAMUK- Central Plant-1	190	4550=>4081+4083+4085	4541+4542+4543+4544+4545+4546=>4073+4074+4075+4076+4077+4078+4079+4080	12/8/2000 23:59
TAMUK- Central Plant-2	191	4093	4393+4394+4395+4396+4397+4398	
J.H. Winters	211	233	1974	
Central Services Building	226	2211	2205+2206+2207+2208	
Austin Convention Center	230	3782=>1471	3778=>1467	5/1/1998 15:00
Main CUP	310	1544+1546+1548+1550+1552	1536+1537+1554+1555+1656+1657	
College of the Mainland	320	1610	1614+1615+1594+1595+1592+1593+1612+1613	
Valle Verde Campus	325	1590	1576+1577+1581+1582	
Rio Grande Campus	326	1653	1637+1638+1645+1646+1647+1648+1649+1650	
Neil Kirkman Building A-Wing	922	2032	2004+2005+2010+2011	

3782=>1471 Channel 3782 is replaced by Channel 1471

5/1/1998 15:00 Time when channels change

Table 1112 Description for channels listed in Table 1111.

Channel	Site	Discription
155	143	Chiller 1 AB
156	143	Chiller 1 CB
157	143	Chiller 2 AB
158	143	Chiller 2 CB
165	143	Chl 1 Energy
167	143	Chl 2 Energy
233	211	ChW Btu
320	125	Central Utility
321	125	CV 480 V feed
322	125	CHW Btu
324	126	CHW
325	126	Chiller
1000	146	ChWP 1 A-B
1001	146	ChWP 1 C-B
1002	146	ChWP 2, 3 A-B
1003	146	ChWP 2, 3 C-B
1004	146	CWP 1 A-B
1005	146	CWP 1 C-B
1006	146	CWP 2, 3 A-B
1007	146	CWP 2, 3 C-B
1008	146	AHU3 A-B
1009	146	AHU3 C-B
1010	146	Chiller 1 A-B
1011	146	Chiller 1 C-B
1012	146	Chiller 2 A-B
1013	146	Chiller 2 C-B
1014	146	AHUs 5-8 A-B
1015	146	AHUs 5-8 C-B
1019	146	ChW Energy
1106	150	Campus ChW
1107	150	Campus ChW Flow
1224	173	Chw Pump1 Phase A
1225	173	Chw Pump1 Phase C
1226	173	Condenser Pumps 1A&1B A
1227	173	Condenser Pumps 1A&1B C
1228	173	Chiller 1 Phase A
1229	173	Chiller 1 Phase C
1230	173	ChW pump 2 Phase A
1231	173	ChW pump 2 Phase C
1232	173	Condenser Pumps 2A&2B A

Table III2 (Continued).

Channel	Site	Discription
1233	173	Condenser Pumps 2A&2B C
1234	173	Chiller 2 Phase A
1235	173	Chiller 2 Phase C
1236	173	Chw Pump 3 Phase A
1237	173	Chw Pump 3 Phase C
1238	173	Condenser Pump 3 A
1239	173	Condenser Pump 3 C
1240	173	Chiller 3 Phase A
1241	173	Chiller 3 Phase C
1249	173	Whole Campus ChW
1251	173	ChW pump 4 Phase A
1252	173	ChW pump 4 Phase C
1253	173	Condenser Pump 4 A
1254	173	Condenser Pump 4 C
1255	173	Chiller 4 Phase A
1256	173	Chiller 4 Phase C
1257	173	ChW pump 5 Phase A
1258	173	ChW pump 5 Phase C
1259	173	Condenser Pump 5 A
1260	173	Condenser Pump 5 C
1261	173	Chiller 5 Phase A
1262	173	Chiller 5 Phase C
1263	173	Cool Tower Fan 1 A
1264	173	Cool Tower Fan 1 C
1265	173	Cool Tower Fan 2&3 A
1266	173	Cool Tower Fan 2&3 C
1467	230	Chil Elec EGY Chil
1471	230	Bldg ChwBtu
1518	125	480 Chiller
1526	146	New Chiller
1536	310	Chlr #1 Elec Energy
1537	310	Chlr #2 Elec Energy
1544	310	Home Eco ChW Energy
1546	310	North Loop ChW Energy
1548	310	South Loop ChW Energy
1550	310	East Loop ChW Energy
1552	310	West Loop ChW Energy
1554	310	ChW Pump #1 Elec Energy
1555	310	ChW Pump #2 Elec Energy
1556	310	ChW Pump #3 Elec Energy

Table III2 (Continued).

Channel	Site	Discription
1557	310	ChW Pump #4 Elec Energy
1576	325	CHIL Elec A
1577	325	CHIL Elec C
1581	325	CHWP Elec A
1582	325	CHWP Elec C
1590	325	Campus Chw
1592	320	Cool Twr Fan 3, 4, 5, 6 A
1593	320	Cool Twr Fan 3, 4, 5, 6 B
1594	320	Chlr 3, 4 Elec A
1595	320	Chlr 3, 4 Elec B
1610	320	Campus ChW Energy
1612	320	Cool Twr Fan 1, 2 A
1613	320	Cool Twr Fan 1, 2 B
1614	320	Chlr 1, 2 Elec A
1615	320	Chlr 1, 2 Elec B
1637	326	CHIL Elec A
1638	326	CHIL Elec C
1645	326	ChW Pump Elec
1646	326	ChW Pump Elec
1647	326	Condenser Pump Elec
1648	326	Condenser Pump Elec
1649	326	Cool Tower Fan
1650	326	Cool Tower Fan
1653	326	Campus ChW
1974	211	CHILLER 1, 2, 3
2004	922	CHILLERS A
2005	922	CHILLERS B
2010	922	CHW PUMPS A
2011	922	CHW PUMPS B
2032	922	CHILLER BTUS
2205	226	TRANE CHLR A
2206	226	TRANE CHLR C
2207	226	CARRIER CHLR A
2208	226	CARRIER CHLR C
2211	226	CHW Btu
3001	150	CHILLER PHASE A
3002	150	CHILLER PHASE B
3003	150	CHILLER PHASE C
3011	150	CHWBTU CAMPUS
3778	230	CHIL ELEC ENERGY

Table III2 (Continued).

Channel	Site	Discription
3782	230	BUILDING BTU
4073	190	0-CHIL 1 ELE EGY
4074	190	1-CHIL 1 ELE EGY
4075	190	2-CHIL 1 ELE EGY
4076	190	3-CHIL 1 ELE EGY
4077	190	8-CHIL 3 ELE EGY
4078	190	9-CHIL 3 ELE EGY
4079	190	11-CHIL 4 ELE EGY
4080	190	13-CHIL 4 ELE EGY
4081	190	1-CP1 LOOP 4
4083	190	2-CP1 LOOP 1
4085	190	4-CP1 LP 2-3
4093	191	0-CP2 CHWP
4380	998	CHILLER1 PH A
4381	998	CHILLER1 PH C
4382	998	CHILLER2 PH A
4383	998	CHILLER2 PH C
4393	191	CHILLER #1 A-B
4394	191	CHILLER #1 B-C
4395	191	CHILLER #1 C-A
4396	191	CHILLER #2 A-B
4397	191	CHILLER #2 B-C
4398	191	CHILLER #2 C-A
4541	190	CHILLER #1 A-B
4542	190	CHILLER #1 B-C
4543	190	CHILLER #1 C-A
4544	190	CHILLER #2 A-B
4545	190	CHILLER #2 B-C
4546	190	CHILLER #2 C-A
4550	190	0-CP2 CHWP

Junior High School

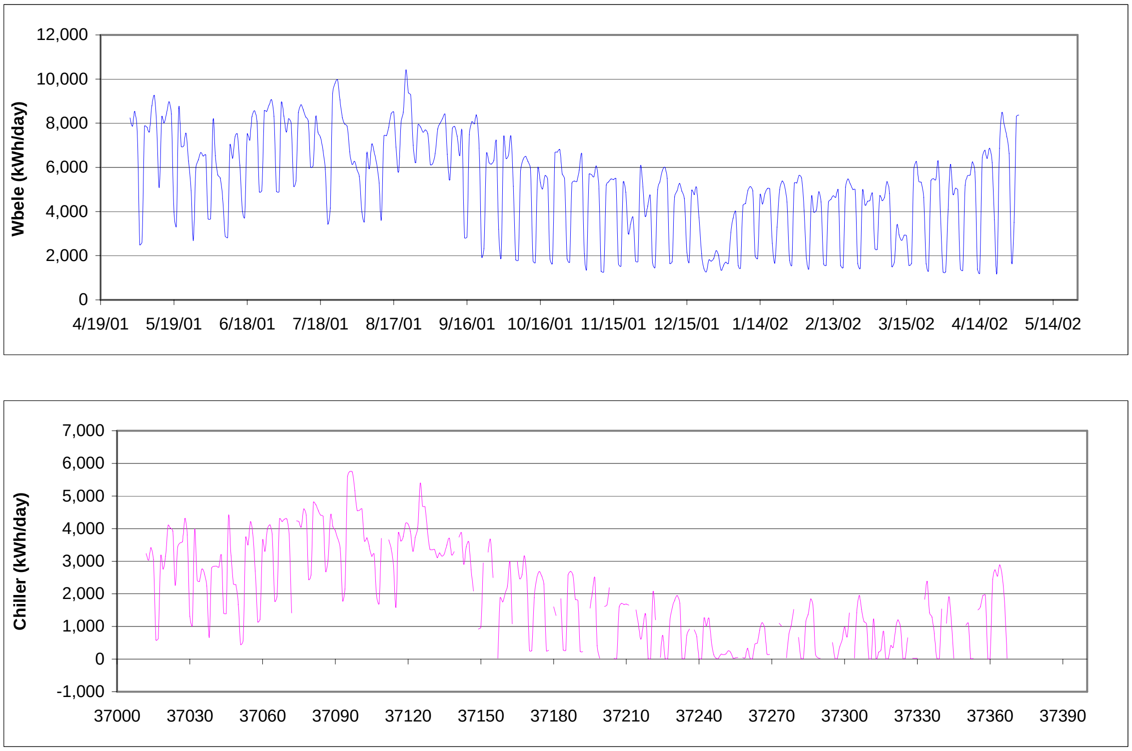
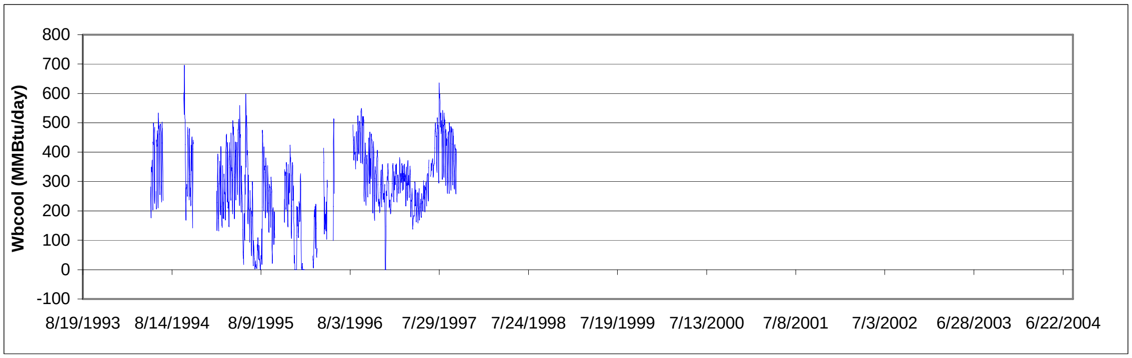
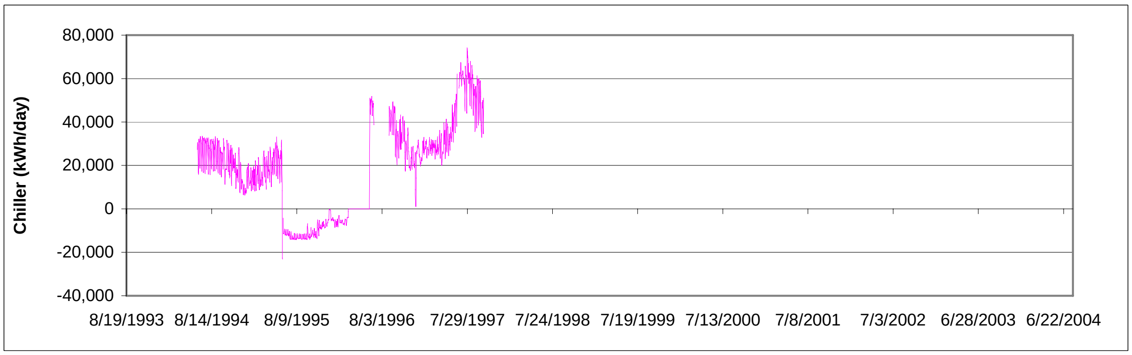


Figure III1 Whole building electricity consumption and electricity consumption by chiller in Junior High School (998).

University of Texas Pan Am





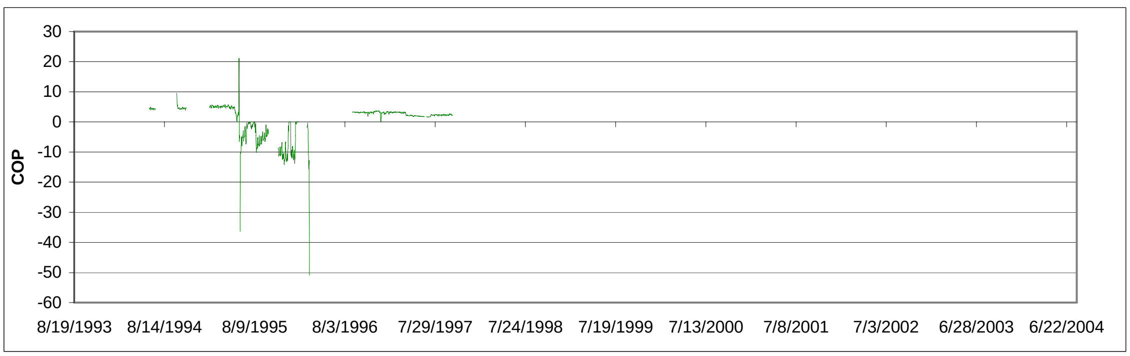
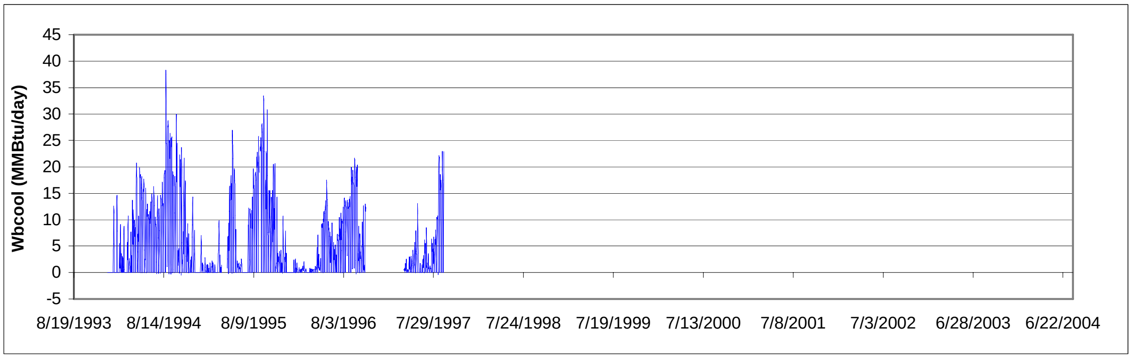
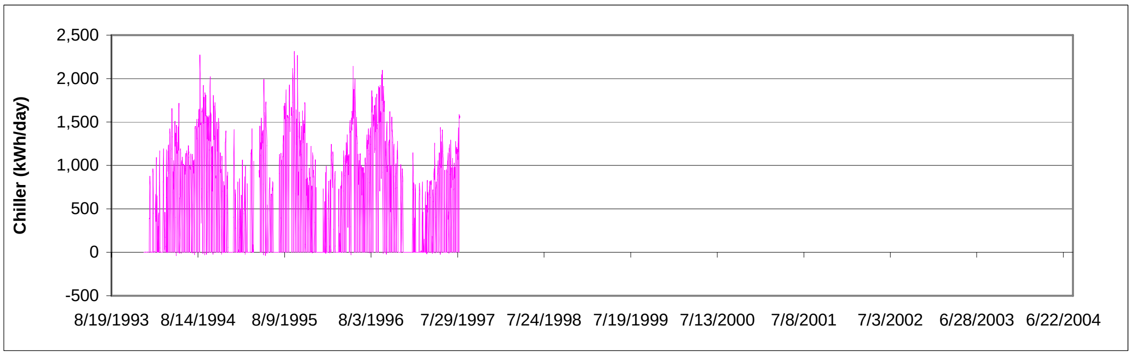


Figure 1112 Electricity consumption, chilled water, & COP of the chiller system in site 125.

Stroman High School





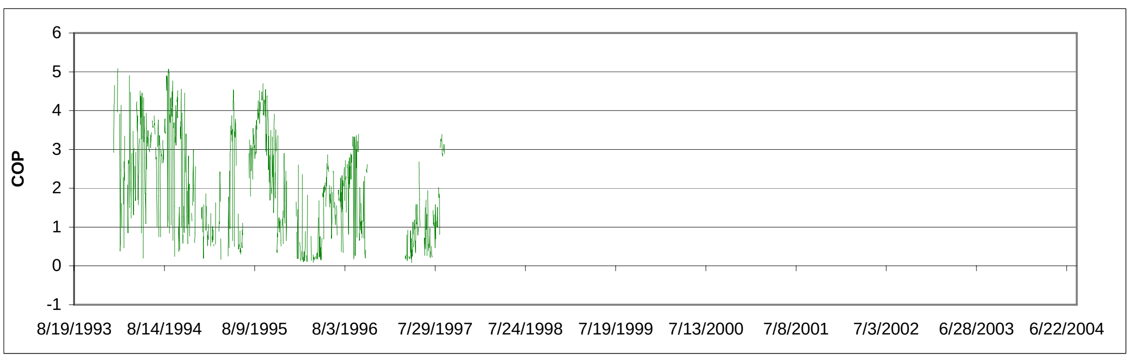


Figure I113 Electricity consumption, chilled water, & COP of the chiller system in site 126.

Delmar College

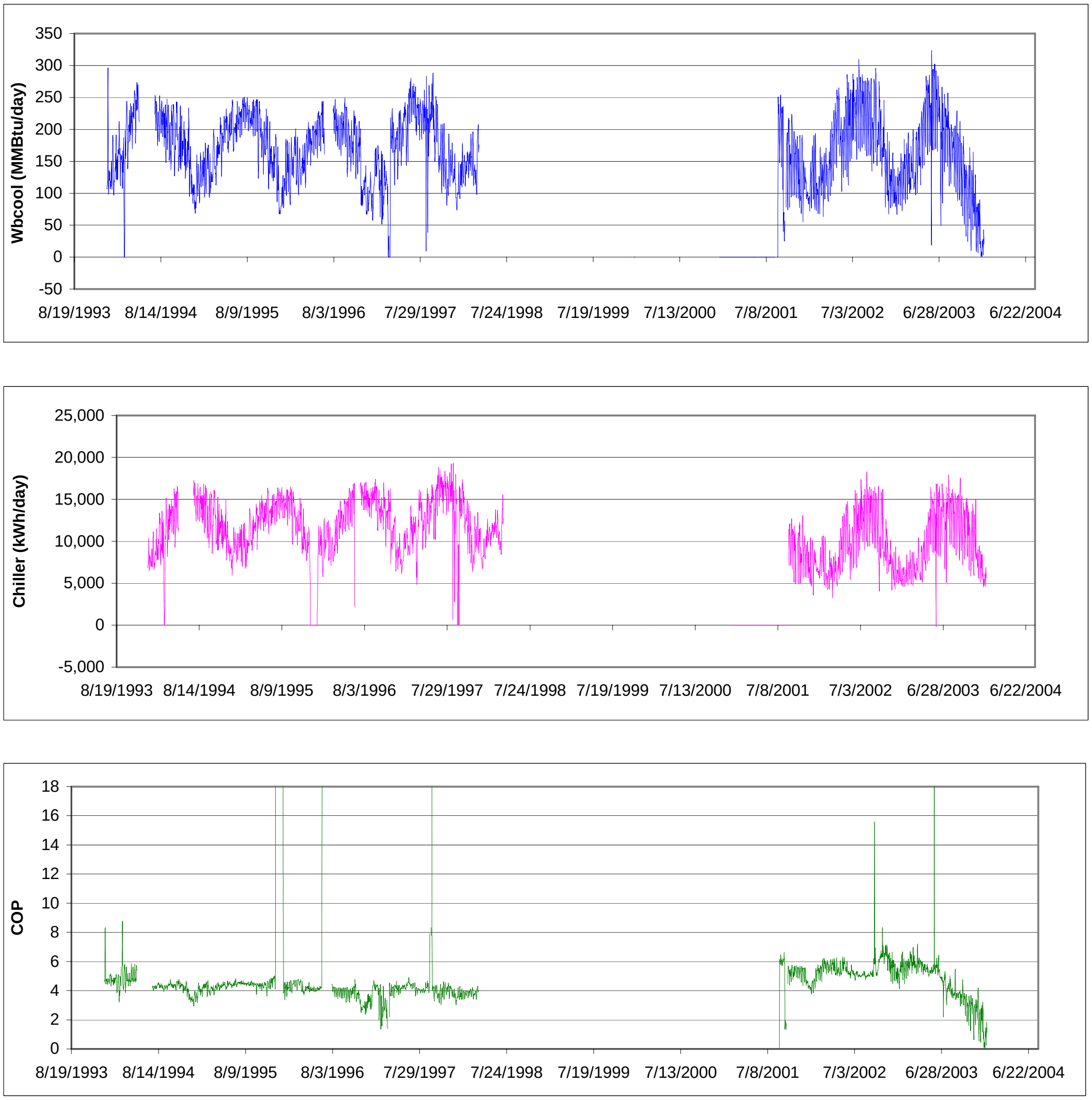


Figure I114 Electricity consumption, chilled water, & COP of the chiller system in site 143.

Government Center (George Allen Building)

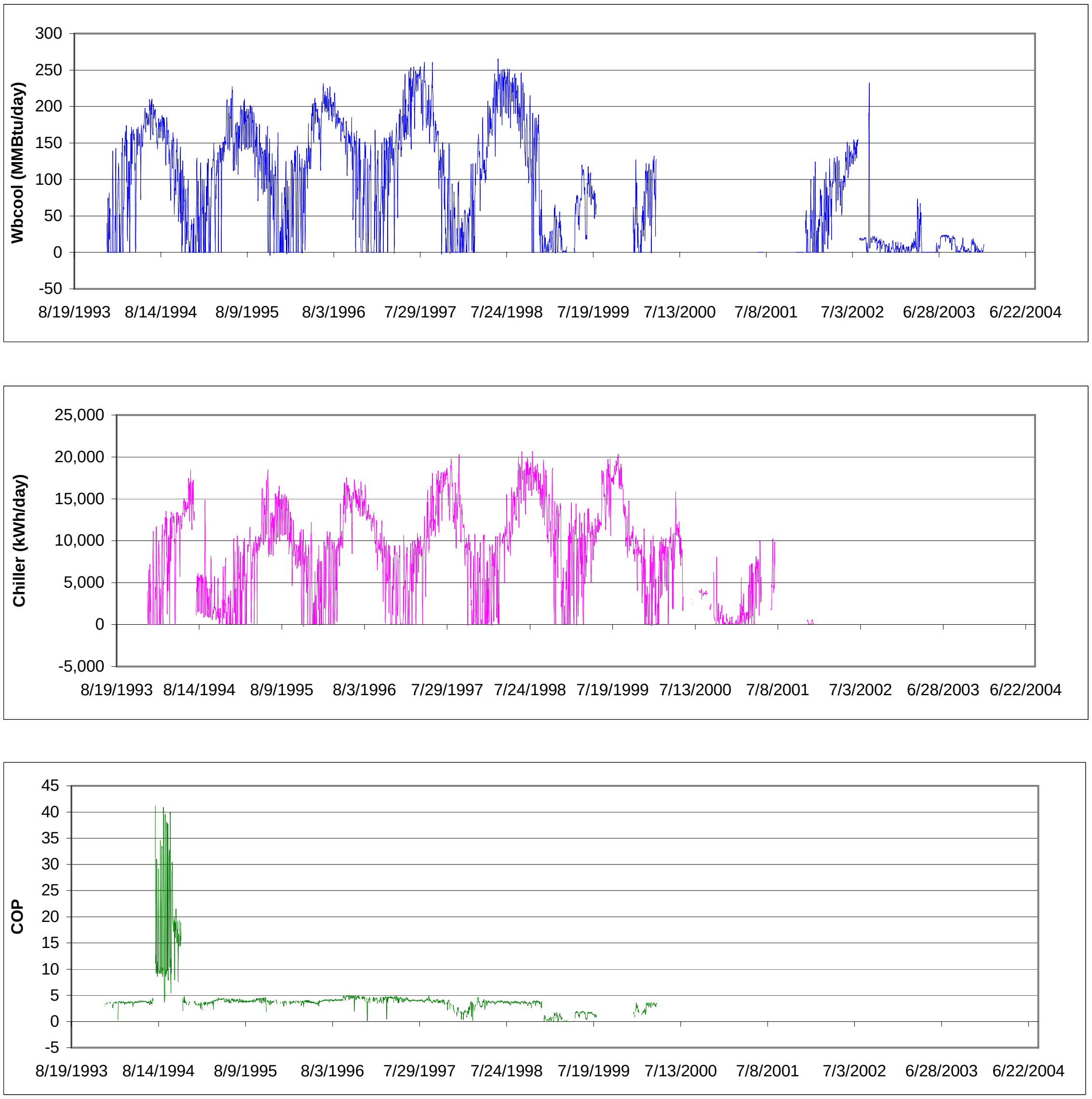
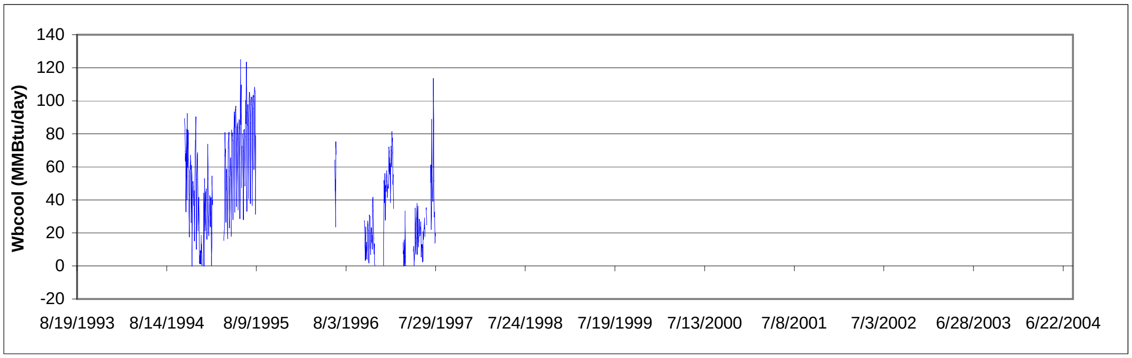
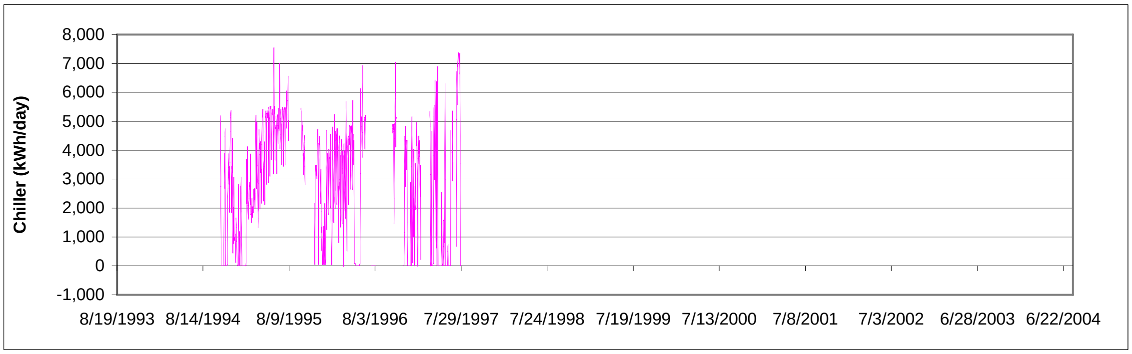


Figure I115 Electricity consumption, chilled water, & COP of the chiller system in site 146.

TSTC Harlingen





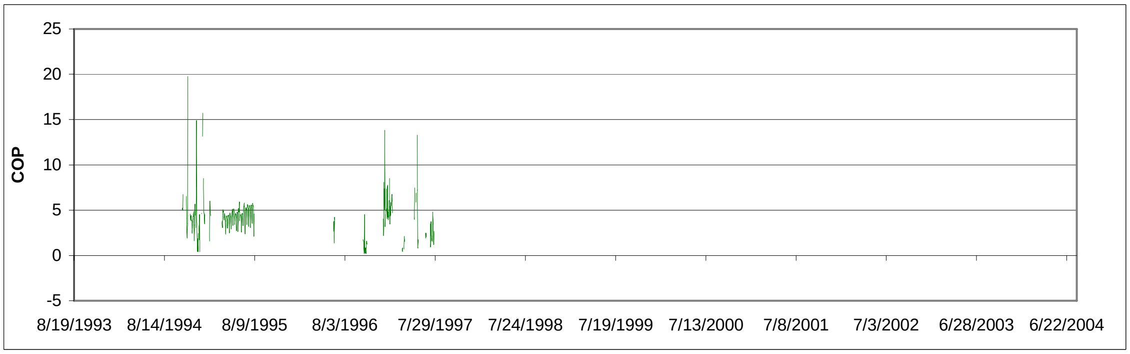


Figure I116 Electricity consumption, chilled water, & COP of the chiller system in site 150.

UTA Thermal Energy Plant

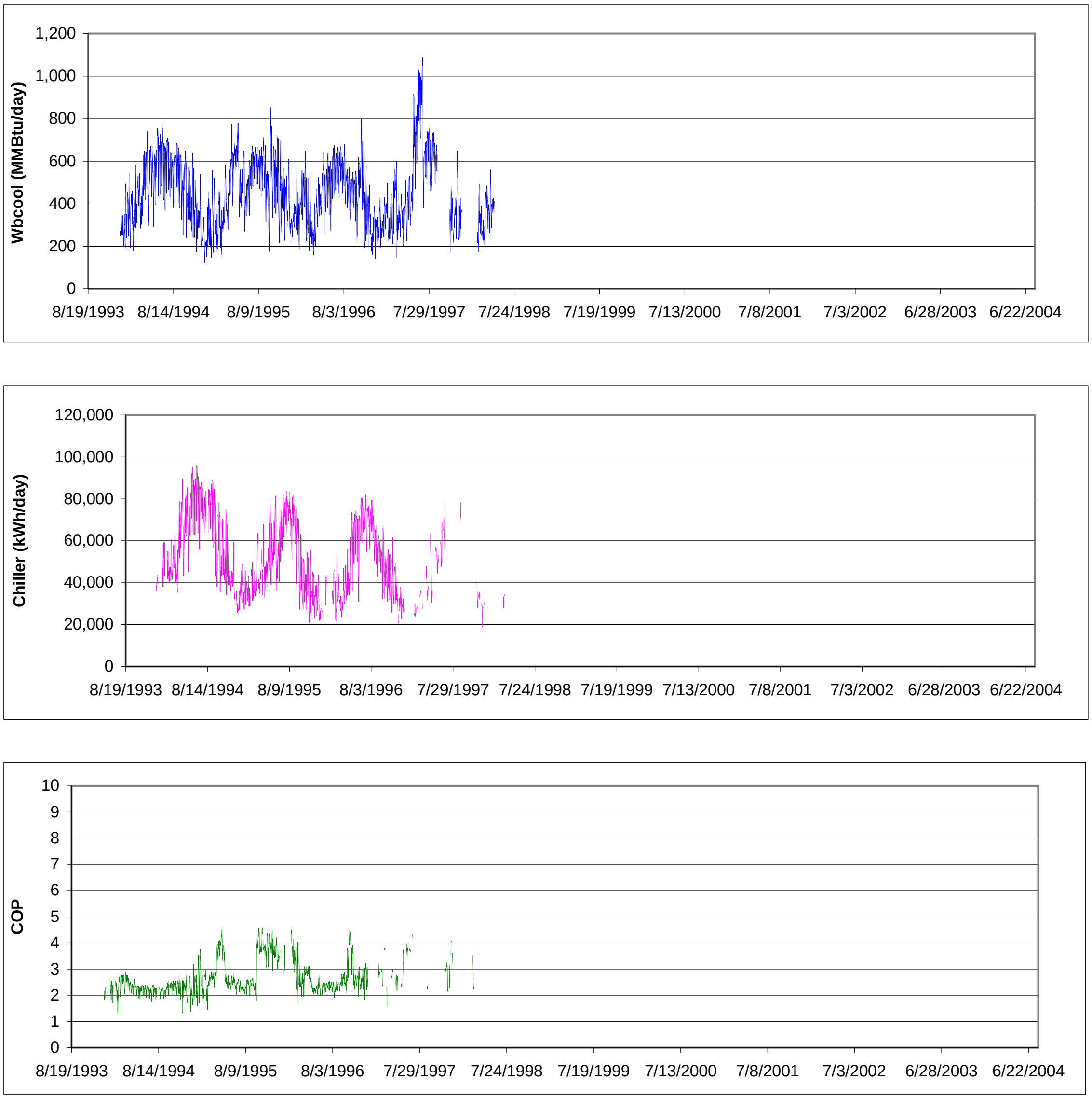


Figure I117 Electricity consumption, chilled water, & COP of the chiller system in site 173.

TAMUK-Central Plant-1

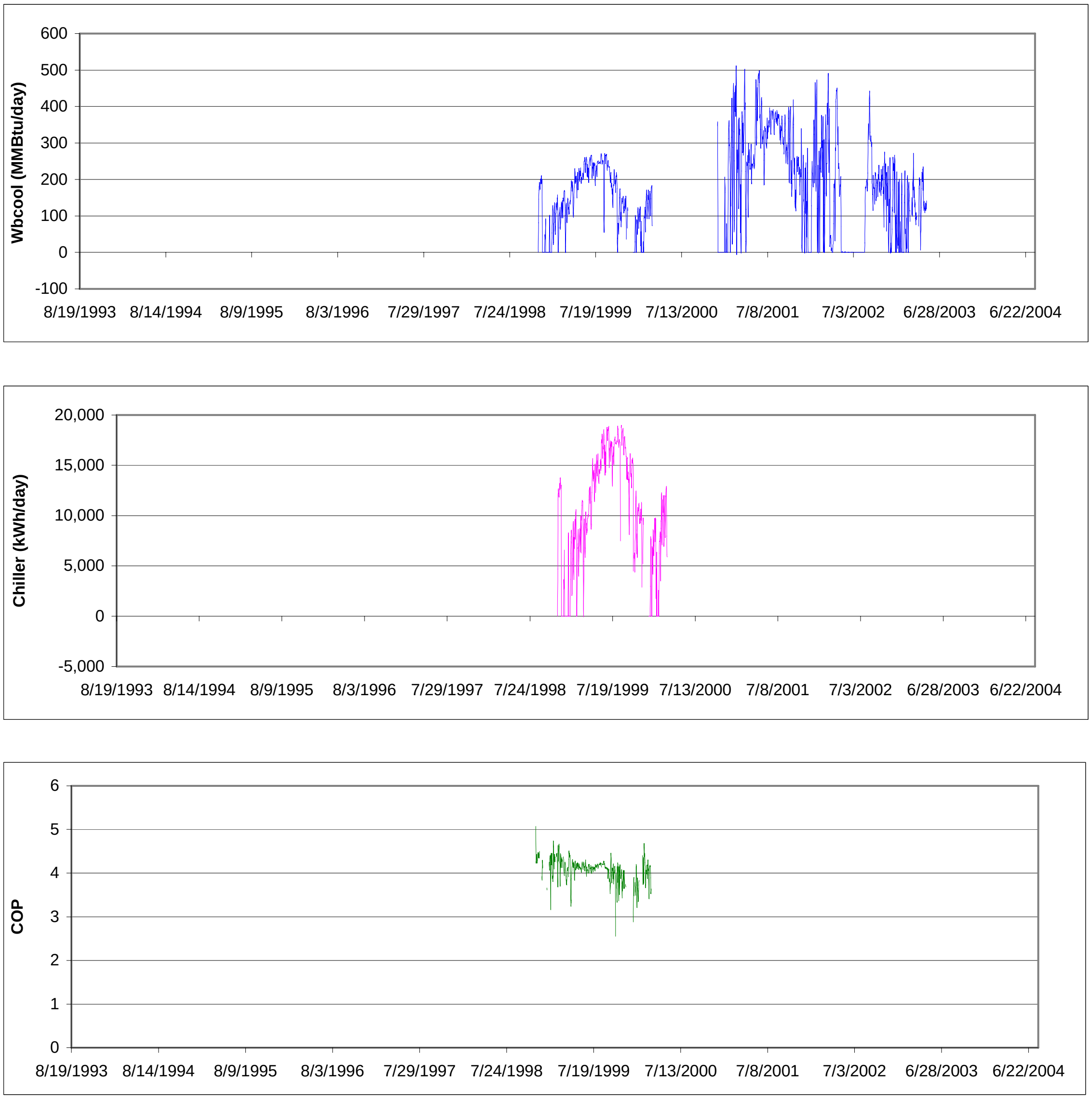


Figure 1118 Electricity consumption, chilled water, & COP of the chiller system in site 190.

TAMUK-Central Plant-2

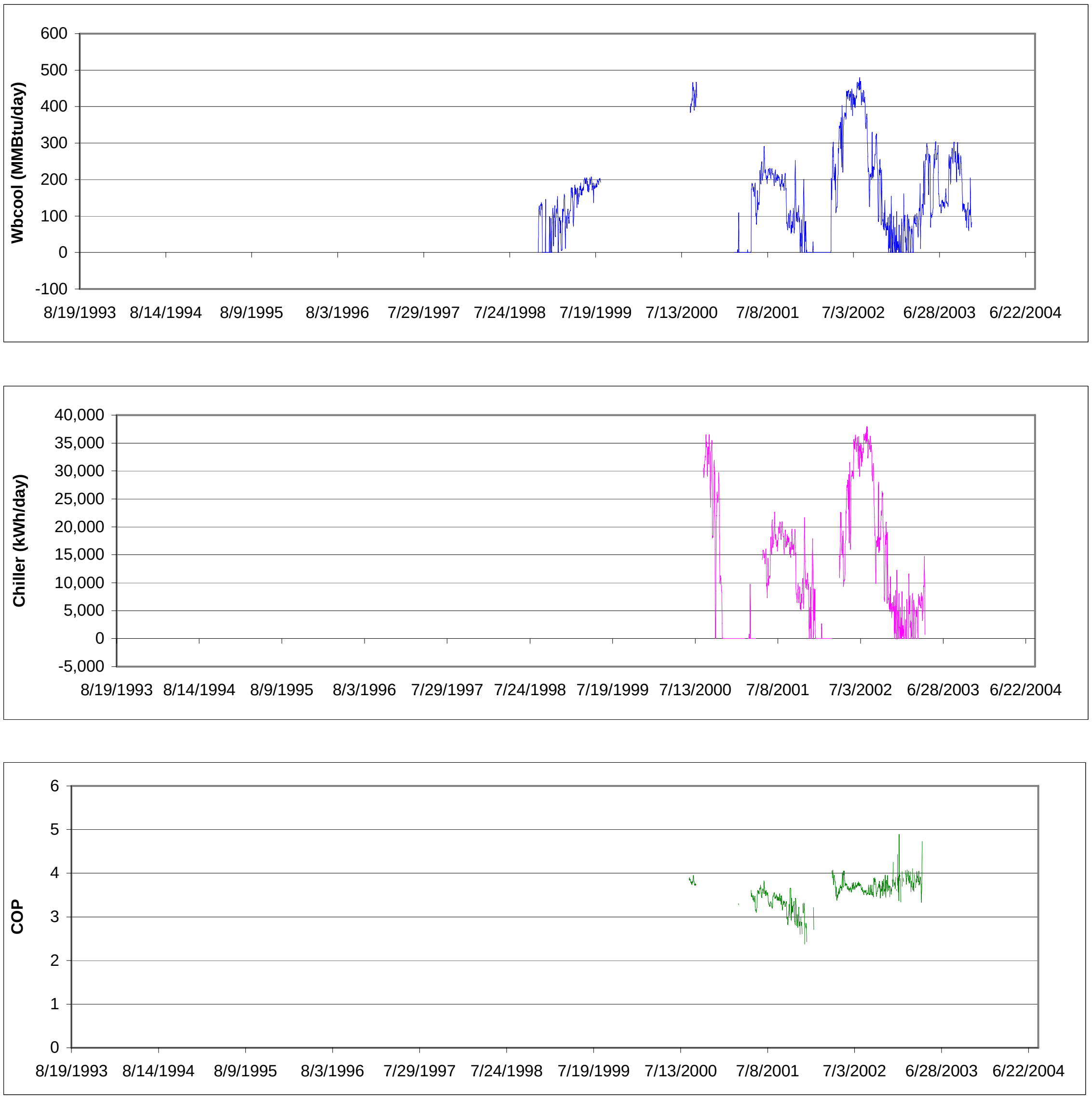


Figure 1119 Electricity consumption, chilled water, & COP of the chiller system in site 191.

