THE PERSISTENCE OF RETRO-COMMISSIONING SAVINGS IN TEN UNIVERSITY BUILDINGS

A Thesis

by

CORY DAWSON TOOLE

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

MASTER OF SCIENCE

May 2010

Major Subject: Mechanical Engineering

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Approved by:

Chair of Committee,	David Claridge
Committee Members,	Jeff Haberl
	W. Dan Turner
Head of Department,	Dennis O’Neal

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ABSTRACT

The Persistence of Retro-commissioning Savings
in Ten University Buildings. (May 2010)
Cory Dawson Toole, B.S., Texas A&M University
Chair of Advisory Committee: Dr. David Claridge

This study evaluated how well energy savings persisted over time in ten university buildings that had undergone retro-commissioning in 1996. The savings achieved immediately following retro-commissioning and in three subsequent years were documented in a previous study (Cho 2002). The current study expanded on this previous study by evaluating the performance of each building over nine additional years. Follow up retro-commissioning work performed in each building during that time was documented, as well as changes to the energy management control system.

Savings were determined in accordance with the methodology outlined in the International Performance Measurement and Verification Protocol (IPMVP 2007), with ASHRAE Guideline 14 also serving as a reference.

Total annualized savings for all buildings in 1997 (the year just after retro-commissioning) were 45(±2)% for chilled water, 67(±2)% for hot water, and 12% for electricity. Combining consumption from the most recent year for each building with valid energy consumption data showed a total savings of 39(±1)% for chilled water, 64(±2)% for heating water, and 22% for electricity. Uncertainty values were calculated in accordance with methodology in the IPMVP and ASHRAE Guideline 14, and were reported at the 90% confidence interval. The most recent year of data for most of the buildings was 2008-2009, although a few of the buildings did not have valid consumption data for that year.

Follow up work performed in the buildings, lighting retrofits, and building metering changes beginning in 2005 were the major issues believed to have contributed to the high level of savings persistence in later years. When persistence trends were evaluated with adjustment for these factors, average savings for the buildings studied were found to degrade over time, and exponential models were developed to describe this degradation.

The study concluded that on average energy savings after retro-commissioning will degrade over time in a way that can be modeled exponentially. It was also concluded that high levels of savings persistence can be achieved through performing retro-commissioning follow up, particularly when significant increases are observed in metered energy consumption data, but also at other times as retro-commissioning procedures and technology continually improve.

DEDICATION

To Janine, my inspiration

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Claridge, and my committee members, Dr. Turner and Dr. Haberl, for their guidance and support throughout the course of this research.

Many thanks also go to my friends and colleagues at the Energy Systems Laboratory, many of whom provided considerable time and support to assist in this research. I would especially like to thank Mr. Song Deng, Dr. Juan Carlos Baltazar, Mr. Qiang Chen, Mr. Chen Xu, Mr. Tim Brundidge, Mr. Hui Chen, and Mrs. Guanjing Lin for their assistance and support.

Finally, thanks to my wife for her patience, love, and constant encouragement, and to my daughters for their patience.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

Page

LIST OF TABLES

Page

CHAPTER I
INTRODUCTION

Building commissioning is a topic that has gained increasing attention in recent years in the commercial building industry. The interest and excitement generated by this phenomenon have been shared by engineers, facility operators, and building owners alike. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) recently published guidelines in an attempt to standardize to some extent the focus and process of commissioning. In *ASHRAE Guideline 0, The Commissioning Process* (2005), commissioning is defined as "a quality-oriented process for achieving, verifying, and documenting that the performance of facilities, systems, and assemblies meets defined objectives and criteria."

The term "commissioning" within the industry normally has reference to new building commissioning, or applying the process at some point within the design, construction, and delivery of a new facility. When this process is applied to existing facilities already in operation, it is commonly referred to as "retro-commissioning." (ASHRAE Guideline 0.5 will adopt the term "existing building commissioning" instead of "retro-commissioning," and this will most likely become the standard terminology in the future. However, this paper will use "retro-commissioning," since it is the most common designation at the current time.) The retro-commissioning process has not been standardized within the industry to the degree that new building commissioning has, and various definitions exist among those that provide these services. The Oregon Office of Energy gives a broad definition of retro-commissioning that might be considered representative. In its *Retrocommissioning Handbook for Facility Managers* (PECI 2001), it states the following:

"Existing-building commissioning, also known as retro-commissioning, is an event in

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This thesis follows the style of *ASHRAE Transactions*.

the life of a building that applies a systematic investigation process for improving or optimizing a building's operation and maintenance. It may or may not emphasize bringing the building back to its original intended design. In fact, the original design documentation may no longer exist or be relevant. The goals and objectives for applying the process, as well as the level of rigor, may vary depending on the current needs of the owner, budget, and condition of the equipment. The retro-commissioning process most often focuses on dynamic energy-using systems with the goal of reducing energy waste, obtaining energy cost savings, and identifying and fixing existing problems."

The Energy Systems Laboratory at Texas A&M developed and trademarked a process known as Continuous Commissioning® (CC®), taking the traditional scope of retro-commissioning a step further. The Continuous Commissioning® Guidebook for Federal Energy Managers states the following: "Continuous Commissioning® (CC®) is an ongoing process to resolve operating problems, improve comfort, optimize energy use and identify retrofits for existing commercial and institutional buildings and central plant facilities." This process, which has been around for well over a decade, has been shown to produce average energy savings of about 20%, with a payback period nearly always less than three years (Claridge et al. 2004). For purposes of this report, any commissioning performed to an existing building (including Continuous Commissioning®) will be referred to as retro-commissioning.