J.H. Winters

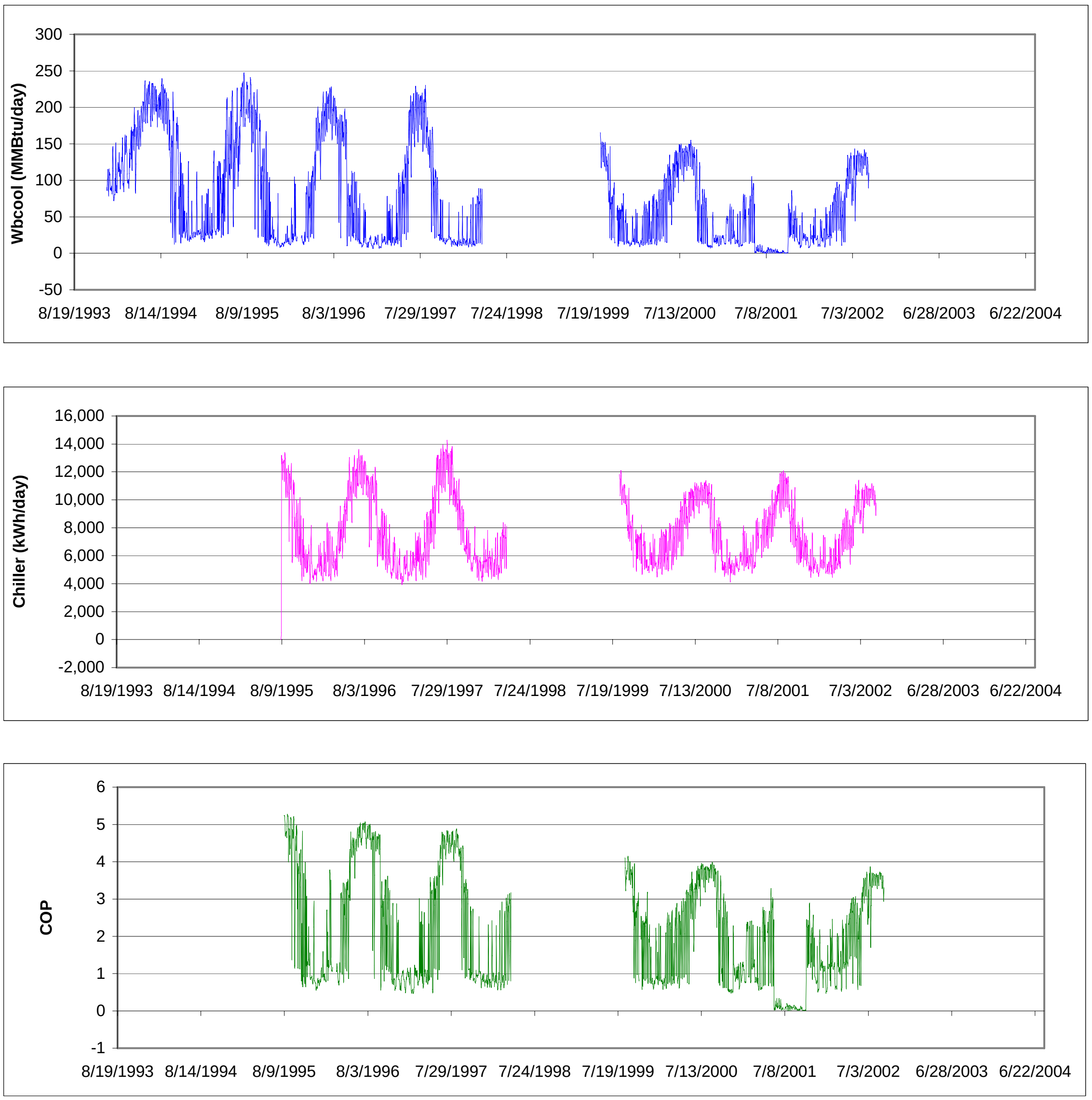
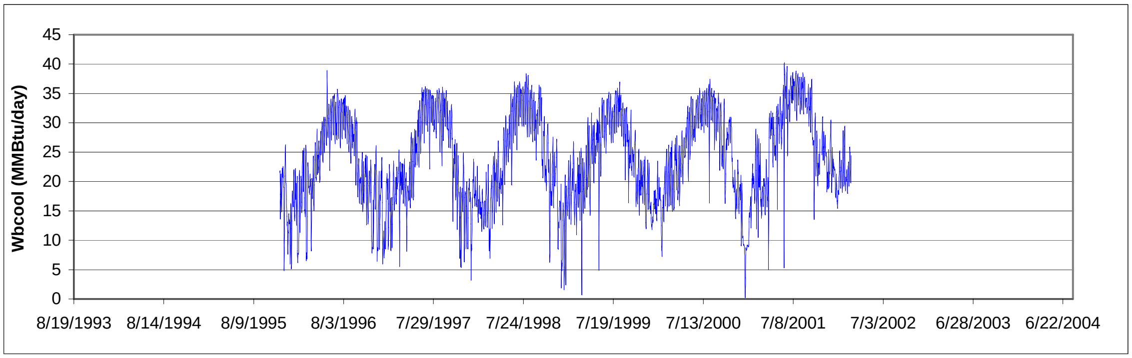
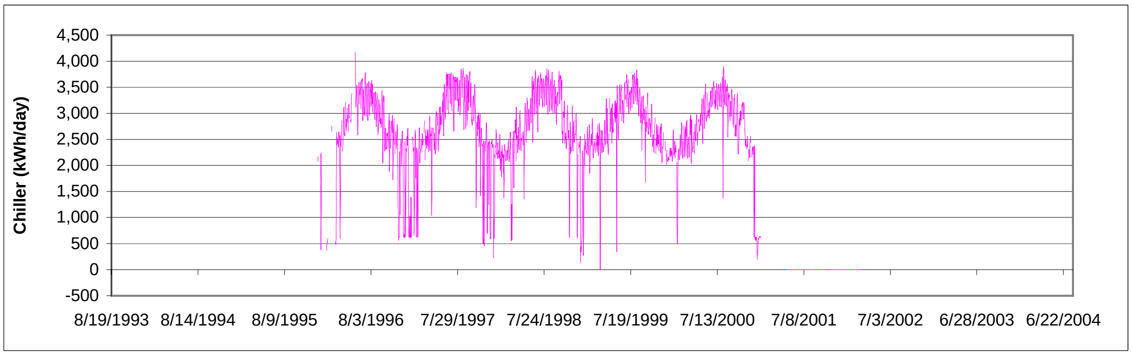


Figure III10 Electricity consumption, chilled water, & COP of the chiller system in site 211.

Central Services Building





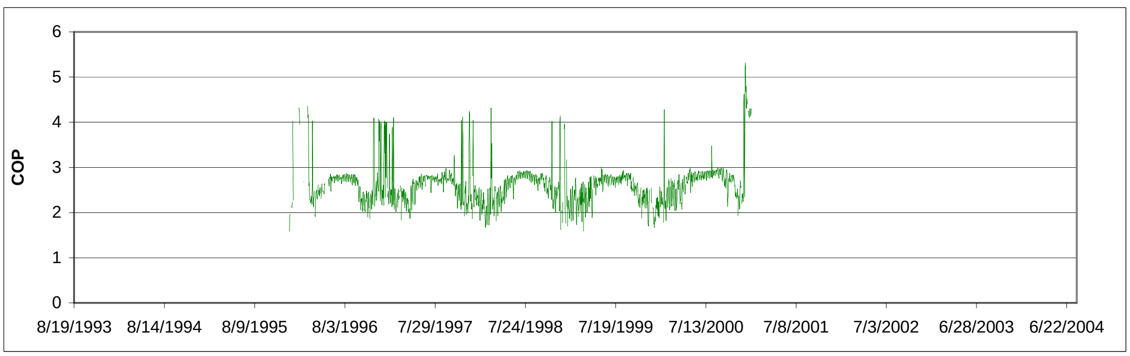


Figure III11 Electricity consumption, chilled water, & COP of the chiller system in site 226.

Austin Convention Center

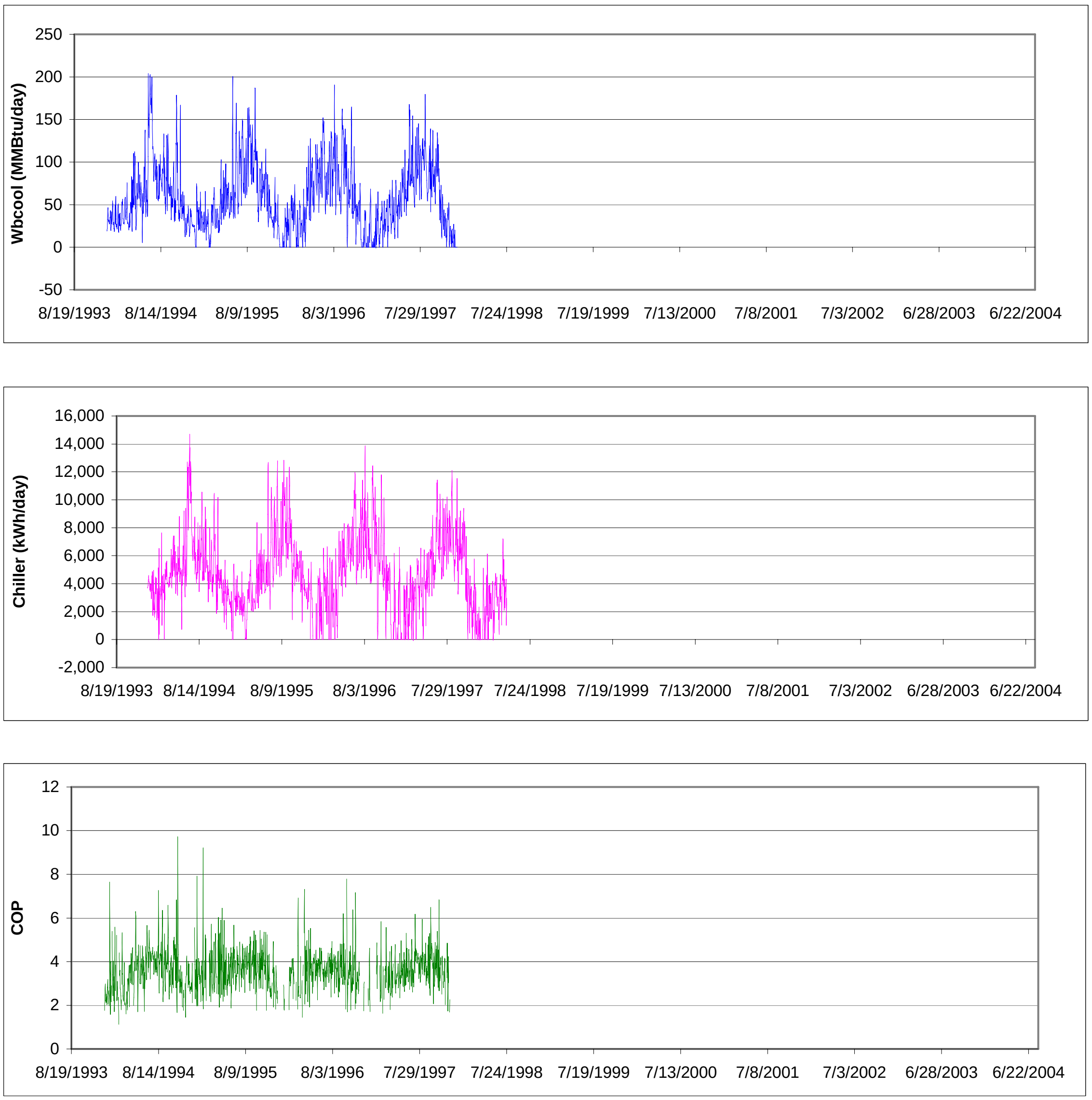
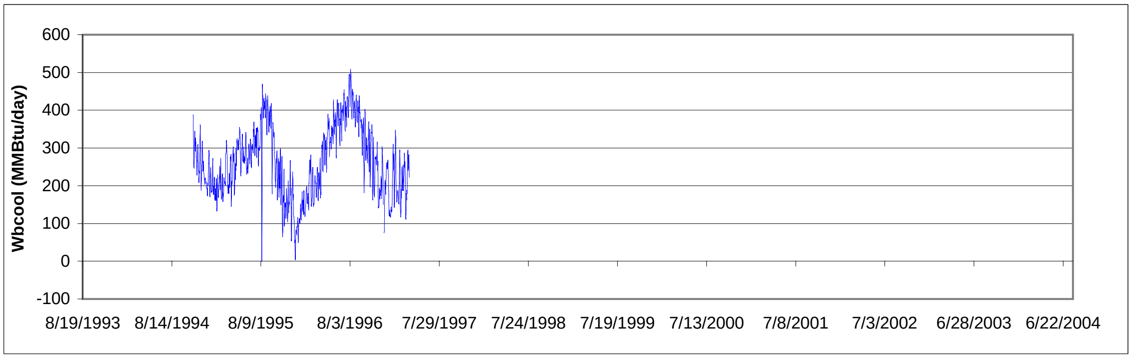
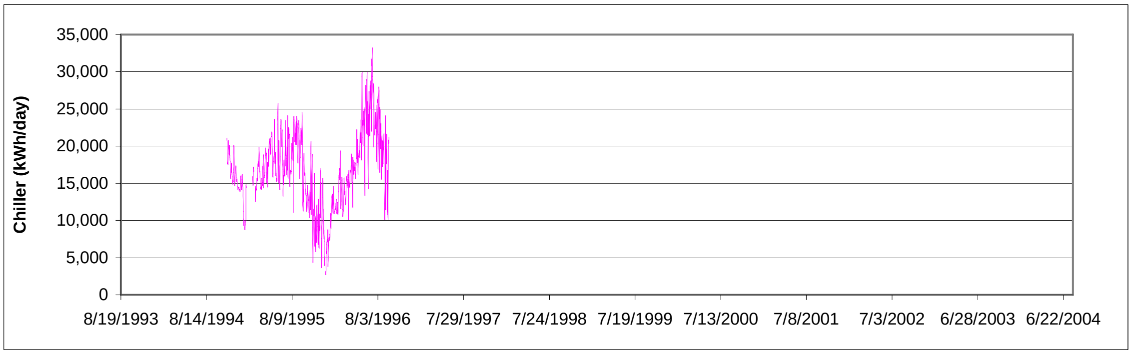


Figure III12 Electricity consumption, chilled water, & COP of the chiller system in site 230.

Main CUP





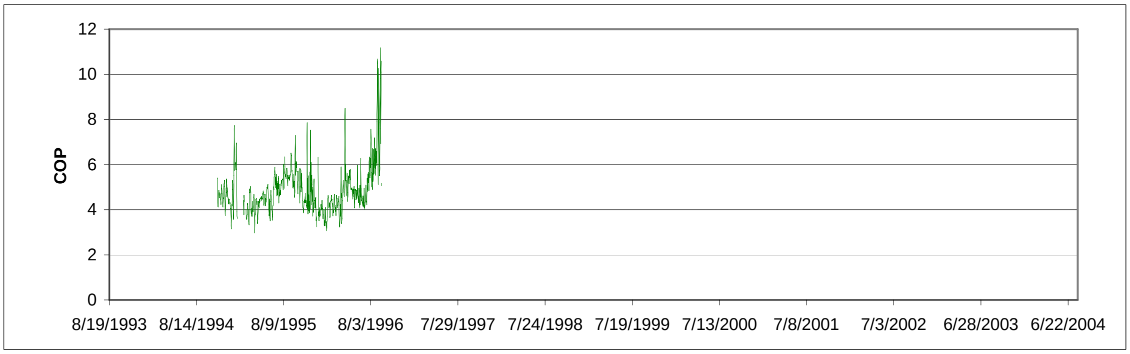
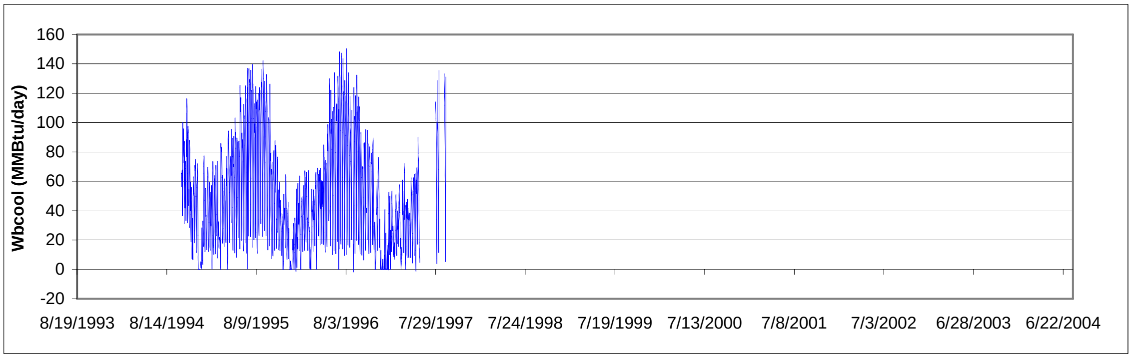
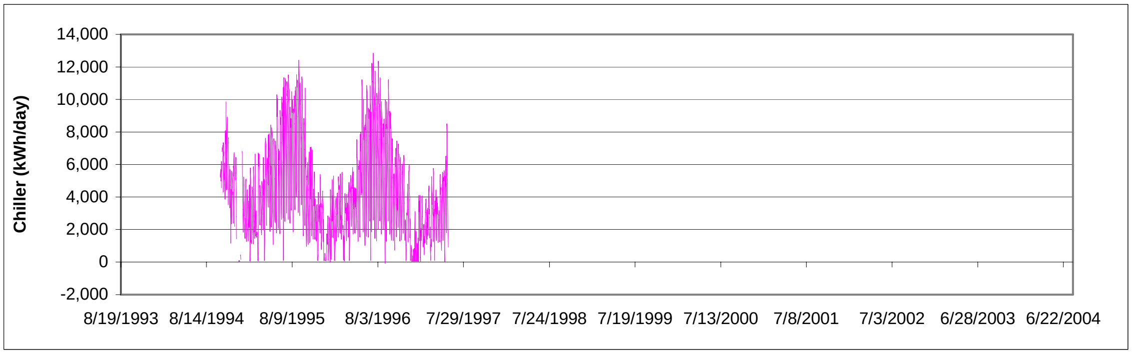


Figure III13 Electricity consumption, chilled water, & COP of the chiller system in site 310.

College of Mainland





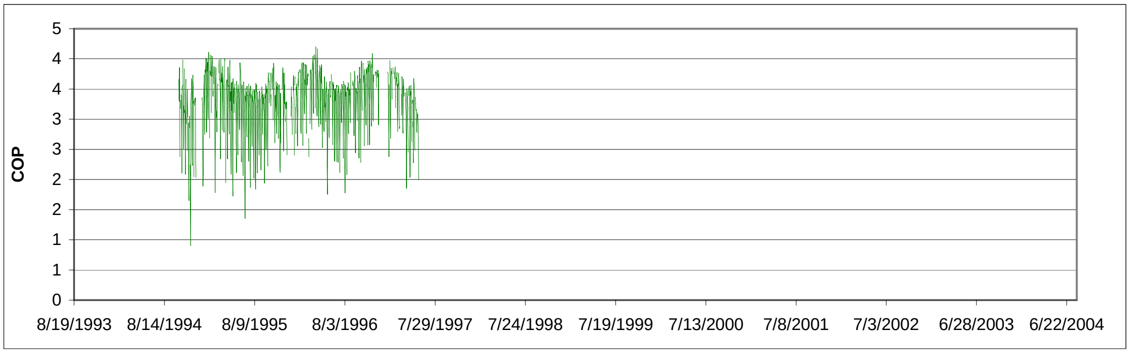


Figure III14 Electricity consumption, chilled water, & COP of the chiller system in site 320.

Valle Verde Campus

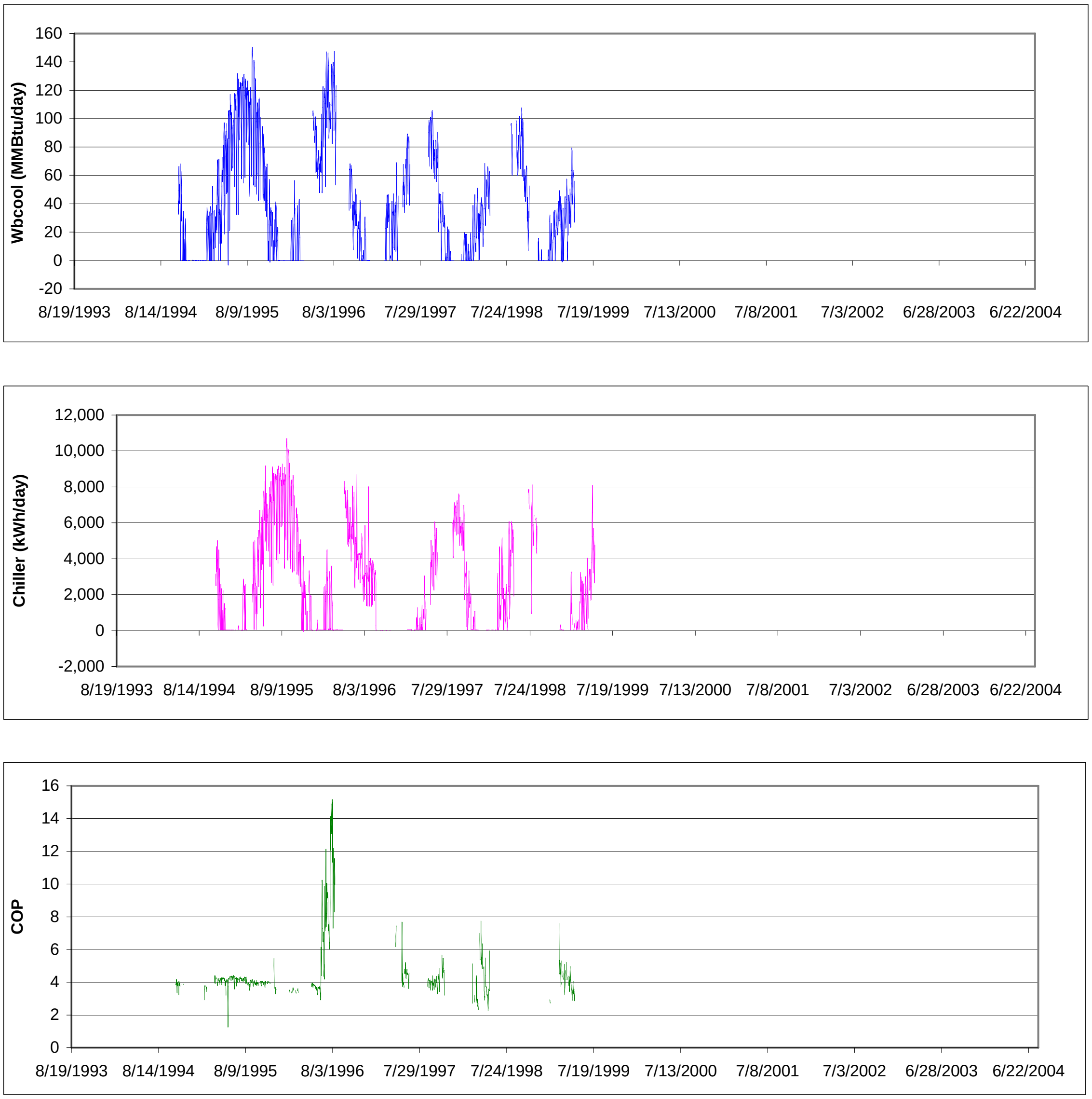
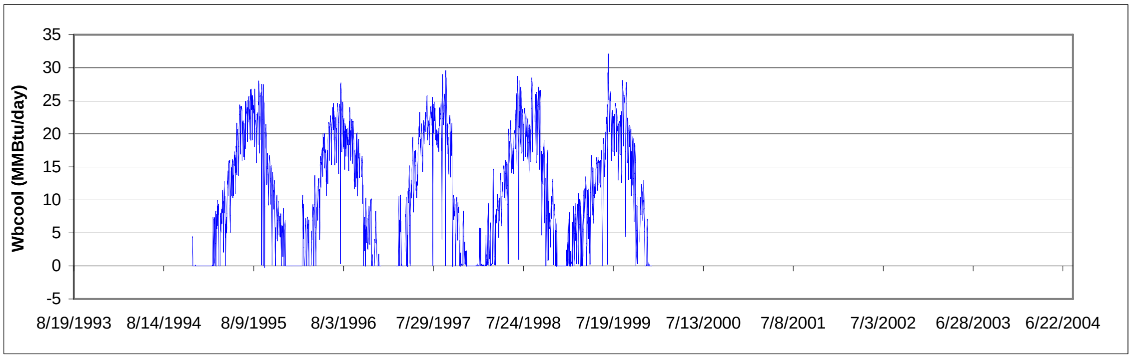
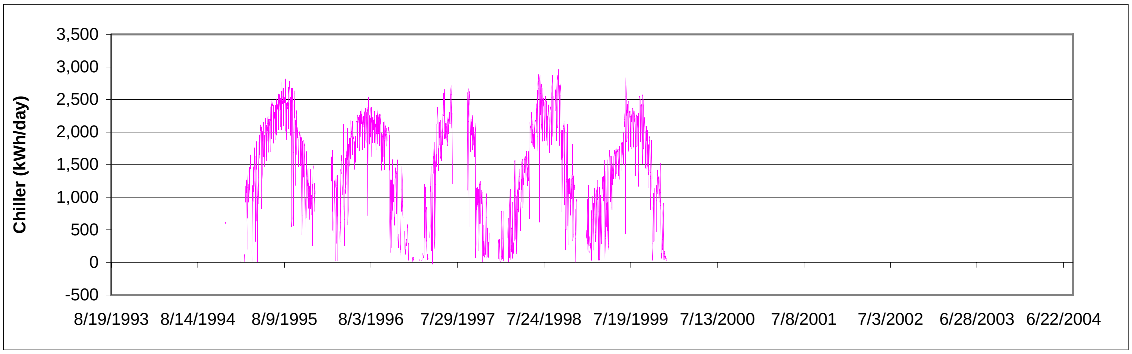


Figure III15 Electricity consumption, chilled water, & COP of the chiller system in site 325.

Rio Grande Campus





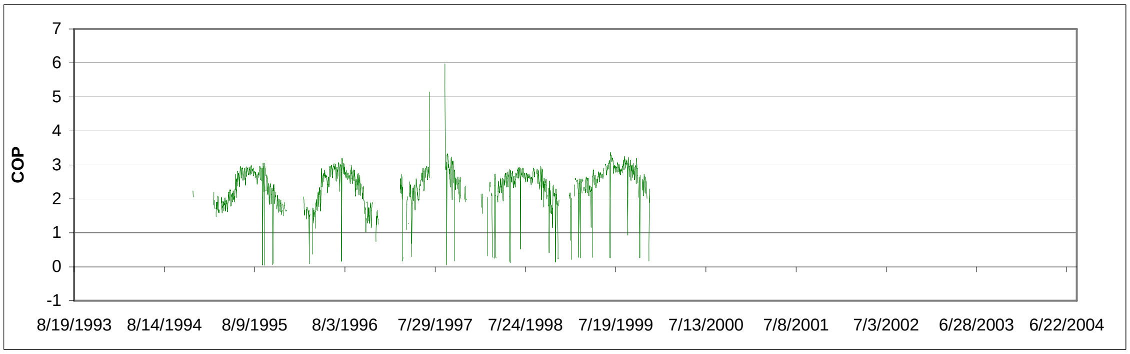


Figure III16 Electricity consumption, chilled water, & COP of the chiller system in site 326.

Neil Kirkman Building A-Wing

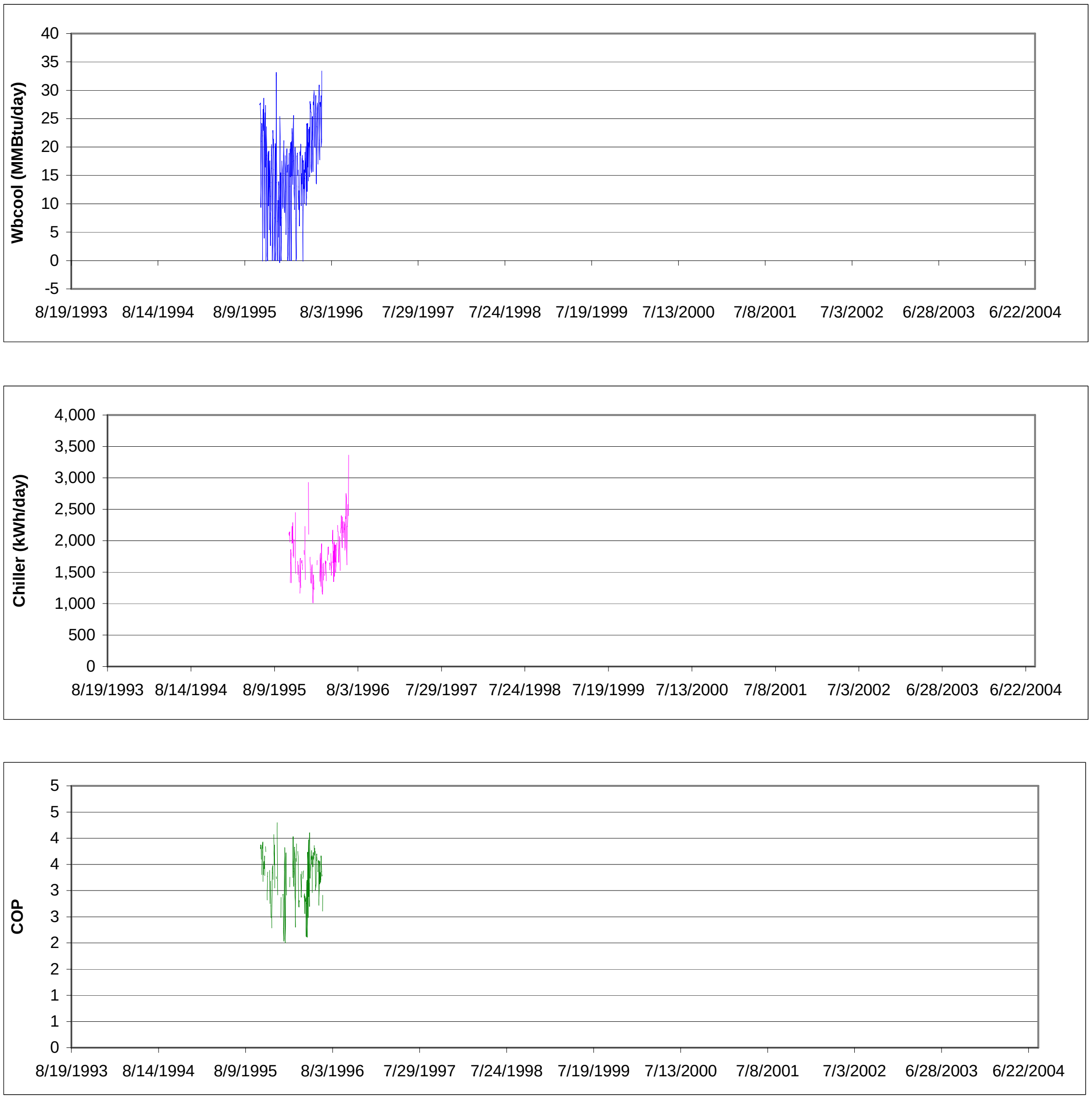


Figure III17 Electricity consumption, chilled water, & COP of the chiller system in site 922.

APPENDIX IV

DAILY ENERGY CONSUMPTION FOR TESTING FACILITIES

Zachry Engineering Center (1)

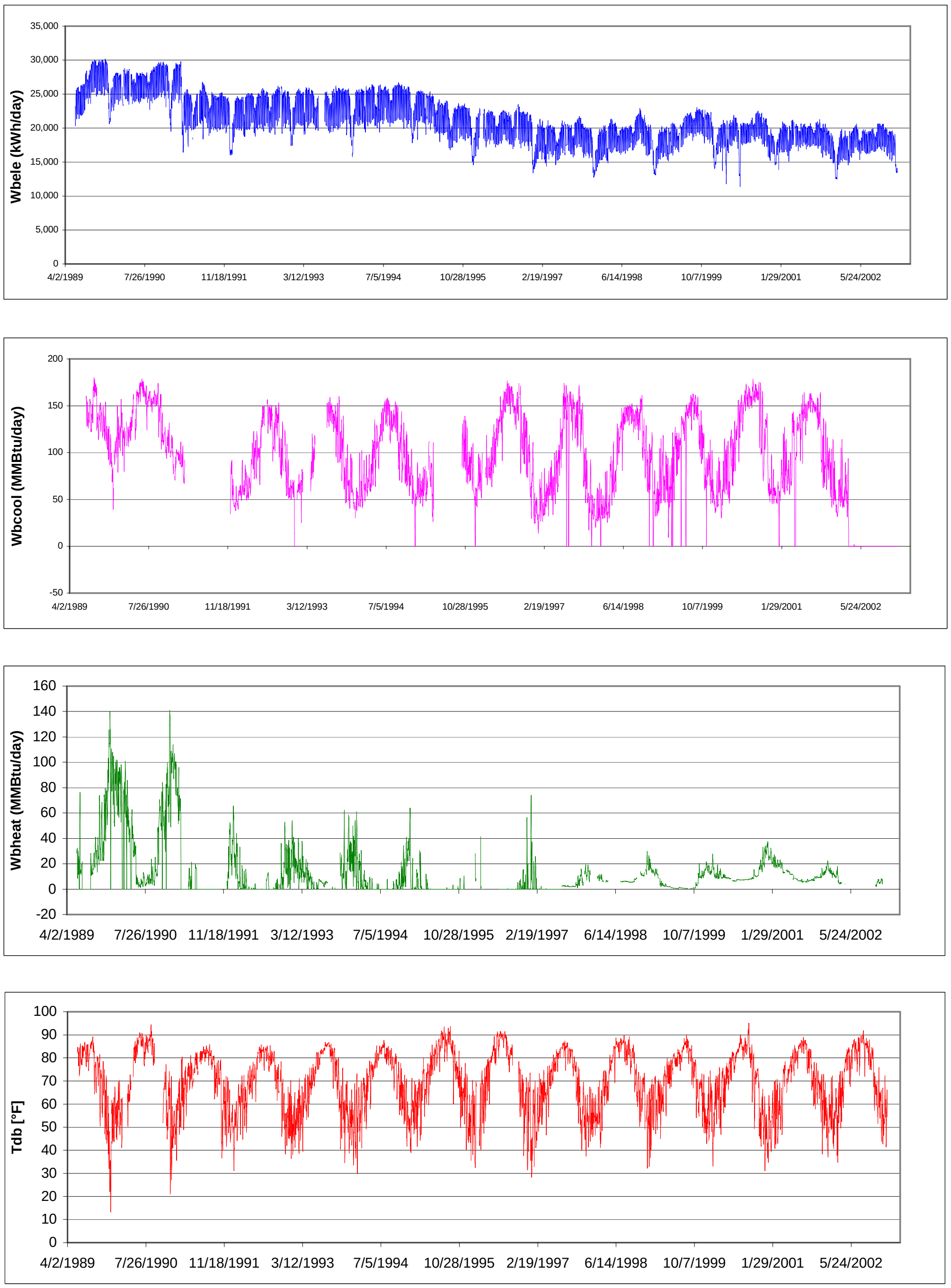


Figure IV1 Daily energy consumption and Tdb time series for site 1.
(It seems that there is a scale problem with wbcool data ; modification is made by doubling the consumption since 1997)

Education Building (100)

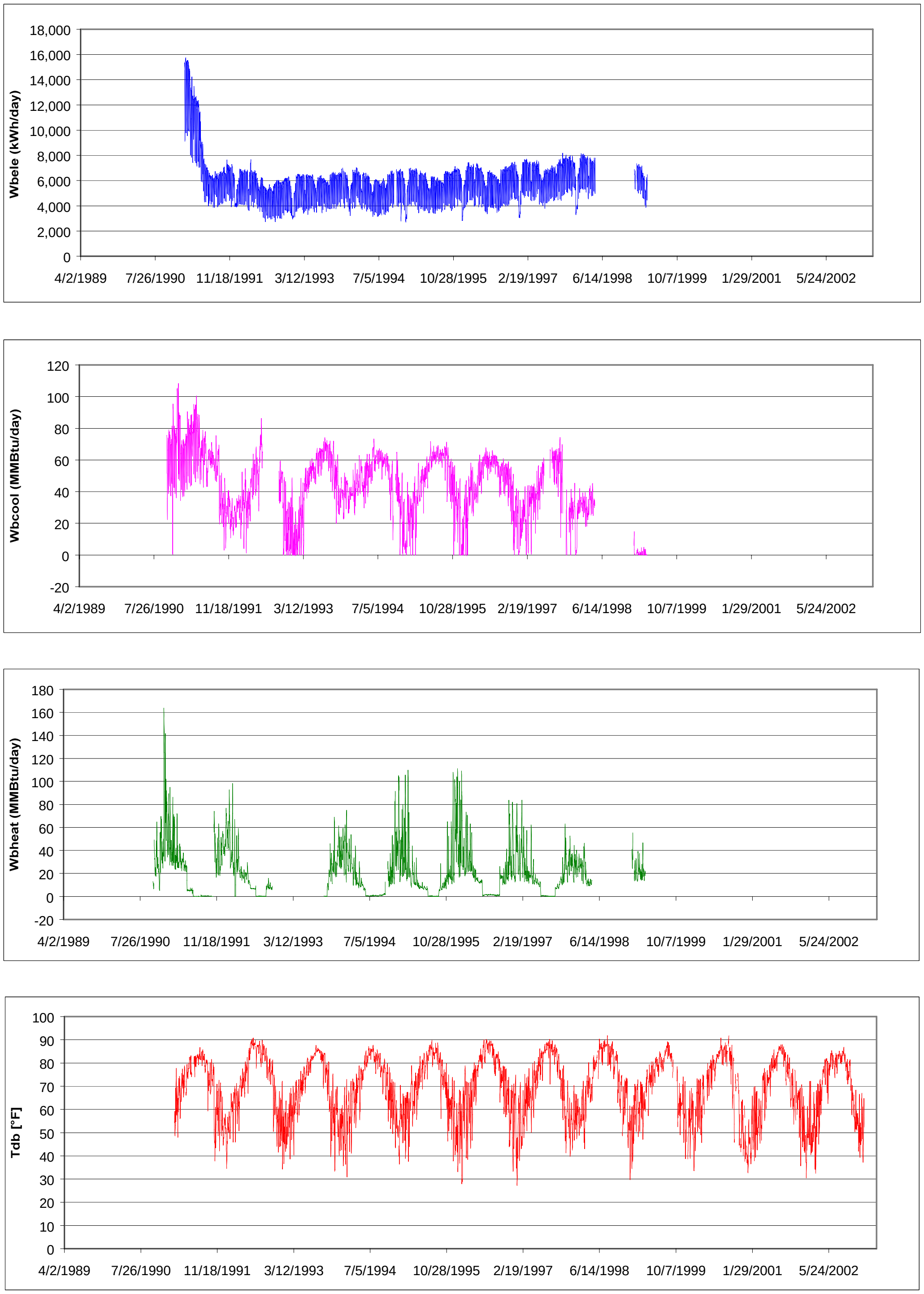


Figure IV2 Daily energy consumption and Tdb time series for site 100.

University Teaching Center (101)

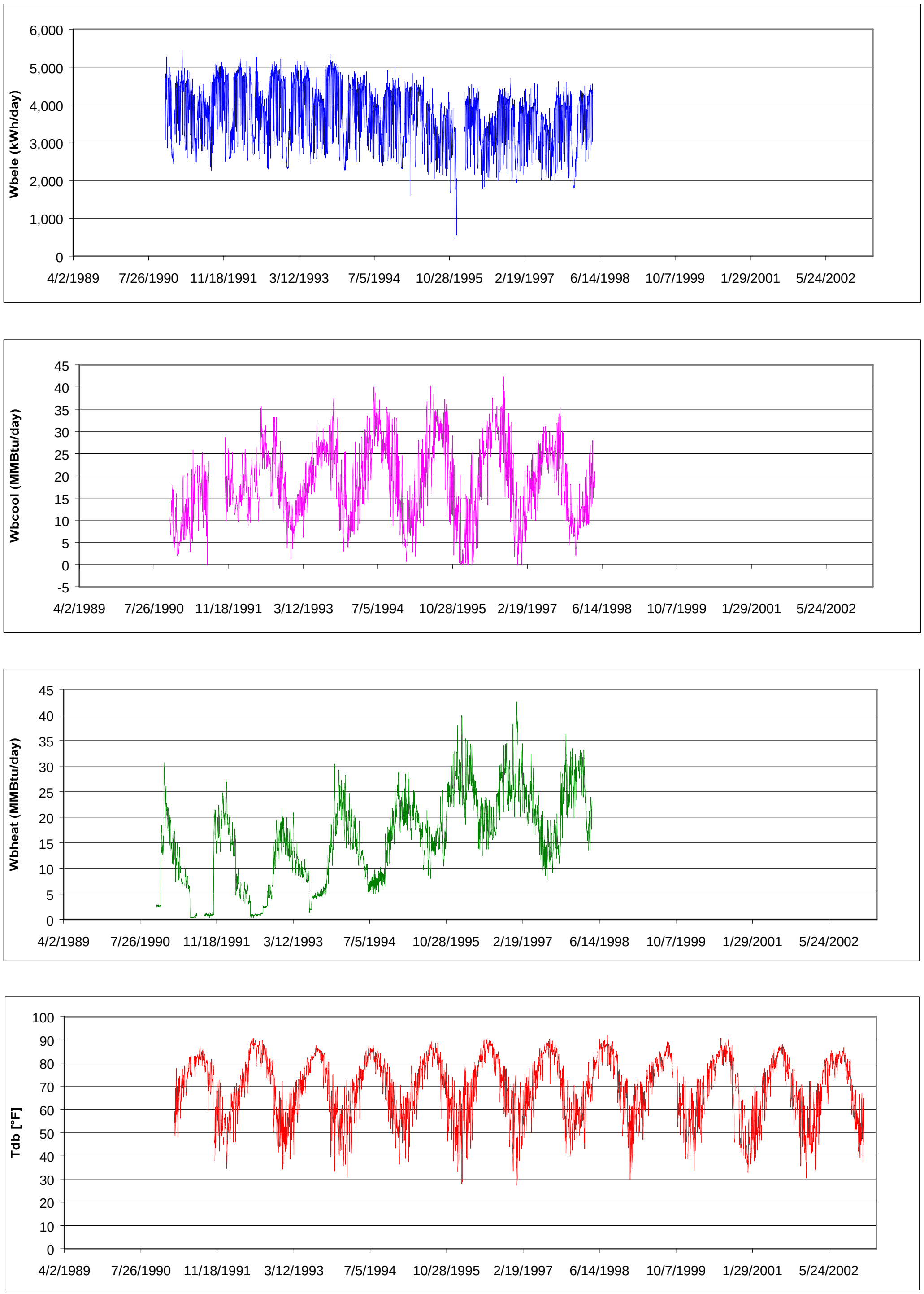


Figure IV3 Daily energy consumption and Tdb time series for site 101.

Perry Castaneda Library (102)

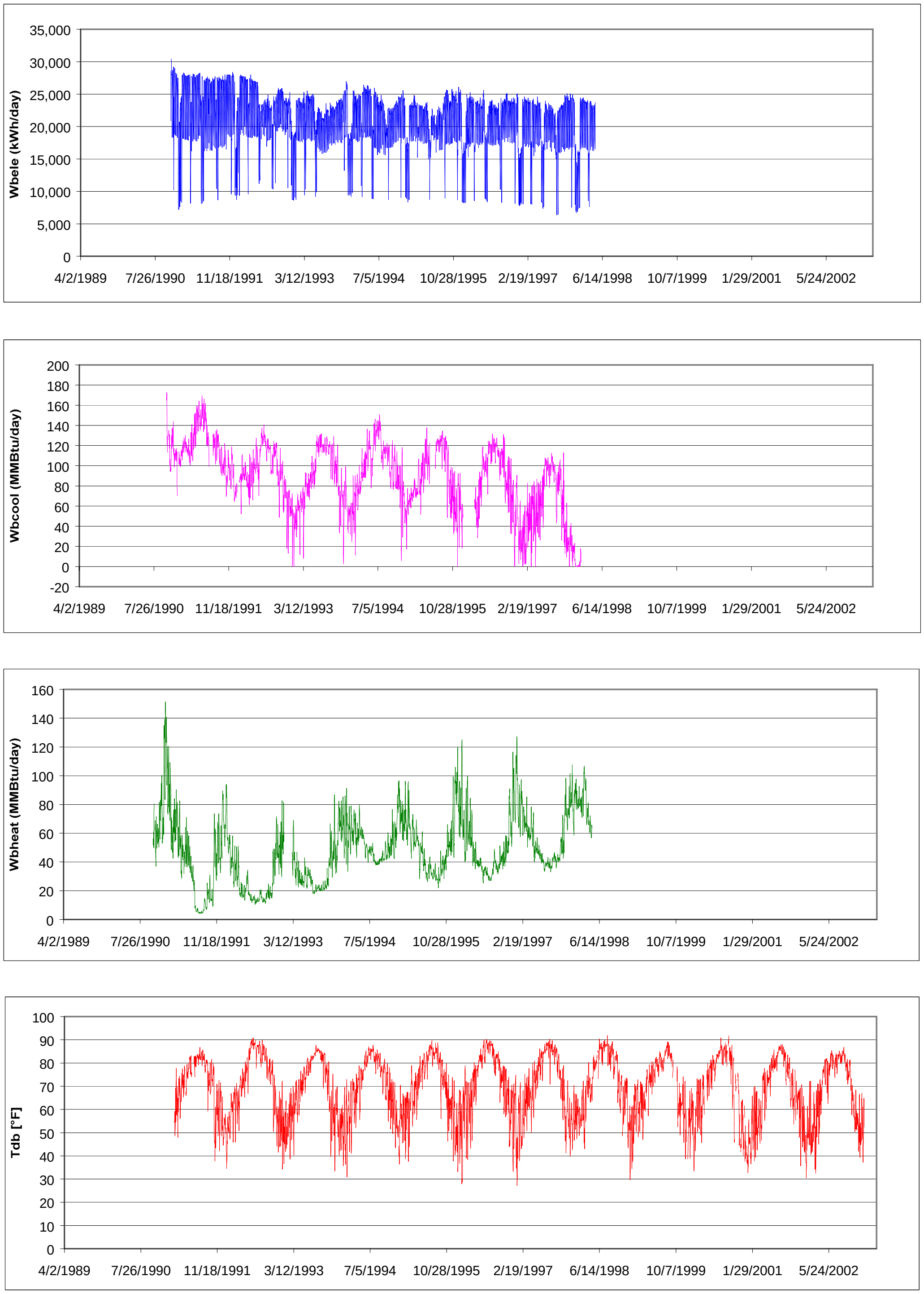


Figure IV4 Daily energy consumption and Tdb time series for site 102.

Garrison Hall (103)

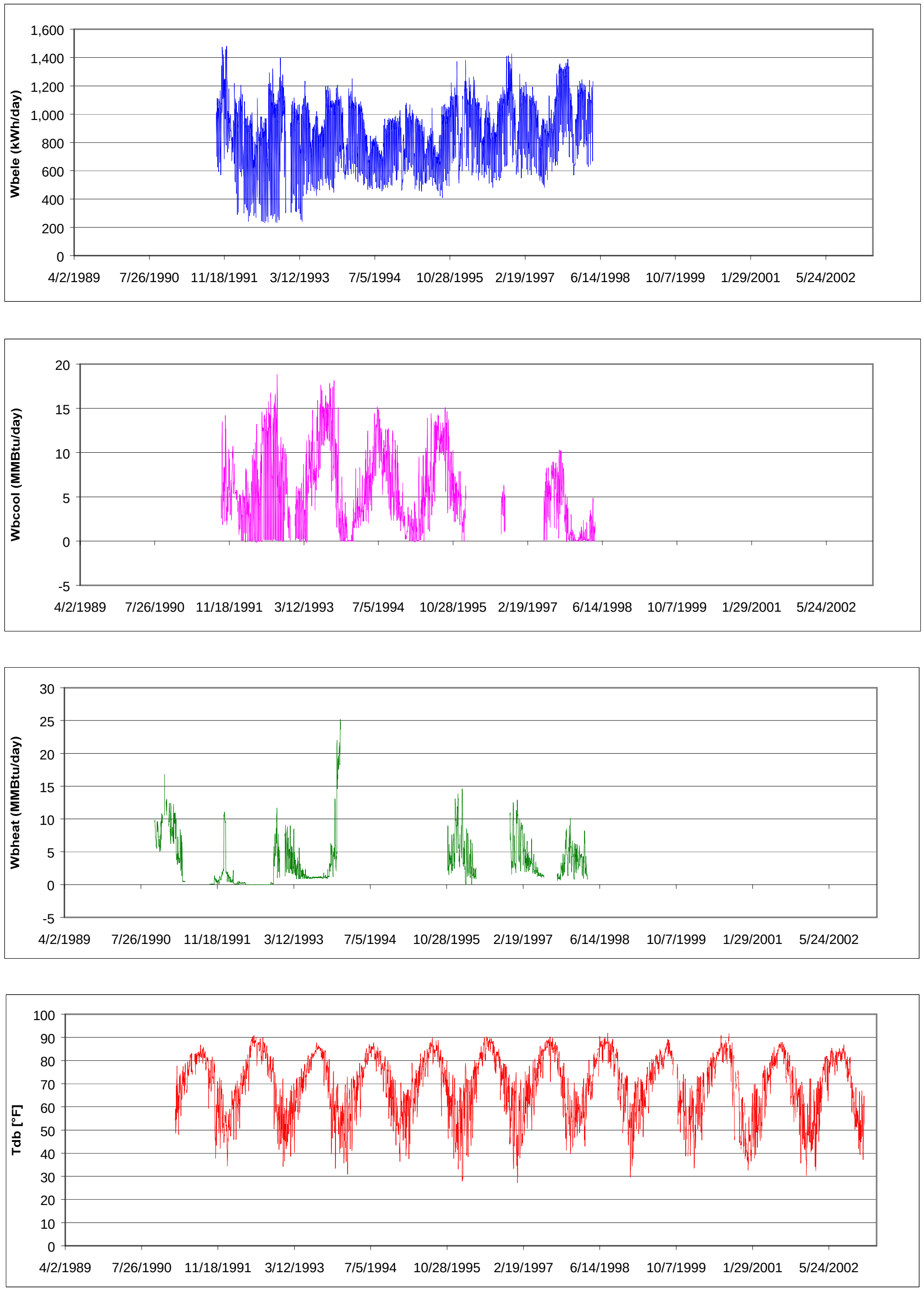


Figure IV5 Daily energy consumption and Tdb time series for site 103.

Gearing Hall (104)

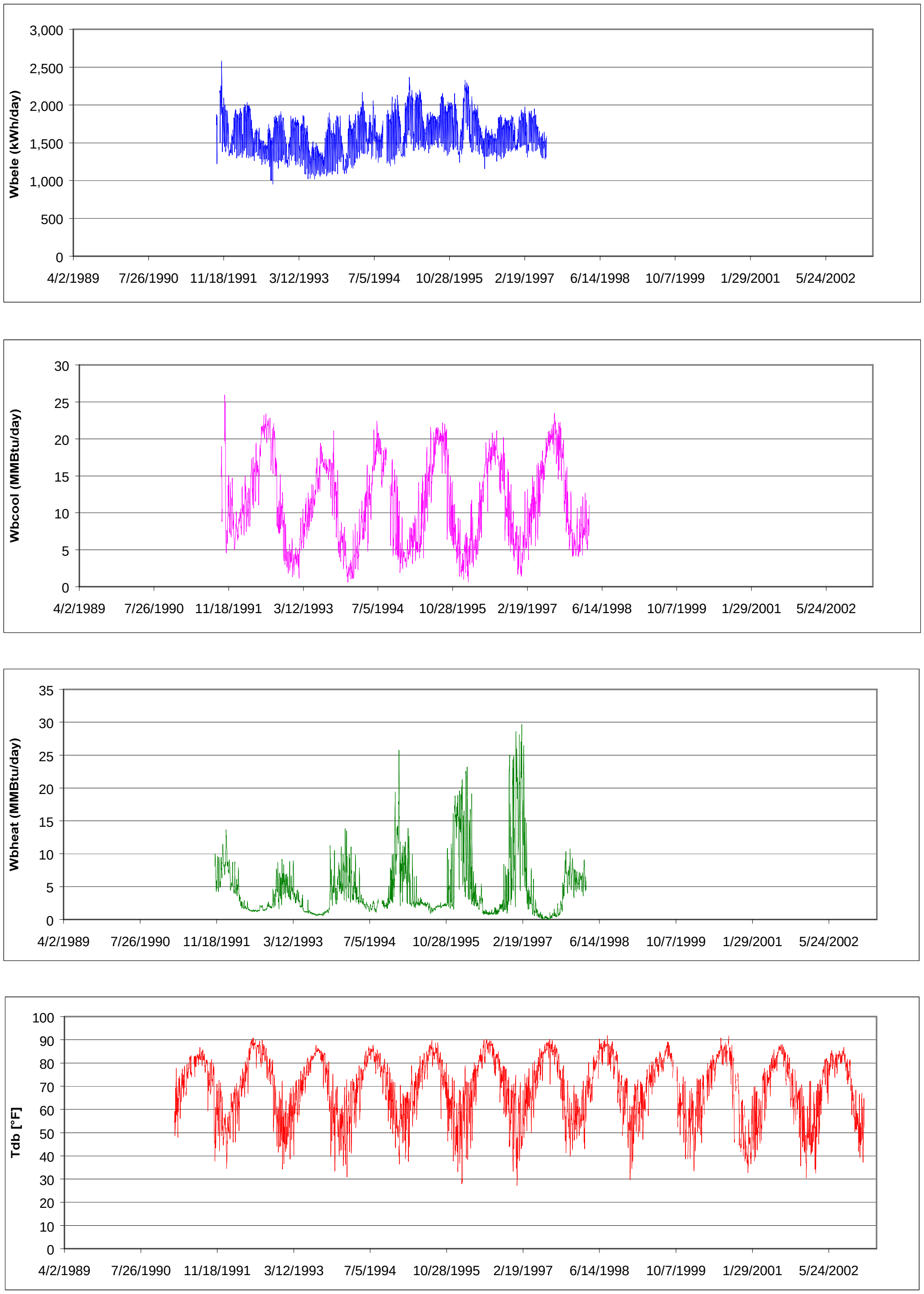


Figure IV6 Daily energy consumption and Tdb time series for site 104.

Waggener Hall (105)

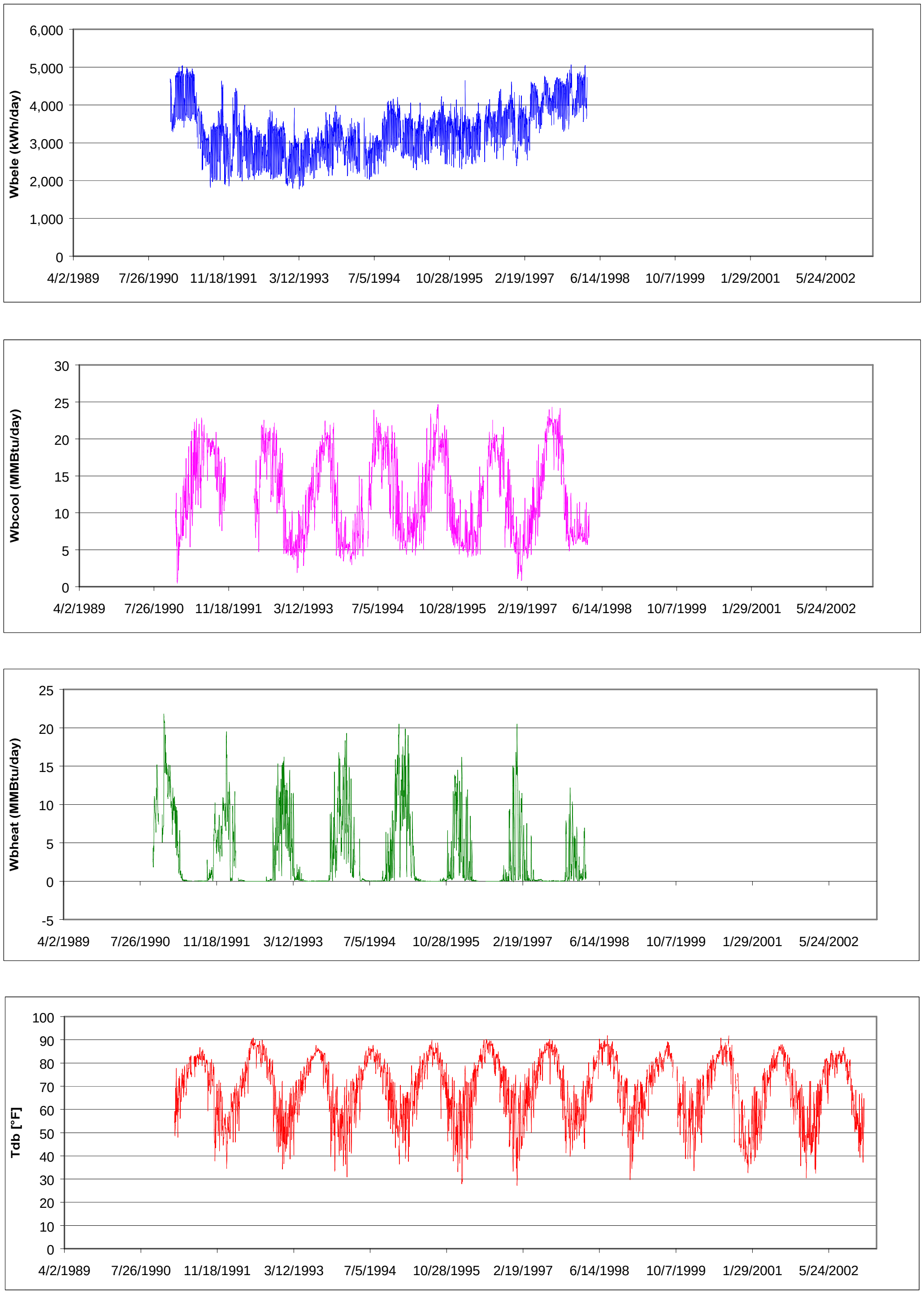
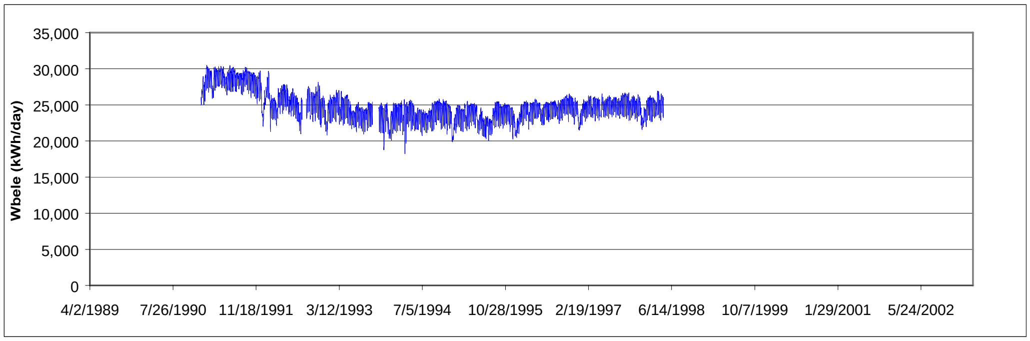
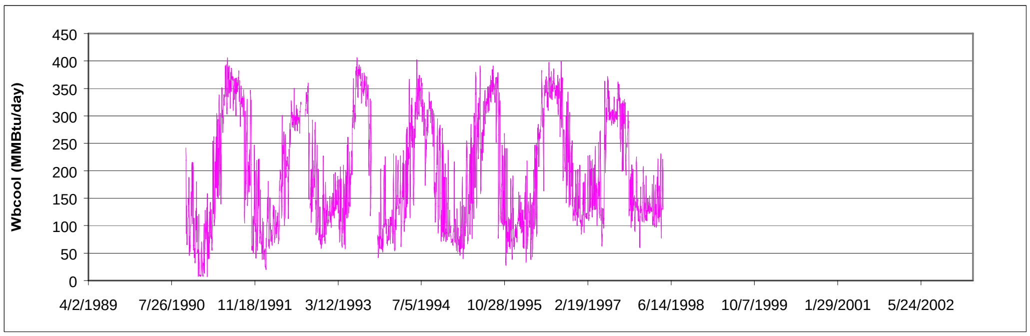
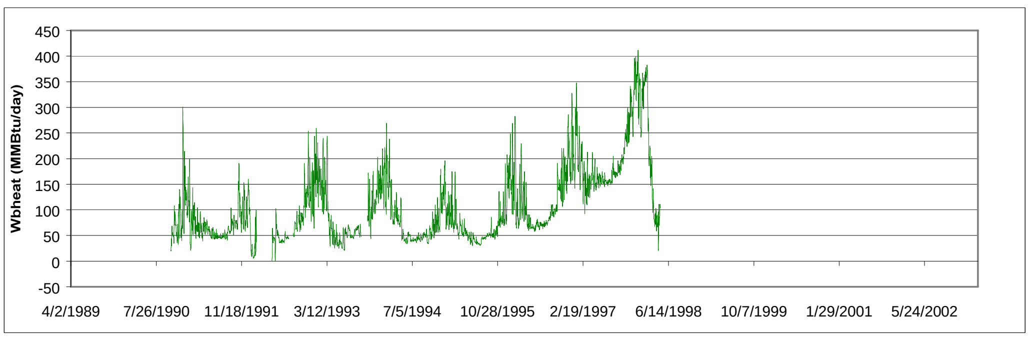


Figure IV7 Daily energy consumption and Tdb time series for site 105.

Welch Hall (106)







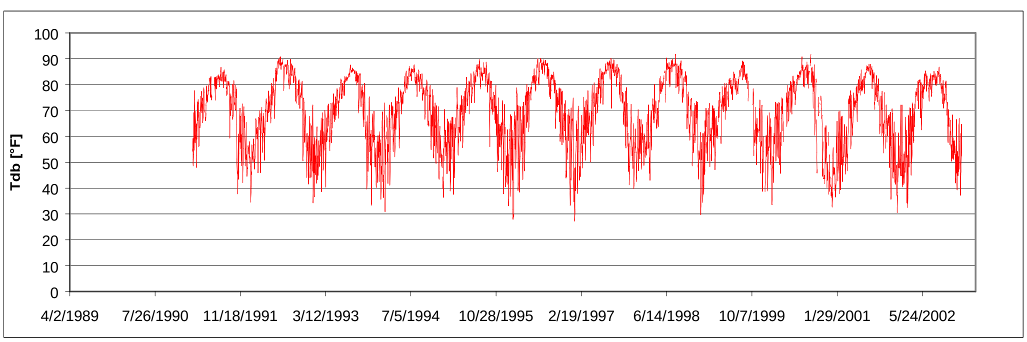


Figure IV8 Daily energy consumption and Tdb time series for site 106.

Burdine Hall (107)

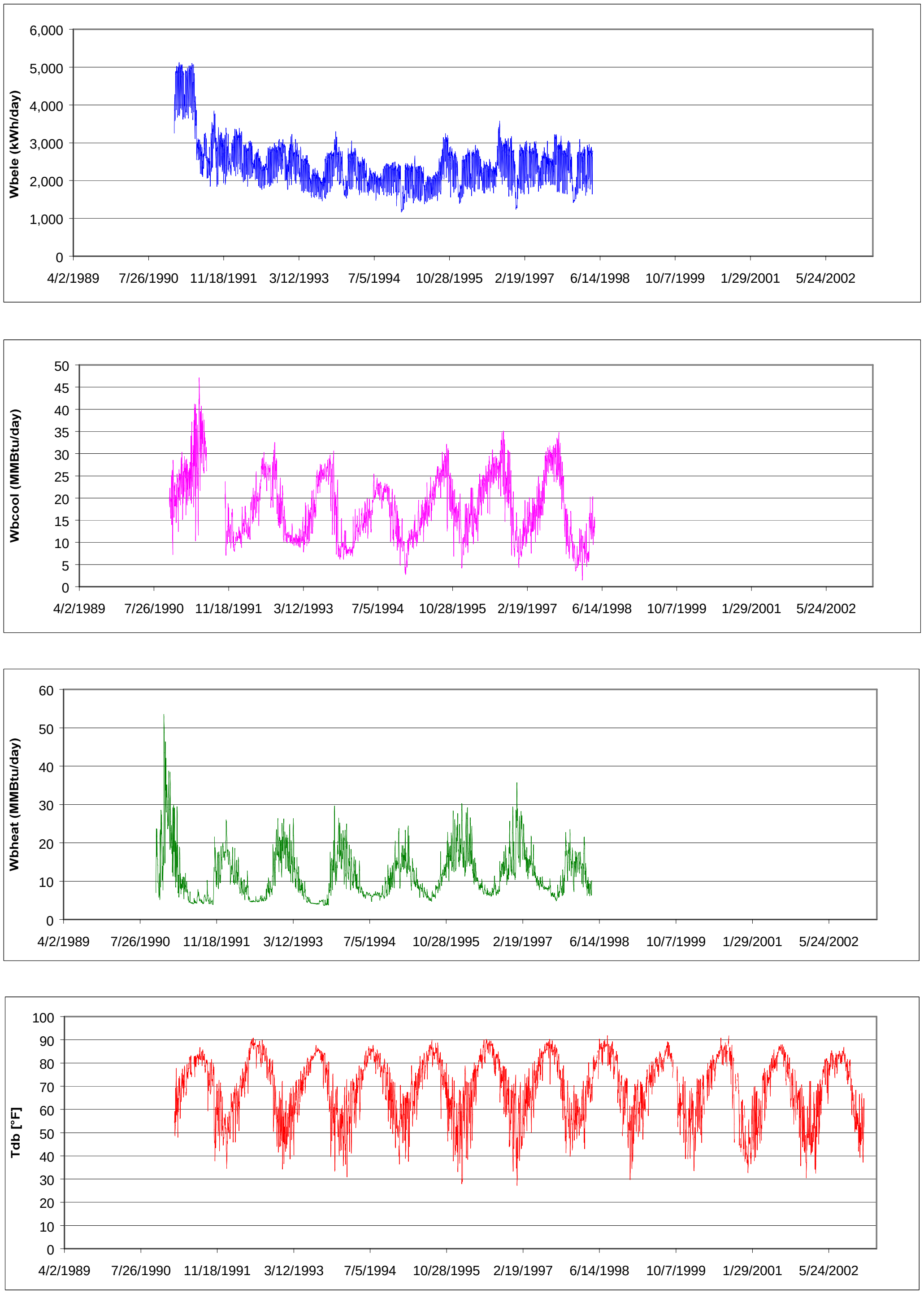
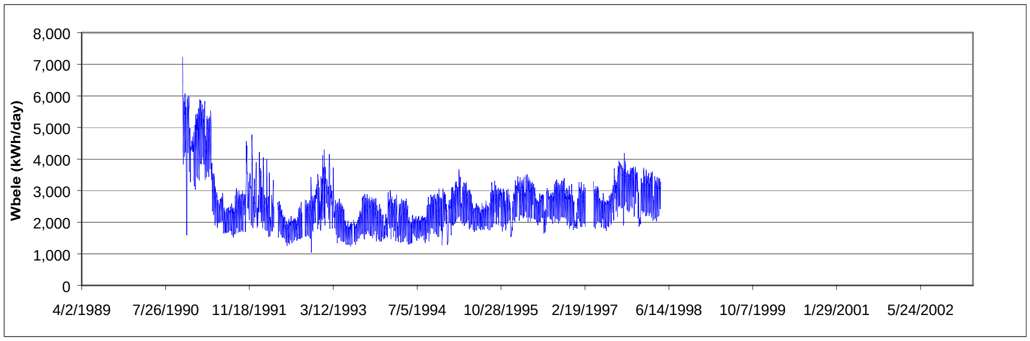
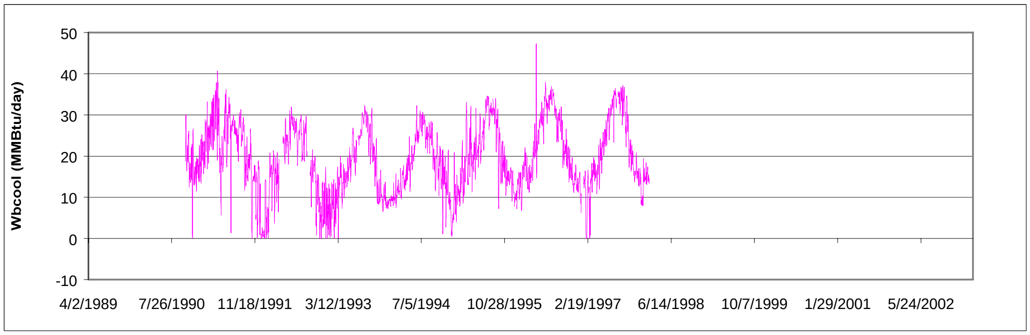
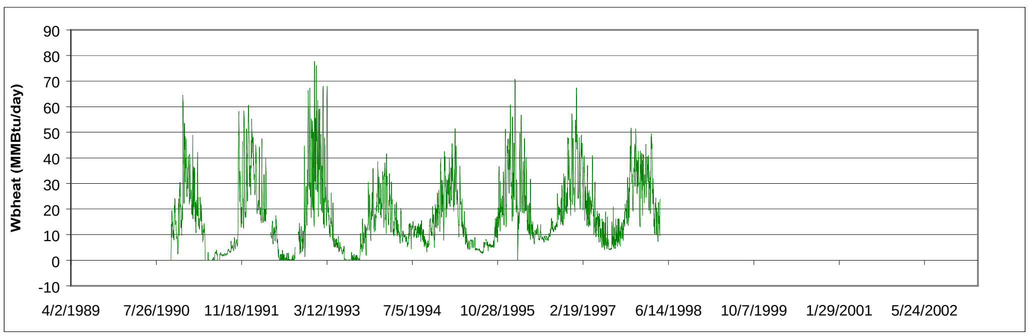


Figure IV9 Daily energy consumption and Tdb time series for site 107.

Nursing Building (108)







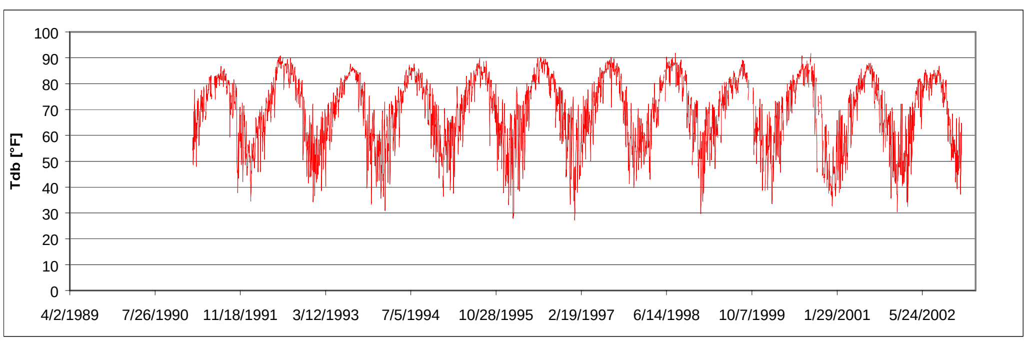


Figure IV10 Daily energy consumption and Tdb time series for site 108.

University Hall (111)

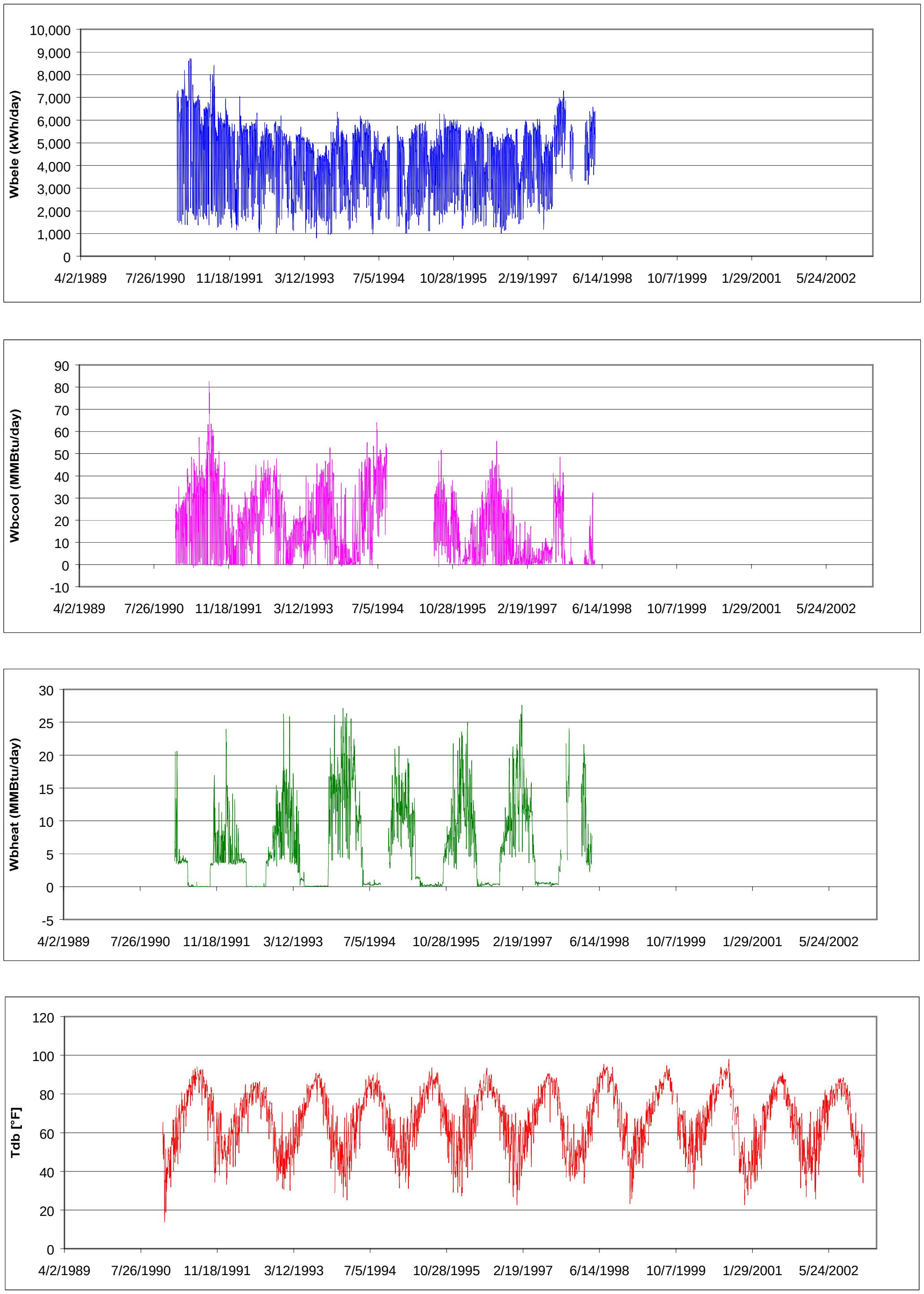


Figure IV11 Daily energy consumption and Tdb time series for site 111.

Business Building (112)

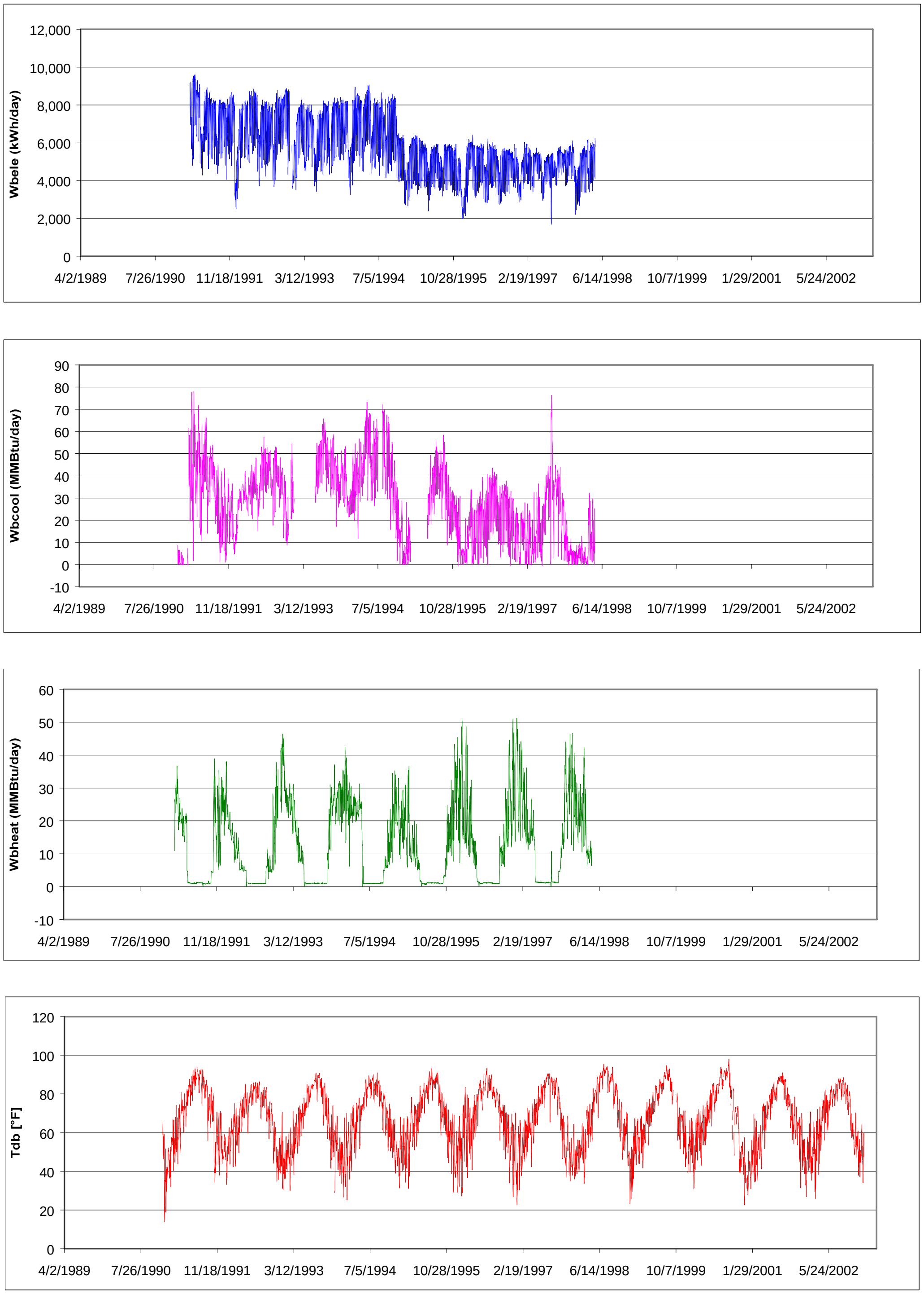
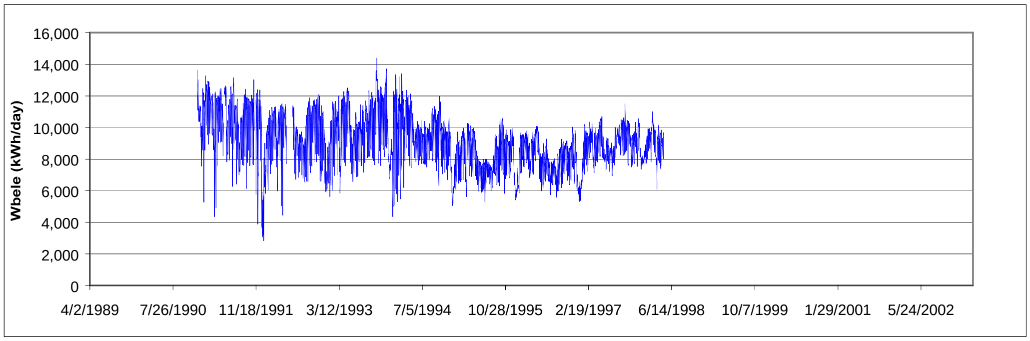
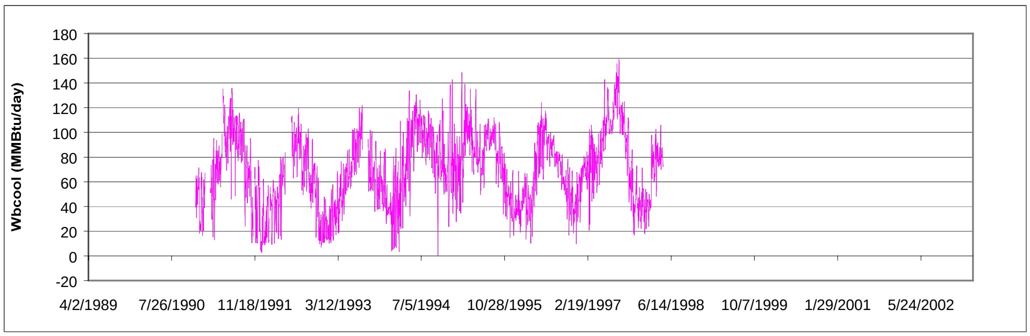
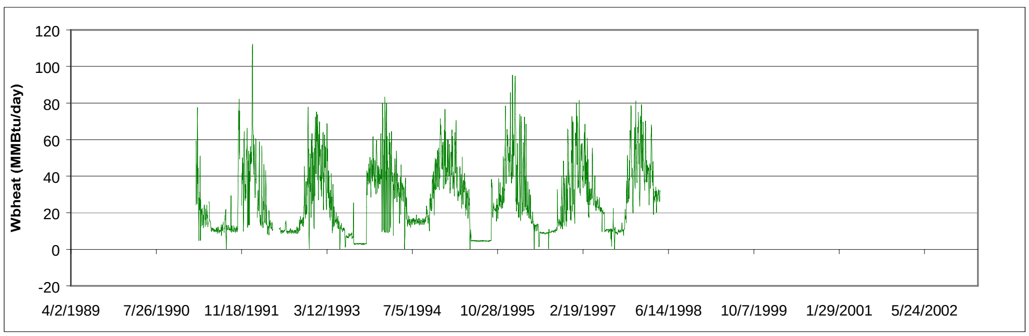


Figure IV12 Daily energy consumption and Tdb time series for site 112.

Fine Arts Building (113)







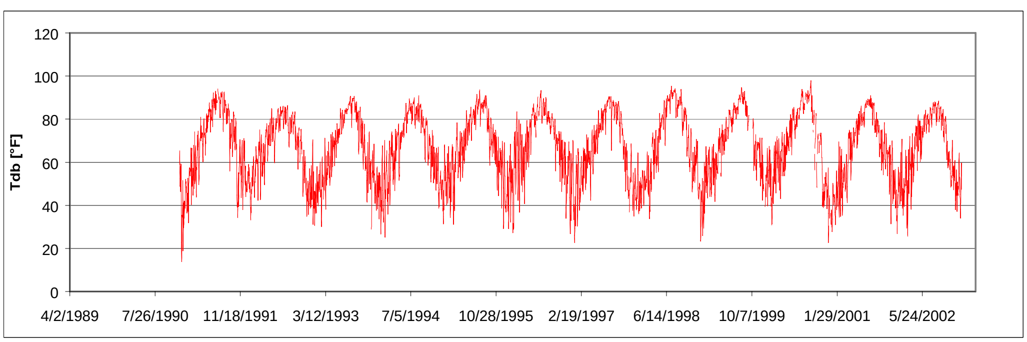
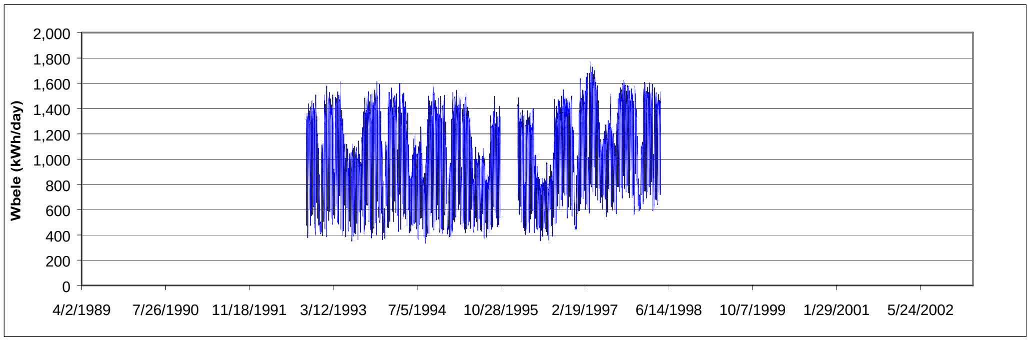
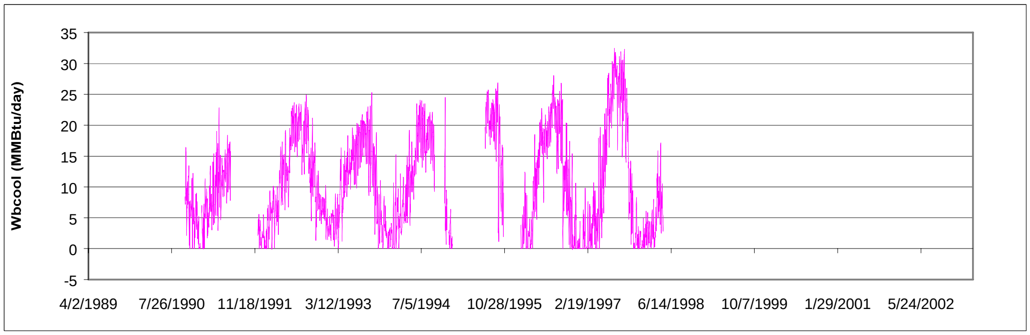
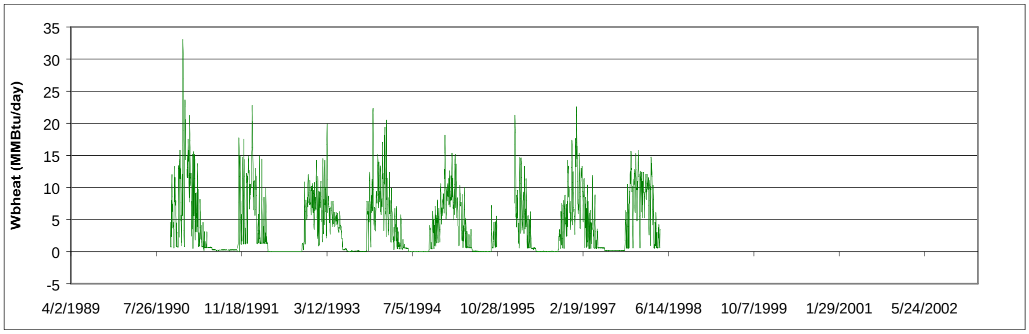


Figure IV13 Daily energy consumption and Tdb time series for site 113.

R.A. Steindam Hall (115)







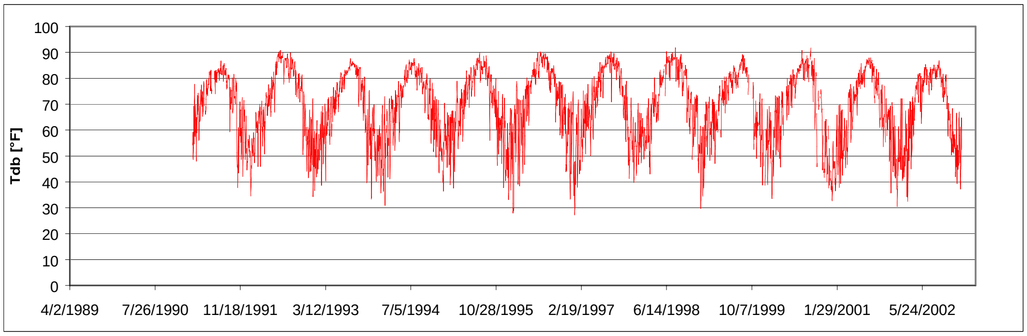


Figure IV14 Daily energy consumption and Tdb time series for site 115.