Despite thorough documentation of savings achieved by retro-commissioning, little has been recorded on the long term savings of these projects. A total of only 42 buildings have been evaluated from a persistence of retro-commissioning savings perspective. The first study to examine this in detail evaluated the persistence of energy savings in ten university buildings that had undergone retro-commissioning in 1996 or 1997 (Cho 2002). The documented savings in each of four years following retro-commissioning were evaluated and compared, to determine how well they had persisted. With a few exceptions, the energy savings achieved in the year following retro-commissioning were shown to have high levels of persistence.

The current study seeks to follow up on the results of this study. Using the same ten buildings, but with a greatly expanded period of time, the levels of persistence of original retro-commissioning benefits will be evaluated. Any significant changes in consumption will be examined, and conclusions will be drawn with regard to the trends observed. It is hoped in this way that the fledgling field of knowledge currently available with regard to persistence of commissioning benefits can be expanded, further improving and validating the overall commissioning process.

1.1 Building Descriptions

The ten buildings studied are all located on the campus of Texas A&M University in College Station, TX. Each of the buildings is supplied with hot water and chilled water from a central plant. A brief description of each of the ten buildings examined in this study follows.

1.1.1 Blocker Building

The Blocker Building is a six-story facility with a total conditioned area of 255,490 square feet. It was constructed in 1981, and consists primarily of classrooms, offices, and computer labs. The HVAC system consists of 12 dual-duct variable air volume air handling units, two outside air pre-treat units, three exhaust fans, two chilled water pumps, and two hot water pumps. The pumps and air handling units have Direct Digital Control (DDC), while the exhaust fans have either manual or thermostatic control.

1.1.2 Eller O&M Building

The Eller O&M building was constructed in 1973 and is located on the main campus of Texas A&M University. It is home to the Oceanography, Meteorology, and Geography departments, and consists primarily of offices, laboratories, and classrooms. The building has fifteen floors (including basement) for a total area of 180,316 square feet. The HVAC system in the building consists of four dual-duct variable air volume air handling units and two constant speed multizone air handling units. Each of the air handling units and terminal boxes is operated with DDC.

1.1.3 G. Rollie White Coliseum

G. Rollie White Coliseum is a 177,838 square foot facility constructed in 1955. Air conditioning systems were added in 1966. The facility consists primarily of a volleyball arena, activity rooms, and offices. The HVAC system includes 13 constant volume, single zone heating and cooling air handling units serving the arena area, five single zone heating and cooling units serving classroom and office areas, and an additional 38 four-pipe fan coil units serving individual classrooms and offices. The 13 arena units have some DDC, but all other equipment is pneumatically controlled.

1.1.4 Harrington Tower

Harrington Tower is a 130,844 square foot, eight-story building constructed in 1973, consisting primarily of offices and classrooms. The HVAC system includes one large dual-duct variable air volume air handling unit serving most of the building, three smaller single zone air handling units with reheat serving the first floor, and a fan coil unit conditioning a server room. The air handling units, relief fans, and pumps all have DDC. The large air handling unit has economizer capability.

1.1.5 Kleberg Building

The Kleberg building is a four-story building and a basement with a total conditioned area of 165,031 square feet. It was completed in 1978, and primarily consists of classrooms, offices and laboratories. The HVAC system includes two single-duct variable air volume air handling units, two single-duct constant air volume air handling units, two chilled water pumps, and eight exhaust fans. The variable air volume air handling units, the exhaust fans, and the chilled water pumps have DDC.

1.1.6 Koldus Building

The Koldus building is a two-story building with a total conditioned area of 97,920 square feet. It was constructed in 1992, and consists primarily of offices. The HVAC system consists of five single-duct variable air volume air handling units, five single-duct constant air volume air handling units, four exhaust fans, two chilled water pumps, and two hot water pumps. The air-handling units, chilled water pumps, and hot water pumps have DDC.

1.1.7 Richardson Petroleum Building

The Richardson Petroleum building is a 10-story building with a basement, two penthouses, and a total conditioned area of 113,700 square feet. It was constructed in 1990, and consists primarily of classrooms, offices, and laboratories. The HVAC system consists of seven single-duct variable air volume air handling units, two single-duct constant air volume air handling units, 57 exhaust fans, two chilled water pumps, and two hot water pumps. The air handling units, chilled water pumps, and hot water pumps have DDC. The exhaust fans are either manually or thermostatically controlled.

1.1.8 Veterinary Medical Center Addition

The Veterinary Medical Center addition is a five-story building with a total conditioned area of 114,666 square feet. It was constructed in 1993, and consists primarily of offices, laboratories, and classrooms. The HVAC system includes five single-duct variable air volume air handling units, 11 exhaust fans, two chilled water pumps, and two hot water pumps. Four of the five air handling units are 100% outside air units with heat recovery coils. The air handling units, exhaust fans, chilled water pumps, and hot water pumps all have DDC.

1.1.9 Wehner Building

The Wehner building is a four-story building with a total conditioned area of 192,000 square feet. It was constructed in 1995, with a four-story addition completed in 2002, and consists mainly of classrooms, offices, computer labs, and conference rooms. The HVAC system consists of six dual-duct variable air volume air handling units for the main building, three single-duct variable air volume air handling units also for the main building, four single-duct variable air volume air handling units for the addition, one single-duct constant air volume air handling unit for the addition, two chilled water pumps, two hot water pumps, and eight exhaust fans. The air handling units, exhaust fans, chilled water pumps, and hot water pumps all have DDC.