Painter Hall (116)

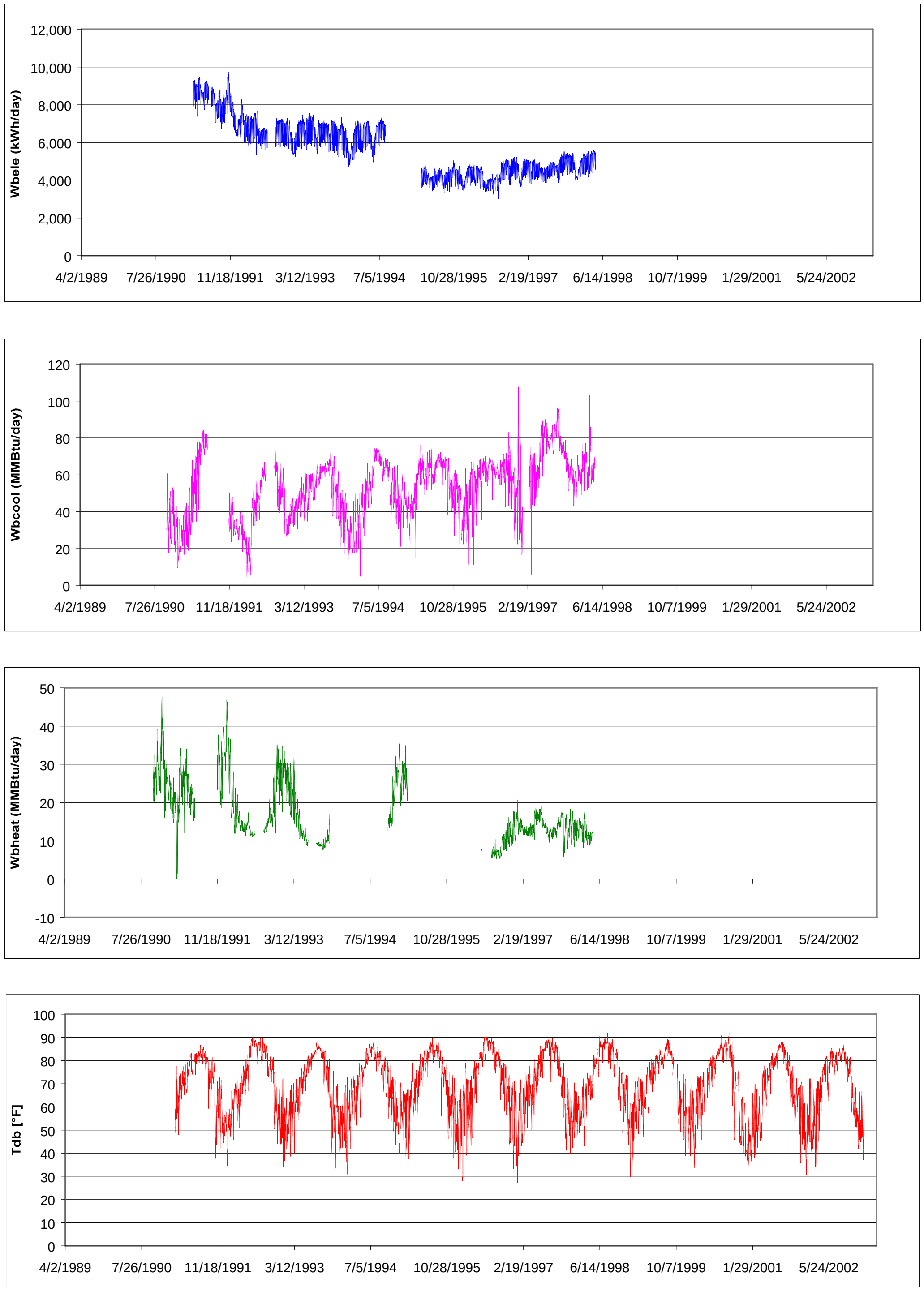
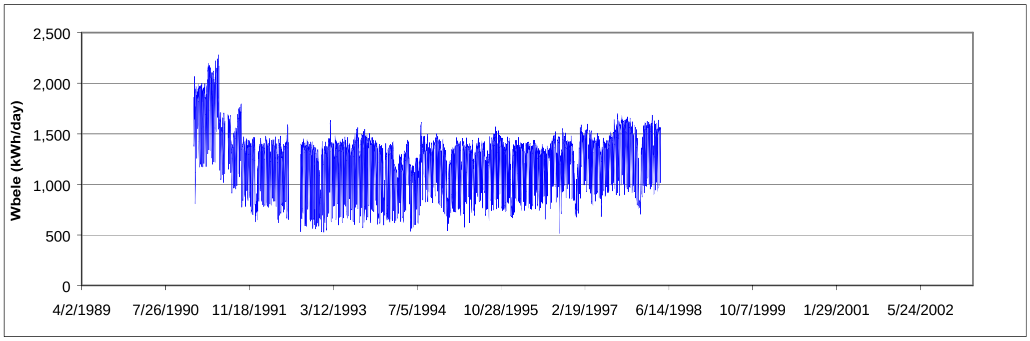
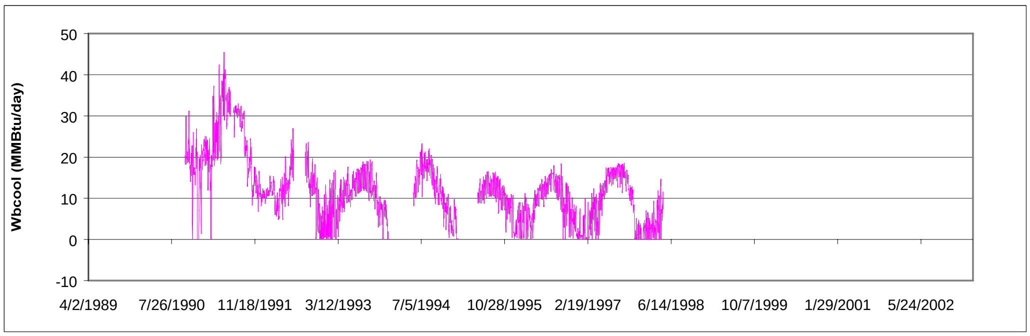
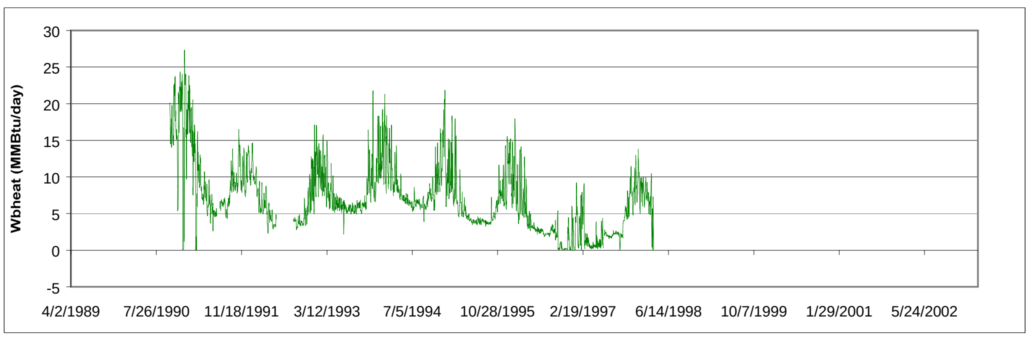


Figure IV15 Daily energy consumption and Tdb time series for site 116.

W.C. Hogg Building (117)







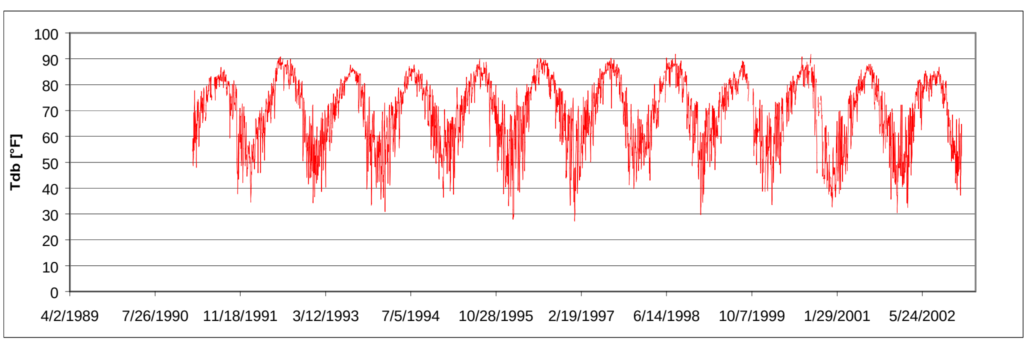


Figure IV16 Daily energy consumption and Tdb time series for site 117.

Medical School Building (124)

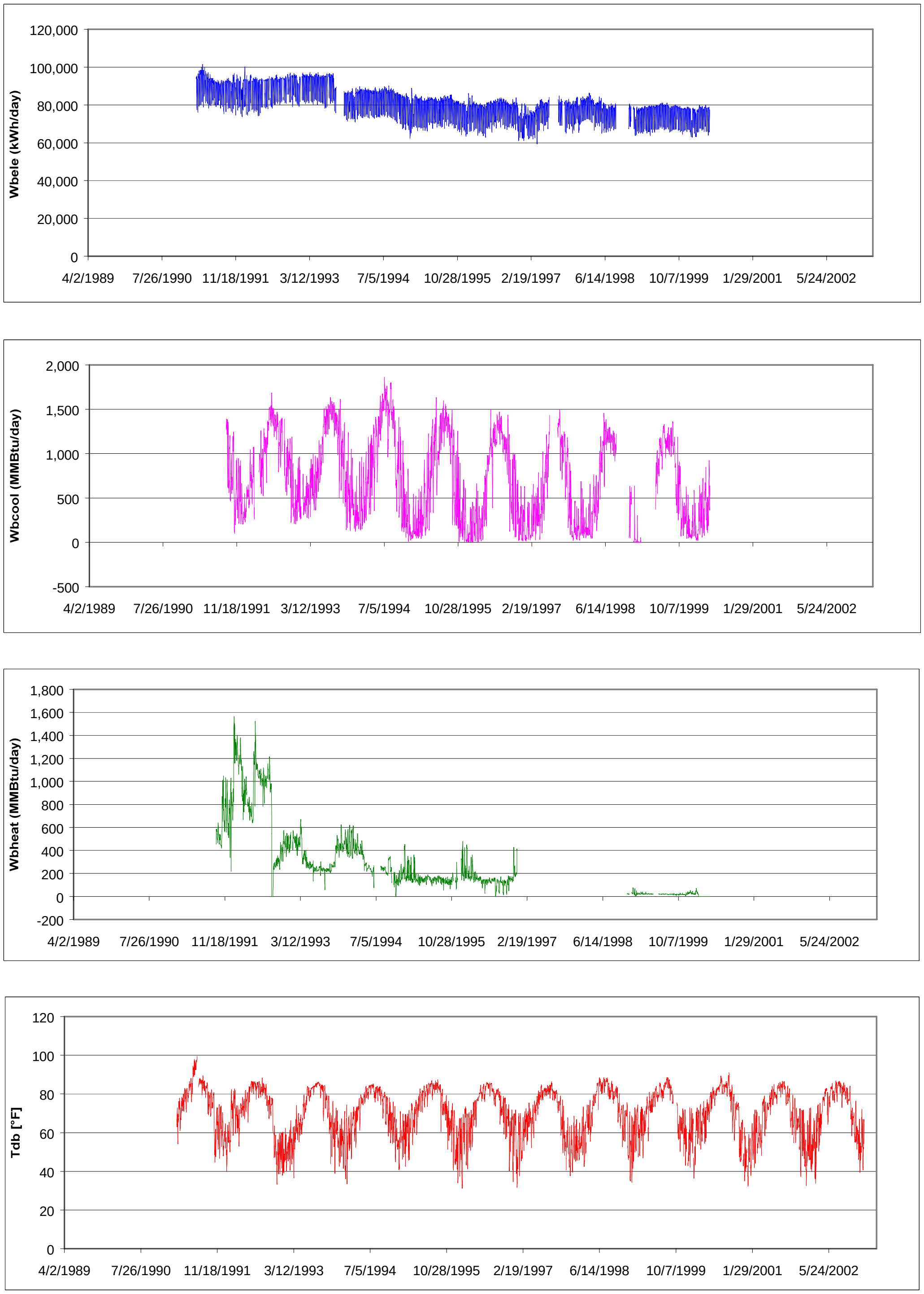


Figure IV17 Daily energy consumption and Tdb time series for site 124.

College of Business Administration (165)

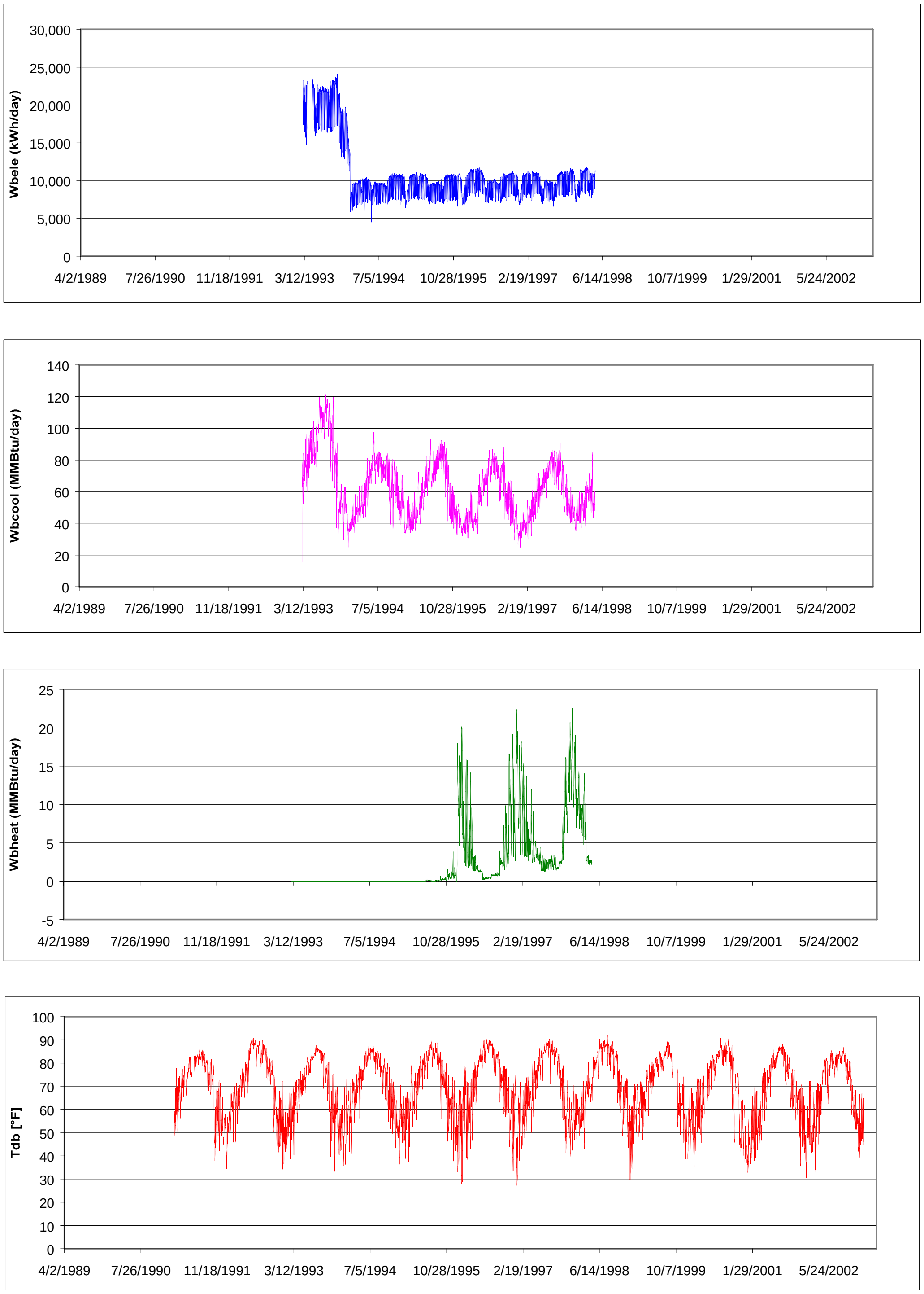


Figure IV18 Daily energy consumption and Tdb time series for site 165.

Graduate School of Business (166)

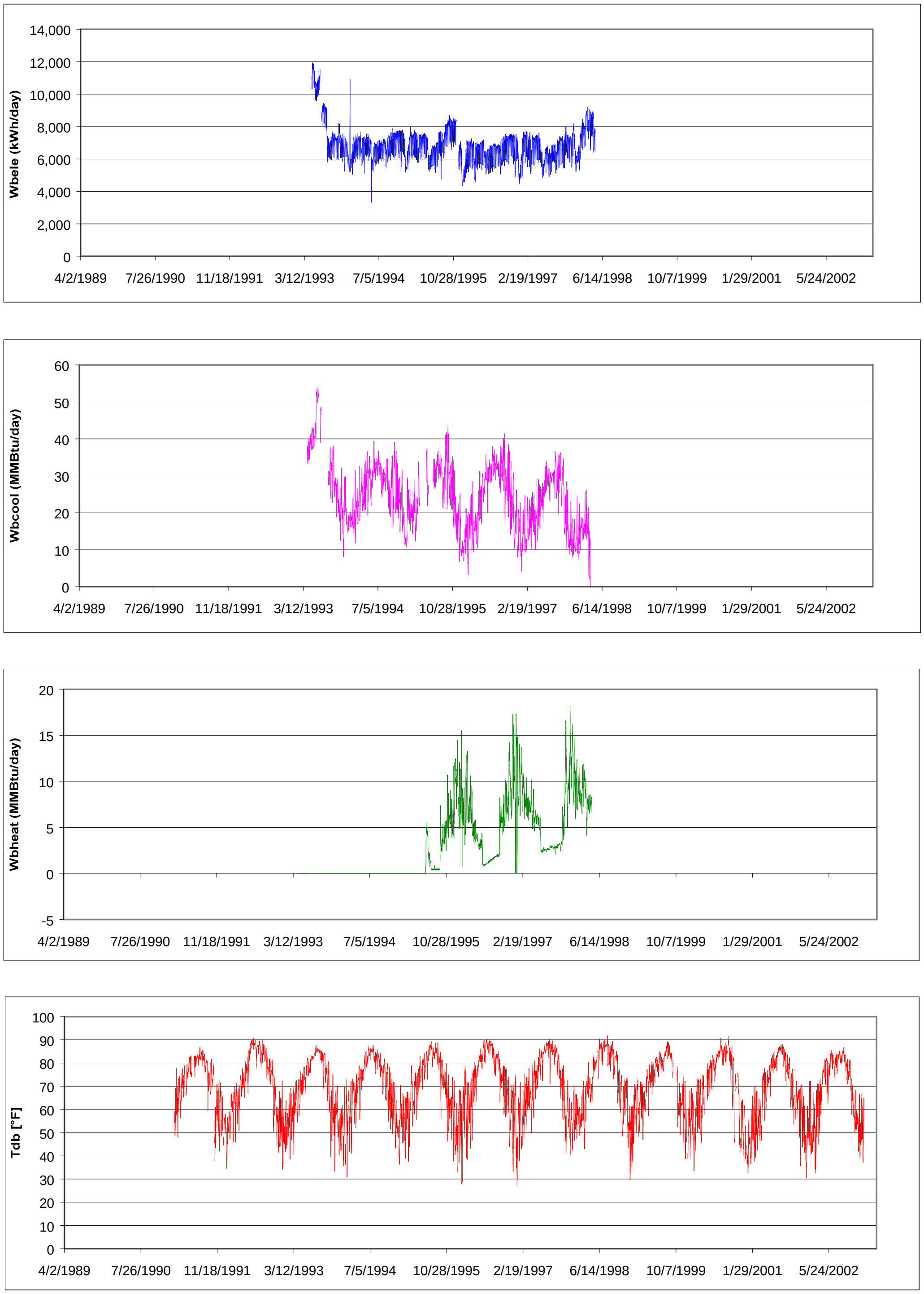


Figure IV19 Daily energy consumption and Tdb time series for site 166.

Texas Tech University-Biology Building (187)

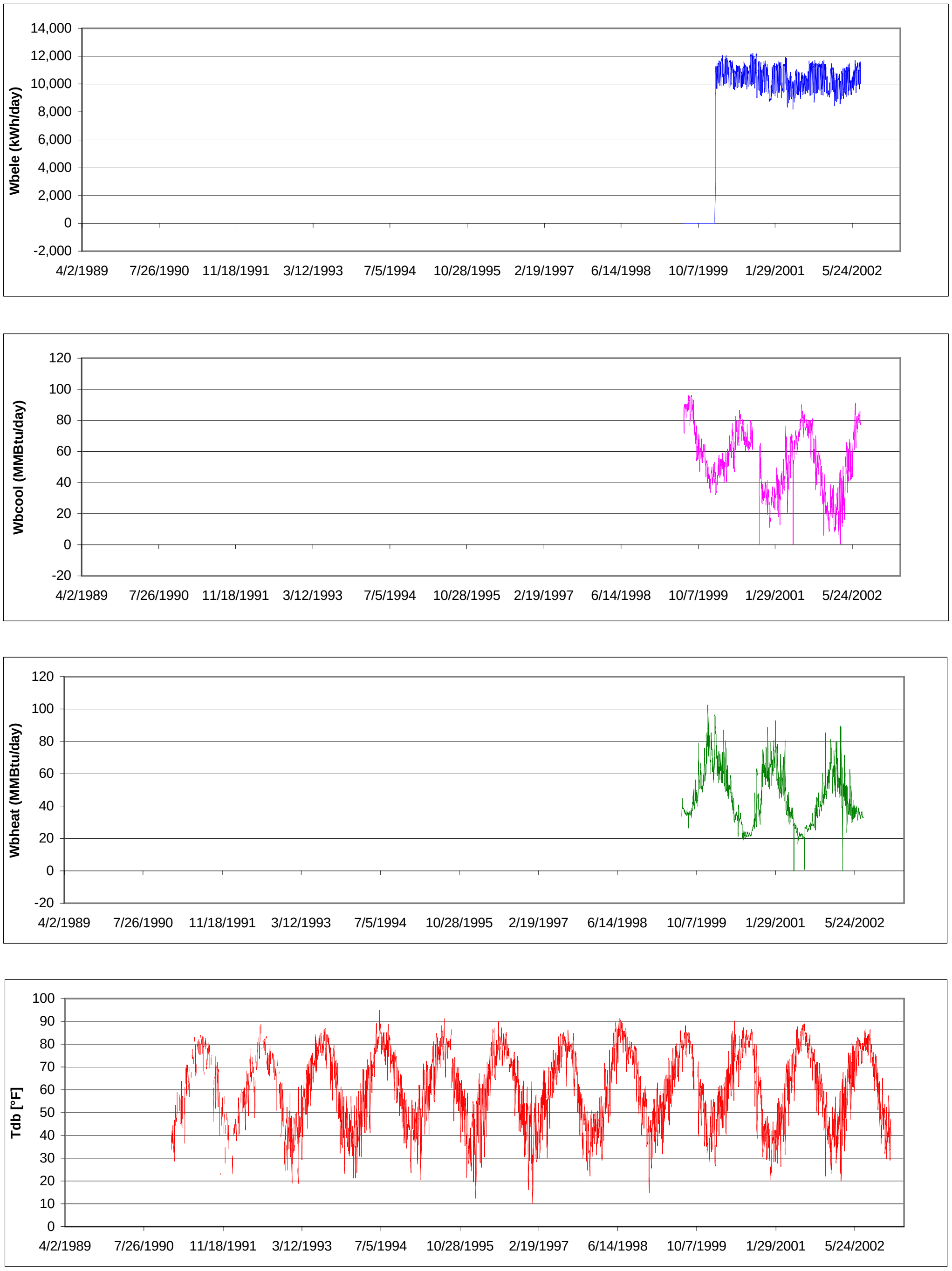


Figure IV20 Daily energy consumption and Tdb time series for site 187.

Texas Tech University-Science Building (188)

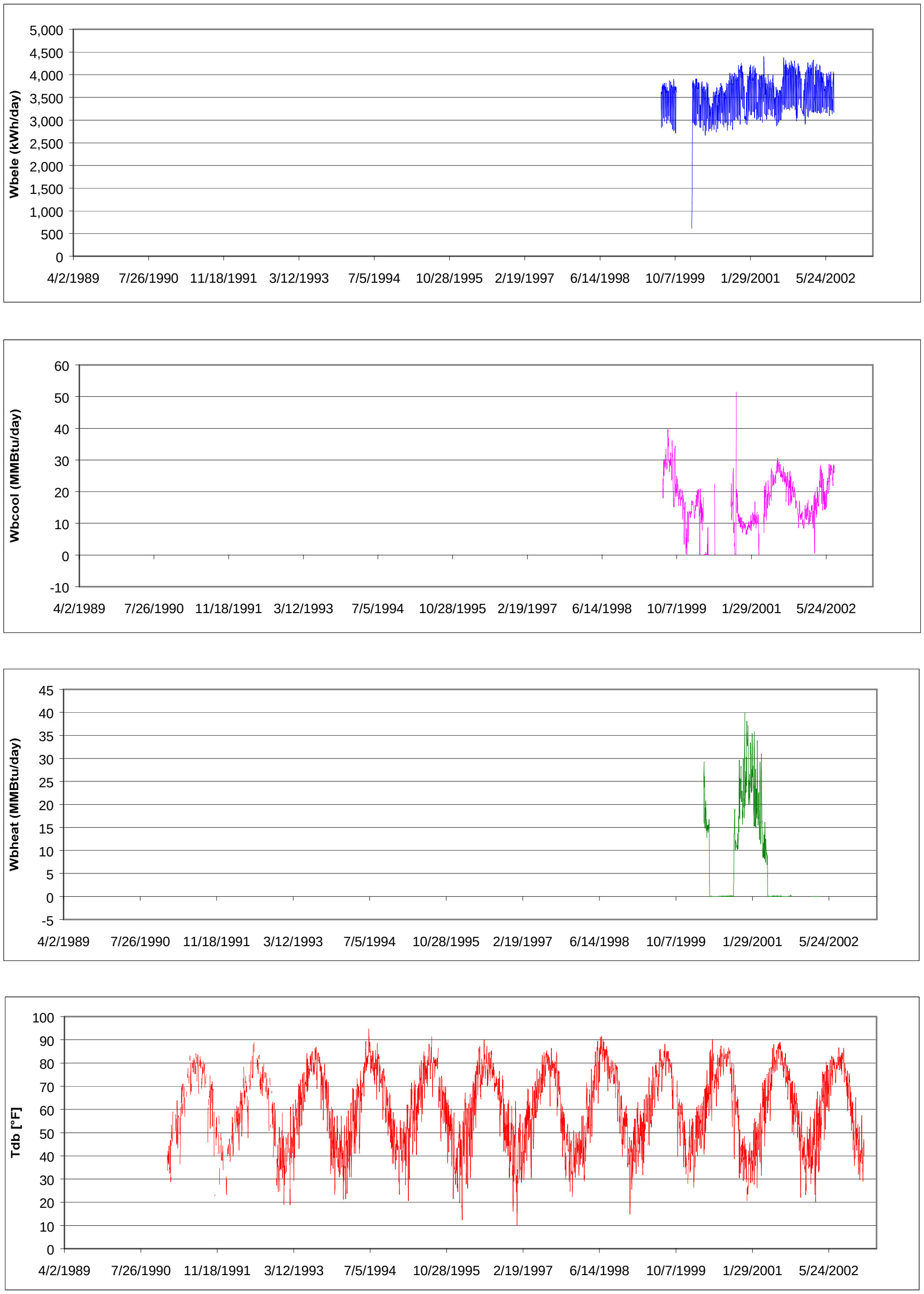


Figure IV21 Daily energy consumption and Tdb time series for site 188.

Texas Tech University-Chemistry North (189)

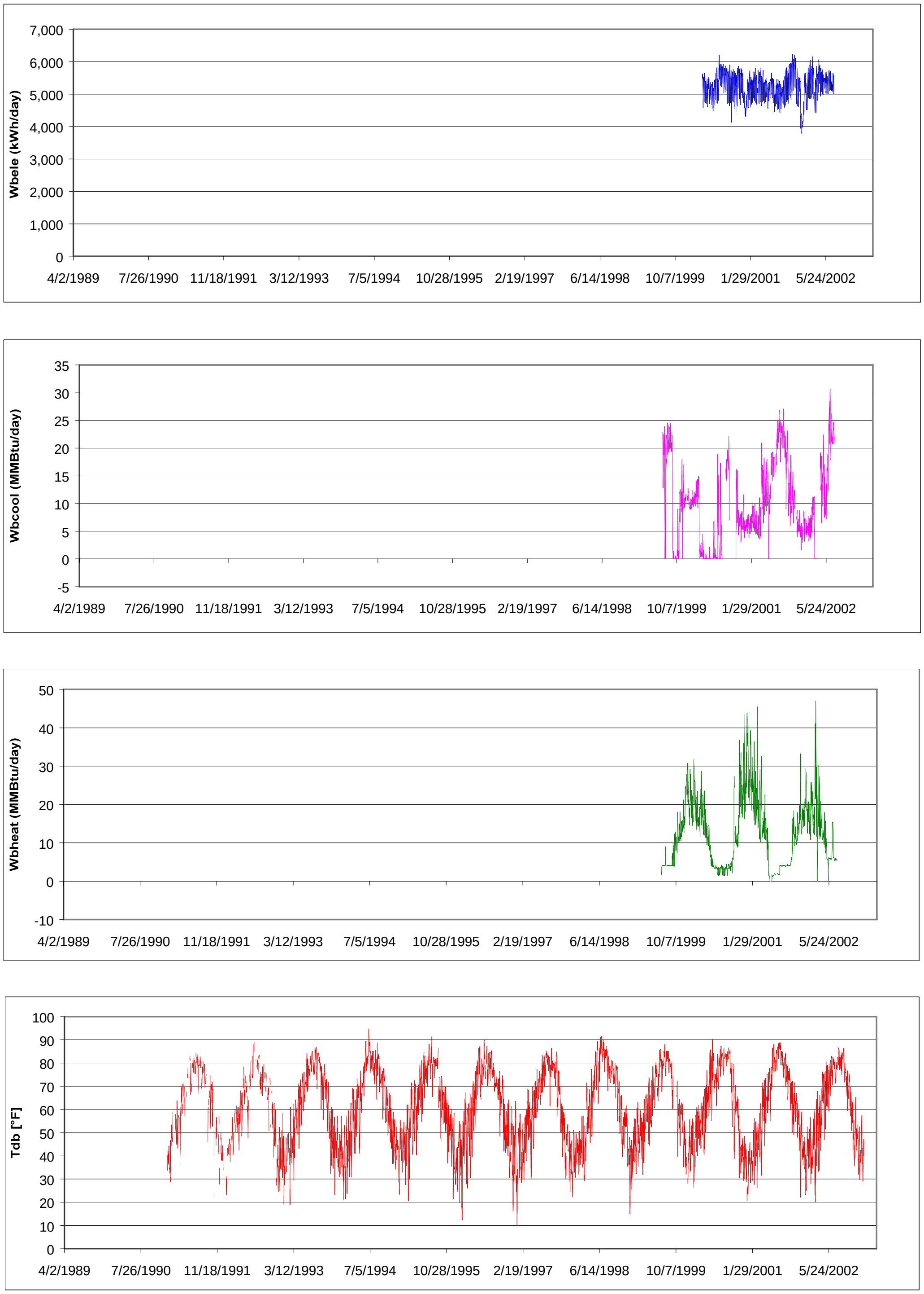


Figure IV22 Daily energy consumption and Tdb time series for site 189.

Texas Tech University-Chemistry South (195)

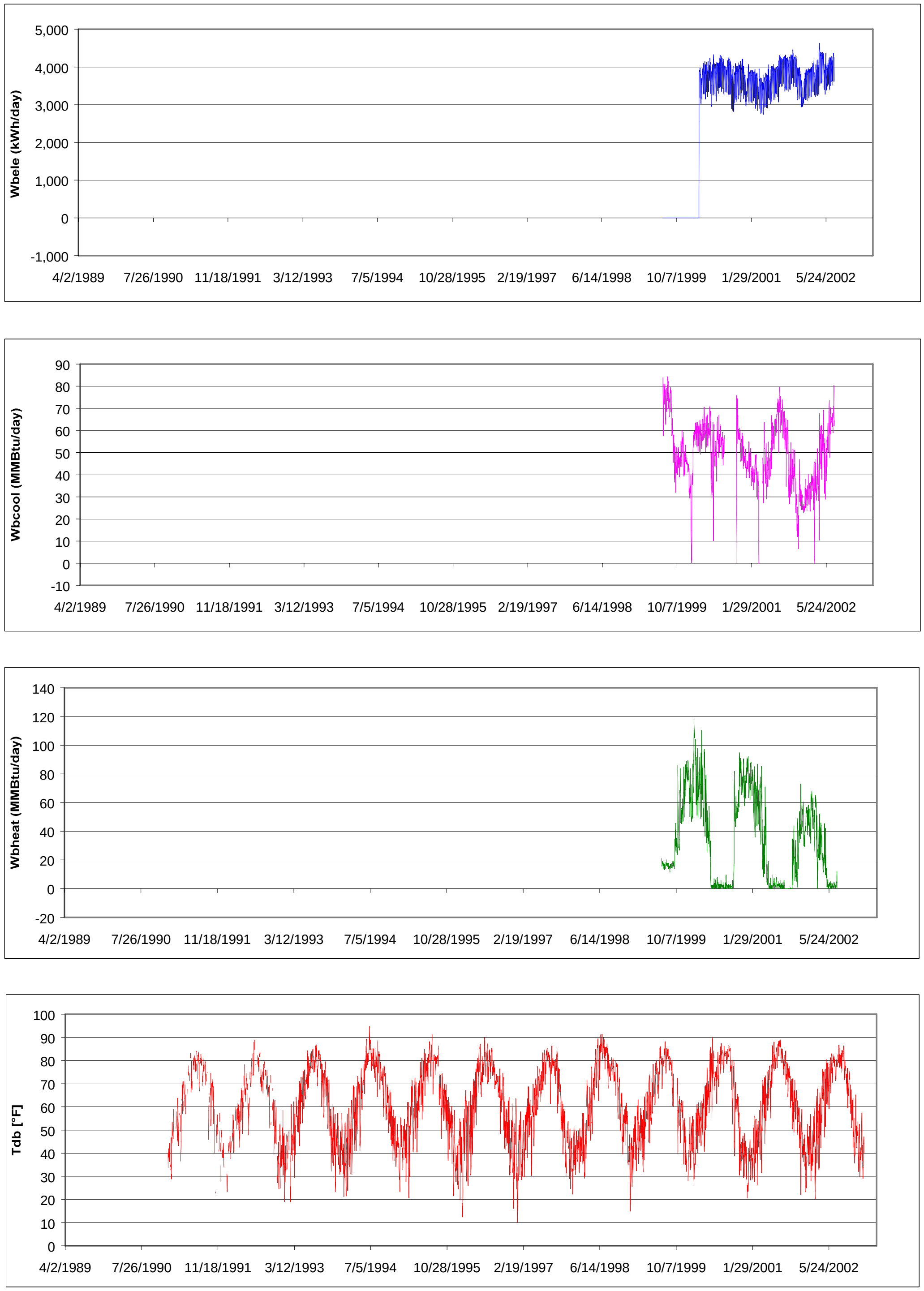


Figure IV23 Daily energy consumption and Tdb time series for site 195.

Texas Tech University-Law School (197)

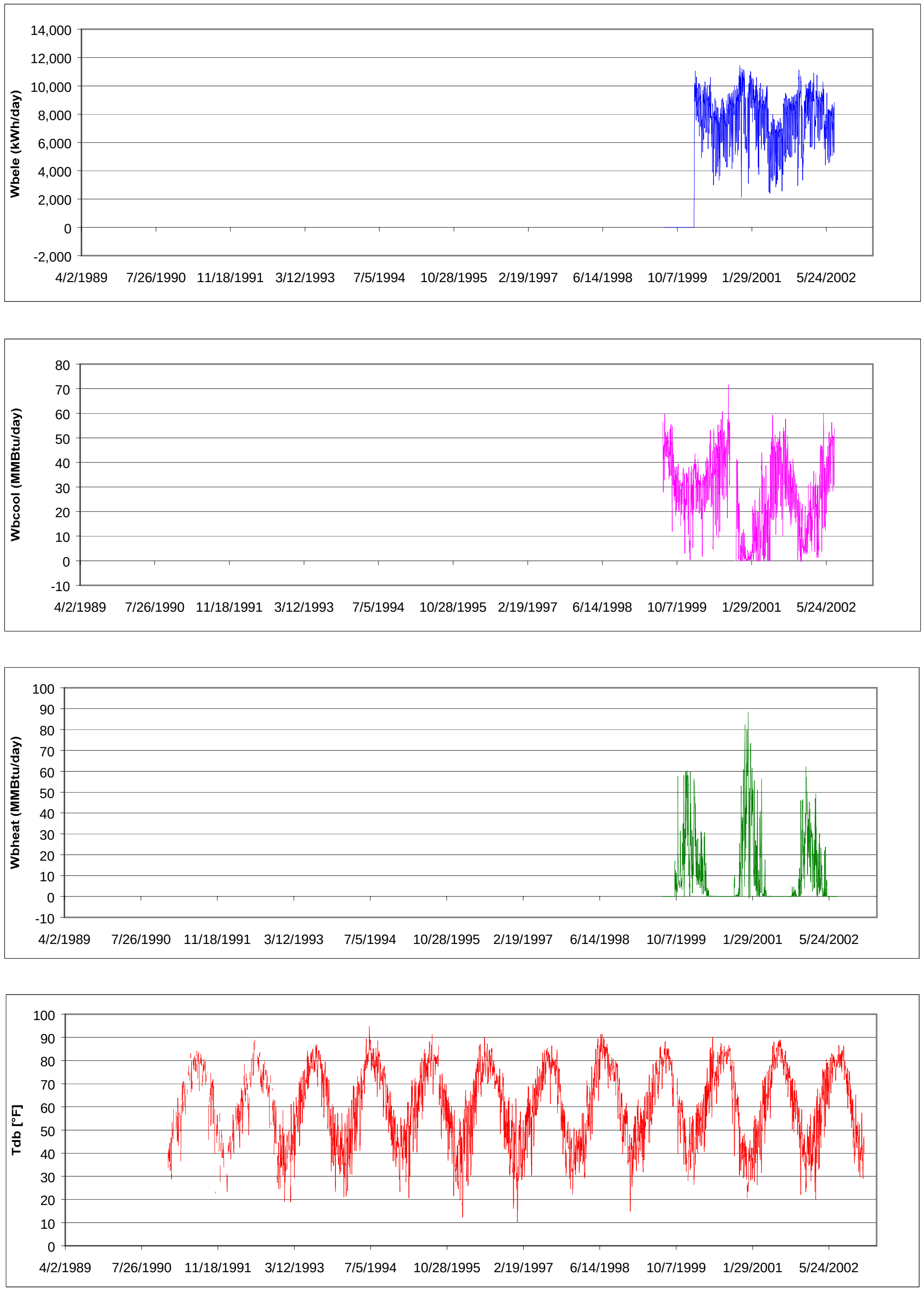


Figure IV24 Daily energy consumption and Tdb time series for site 197.

John H. Reagan (203)

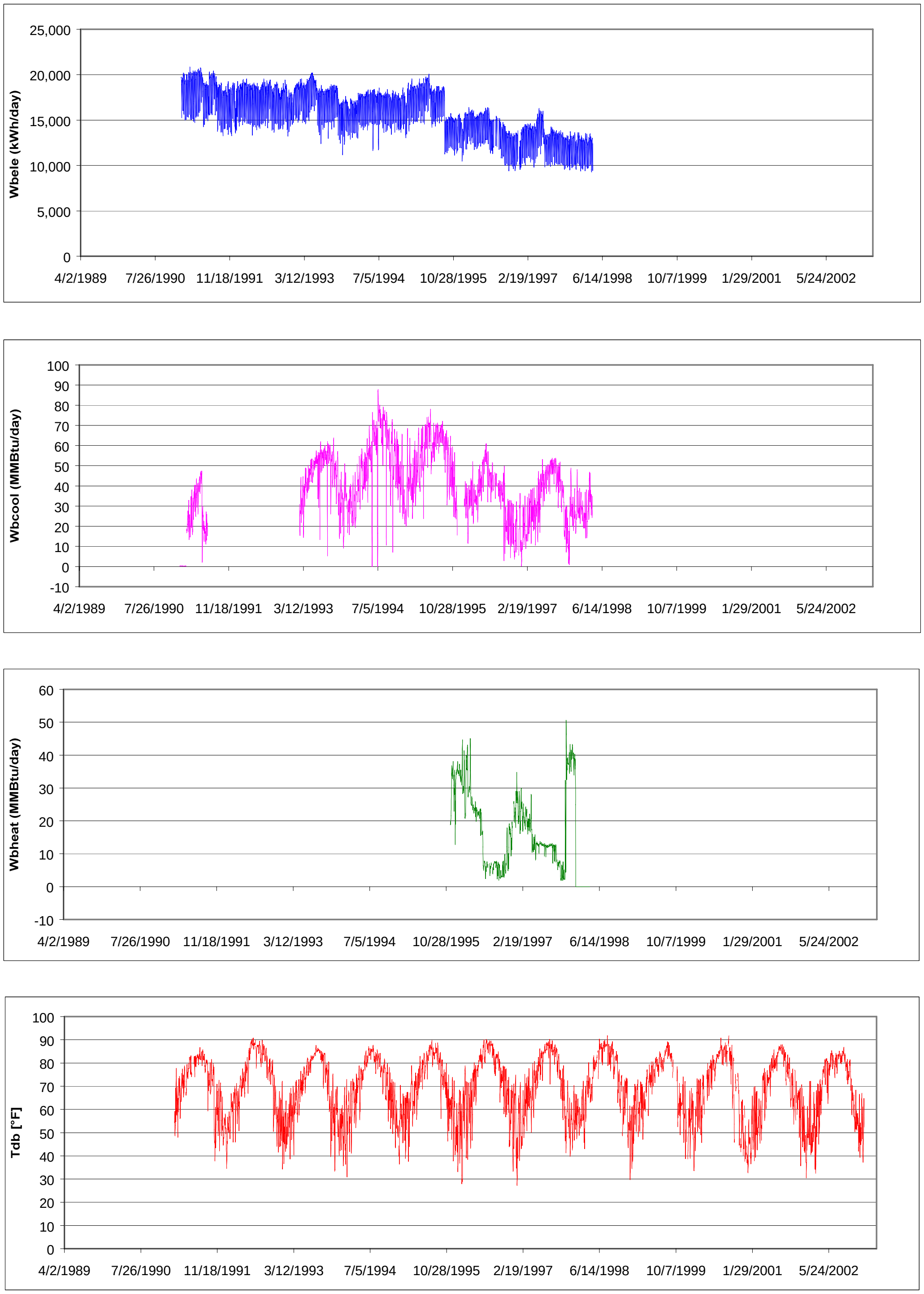
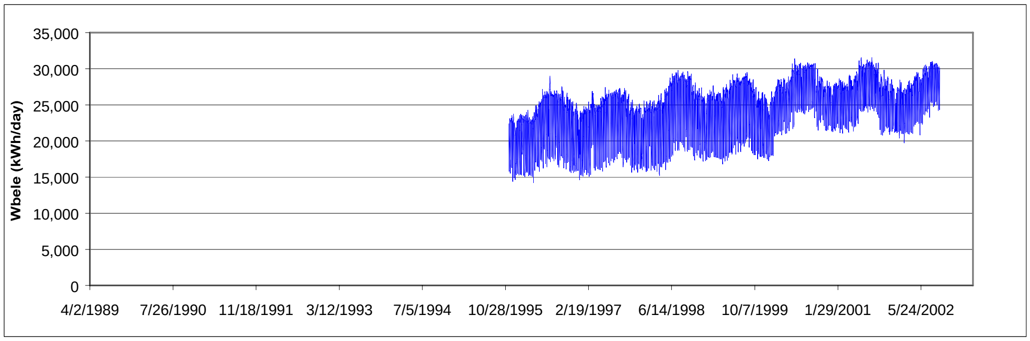
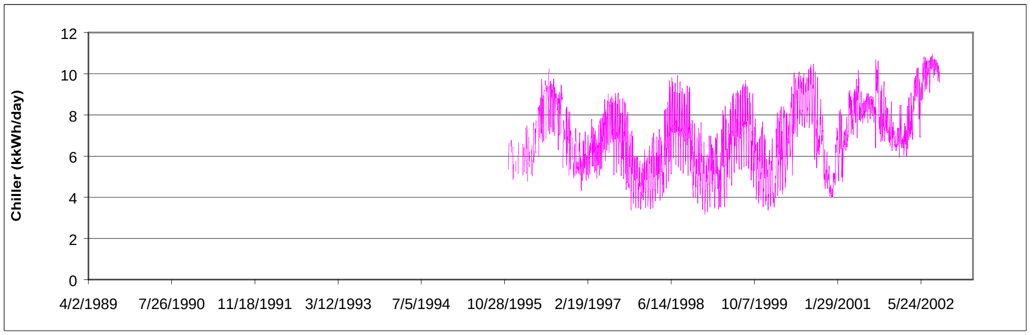
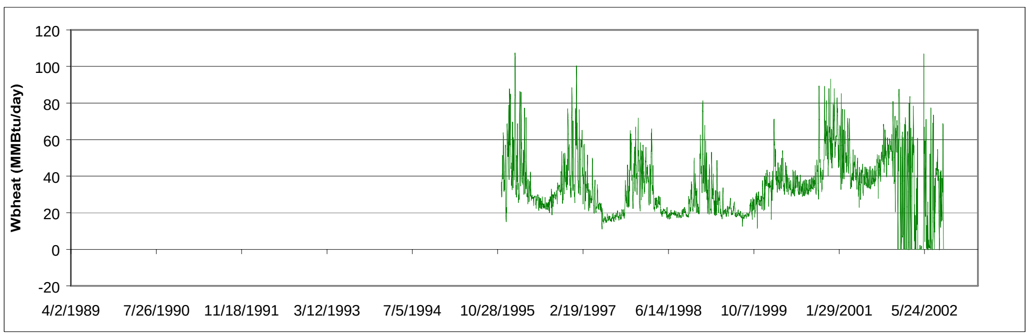


Figure IV25 Daily energy consumption and Tdb time series for site 203.

Brown Heatly Building (236)







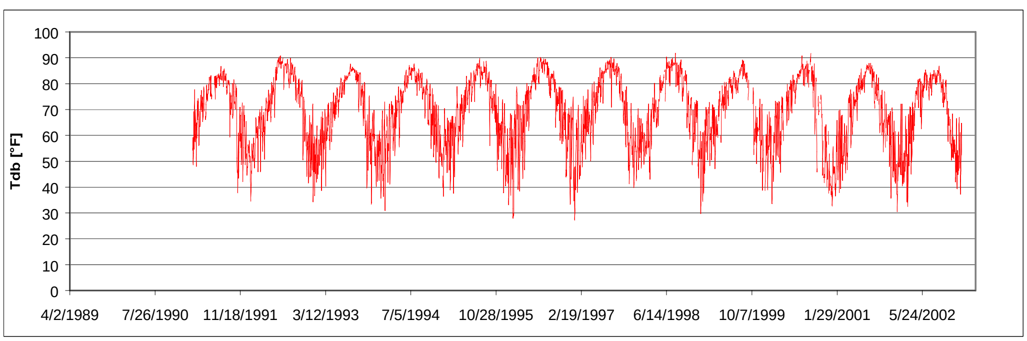
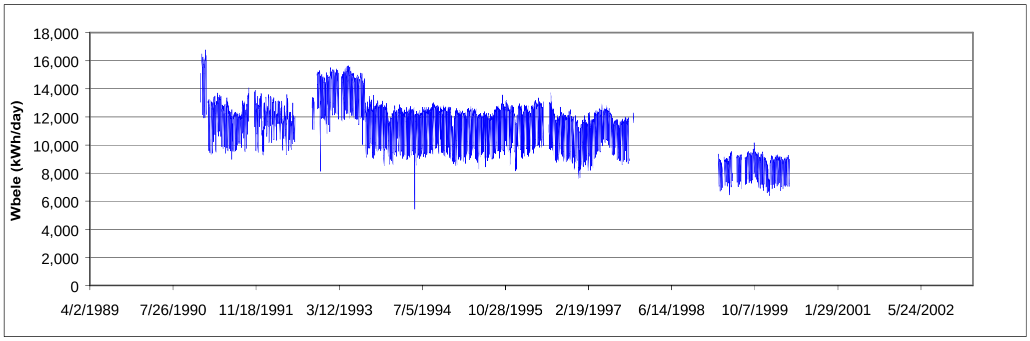
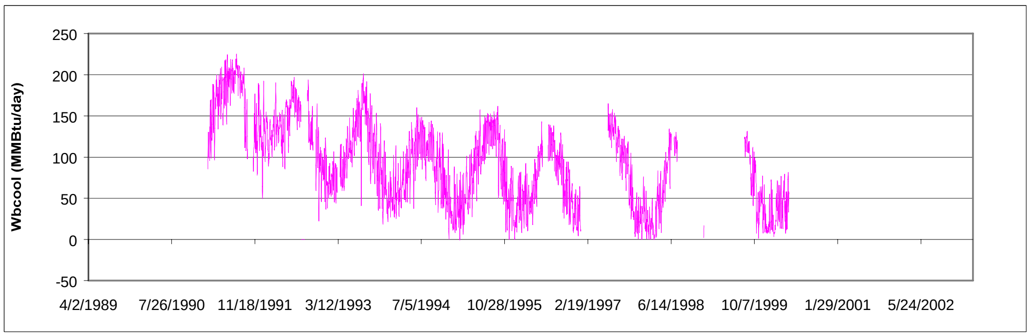
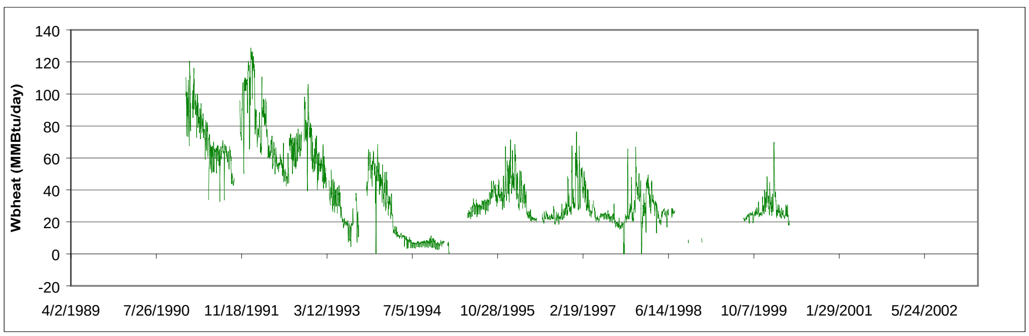


Figure IV26 Daily energy consumption and Tdb time series for site 236.

School of Public Health (300)







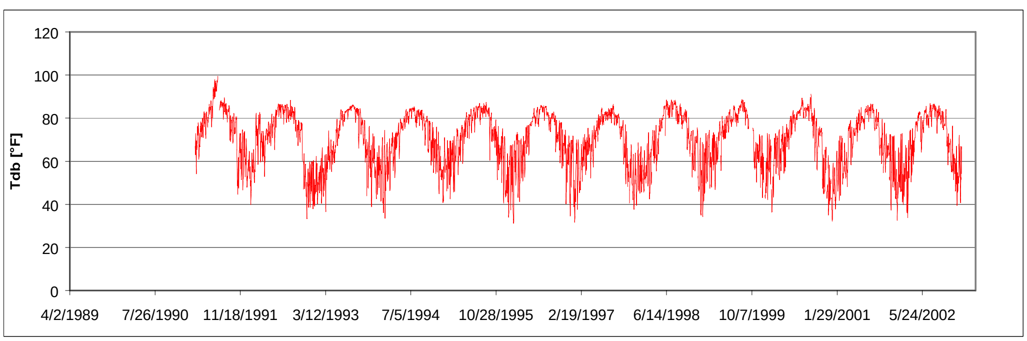


Figure IV27 Daily energy consumption and Tdb time series for site 300.

As the wet-bulb temperature or relative humidity (RH) for the School of Public Health (300) during 3/91 – 3/92 is unavailable, wet-bulb temperature data was derived from dry-bulb temperature data using the long-term average data in AFM-88 (DAAN, 1978).

John Sealy North (400)

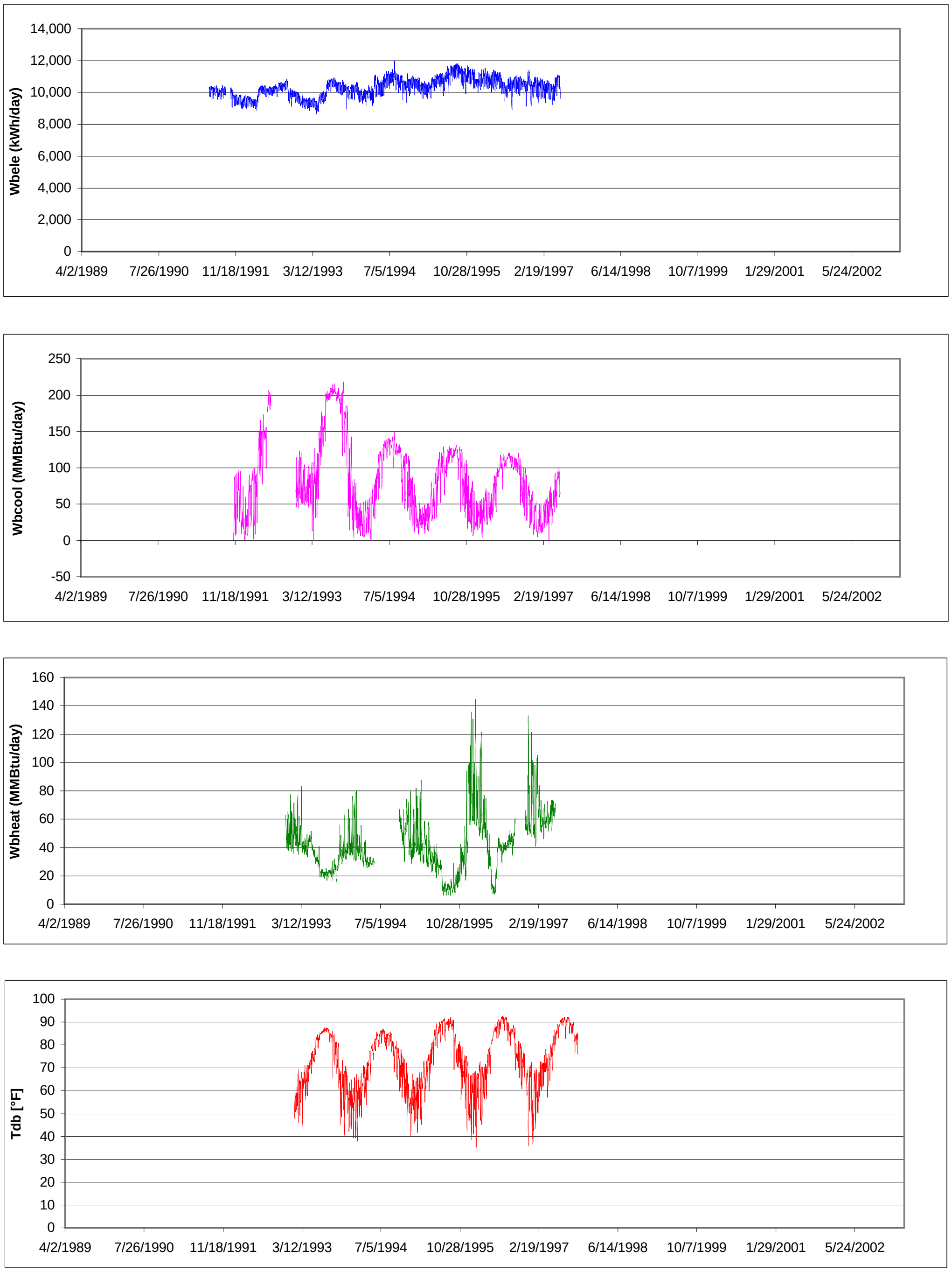


Figure IV28 Daily energy consumption and Tdb time series for site 400.

Moody Library (403)

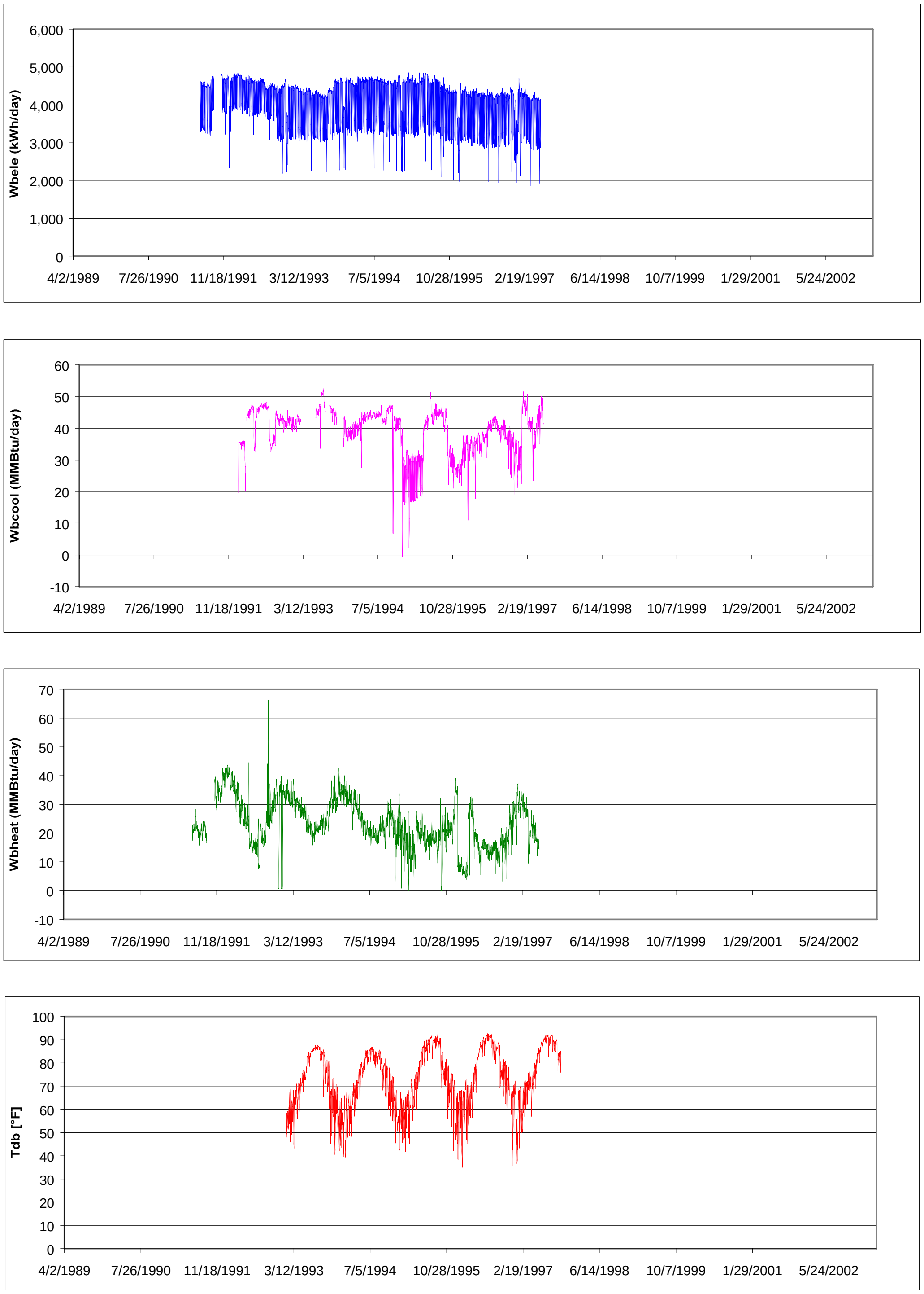


Figure IV29 Daily energy consumption and Tdb time series for site 403.

John Sealy South Towers (404)

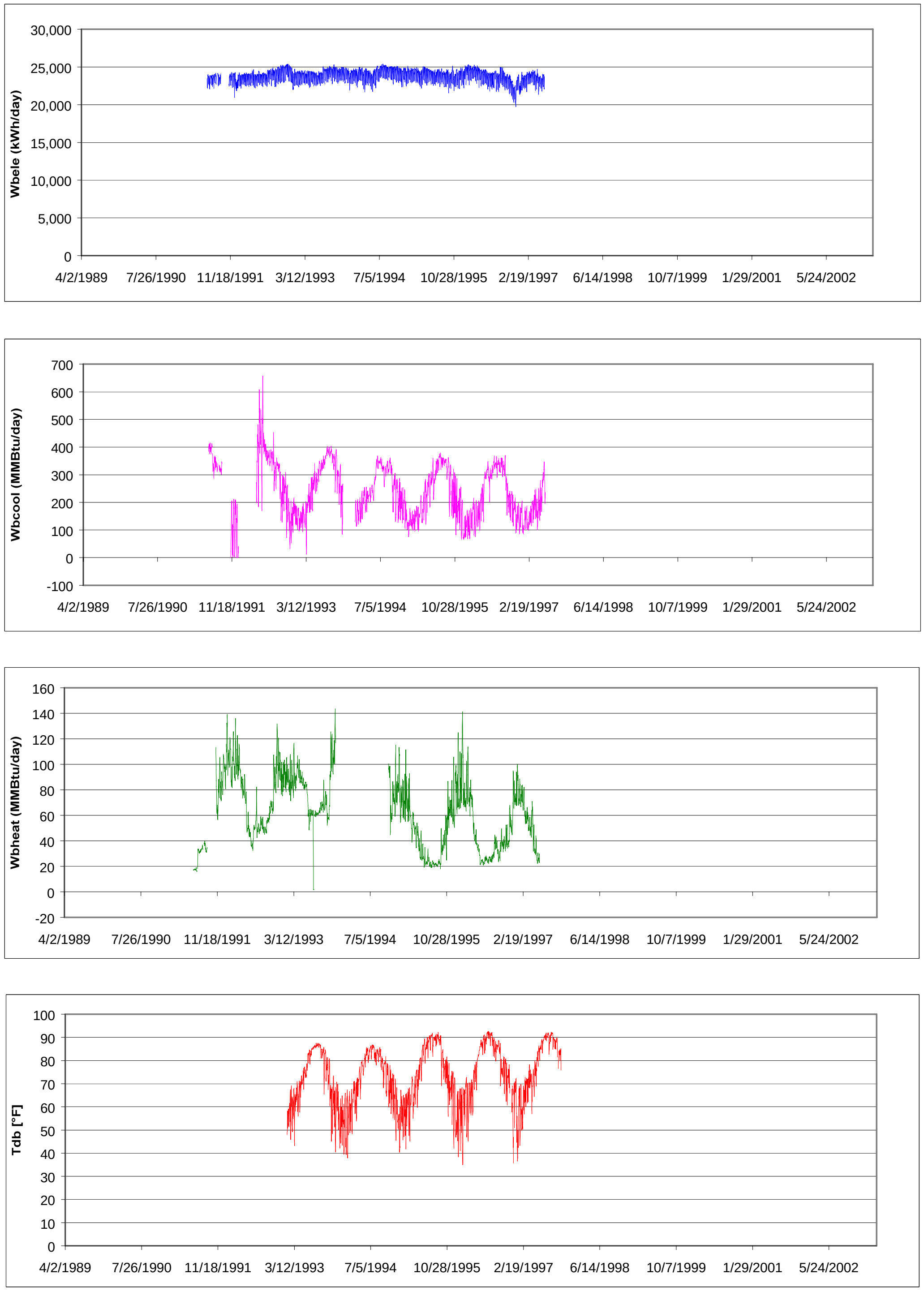


Figure IV30 Daily energy consumption and Tdb time series for site 404.

Evans Library (Old) (491)

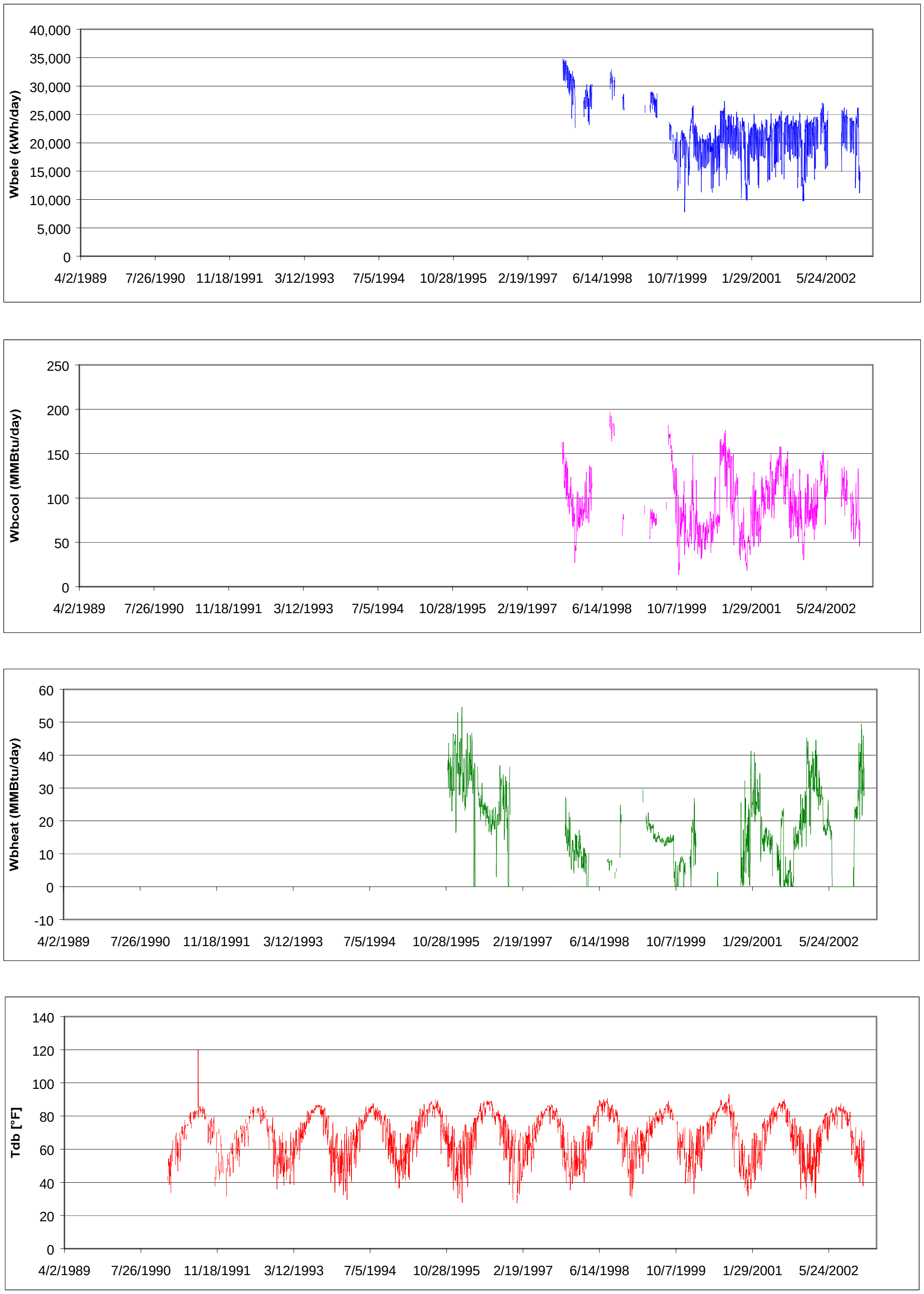
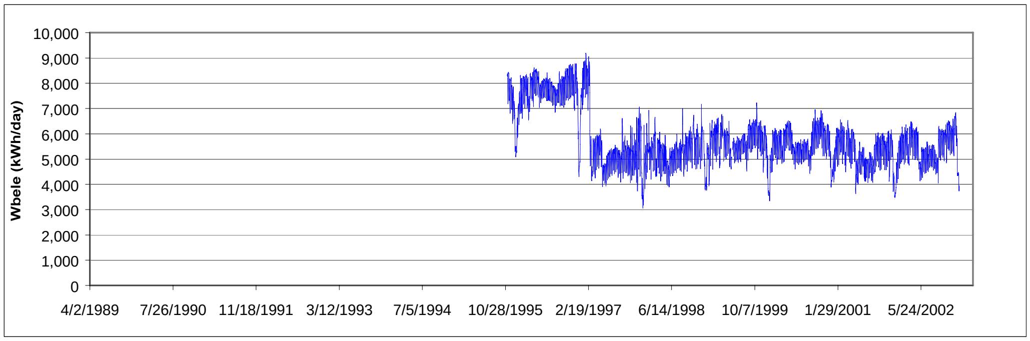
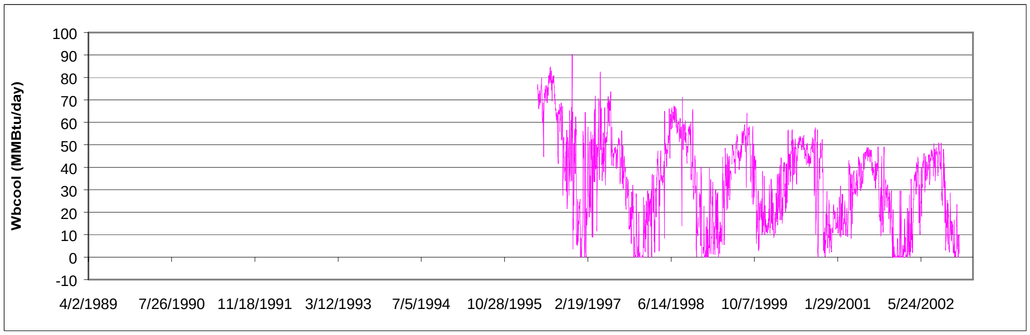
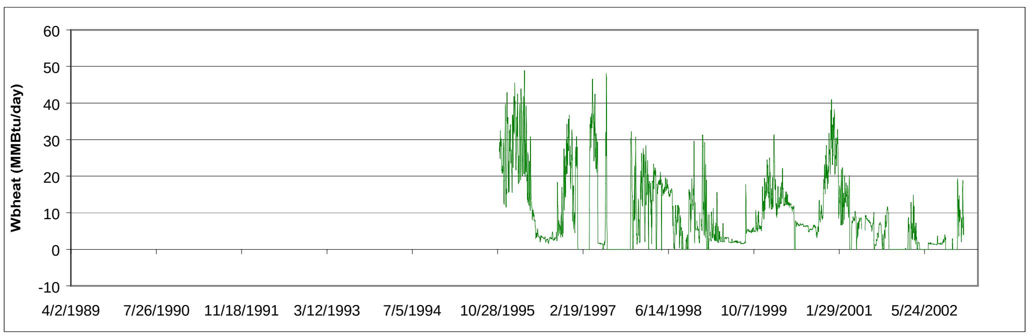


Figure IV31 Daily energy consumption and Tdb time series for site 491.

E. Langford Architecture Center (494)







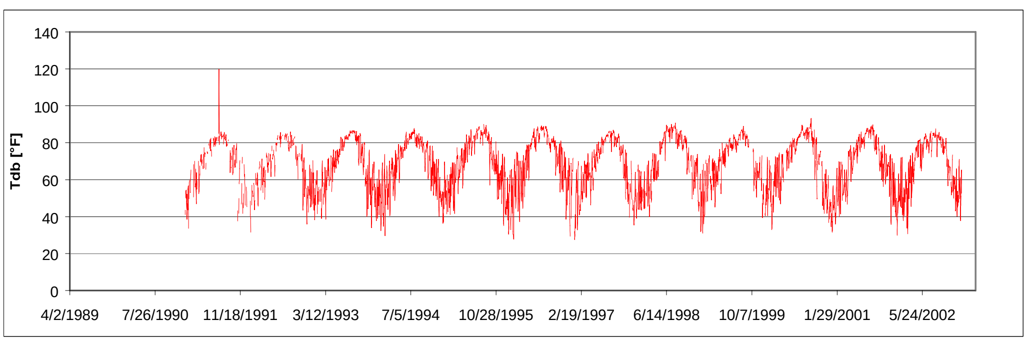
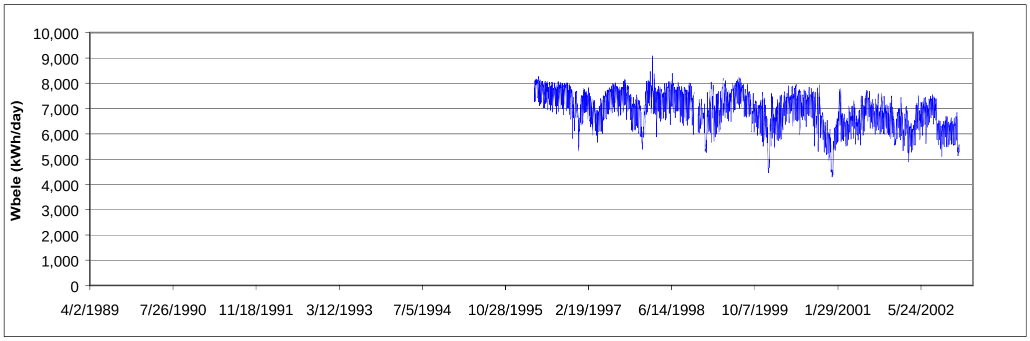
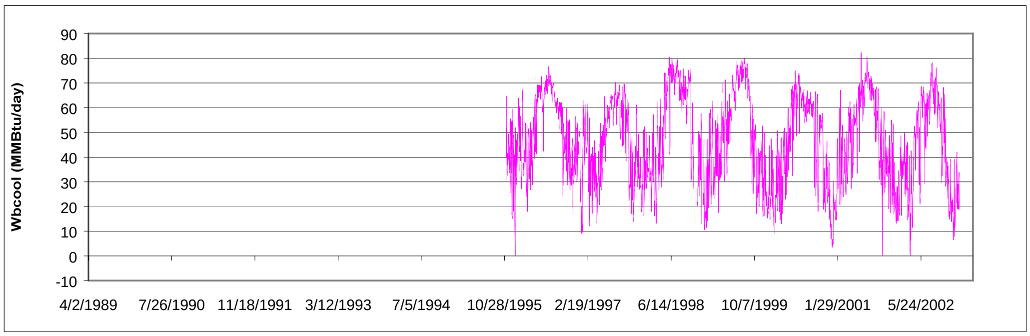
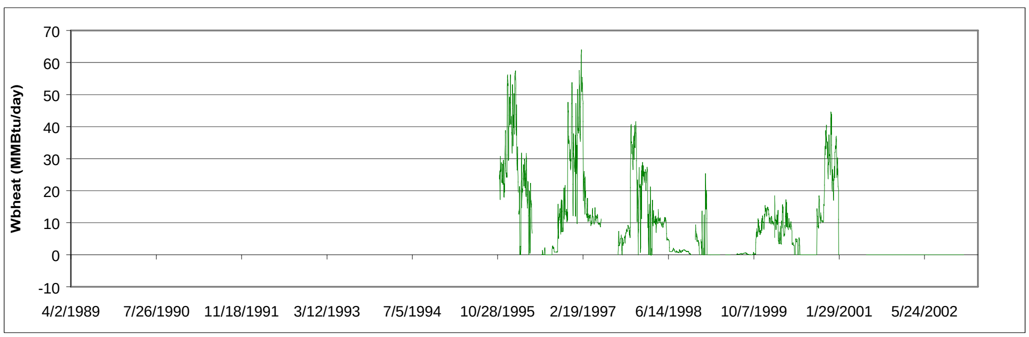


Figure IV32 Daily energy consumption and Tdb time series for site 494.

Biological Sciences West Building (496)







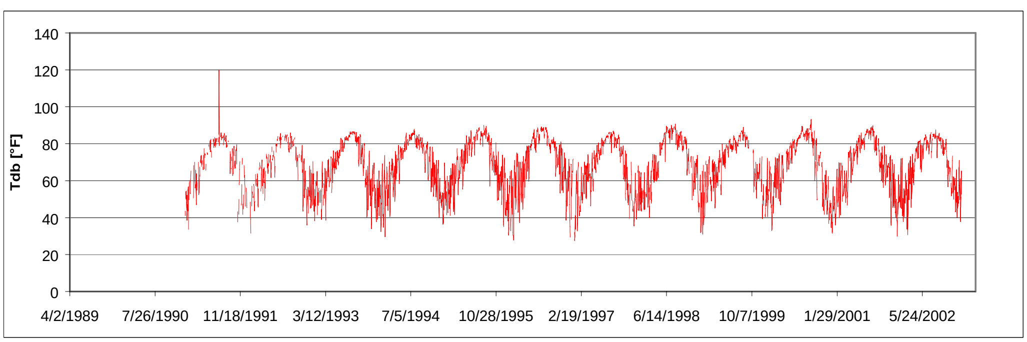


Figure IV33 Daily energy consumption and Tdb time series for site 496.

Teague (497)

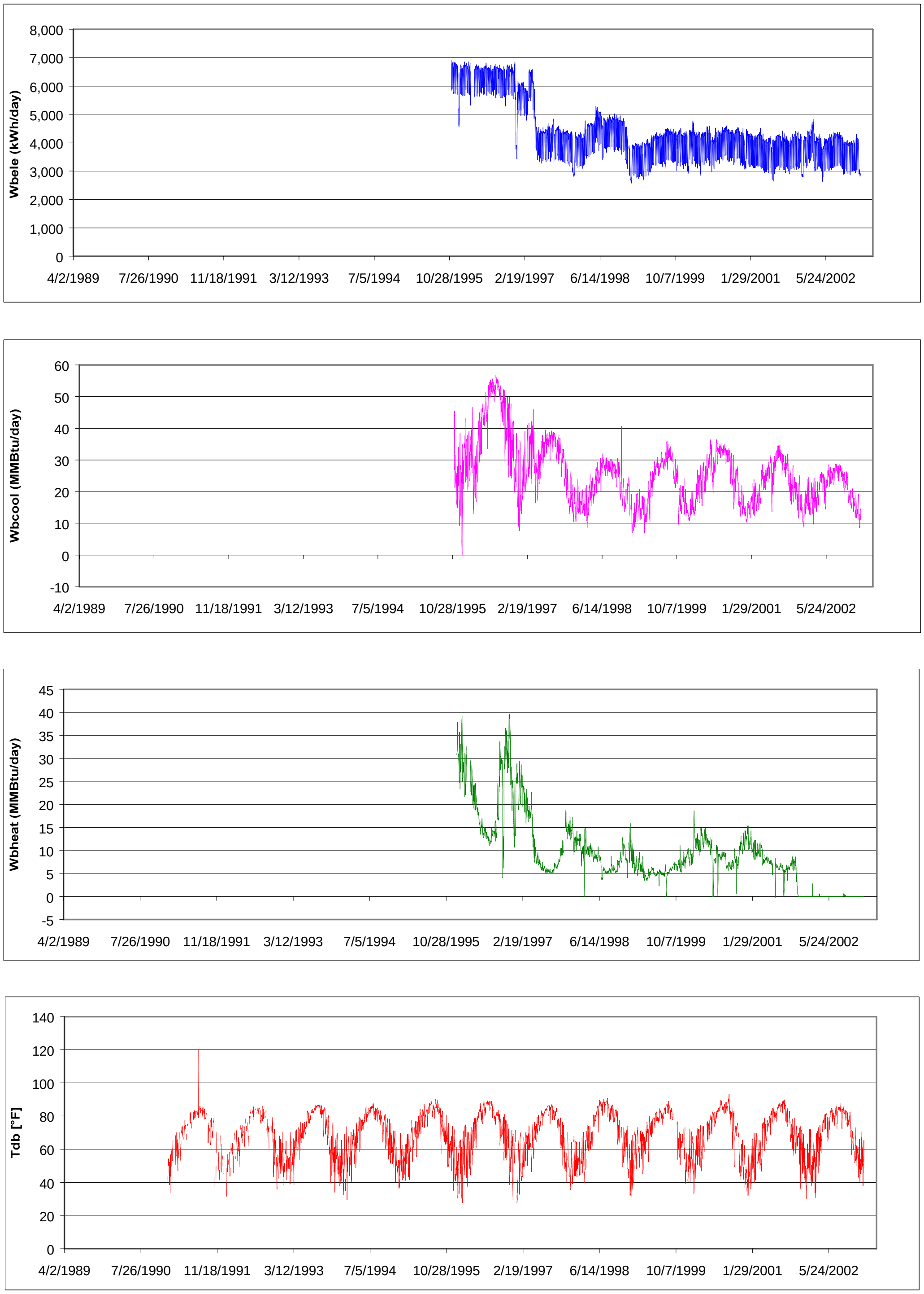


Figure IV34 Daily energy consumption and Tdb time series for site 497.

APPENDIX V

THE RELATIONSHIP BETWEEN ENERGY CONSUMPTION AND WEATHER FOR TESTING FACILITIES

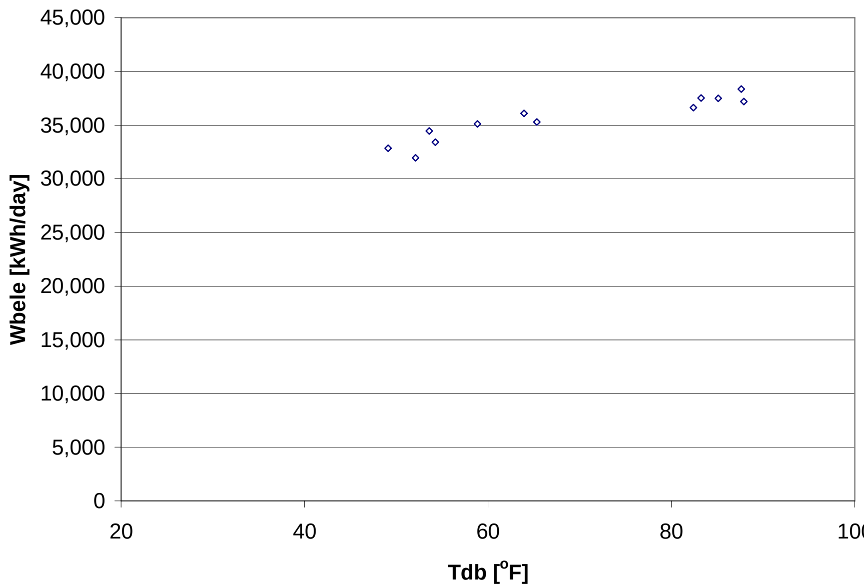


Figure V1 Monthly Wbele consumption vs. Tdb for site 1 during Jan. 90 – Jan. 91 (no Oct. 90).

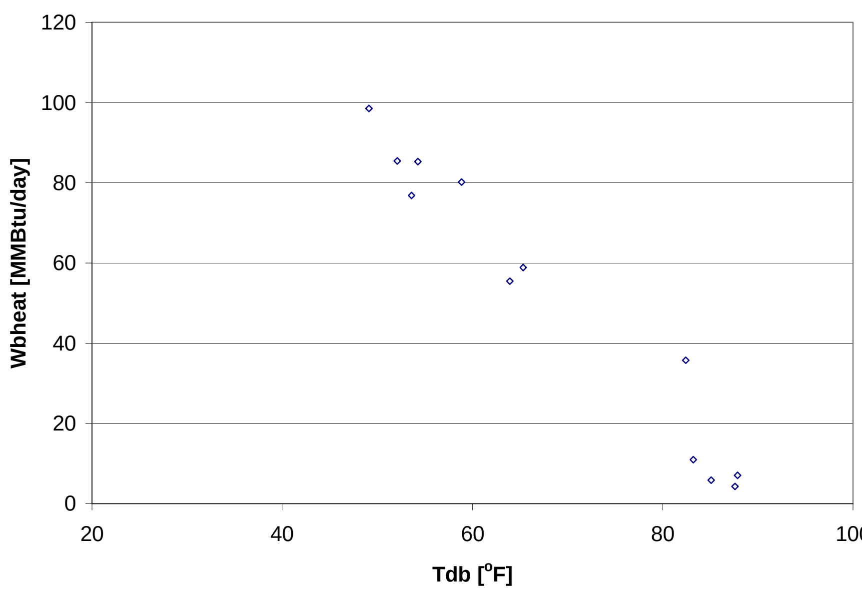


Figure V2 Monthly Wbheat consumption vs. Tdb for site 1 during Jan. 90 – Jan. 91 (no Oct. 90).

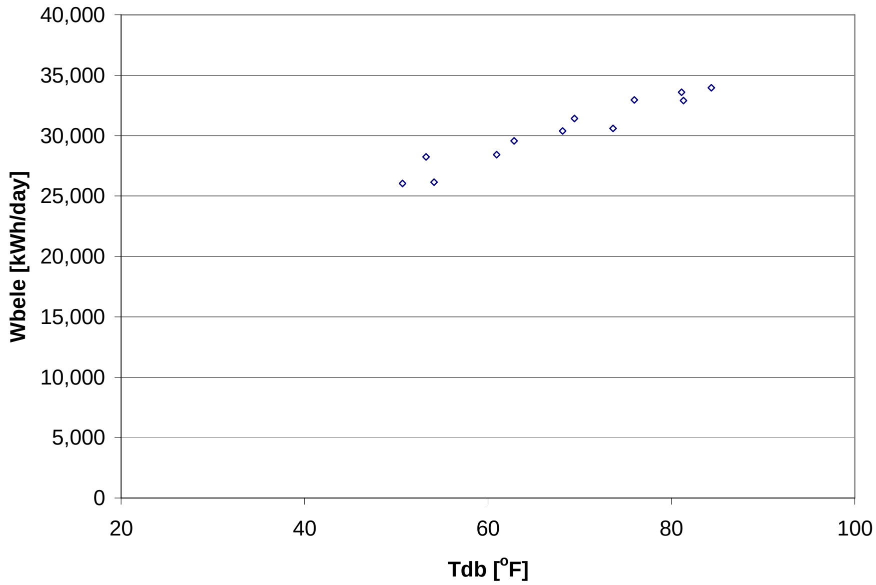


Figure V3 Monthly Wbele consumption vs. Tdb for site 1 during 1994.

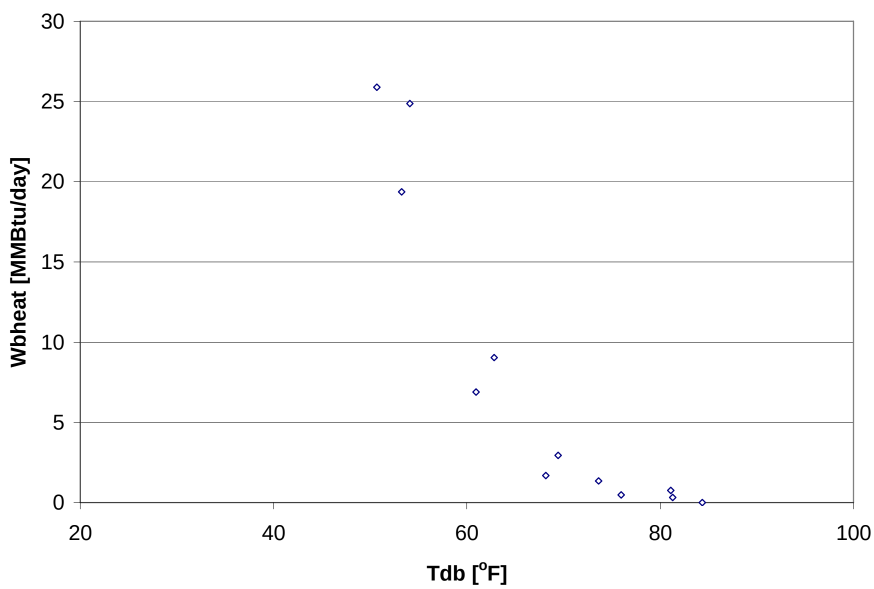


Figure V4 Monthly Wbheat consumption vs. Tdb for site 1 during 1994.