The energy data collected after 2001 include the additional building usage, and do not differentiate between the older and newer sections.

1.1.10 Zachry Engineering Center

The Zachry engineering center is a five-story building (including basement parking garage) totaling 324,400 square feet of area, of which 258,600 square feet is conditioned area. The building was constructed in 1971, consists primarily of offices, labs, and classrooms, and is home to several of the engineering departments on campus. The HVAC system consists of 12 dual-duct air handling units with variable frequency drives supplying air to the majority of the building using variable air volume terminal boxes, five single-duct constant volume units conditioning four large central classrooms and some central office space, two single-duct constant speed units serving the two floors of the penthouse, two single-duct constant speed units serving a transformer room and a server room on the ground floor, a single-duct constant speed unit for a third floor clean room area, and two Liebert units for an old mainframe area. The dual-duct air handling units, their terminal boxes, and three of the interior single-duct air handling units have DDC, while the remaining units are pneumatically controlled. The building underwent a major renovation in 1990 which included converting the constant speed, constant air volume dual-duct air handling units to variable speed, variable air volume units.

1.2 Energy Metering Systems

Energy metering was set up in each of these buildings during the mid-1990s in order to measure and trend chilled water, hot water, and electricity consumption over time. The metering in each building for chilled water and heating water energy consumption utilized insertion probe water temperature sensors on the primary supply and return lines along with a paddle wheel type flow meter in each loop. For electricity, current transducers (CT) and Watt transformers were installed to measure whole building electricity consumption.

Over time, the accuracy of many of the thermal meters became suspect, and a decision was made to update the campus metering to a more modern system. Beginning in 2005, the Texas A&M utilities office began an initiative to replace the metering in campus buildings, an initiative which is still ongoing at this time. The paddle wheel flow meters are being replaced with insertion-type magnetic flow tube type meters. These meters typically have better accuracy, are less prone to drift, and create less pressure drop in the system than the paddle wheel meters. The new metering continues to use insertion probe water temperature sensors on the primary loops, and also continues to use CT type energy meters for whole building electricity consumption measurement. The year 2004 was the last year any of the ten buildings displayed reliable data from the old metering system. Data from the new metering system began to appear in mid-2005. As of the data periods represented in this study, seven of the buildings have had the new metering system installed: Blocker, G. Rollie White, Harrington Tower, Kleberg, Koldus, Wehner, and Zachry.

While the difference in the accuracy of the metering systems is not significant relative to the modeling uncertainty that will be described later, a potential source of bias relative to the calibration of the two metering systems is introduced. Calibration documentation does exist for earlier years for the old metering system, but none to compare the current metering system with the previous system. This study ignores any bias from meter calibration discrepancies, with the exception of the hot water meter in the Koldus building, which will be described further hereafter. Any further work done that compares consumption data prior to 2005 with data thereafter must also deal with the potential discrepancies caused by this metering change.

CHAPTER II
LITERATURE REVIEW

2.1 Introduction

In recent years the topic of persistence of benefits from commissioning has gained more interest both for existing building retro-commissioning and new building commissioning. Several studies have been performed and published examining both aspects of this topic. This review will summarize the key results of these studies. The categories presented are persistence of commissioning measures in existing buildings, persistence of commissioning measures in new buildings, strategies for improving persistence in new and existing buildings, and related reports. While a few studies in persistence of energy savings have been performed in the past (see Vine 1992), the topic as it relates specifically to commissioning and retro-commissioning is relatively new, and the most relevant projects identified in the literature to date involve a total of 42 buildings as noted below:

- 10 Retro-commissioned Buildings at Texas A&M University – Claridge et al. (2002, 2004)
- 3 Retro-commissioned Buildings at Texas A&M University – Engan (2007)
- 8 Retro-commissioned Buildings in Sacramento, California – Bourassa et al. (2004)
- 8 Retro-commissioned Buildings in Oregon – Peterson (2005)
- 1 Retro-commissioned Building in Colorado – Selch and Bradford (2005)
- 2 Retro-commissioned Buildings from Utility Program – Eardley (2007)
- 10 Commissioned New Buildings – Friedman et al. (2002, 2003a, 2003b).

While other studies were looked at, these seven studies were reviewed in detail.

2.2 Persistence of Commissioning Measures in Existing Buildings

2.2.1 10 Buildings at Texas A&M

A study was performed in 2000 to evaluate the persistence of savings in 10 buildings on a university campus three years after the buildings participated in retro-commissioning (Turner, et al. 2001, Cho 2002, Claridge et al. 2002, 2004, Chen et al. 2002, Liu et al. 2002). The objectives of the study were to determine quantitatively how much savings degradation occurred and the major causes of any observed degradation. The investigation did not focus on the detailed measures implemented in each building, but rather on the degree to which the measures implemented in the retro-commissioning process had been maintained, as indicated by examination of energy use data, the retro-commissioning reports, and the control settings in place on the main energy management control system.

The study was conducted in five major parts. First, buildings were selected to be studied. Second, savings calculations were performed based on energy usage data from the different periods needed. Third, field examination and commissioning follow-up was conducted on two buildings in which major savings degradation occurred. Fourth, operational and controls changes that could have contributed to changes in building performance after retro-commissioning were identified. Fifth, calibrated simulations of some of the buildings were performed to verify the effects of the identified changes on energy consumption.