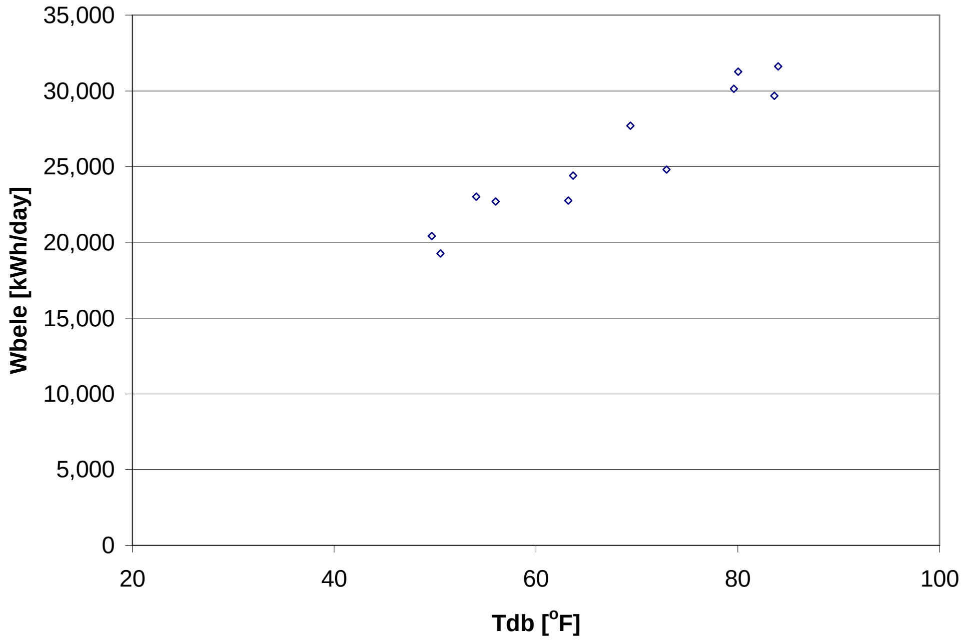


Figure V5 Monthly Wbele consumption vs. Tdb for site 1 during 1997.

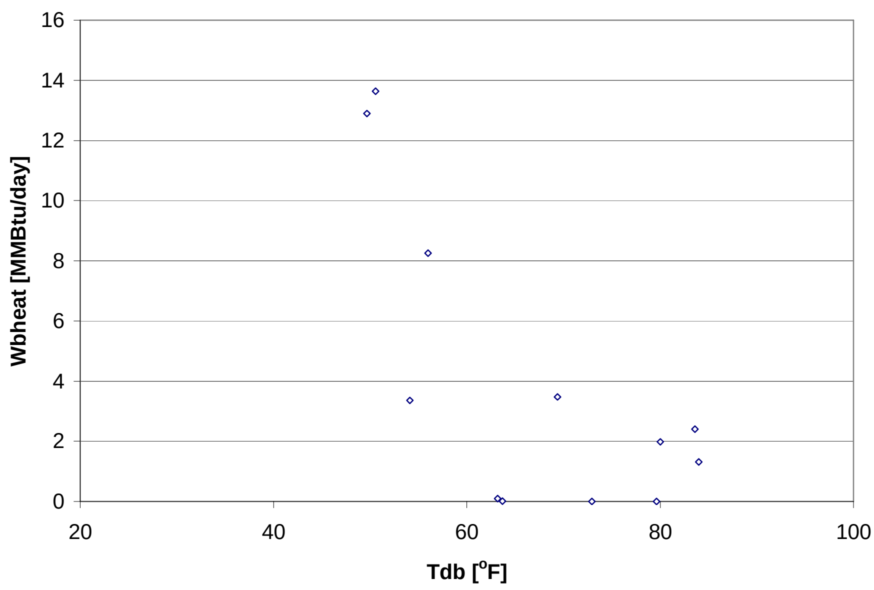


Figure V6 Monthly Wbheat consumption vs. Tdb for site 1 during 1997.

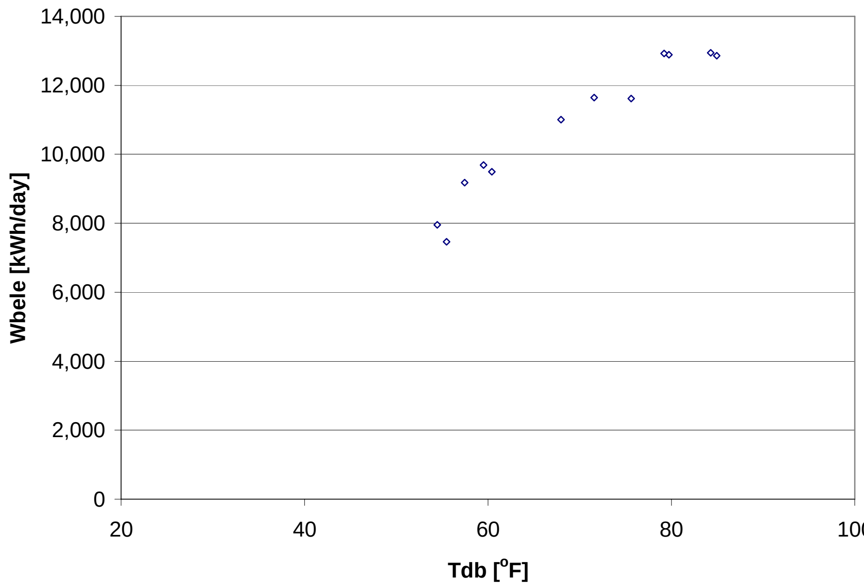


Figure V7 Monthly Wbele consumption vs. Tdb for site 100 during 1995.

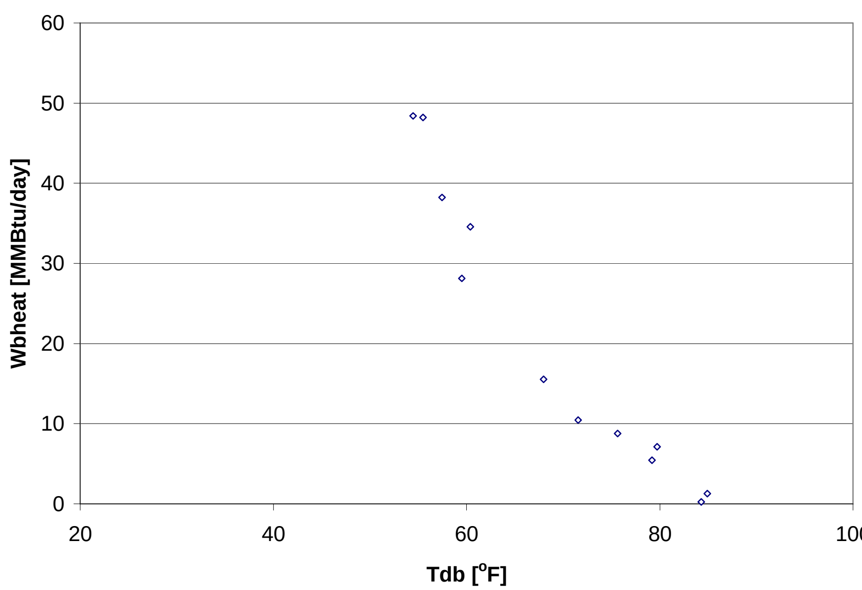


Figure V8 Monthly Wbheat consumption vs. Tdb for site 100 during 1995.

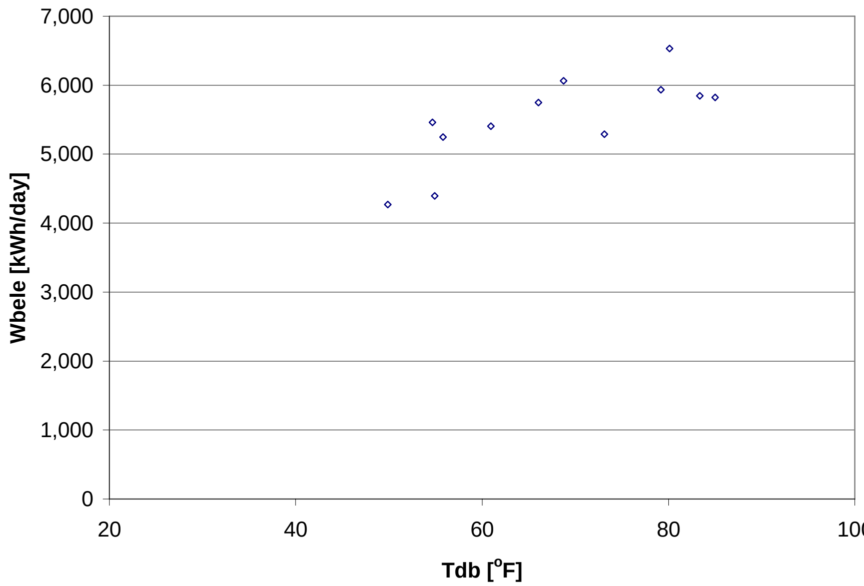


Figure V9 Monthly Wbele consumption vs. Tdb for site 101 during 1993.

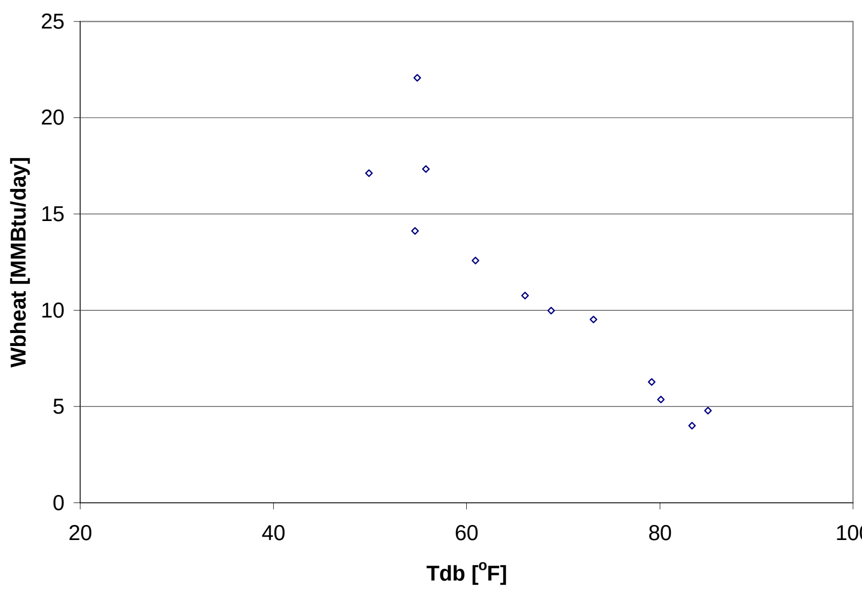


Figure V10 Monthly Wbheat consumption vs. Tdb for site 101 during 1993.

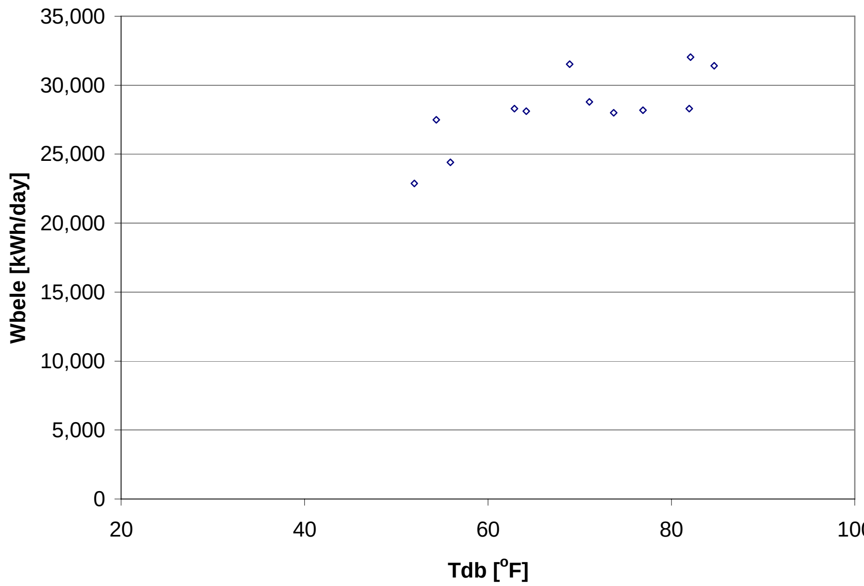


Figure V11 Monthly Wbele consumption vs. Tdb for site 102 during 1994.

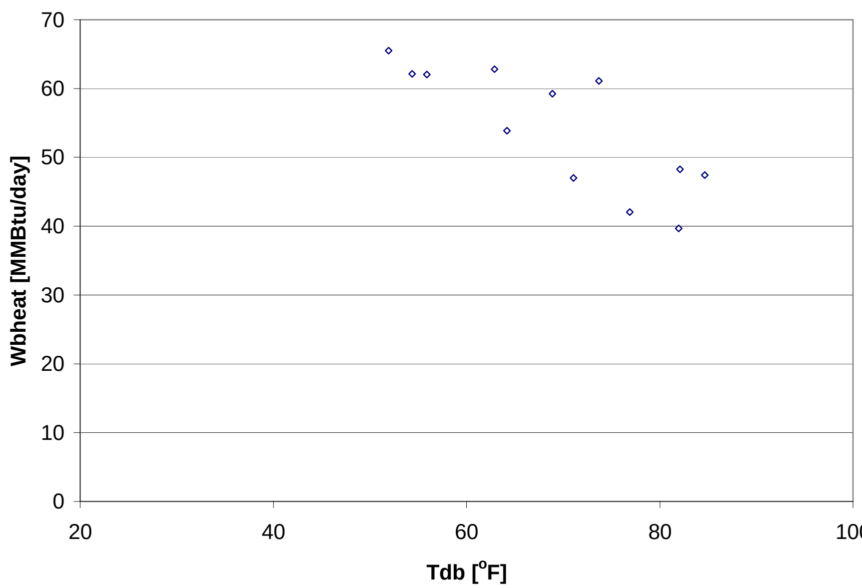


Figure V12 Monthly Wbheat consumption vs. Tdb for site 102 during 1994.

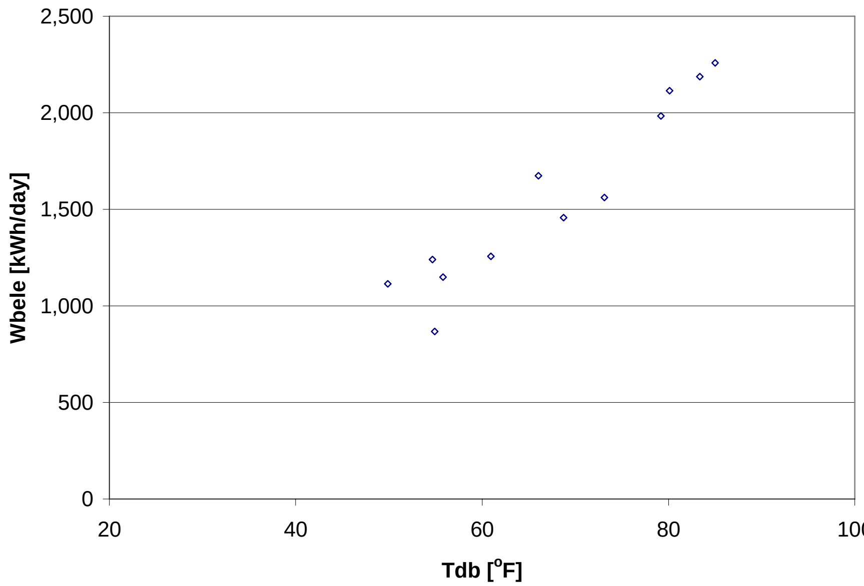


Figure V13 Monthly Wbele consumption vs. Tdb for site 103 during 1993.

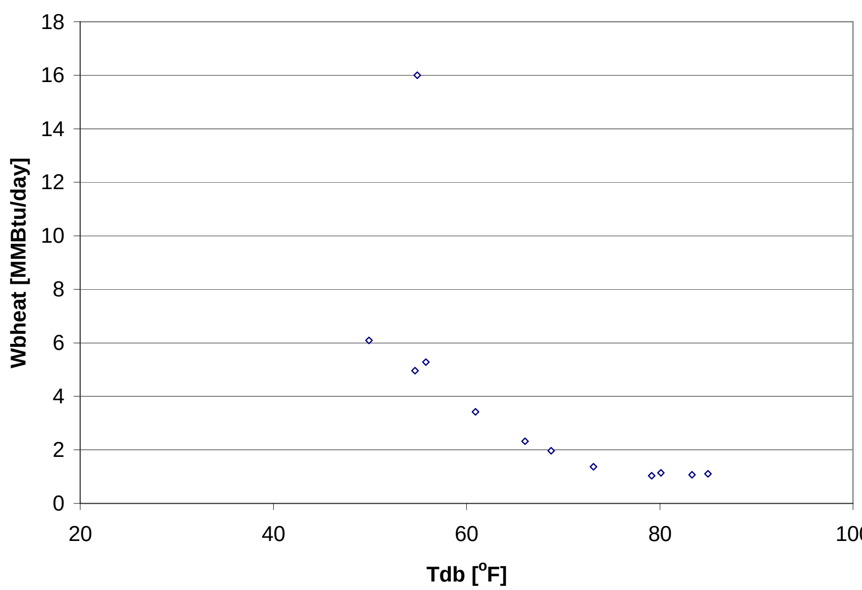


Figure V14 Monthly Wbheat consumption vs. Tdb for site 103 during 1993.

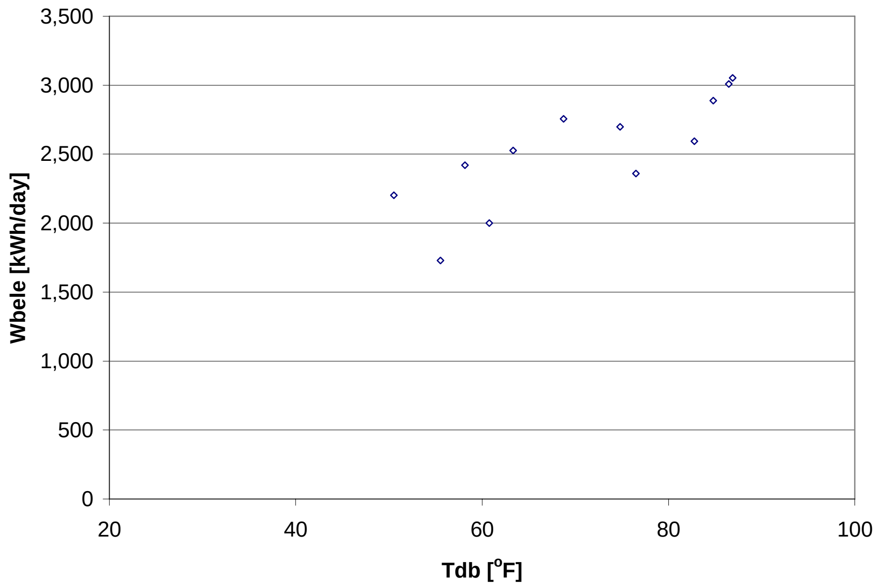


Figure V15 Monthly Wbele consumption vs. Tdb for site 104 during 1992.

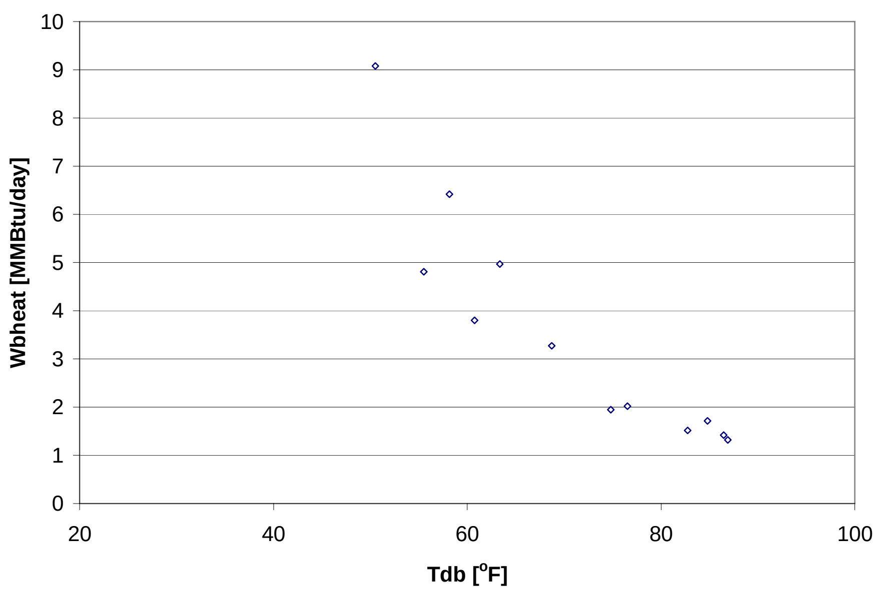


Figure V16 Monthly Wbheat consumption vs. Tdb for site 104 during 1992.

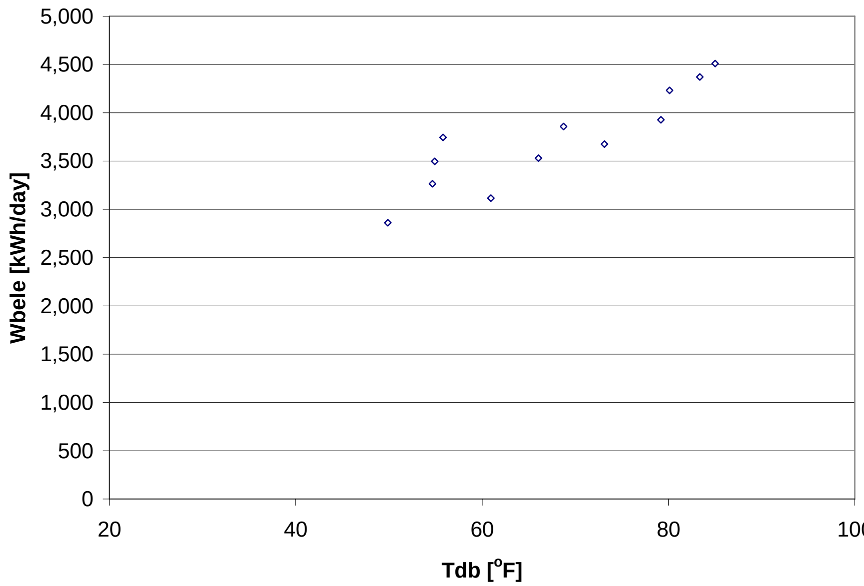


Figure V17 Monthly Wbele consumption vs. Tdb for site 105 during 1993.

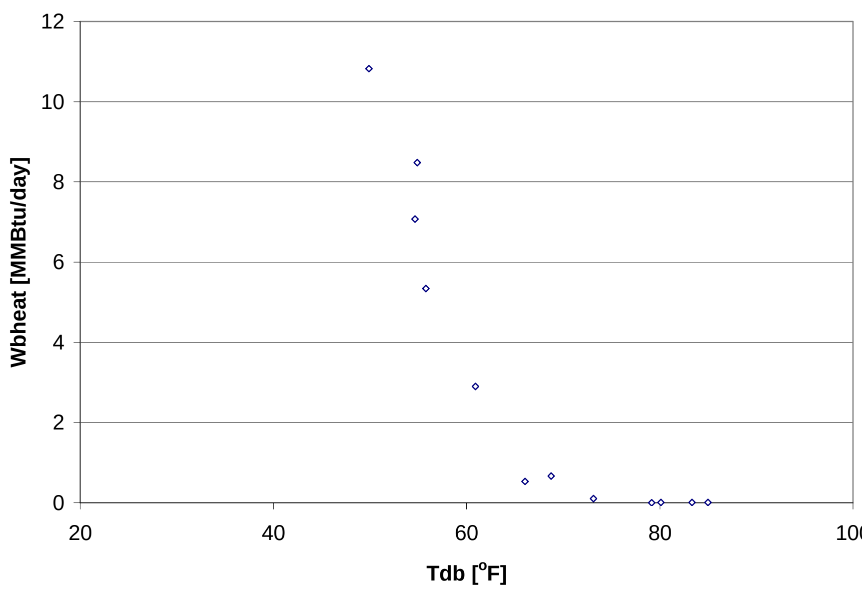


Figure V18 Monthly Wbheat consumption vs. Tdb for site 105 during 1993.

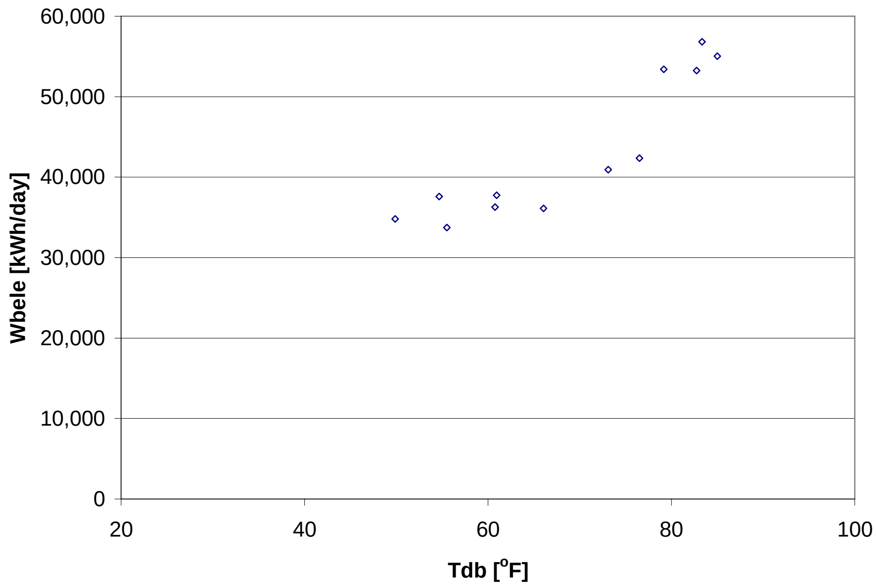


Figure V19 Monthly Wbele consumption vs. Tdb for site 106 during Sep. 1992 – Aug. 1993.

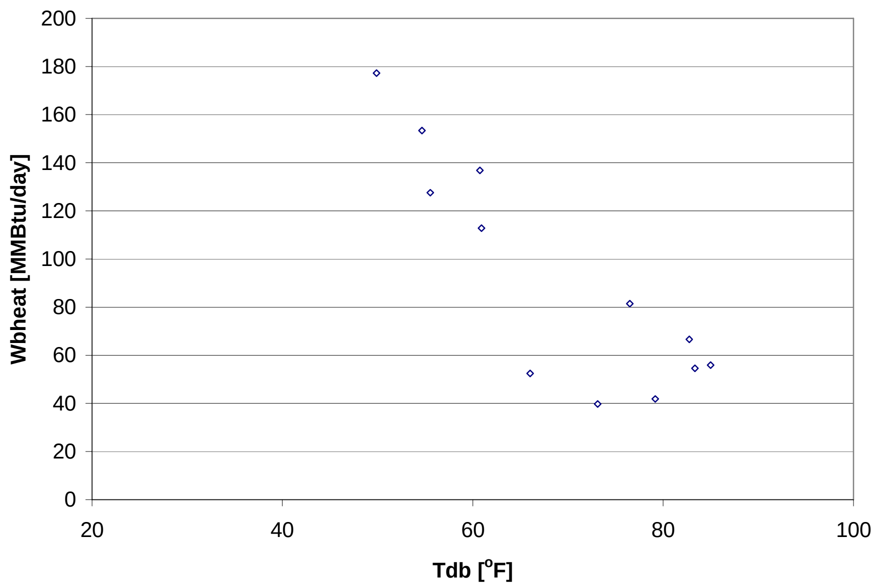


Figure V20 Monthly Wbheat consumption vs. Tdb for site 106 during Sep. 1992 – Aug. 1993.

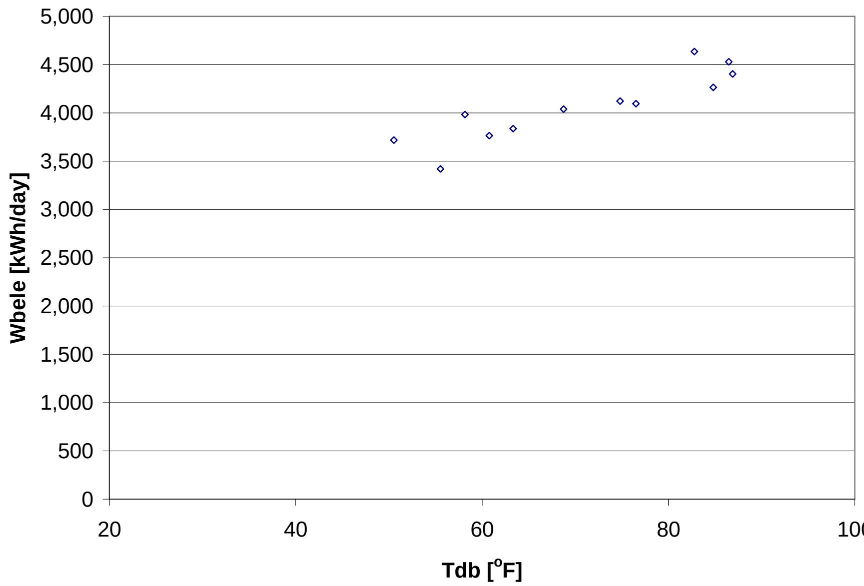


Figure V21 Monthly Wbele consumption vs. Tdb for site 107 during 1992.

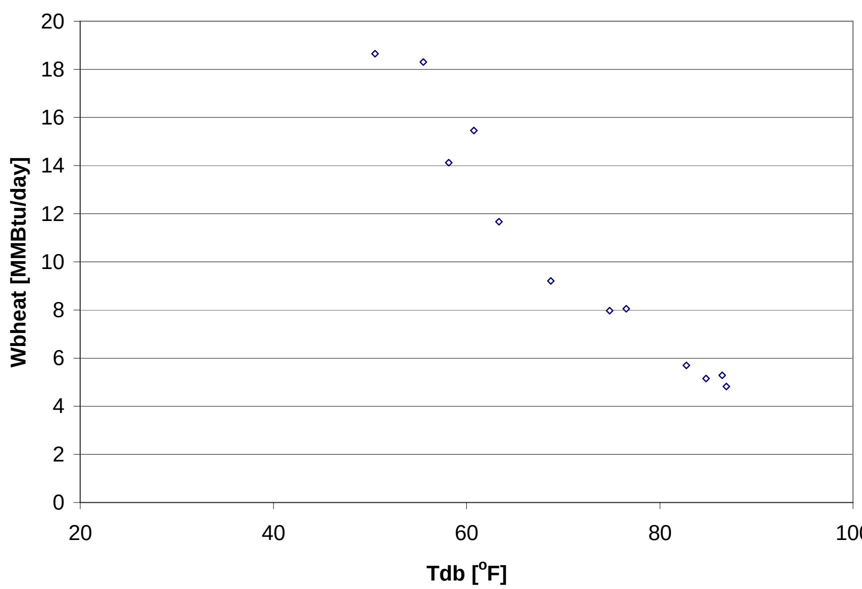


Figure V22 Monthly Wbheat consumption vs. Tdb for site 107 during 1992.

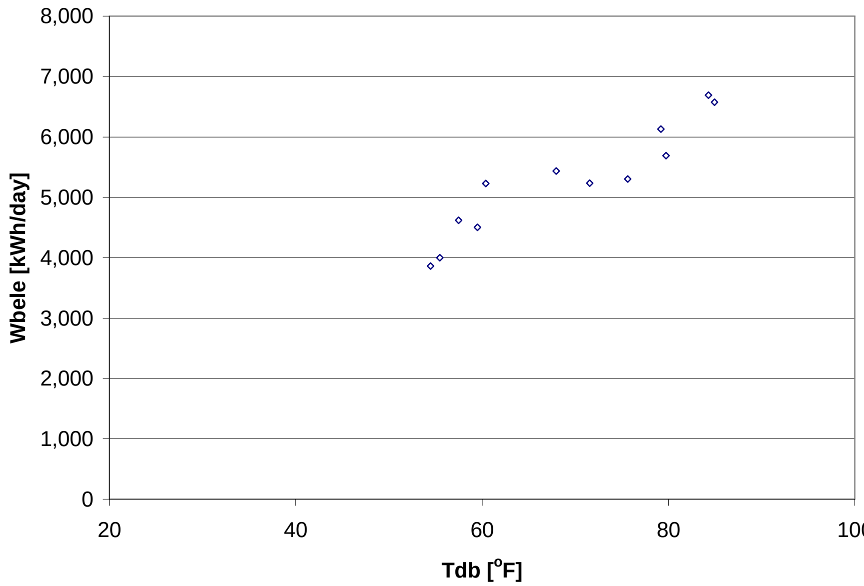


Figure V23 Monthly Wbele consumption vs. Tdb for site 108 during 1995.

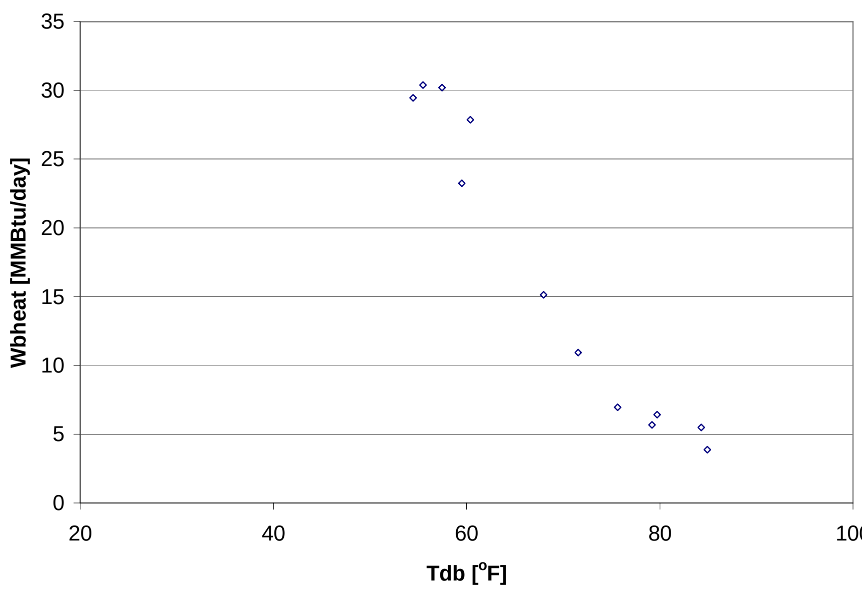


Figure V24 Monthly Wbheat consumption vs. Tdb for site 108 during 1995.

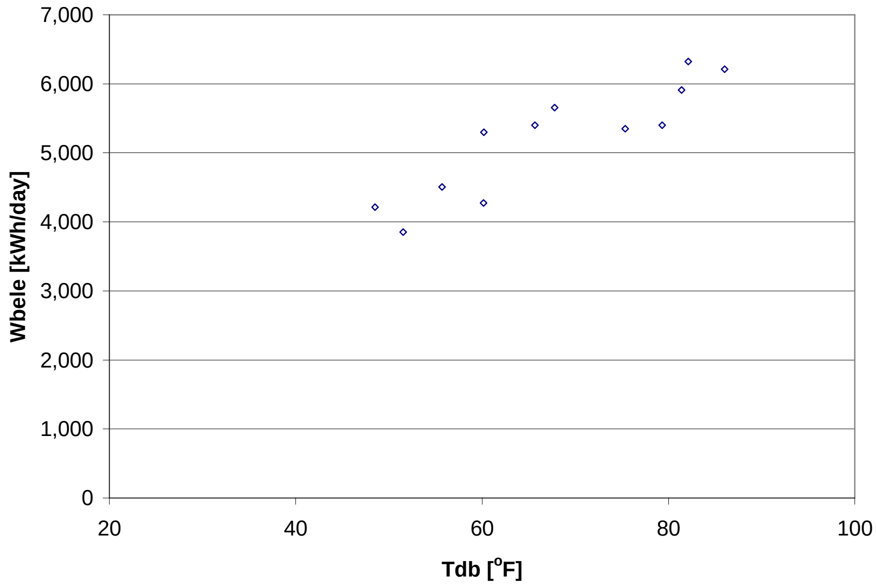


Figure V25 Monthly Wbele consumption vs. Tdb for site 111 during 1996.

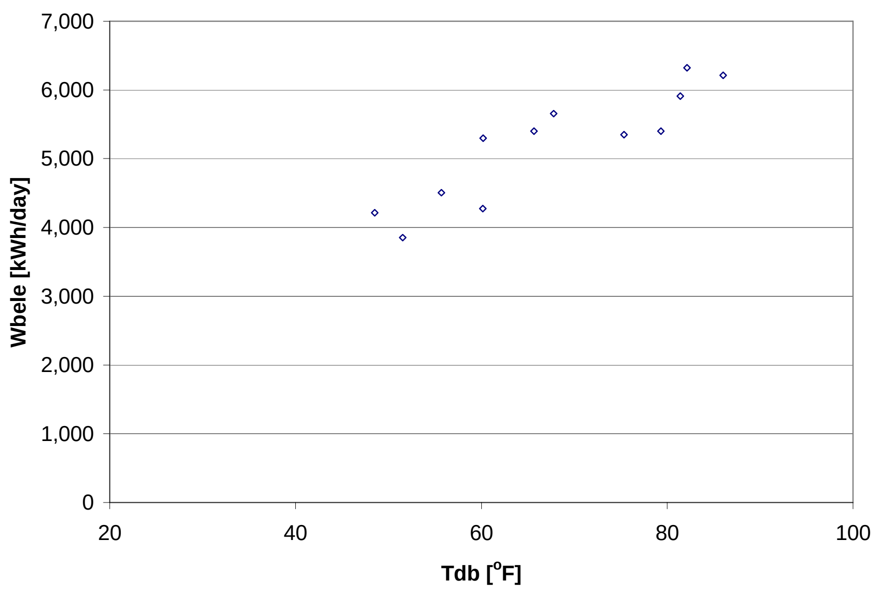


Figure V26 Monthly Wbheat consumption vs. Tdb for site 111 during 1996.

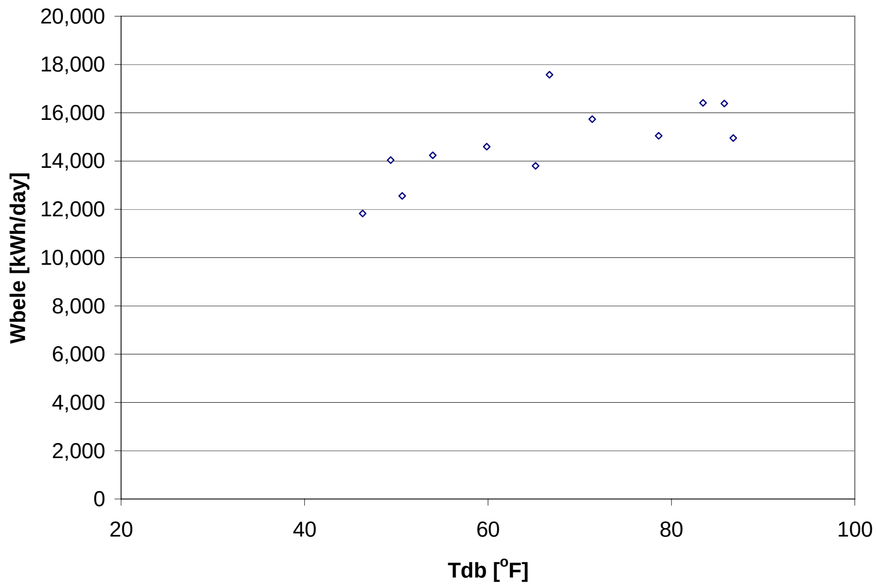


Figure V27 Monthly Wbele consumption vs. Tdb for site 112 during July 1993 – June 1994.

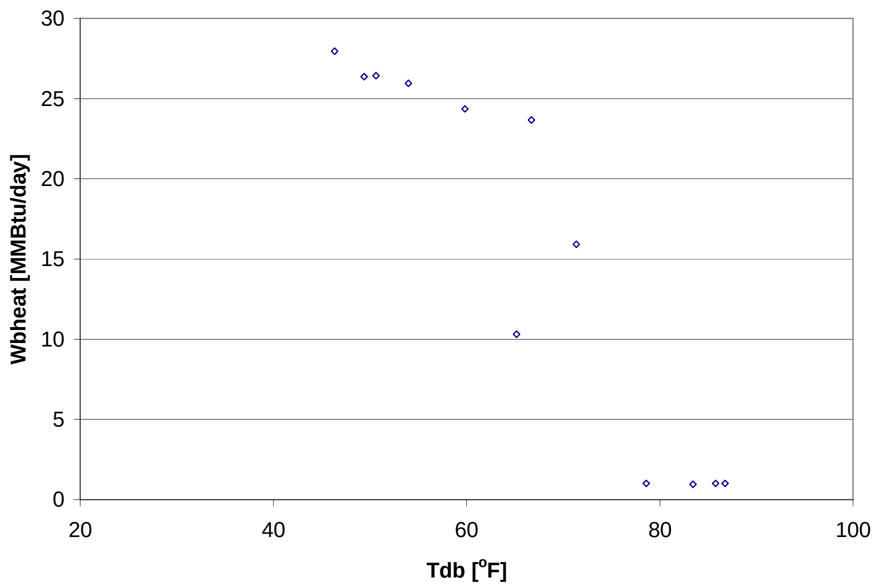


Figure V28 Monthly Wbheat consumption vs. Tdb for site 112 during July 1993 – June 1994.

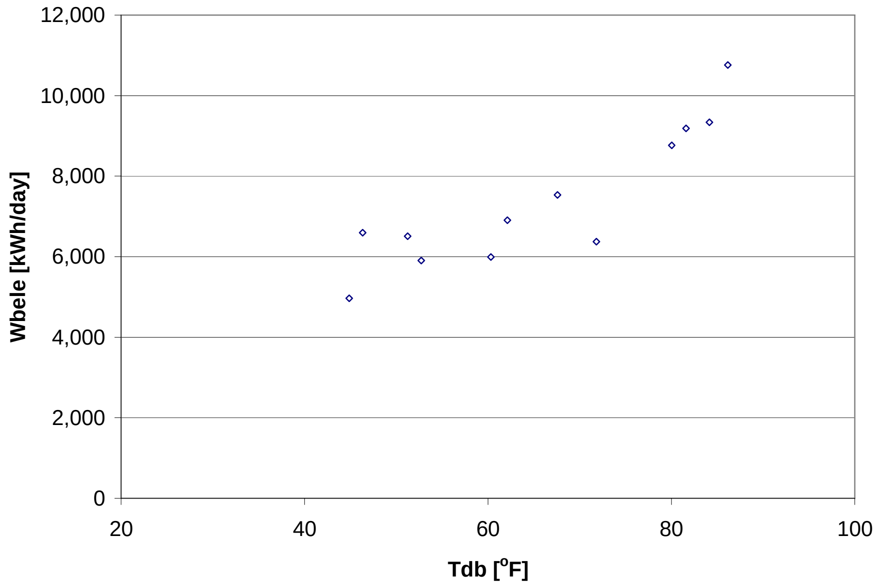


Figure V29 Monthly Wbele consumption vs. Tdb for site 112 during July 1997.

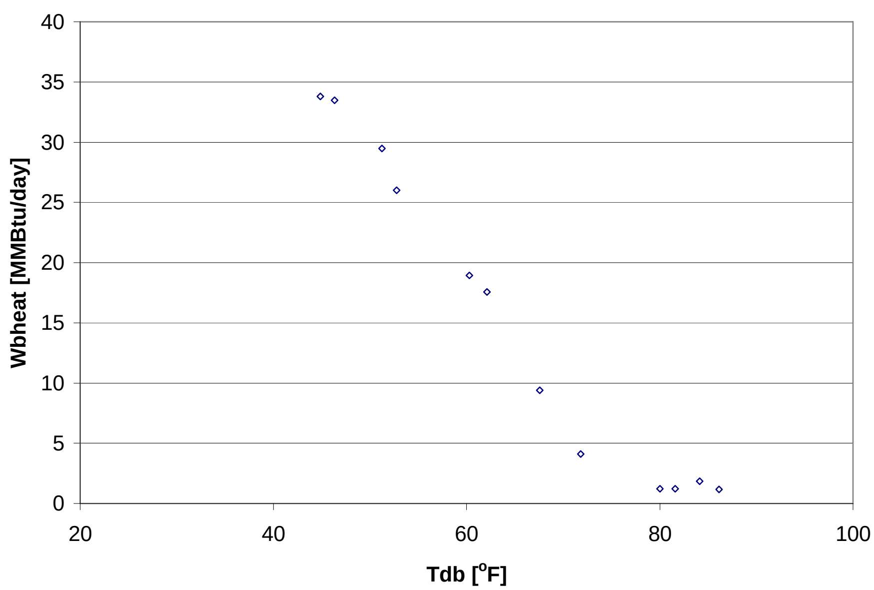


Figure V30 Monthly Wbheat consumption vs. Tdb for site 112 during July 1997.

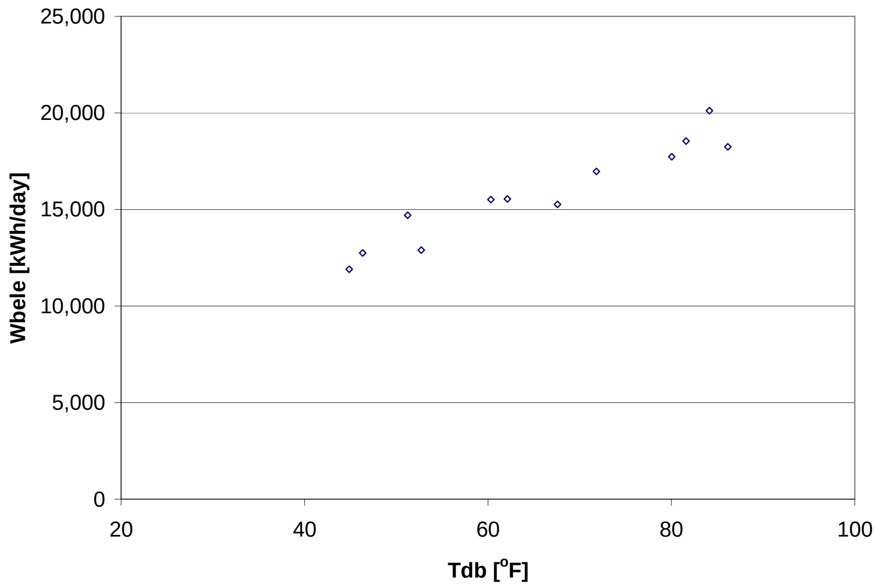


Figure V31 Monthly Wbele consumption vs. Tdb for site 113 during 1997.

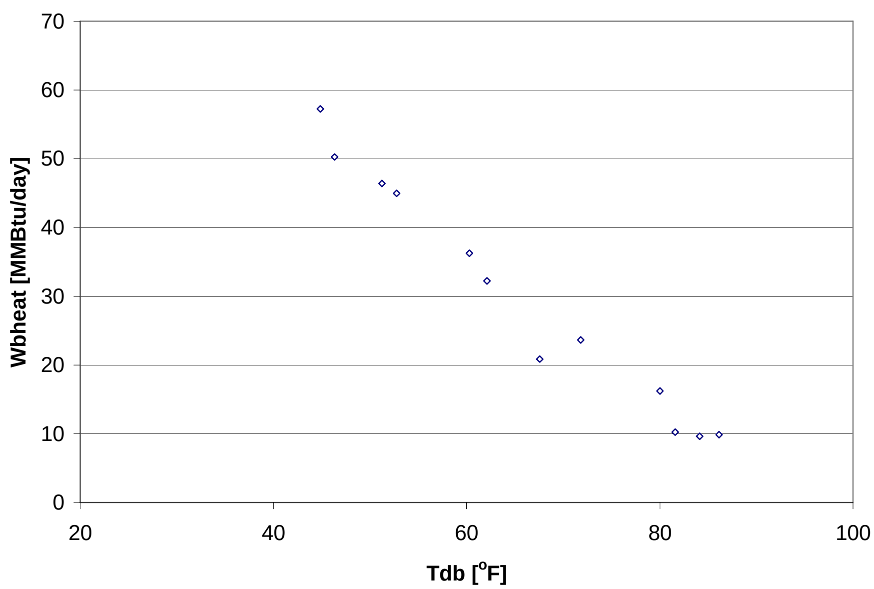


Figure V32 Monthly Wbheat consumption vs. Tdb for site 113 during 1997.

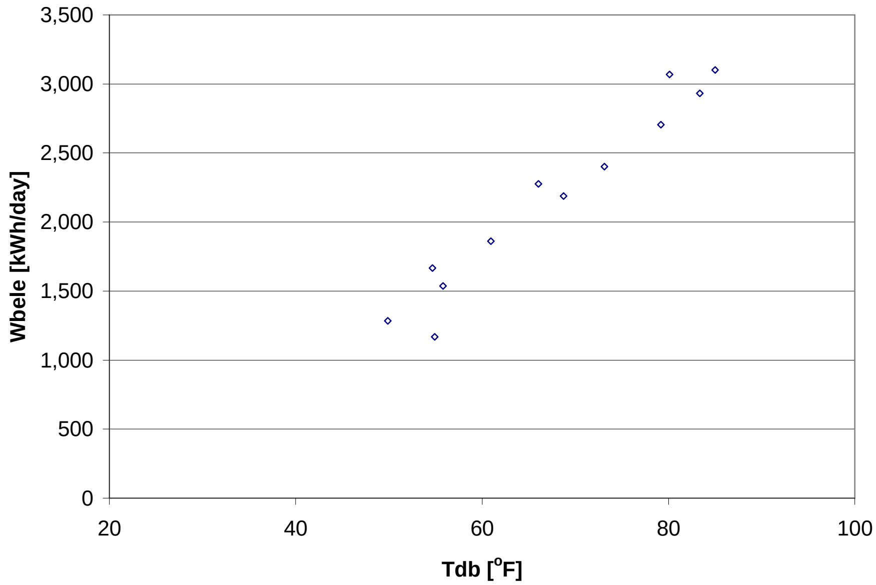


Figure V33 Monthly Wbele consumption vs. Tdb for site 115 during 1993.

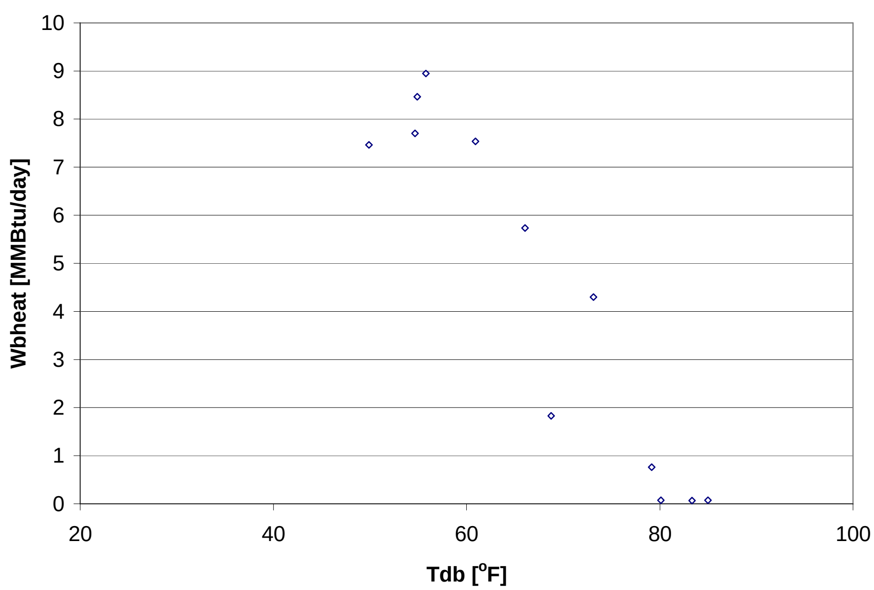


Figure V34 Monthly Wbheat consumption vs. Tdb for site 115 during 1993.

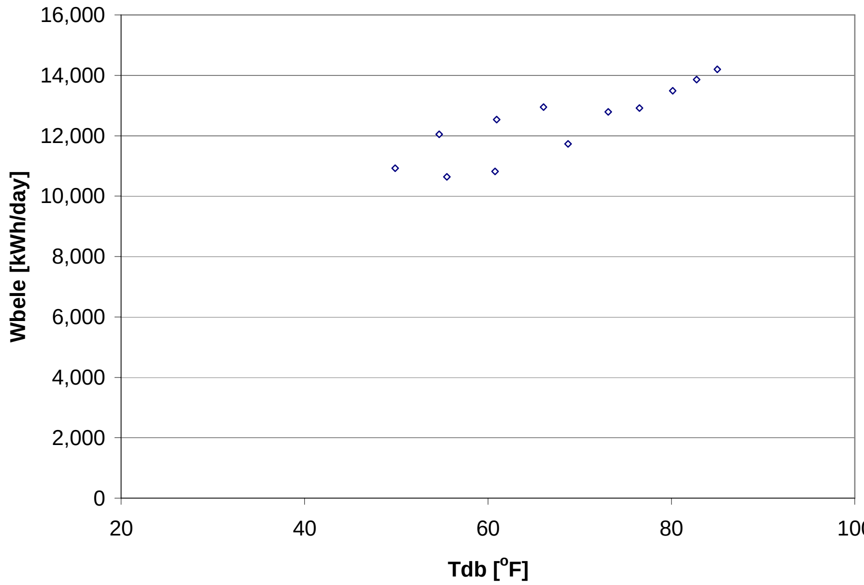


Figure V35 Monthly Wbele consumption vs. Tdb for site 116 during Sep. 1992 – Aug. 1993.

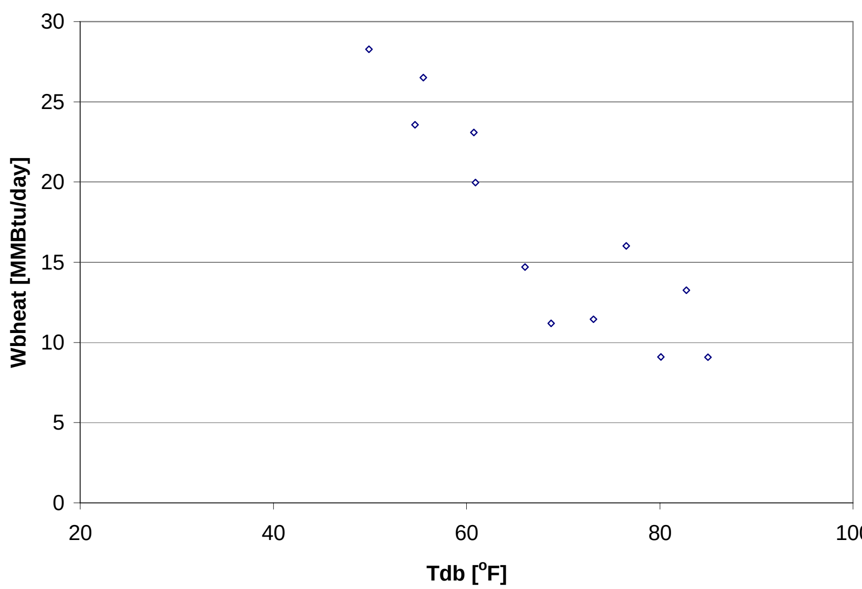


Figure V36 Monthly Wbele consumption vs. Tdb for site 116 during Sep. 1992 – Aug. 1993.

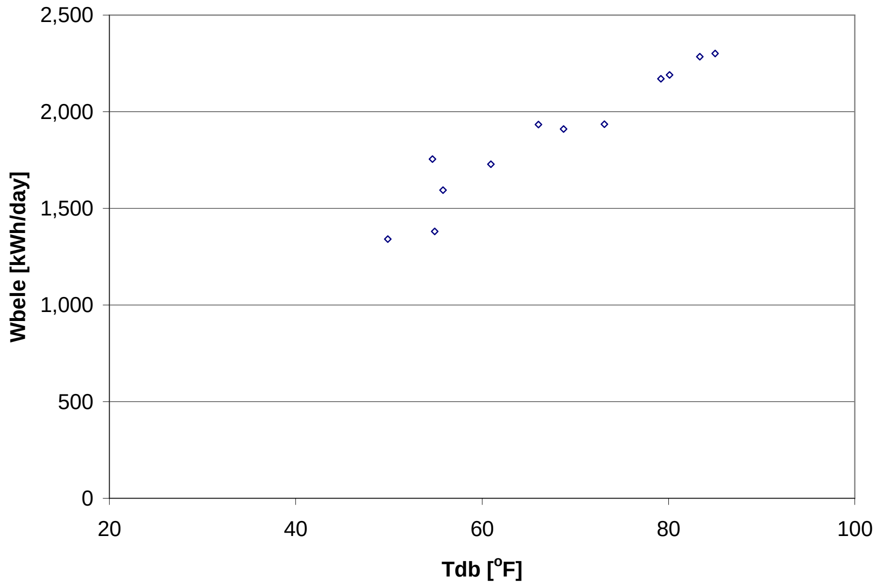


Figure V37 Monthly Wbele consumption vs. Tdb for site 117 during 1993.

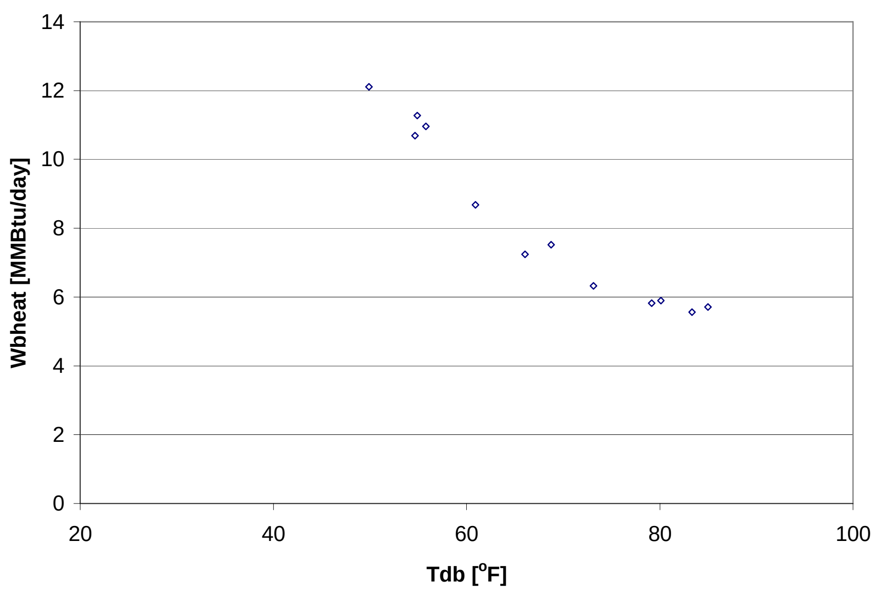


Figure V38 Monthly Wbheat consumption vs. Tdb for site 117 during 1993.

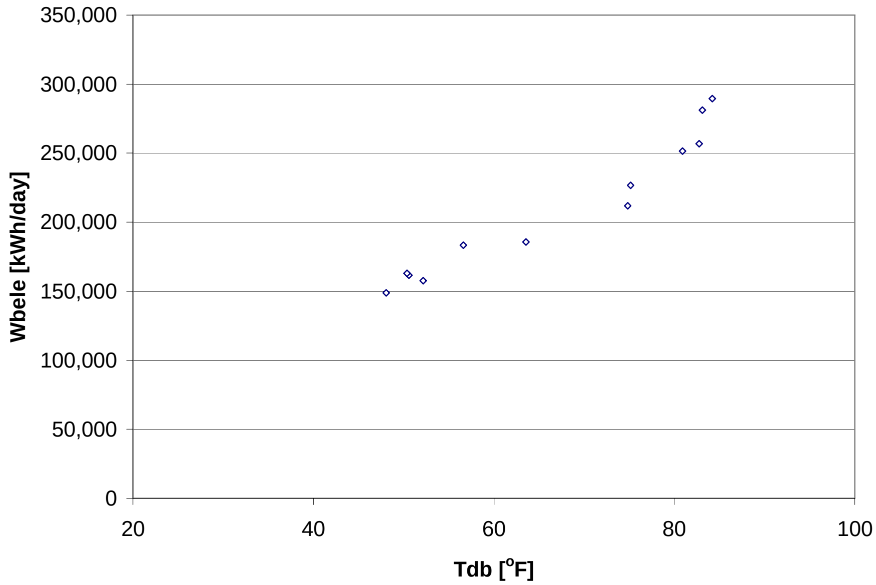


Figure V39 Monthly Wbele consumption vs. Tdb for site 124 during May 1992 – April 1993.

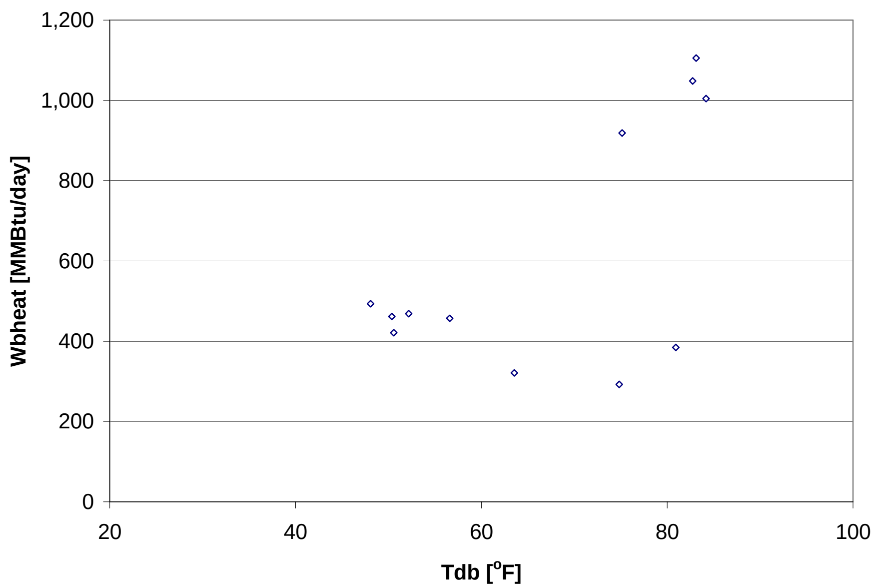


Figure V40 Monthly Wbele consumption vs. Tdb for site 124 during May 1992 – April 1993.

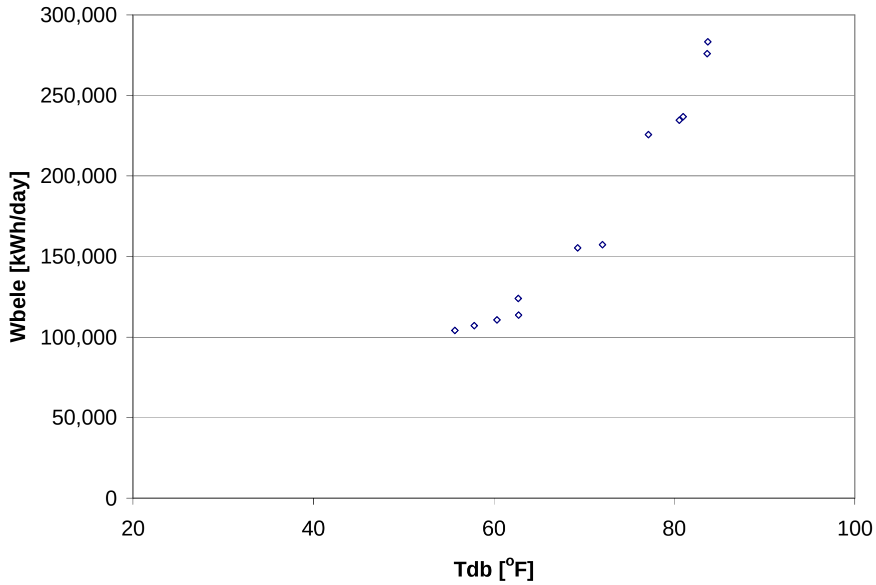


Figure V41 Monthly Wbele consumption vs. Tdb for site 124 during 1995.

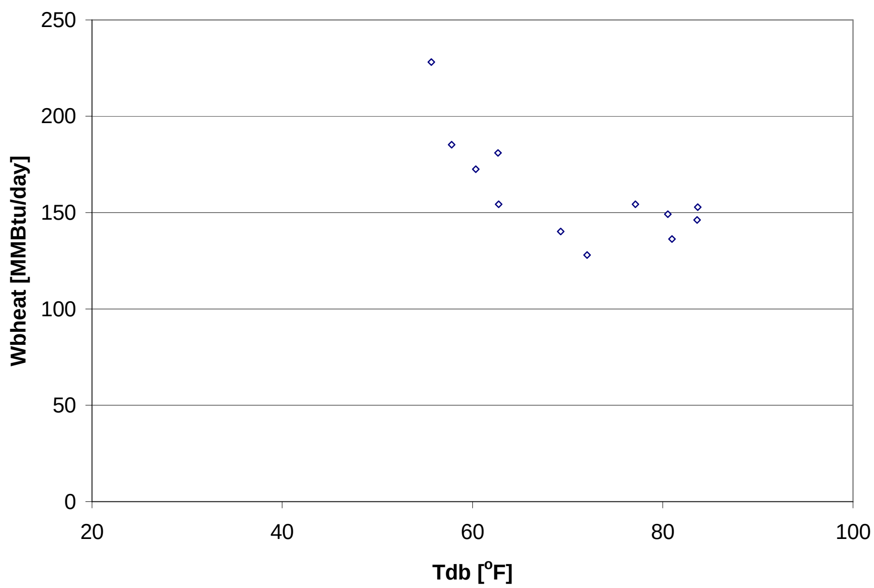


Figure V42 Monthly Wbheat consumption vs. Tdb for site 124 during 1995.

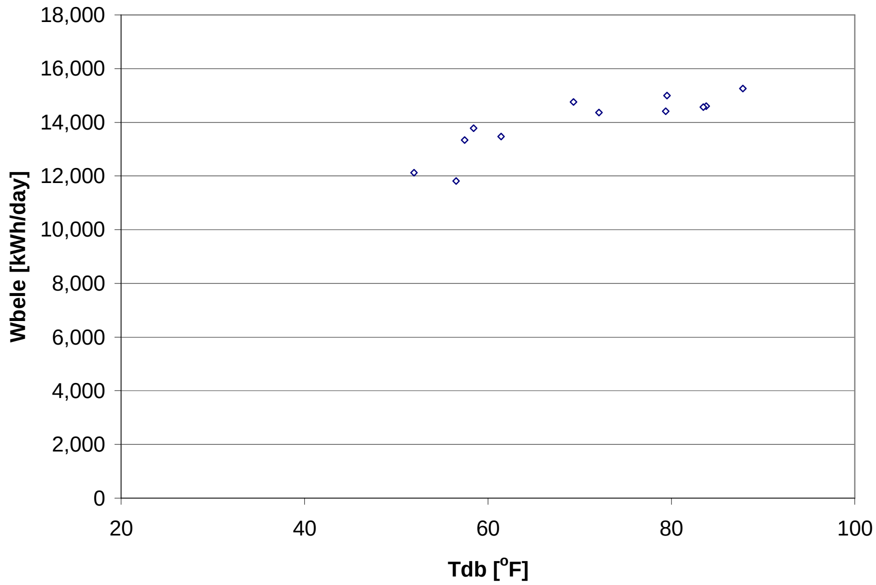


Figure V43 Monthly Wbele consumption vs. Tdb for site 165 during 1996.

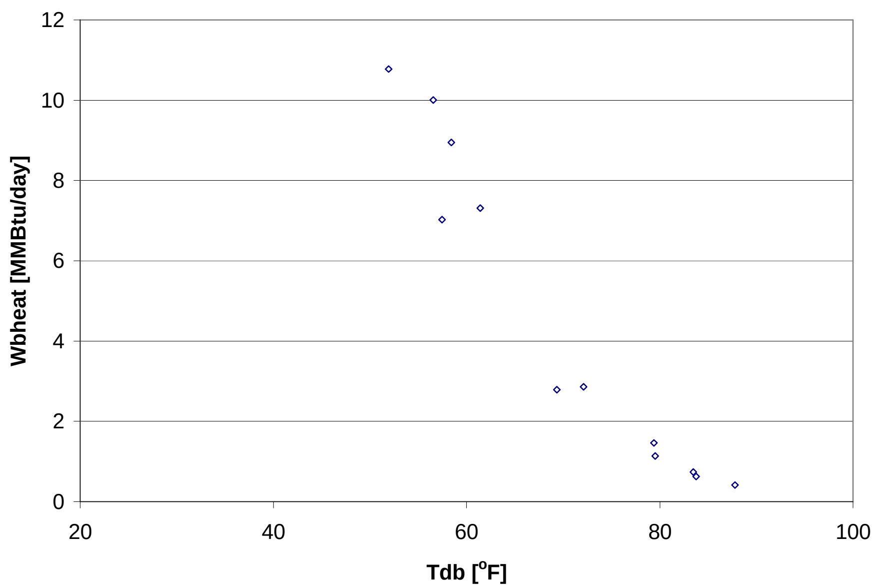


Figure V44 Monthly Wbheat consumption vs. Tdb for site 165 during 1996.

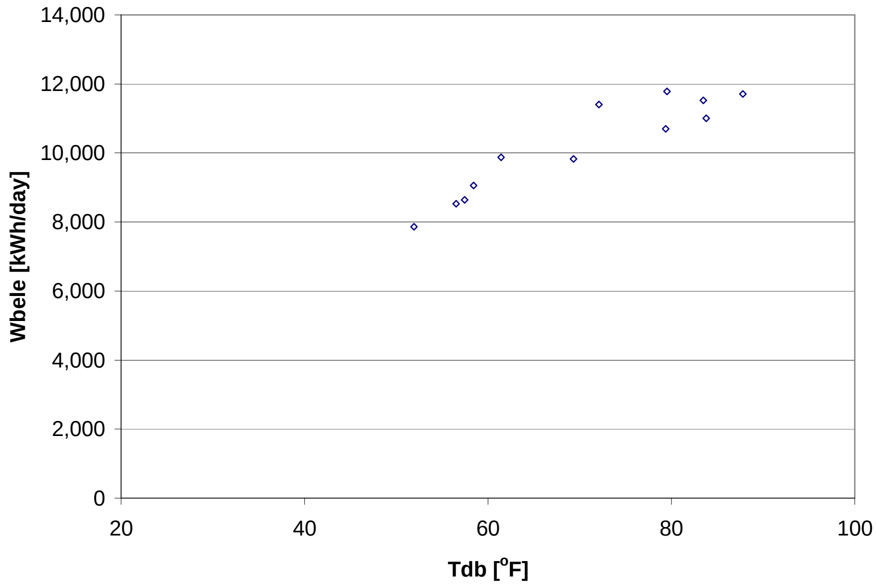


Figure V45 Monthly Wbele consumption vs. Tdb for site 166 during 1996.

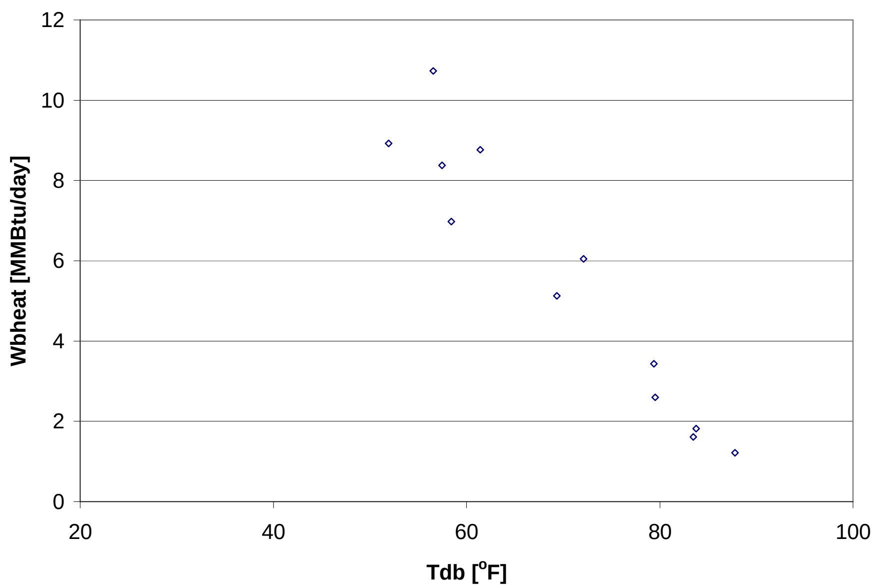


Figure V46 Monthly Wbheat consumption vs. Tdb for site 166 during 1996.

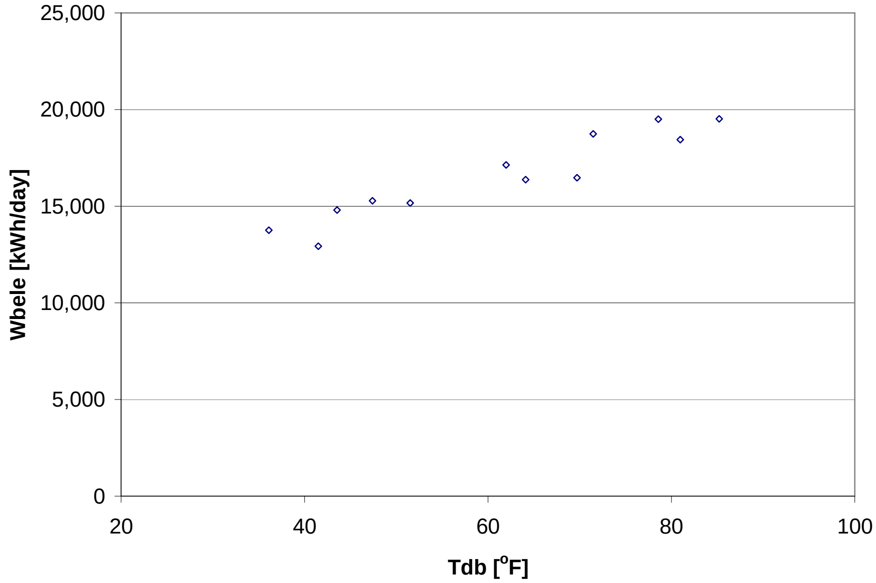


Figure V47 Monthly Wbele consumption vs. Tdb for site 187 during 2001.

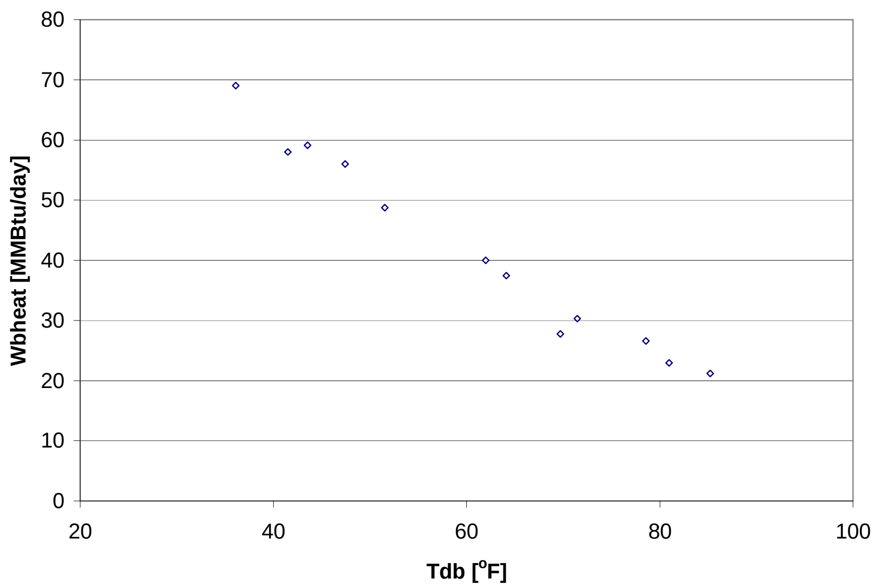


Figure V48 Monthly Wbheat consumption vs. Tdb for site 187 during 2001.

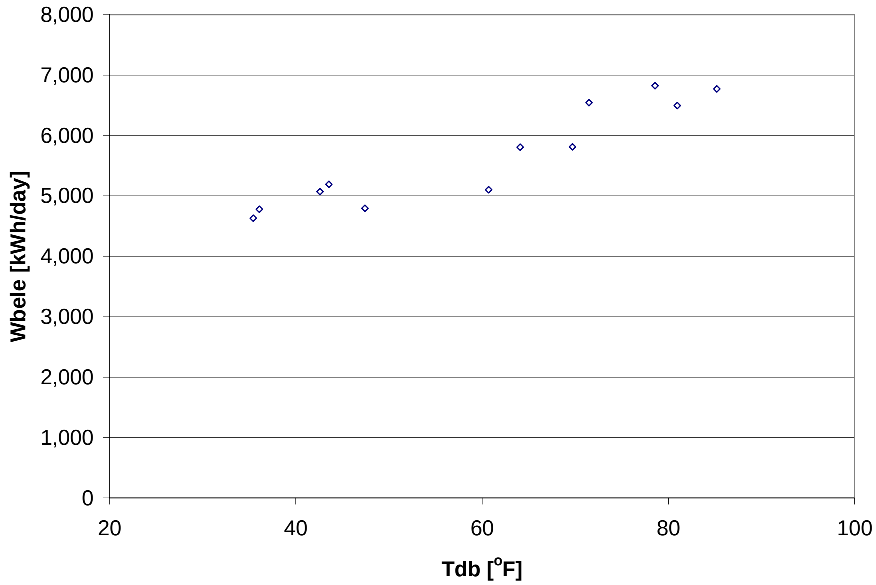


Figure V49 Monthly Wbele consumption vs. Tdb for site 188 during Oct. 2000 – Sep. 2001.

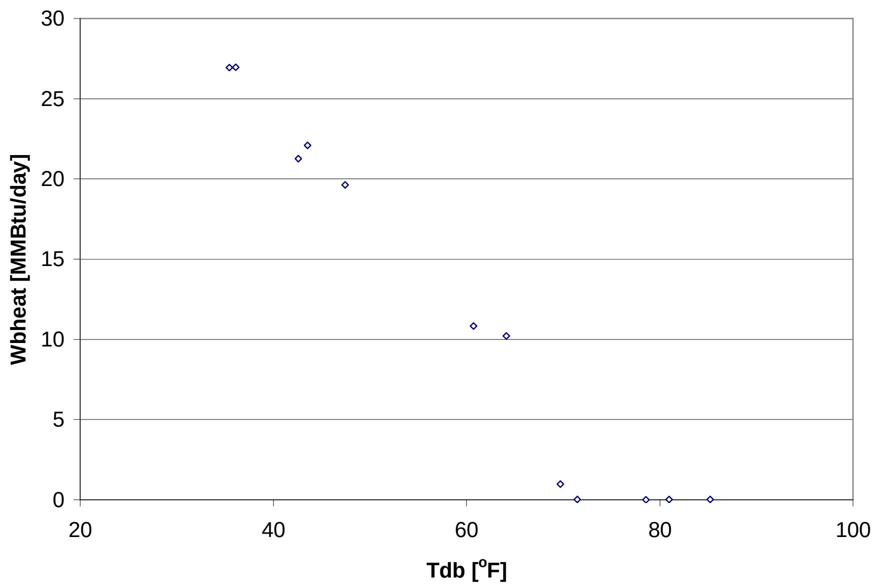


Figure V50 Monthly Wbheat consumption vs. Tdb for site 188 during Oct. 2000 – Sep. 2001.

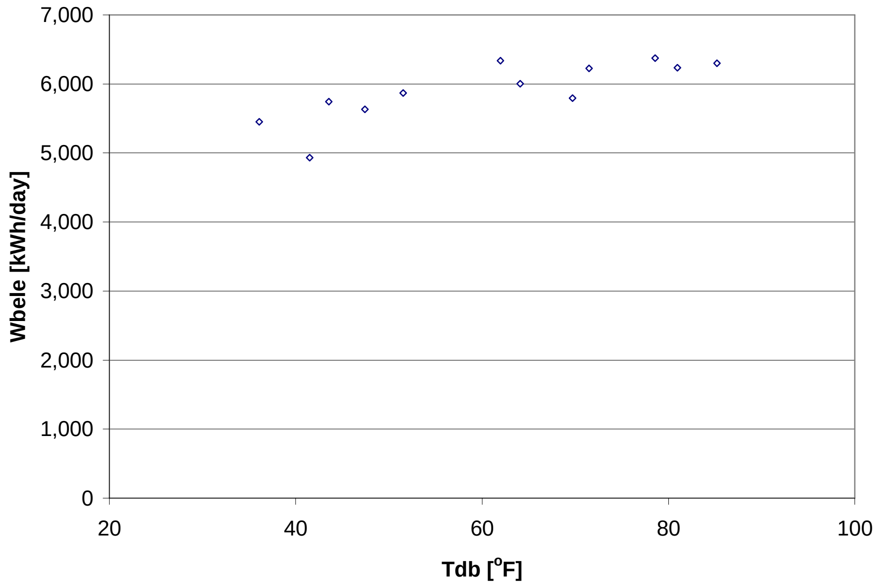


Figure V51 Monthly Wbele consumption vs. Tdb for site 189 during 2001.

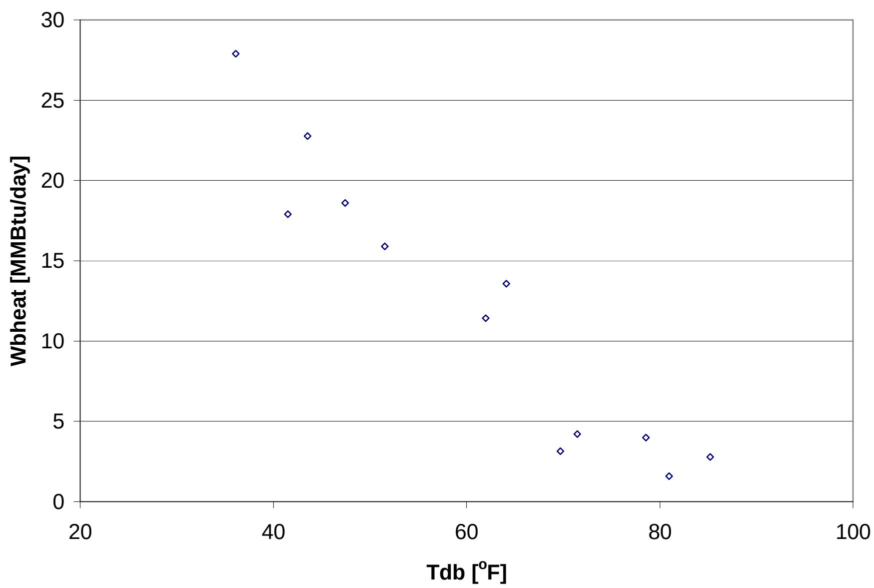


Figure V52 Monthly Wbheat consumption vs. Tdb for site 189 during 2001.

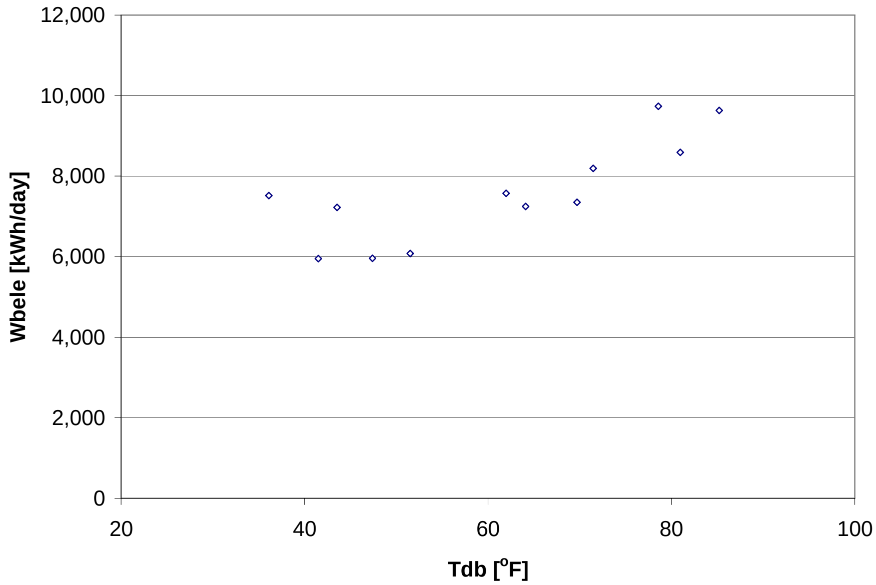


Figure V53 Monthly Wbele consumption vs. Tdb for site 195 during 2001.

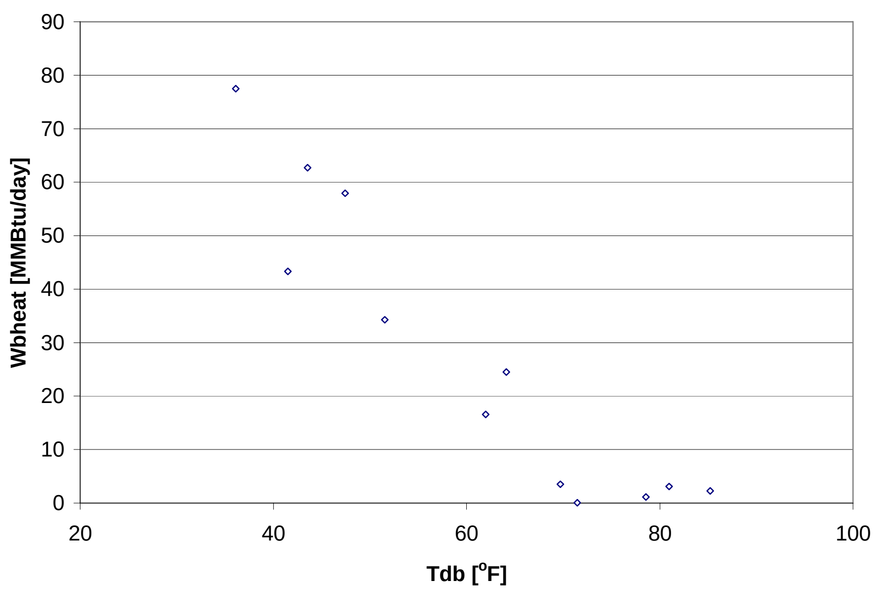


Figure V54 Monthly Wbheat consumption vs. Tdb for site 195 during 2001.

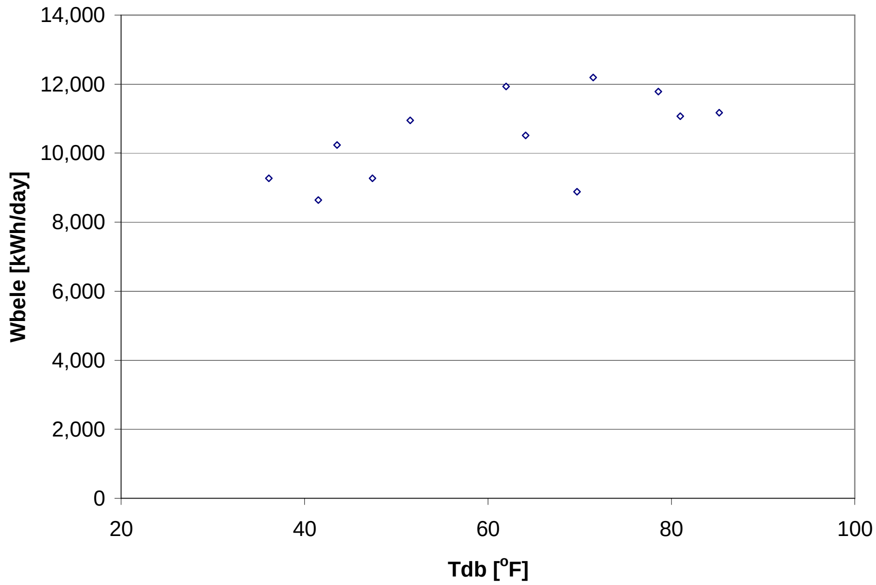


Figure V55 Monthly Wbele consumption vs. Tdb for site 197 during 2001.