A preliminary group of 20 buildings which had been commissioned in 1996 or 1997 was initially selected. An office review of information on the retro-commissioning measures implemented and available information on operating parameters before and after retro-commissioning was then conducted. Based on this review, the 10 buildings with the most complete information concerning the retro-commissioning process and energy consumption data were selected. None of the buildings in this group received capital retrofits during the period 1996-2000. Five buildings were commissioned in 1996 and the other five were finished in 1997. In each of these buildings, commissioning measures were identified by the retro commissioning provider and then implemented by the provider, after receiving the concurrence of the building owner's representative. Since all 10 buildings were located on a university campus, they primarily consisted of classrooms, laboratories, and offices, with one volleyball arena.

The energy usage data for these buildings had been monitored and was obtained beginning with the period shortly before retro-commissioning and ending in 2000 when the study was performed. For comparison purposes, all of the energy data was normalized to a single year of weather data. Because the weather data for the year 1995 most closely approximated average weather conditions for the years studied, it was chosen as the baseline year. Energy use before and after the retro-commissioning process were compared. In this study savings from the retro-commissioning process were determined by using Option C of the International Performance Measurement and Verification Protocol (IPMVP, 2001), which determines savings using measured energy use at the whole facility level. This required that baseline models of the consumption be formulated for each major source of energy use in each building. Chilled water and hot water energy consumption were measured for each year, and three-parameter or four-parameter change-point models of cooling and heating consumption were determined as functions of ambient temperature using a modeling program.

The process of calculating the yearly savings required the development of five separate chilled water models and five hot water models for each building, one for each year, including the baseline model. The consumption and savings for each year were then normalized to 1995 weather by using the models for each year's data with the 1995 temperature data to determine the savings for each year. Electricity savings were determined without normalization since the buildings did not have chillers, and electricity consumption is not appreciably affected by ambient temperature.

Follow-up was performed on two buildings with significant savings degradation. This was done primarily through a field investigation of the buildings to determine what changes had occurred that would produce the changes. Equipment performance and EMCS control settings were examined to evaluate possible causes for degradation.

Information was then gathered on controls and operational changes that had occurred in the buildings during the period studied. This was done by examining the retro-commissioning reports and interviewing the engineers and maintenance personnel who had responsibility for each building. These interviews provided identifiable reasons for many of the changes in savings seen in the buildings.

In order to quantify the effect of each operational or control change identified, it was decided that the energy usage of the buildings would be modeled using a computer simulation program. The rough simulations would then be calibrated until they provided accurate representations of the actual energy use. These simulations would then demonstrate how much of an effect each control or operational change had on the building energy use.

2.2.1.1 Results

All ten buildings showed significantly reduced chilled water and hot water energy consumption since retro-commissioning, although the savings generally decreased somewhat with time. Eight buildings had larger HW savings in 1998 than in 1997 as a consequence of hot water loop optimization conducted in 1997 and final retro-commissioning actions. Overall the electricity consumption remained fairly constant, with three buildings showing small increases in consumption (negative savings). The average electricity savings for the 10 buildings from 1997 to 2000 were 10.8%.

Figures 2-1 and 2-2 show the chilled water and hot water savings trends for the years following the building retro-commissioning.

Overall, chilled water savings for the three years following retro-commissioning averaged 39.3% of the pre-commissioning baseline. Eight of the buildings showed good persistence of savings for chilled water (less than 15 % change during the 3-4 years after retro-commissioning), while the other two displayed significant degradation. The Blocker building had 19% degradation, and the G. R. White Coliseum had a dramatic savings degradation of 38%.

Hot water consumption was reduced significantly in the years following retro-commissioning, but the savings fluctuated widely from year to year. Savings increased from 1997 to 1998 in most buildings due to optimization in the hot water loop in 1997 and some ongoing retro-commissioning work. The 10 buildings averaged hot water savings of 65.0 % after retro-commissioning.

Based on the historic campus energy costs of \$4.67/MMBtu for chilled water, \$4.75/MMBtu for hot water, and \$0.02788/KWh for electricity, the cumulative savings from retro-commissioning in these 10 buildings were \$4,439,000 for the period 1997 - 2000. Only three buildings had year 2000 savings greater than 1998 savings, and the increase in two of these was about 2% of baseline consumption which is well within the range of normal year-to-year variation. The savings of the other buildings decreased.

Table 2-1 summarizes the savings history of this group of 10 buildings. The savings in 1998 following initial retro commissioning corresponded to average energy cost savings of 39% for the 10 buildings. Savings decreased to 32.3% over the next two years – still a highly significant level of savings.

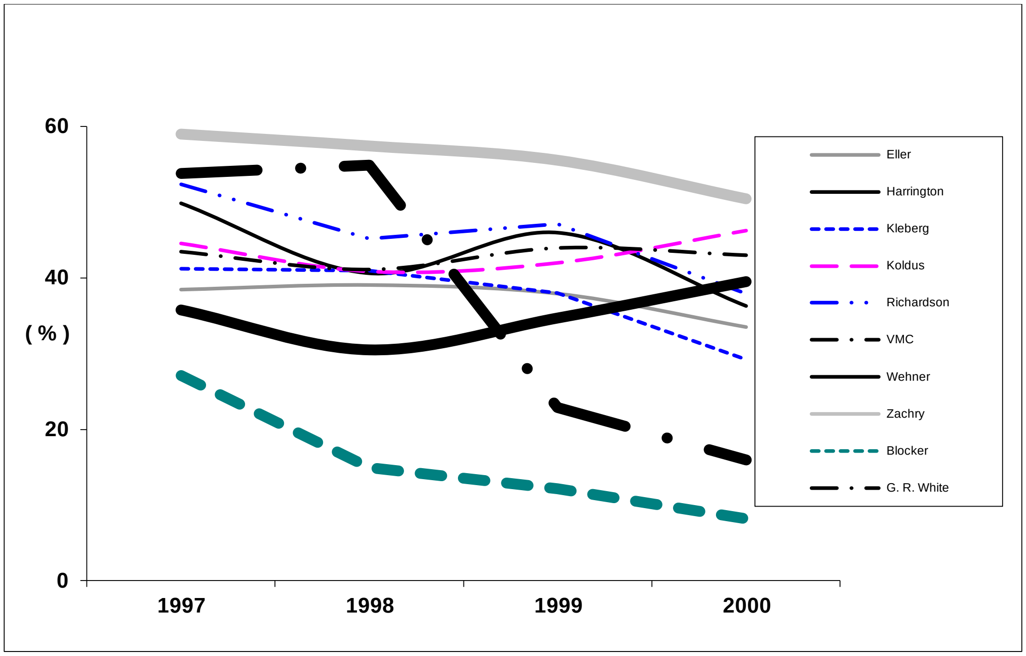


Figure 2 - 1. Chilled water savings persistence after retro-commissioning (Turner et al. 2001).

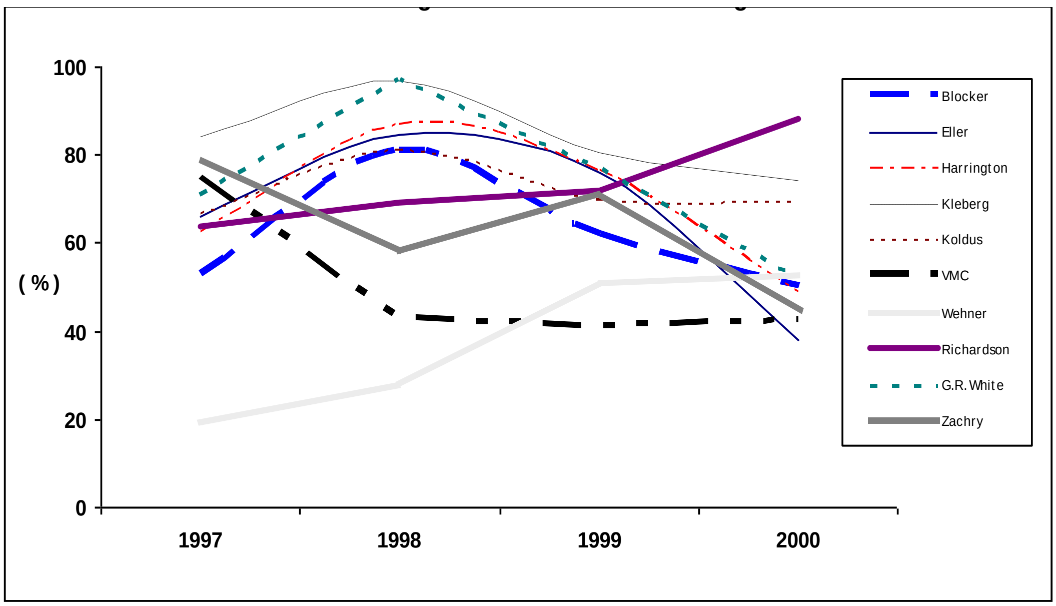


Figure 2 - 2. Hot water savings persistence after retro-commissioning (Turner et al. 2001).

Table 2 - 1. Summary of savings in 10 buildings retro-commissioned at Texas A&M (Turner et al. 2001).

	Baseline Use ($/yr)	1998 Cx Savings ($/yr)	Savings 2 Yrs Later ($/yr)
10 Buildings	$3,049,487	$1,192,000 (39.1%)	$984,516 (32.3%)
8 Buildings	$2,195,307	$723,376 (32.9%)	$666,108 (30.3%)
2 Buildings	$854,180	$468,624 (55%)	$314,408 (37%)

Investigation showed that two of the buildings, G. Rollie White Coliseum and Kleberg, accounted for 3/4 of the total savings degradation, and both had experienced major equipment and controls malfunctions which were the primary causes of their degradation. Following correction of these problems, savings were restored to earlier levels. In the remaining eight buildings, savings changes were rather small, declining from 32.9% to 30.3% in aggregate.

All but one of the group of eight buildings had experienced at least some changes in EMCS control settings. To verify the impact of the EMCS changes on energy consumption, the calibrated simulation process was performed on the four buildings with the most complete data sets. Simulation was conducted for a pre-commissioning period, a post-commissioning period soon after retro-commissioning and for the year 2000 for each building. It was found that the changes in consumption observed following retro-commissioning in these buildings were consistent with those due to the identified controls changes, with an RMS difference of only 1.1%. Control changes accounted for the savings increase observed in the Wehner Building as well as the decreases observed in the other three buildings. This suggests that the changes in savings these four were almost entirely due to the control changes.

Based on the results of this study of 10 buildings, it was concluded that:

- Basic retro-commissioning measures are quite stable
- Savings should be monitored to determine the need for follow-up
- Steps should be taken to inform operators of the impact of planned/implemented control changes.