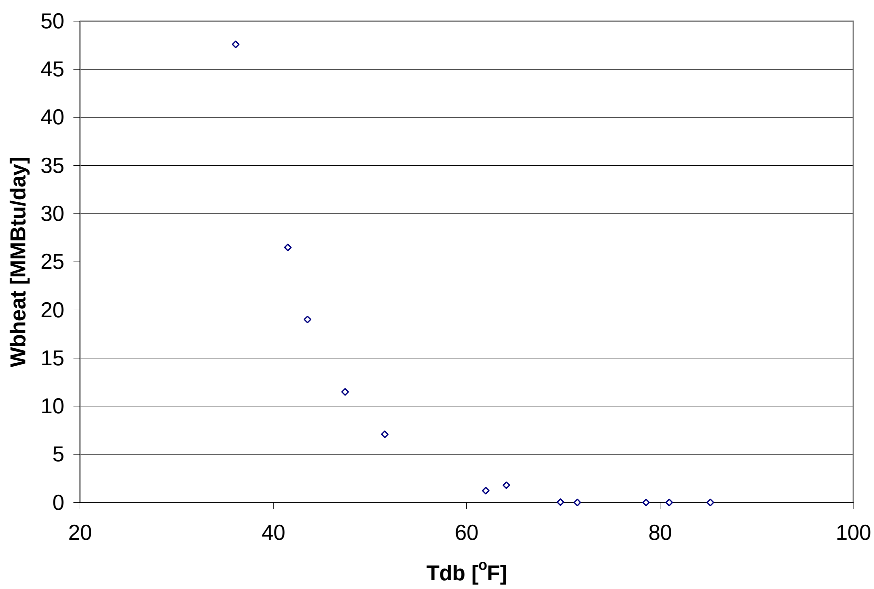


Figure V56 Monthly Wbheat consumption vs. Tdb for site 197 during 2001.

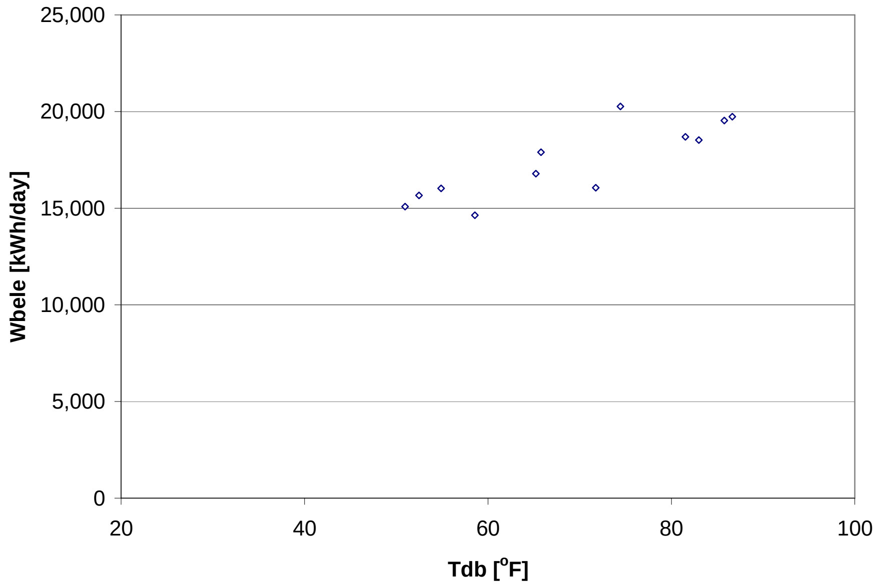


Figure V57 Monthly Wbele consumption vs. Tdb for site 203 during 1997.

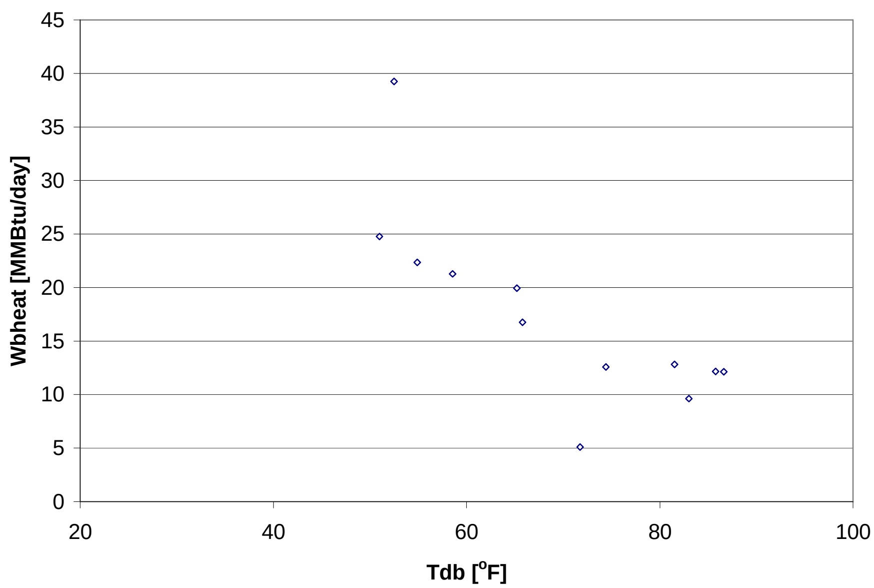


Figure V58 Monthly Wbele consumption vs. Tdb for site 203 during 1997.

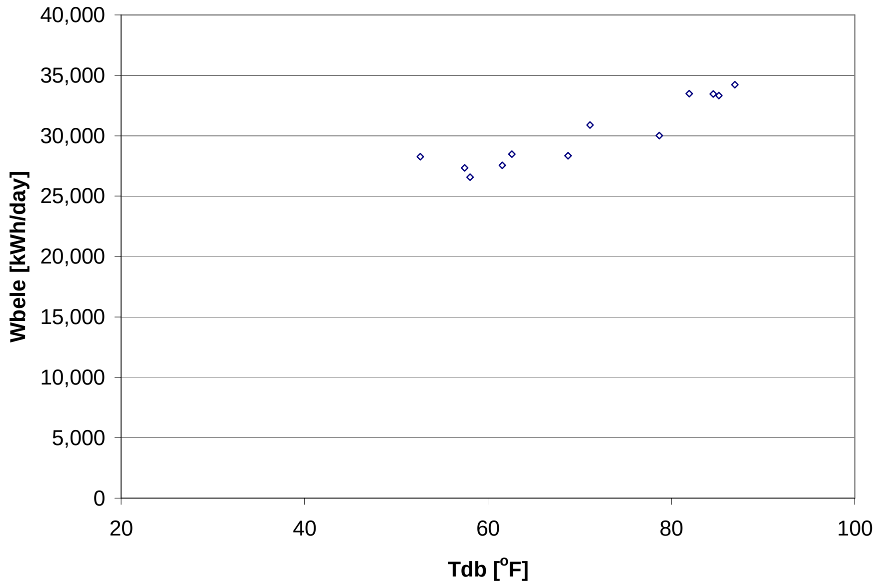


Figure V59 Monthly Wbele consumption vs. Tdb for site 236 during 1998.

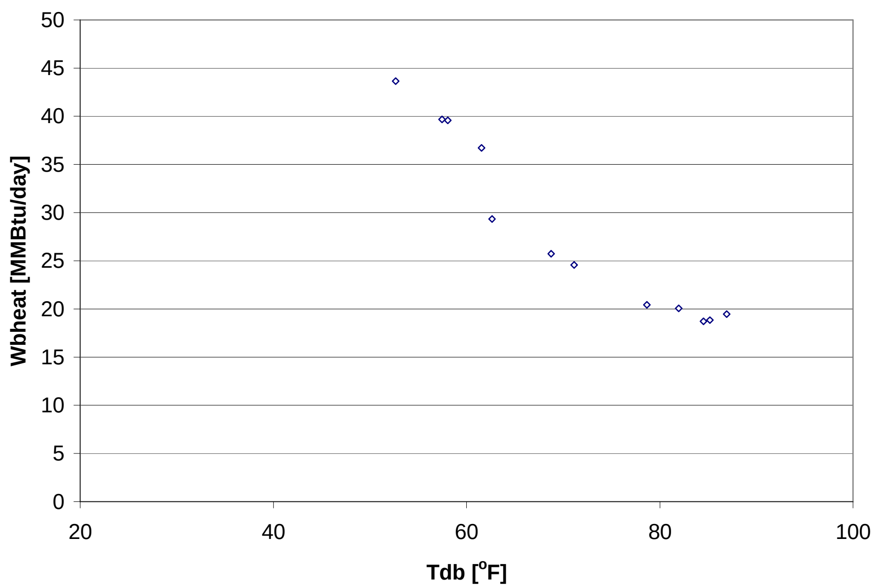


Figure V60 Monthly Wbheat consumption vs. Tdb for site 236 during 1998.

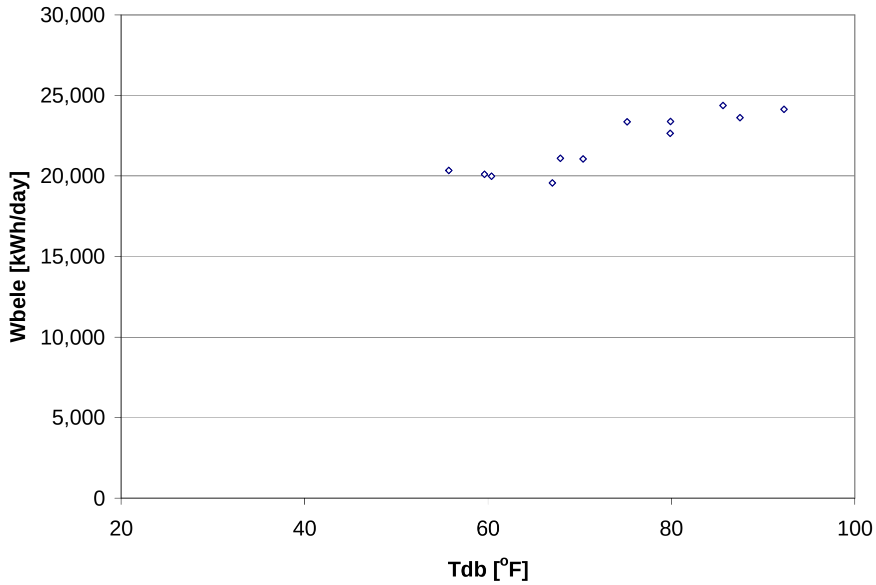


Figure V61 Monthly Wbele consumption vs. Tdb for site 300 during March 1991 – March 1992 (no Oct. 1991).

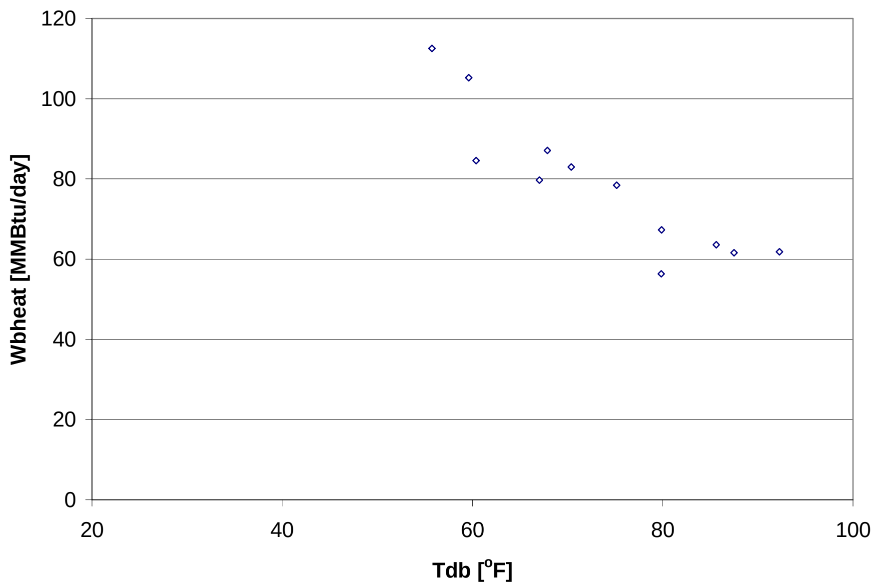


Figure V62 Monthly Wbheat consumption vs. Tdb for site 300 during March 1991 – March 1992 (no Oct. 1991).

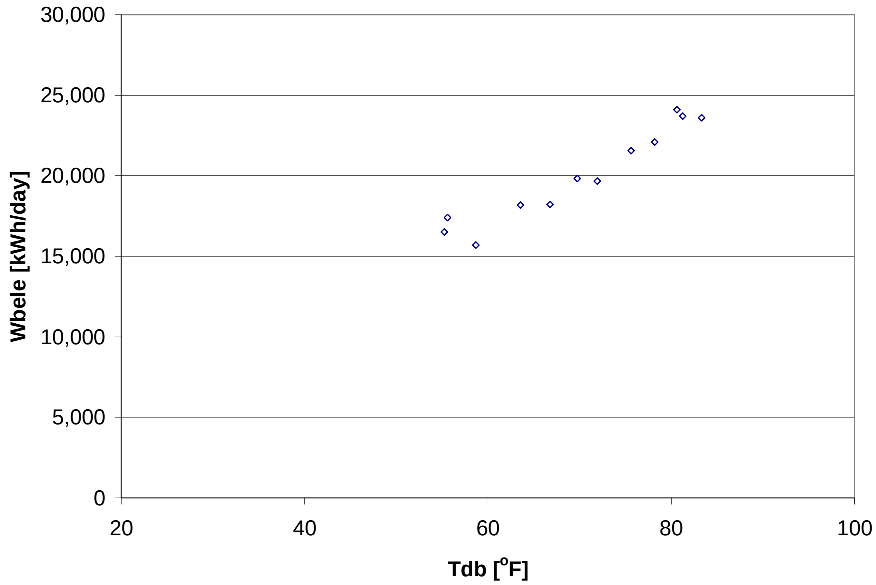


Figure V63 Monthly Wbele consumption vs. Tdb for site 300 during 1994.

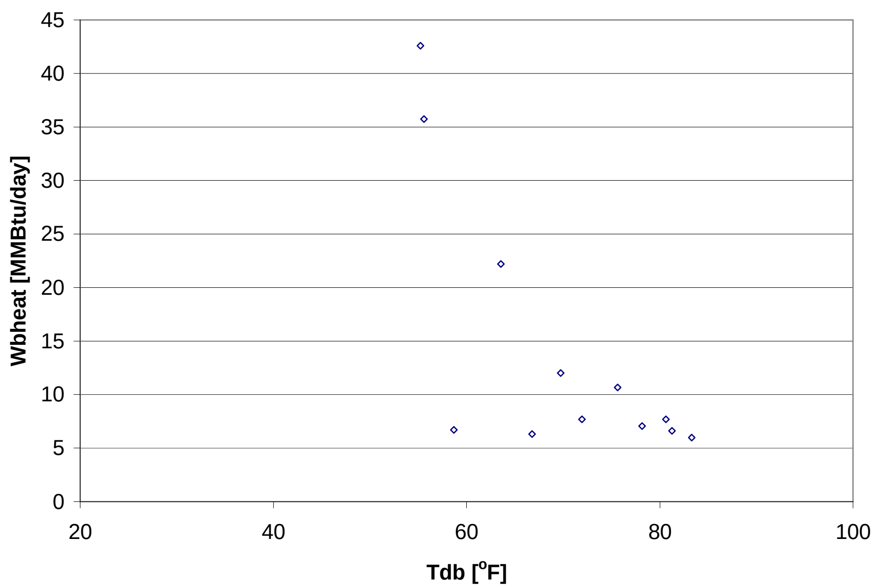


Figure V64 Monthly Wbheat consumption vs. Tdb for site 300 during 1994.

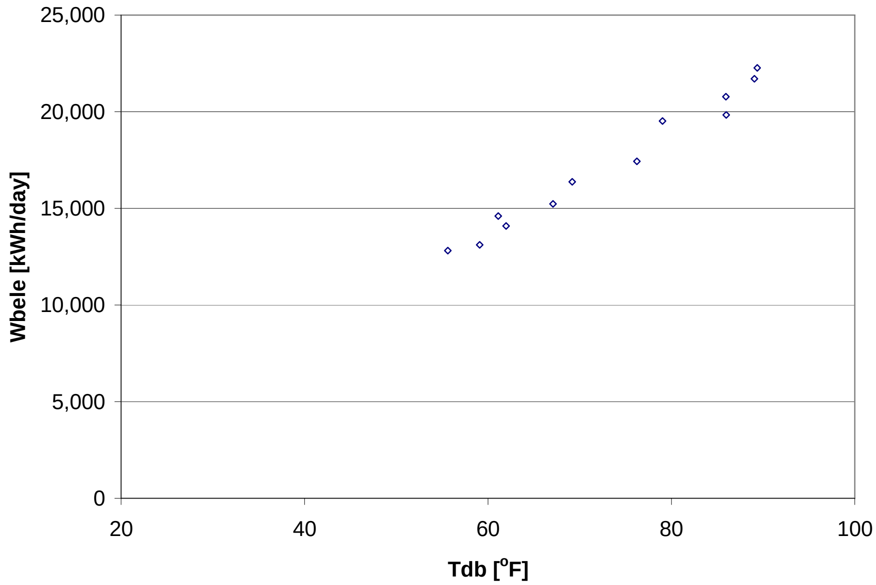


Figure V65 Monthly Wbele consumption vs. Tdb for site 400 during 1995.

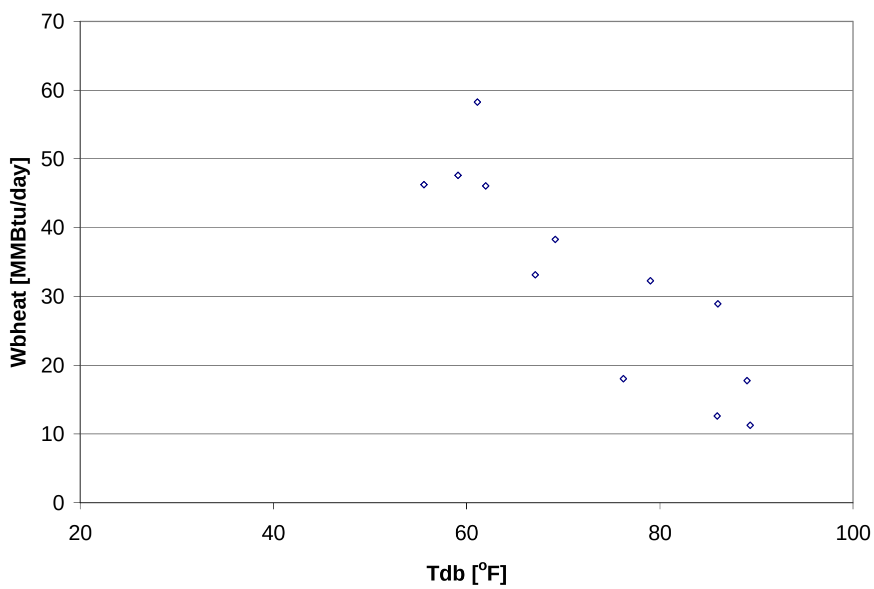


Figure V66 Monthly Wbheat consumption vs. Tdb for site 400 during 1995.

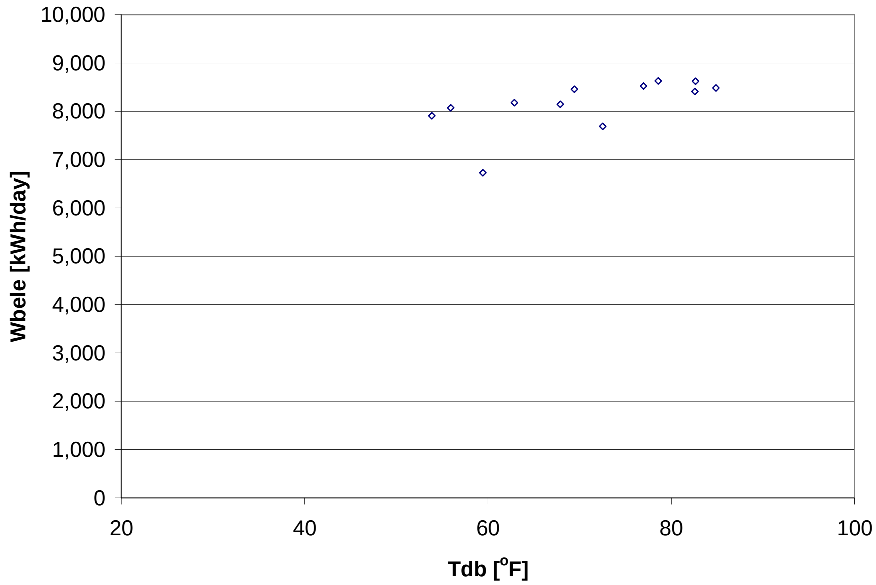


Figure V67 Monthly Wbele consumption vs. Tdb for site 403 during 1994.

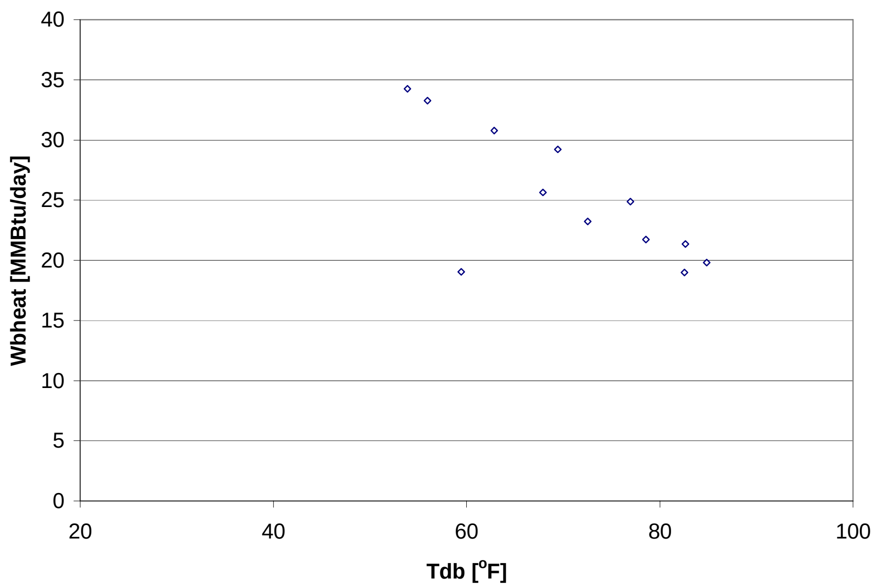


Figure V68 Monthly Wbheat consumption vs. Tdb for site 403 during 1994.

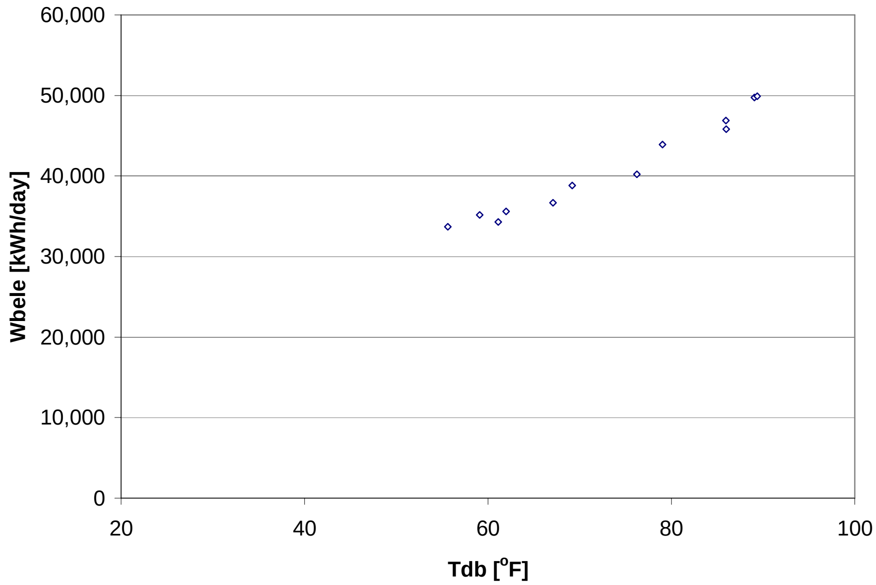


Figure V69 Monthly Wbele consumption vs. Tdb for site 404 during 1995.

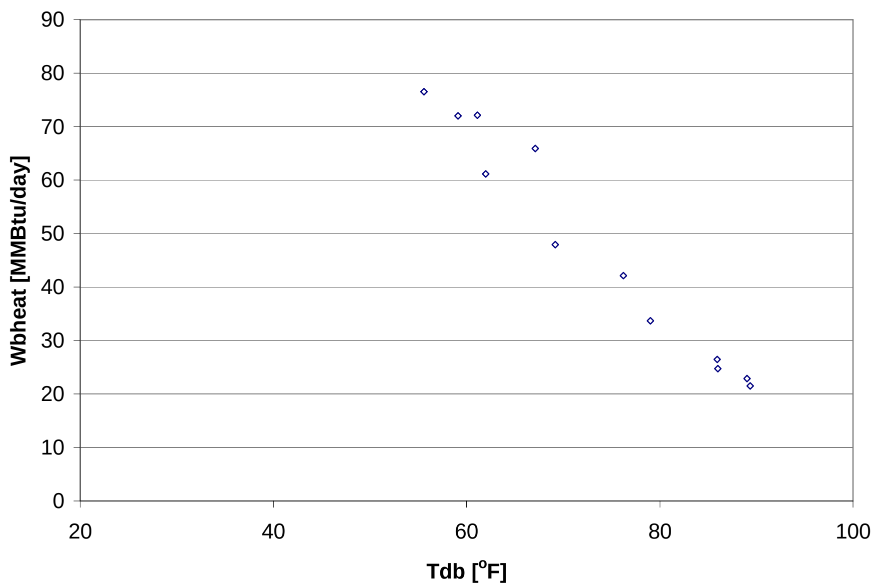


Figure V70 Monthly Wbheat consumption vs. Tdb for site 404 during 1995.

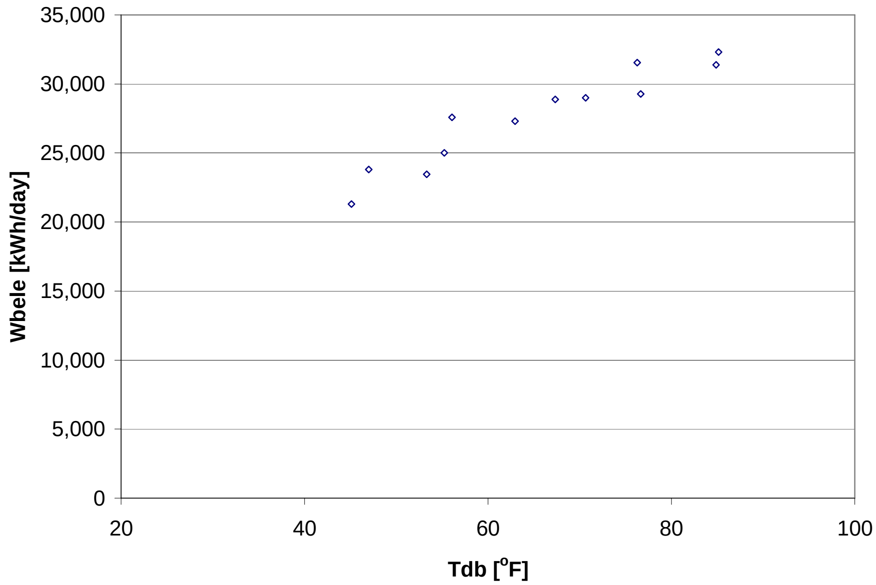


Figure V71 Monthly Wbele consumption vs. Tdb for site 491 during Dec. 2000 – Dec. 2000 (no June 2001).

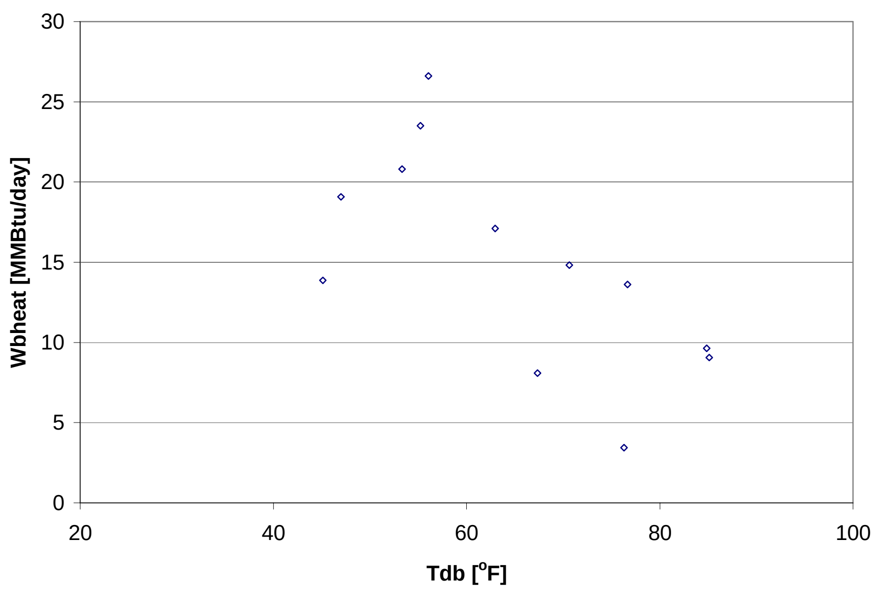


Figure V72 Monthly Wbheat consumption vs. Tdb for site 491 during Dec. 2000 – Dec. 2000 (no June 2001).

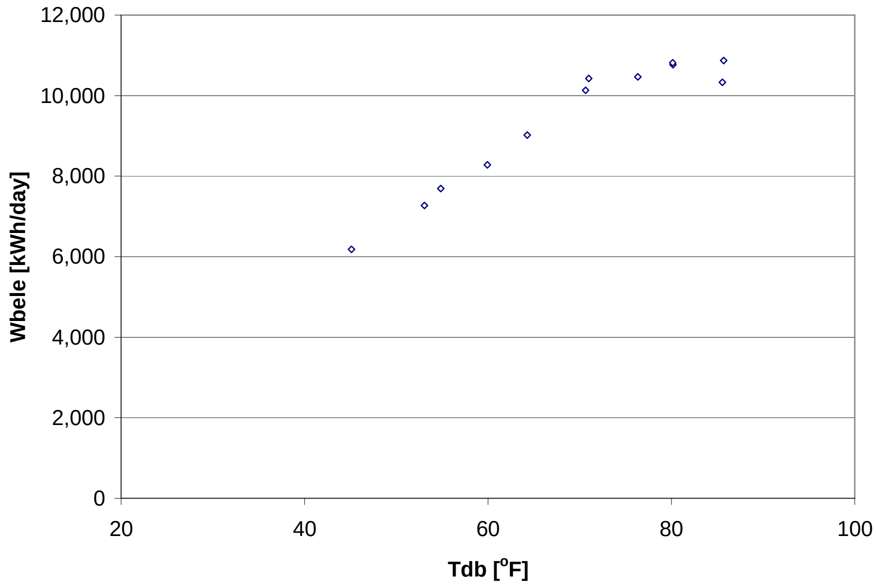


Figure V73 Monthly Wbele consumption vs. Tdb for site 494 during 2000.

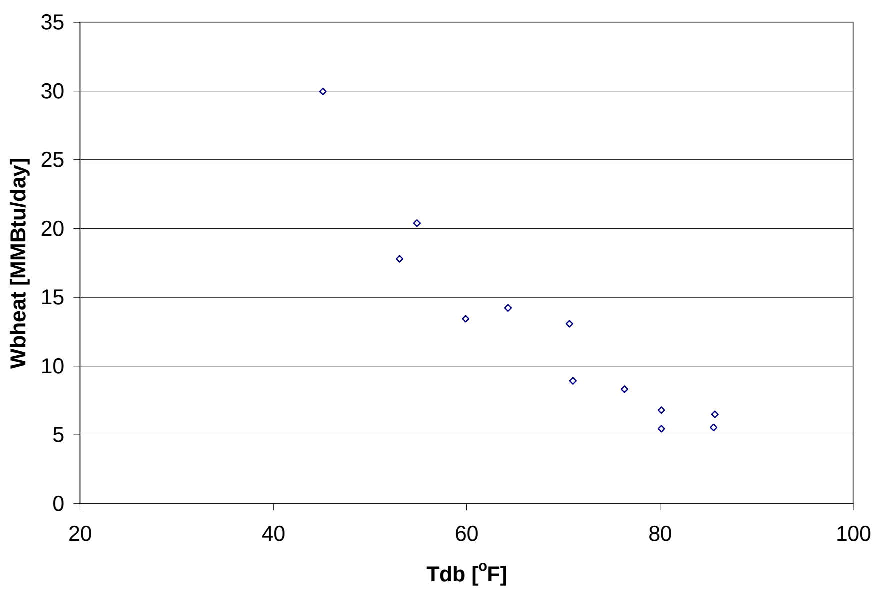


Figure V74 Monthly Wbheat consumption vs. Tdb for site 494 during 2000.

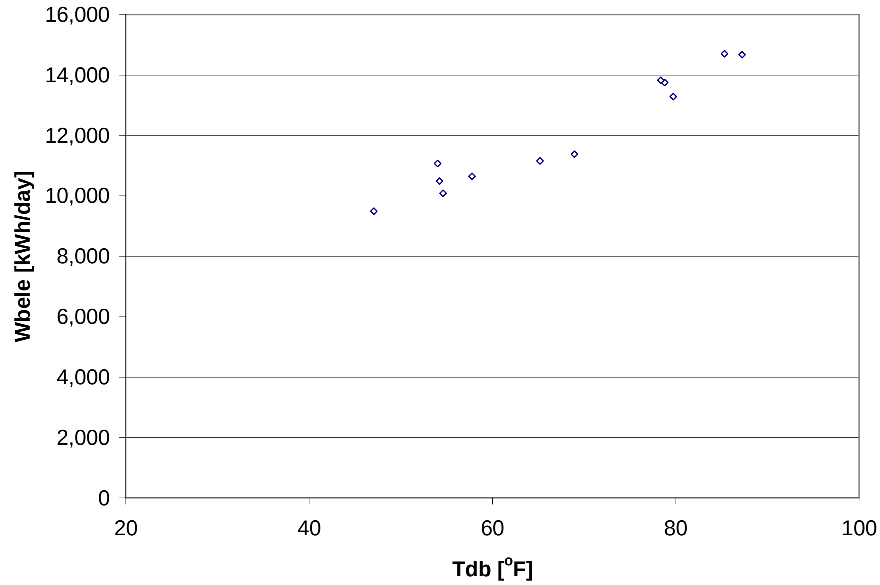


Figure V75 Monthly Wbele consumption vs. Tdb for site 496 during Jan. 1996 – Jan. 1997 (March 1996).

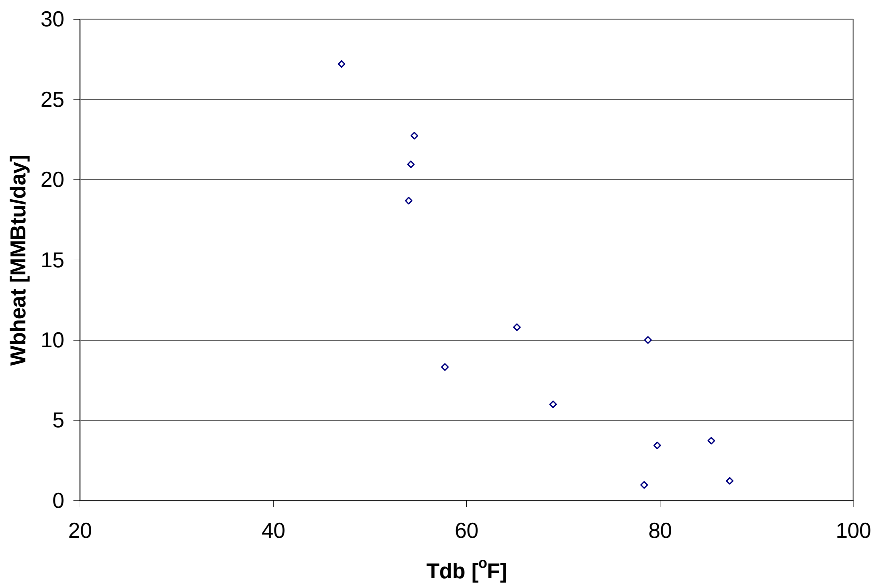


Figure V76 Monthly Wbheat consumption vs. Tdb for site 496 during Jan. 1996 – Jan. 1997 (March 1996).

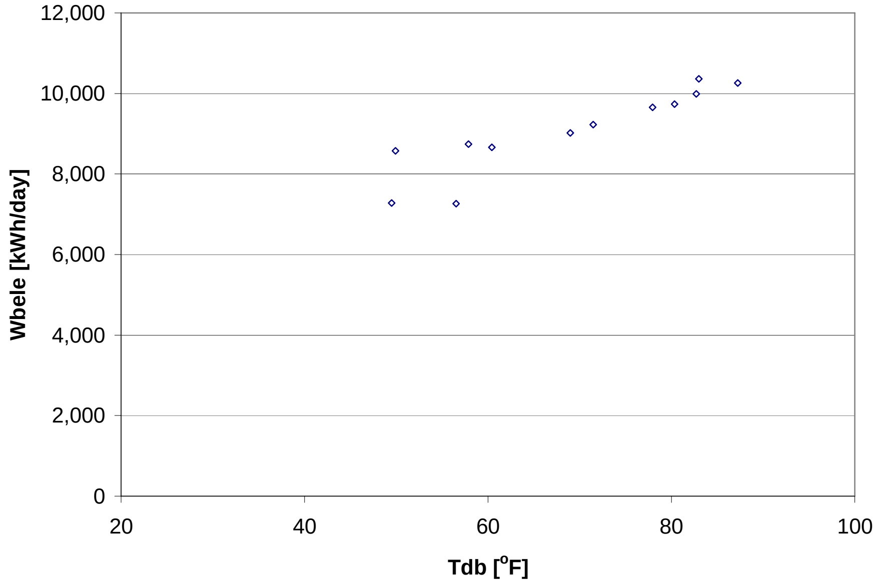


Figure V77 Monthly Wbele consumption vs. Tdb for site 497 during Sep. 1997 – Aug. 1998.

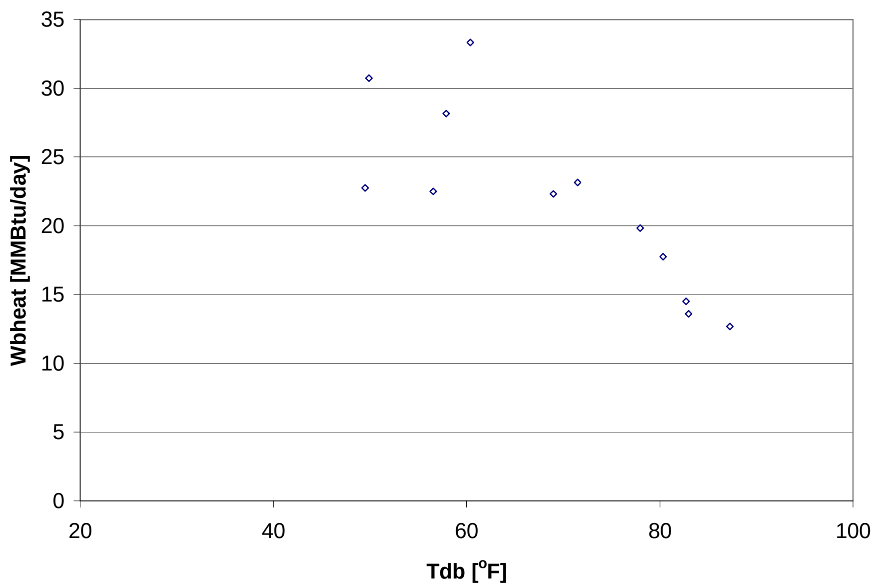


Figure V78 Monthly Wbheat consumption vs. Tdb for site 497 during Sep. 1997 – Aug. 1998.

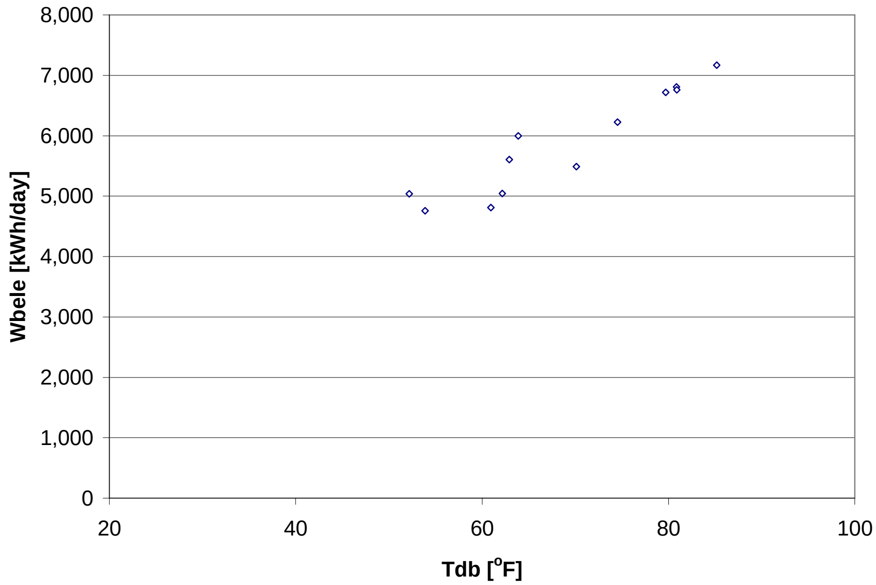


Figure V79 Monthly Wbele consumption vs. Tdb for site 497 during 1999.

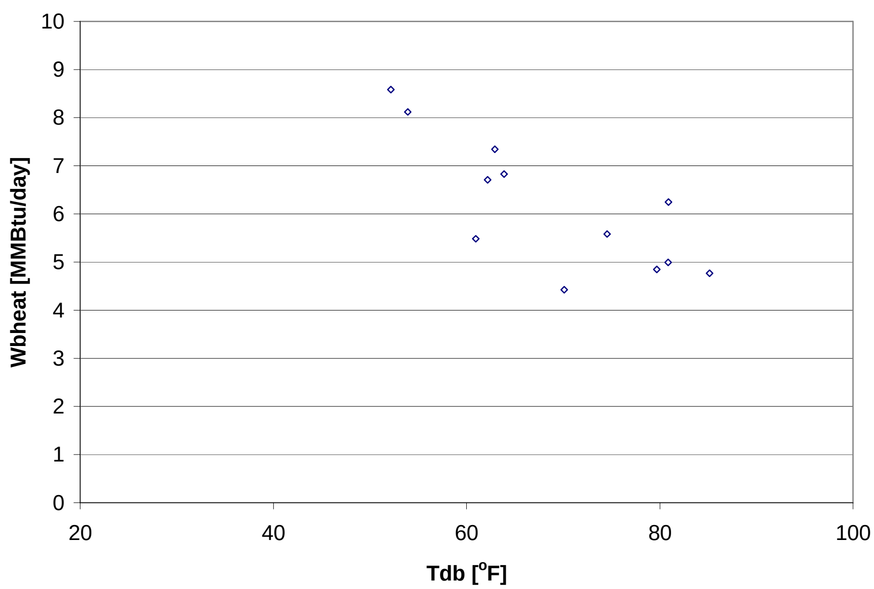


Figure V80 Monthly Wbheat consumption vs. Tdb for site 497 during 1999.

VITA

Name:	Yiwen Zhu
Address:	3809 N. Braeswood BLVD Apt. 2 Houston, TX, 77025

Education:	Texas A&M University College Station, TX, United States Ph.D., 2005, Mechanical Engineering
	Tsinghua University Beijing, People's Republic of China M.S., 1995, Thermal Engineering
	Tongji University Shanghai, People's Republic of China B.S., 1990, Thermal Engineering