2.2.2 Three Buildings at Texas A&M

In 2007, a study was performed at Texas A&M by Engan that involved the persistence of commissioning benefits. This study examined two aspects of the issue. It tracked the persistence of savings in three existing buildings at Texas A&M that had undergone retro-commissioning. It also compared the variability of consumption savings and the persistence of savings from the Normalized Annual Consumption (NAC) and standard International Performance Measurement and Verification Protocol (IPMVP) weather normalization approaches, using Options C and D of the IPMVP.

Three buildings were selected that had undergone retro-commissioning in 1996 or 1997. In order to quantify savings from retro-commissioning and their persistence, Option C of the IPMVP was employed. The NAC weather normalization approach was employed for this, using a long-term average College Station, Texas, weather year as the “normal” weather year. The normalized annual consumption for each building for each year was then determined using regression models as outlined in Option C. Energy balance plots were used to aid in screening the data quality of the measured consumption data. In buildings where insufficient pre-commissioning baseline data were available, calibrated simulations of the first post-commissioning year were performed, and the parameters were changed to match pre-commissioning conditions as outlined in the retro-commissioning reports. This new simulation was then used to obtain a pre-commissioning baseline, in accordance with Option D of the IPMVP.

The results are shown in Figures 2-3, 2-4, 2-5, and 2-6 that follow.

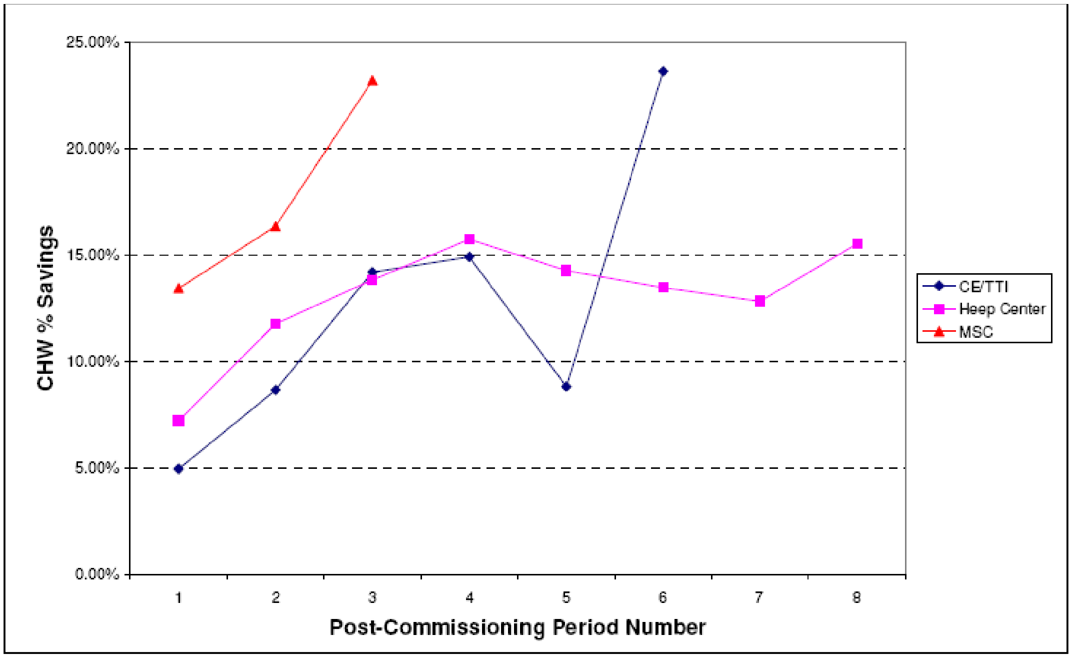


Figure 2 - 3. Post-commissioning chilled water percent savings for CE/TTI, Heep Center, and MSC (Engan 2007).

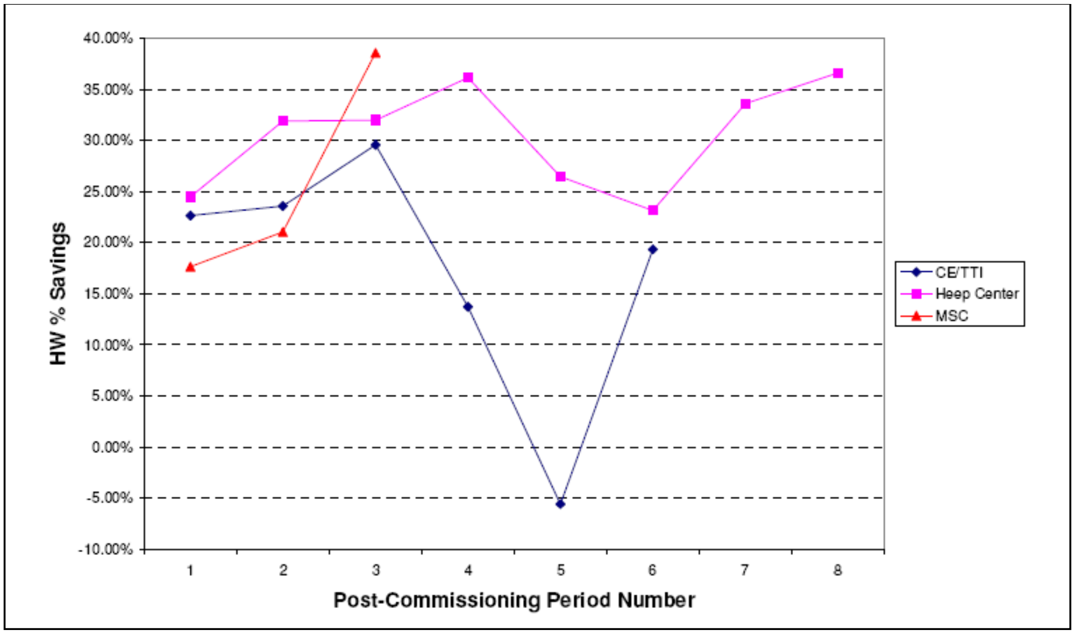


Figure 2 - 4. Post-commissioning hot water percent savings for CE/TTI, Heep Center, and MSC (Engan 2007).

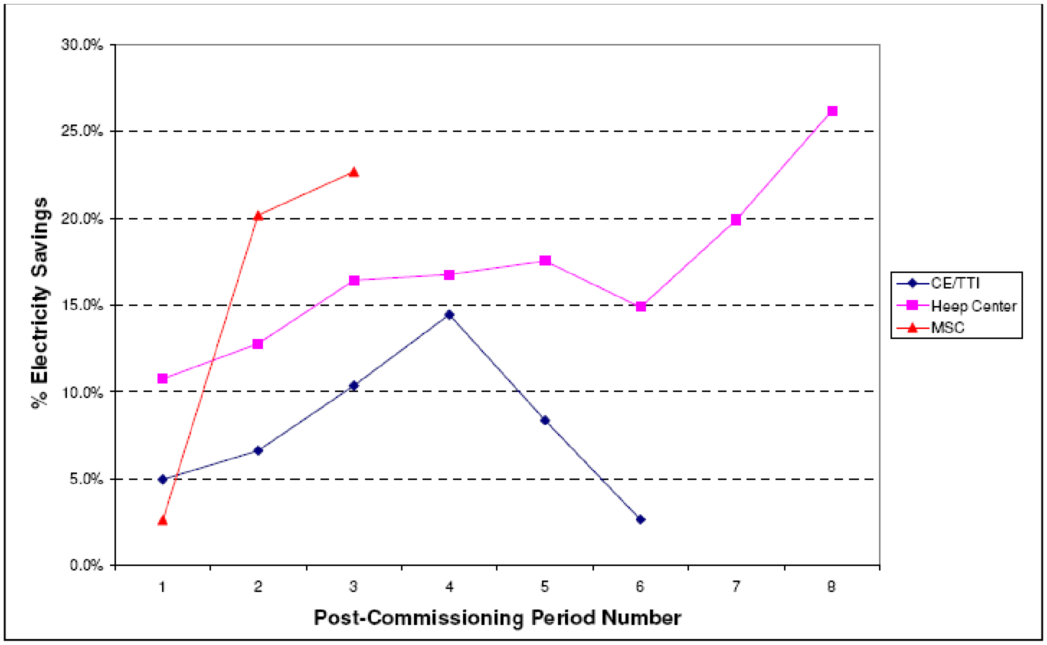


Figure 2 - 5. Post-commissioning electricity percent savings for CE/TTI, Heep Center, and MSC (Engan 2007).

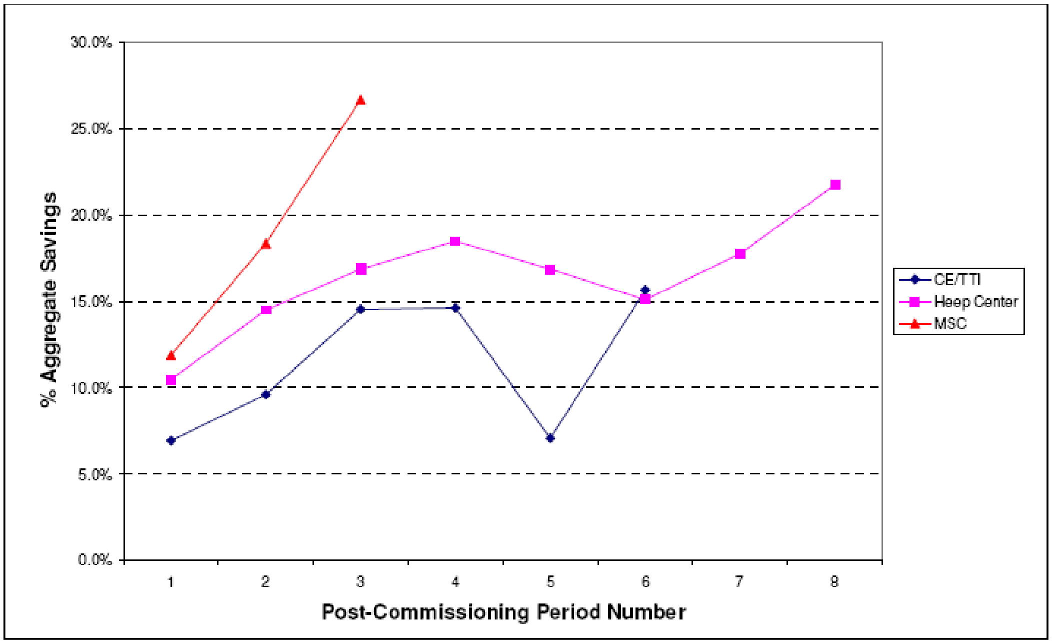


Figure 2 - 6. Post-commissioning aggregate site percent savings for CE/TTI, Heep Center, and MSC (Engan 2007).

Aggregate site savings for the three buildings averaged 11.4%, 16.5%, and 19.0% over the periods surveyed. Persistence of savings was favorable, as all three buildings displayed an increase in aggregate savings from the first year post-commissioning to the most recent year. It was noted that two of the buildings underwent follow up retro-commissioning, which assisted in maintaining savings.

The other part of this study focused on weather normalization approaches. Specifically, the variability in commissioning savings was compared between the NAC and standard IPMVP normalization approaches. This was done by utilizing the consumption data from one of the aforementioned buildings, and testing the approaches. Specifically, savings were determined for each year using Option C with the NAC approach, using Option D with the NAC approach, using Option C with the standard IPMVP approach, and using Option D with the standard IPMVP approach. The NAC approach determines savings as the difference between pre- and post-commissioning consumption during a "normal" weather year, which is often a manufactured "year" consisting of long-term weather data averages. This study used the NAC approach with each of 29 weather years obtained from the National Climatic Data Center (NCDC), including one which was a long-term average of all of the others. The standard IPMVP approach is to normalize the pre-commissioning baseline consumption data to the weather year wherein savings are desired to be determined. This normalized consumption is then compared with actual measured data from the post-commissioning year. In order to increase the sample size from this approach, this study assigned a random weather year to each year of data. The consumption data for that year were then normalized to the random weather year, as were the pre-commissioning data, and savings were determined. This random assignment was then repeated 28 more times for each year, for a total of 29 runs.

Variability of savings was quantified by the average standard deviation of the 29 percent savings results across all post-commissioning periods for each method. For the combined chilled and hot water savings, the average standard deviation was 0.39% savings for Option D using the NAC weather normalization approach, 0.57% savings for

Option D using the standard IPMVP weather normalization approach, 0.71% savings for Option C with regression models using the NAC weather normalization approach, and 0.98% savings for Option C with regression models using the standard IPMVP weather normalization approach. The variability of savings persistence results deviated some from the variability of savings results. For the combined chilled and hot water persistence of savings, the average standard deviation across all post-commissioning periods was 0.48% persistence for Option D using the NAC weather normalization approach, 0.55% persistence for Option D using the standard IPMVP weather normalization approach, 0.52% persistence for Option C with regression models using the NAC weather normalization approach, and 1.26% persistence for Option C with regression models using the standard IPMVP weather normalization approach.

The NAC weather normalization approach showed less overall variability in savings and persistence than the standard IPMVP weather normalization approach. Option D of the IPMVP generally showed less variability in savings and persistence of savings than Option C with regression models.

2.2.3 Eight Buildings in SMUD Program in Sacramento

In 2003, a study was performed by Bourassa et al. (2004) on eight buildings which had undergone retro-commissioning through the Sacramento Municipal Utility District (SMUD) retro-commissioning program. The objective of the study was to determine the extent to which retro-commissioning measures were implemented, and the magnitude and persistence of energy savings achieved. Another objective was to see if the two primary goals of the SMUD retro-commissioning program had been met: reduced overall annual building energy consumption, and improved energy efficiency awareness and focus in the customer. The eight buildings selected for the study consisted of six office buildings, one laboratory, and one hospital. Four of the buildings participated in retro-commissioning in 1999, and the other four in 2000. In this program, the retro-commissioning provider worked with the building operators to develop the recommended measures. The measures selected for adoption were subsequently implemented by the building staff and/or contractors over a period of up to two years.

2.2.3.1 Energy Analysis

The energy savings obtained in the years following retro-commissioning were determined and compared. In order to be able to compare energy savings in the different buildings over the years examined, baseline energy consumption was established for each building based on pre-retro-commissioning energy use. Electricity use data were collected from monthly utility bills for each building. Four buildings also had metered data recorded at 15 minute intervals. Gaps in utility bills were filled from site records or regression analysis.

The energy consumption data were normalized to a common weather year and to a common billing cycle of 30.5 days. The savings were calculated using spreadsheets, based on the normalized data, which allowed for a simpler and more robust statistical comparison. Another set of savings was also calculated, based on the retro-commissioning report predictions. Adjustments were made for a capital retrofit in one of the buildings. The cost of retro-commissioning was also estimated for each of the buildings, based on three categories: SMUD's retro-commissioning costs, the site's retro-commissioning costs, and the retro-commissioning measure implementation costs. Based on the estimated costs and savings, simple payback periods for retro-commissioning at each of the sites were calculated and compared.

The electrical savings observed for each building over the years following retro-commissioning are shown in Figure 2-7.

The aggregate savings for the sites are shown in Figure 2-8. The buildings are grouped together according to the number of years of data available after retro-commissioning. Note that the "three year" line in the figure includes the data from the "four year" line plus data from three additional buildings, while the "two year" line simply adds data from one more building. Comparison with the data in Figure 2-7 suggests that the peak in year 3 may be largely due to the one building whose savings peaked in year 3.

These plots demonstrate the observed trend in energy savings for the commissioned buildings. During the first two years the savings generally increased. This was expected because of the length of time needed for the retro-commissioning measures to be implemented. In the third year the savings began to level off, and the fourth year generally showed a declination in the electricity savings. A comparison with the predicted savings estimated in the retro-commissioning reports revealed that on average these reports underestimated the savings by 27.5%.

The average electricity savings for all the sites over all the years was 7.3% per year. Natural gas usage was only able to be obtained for four of the buildings. The savings for natural gas were considerably lower, but since Sacramento is dominated by cooling needs, the lower natural gas savings only reduced the average total energy savings in these four buildings to 6.1% per year.

The payback periods for the retro-commissioning projects all proved to be attractive, with the longest period being 2.3 years.

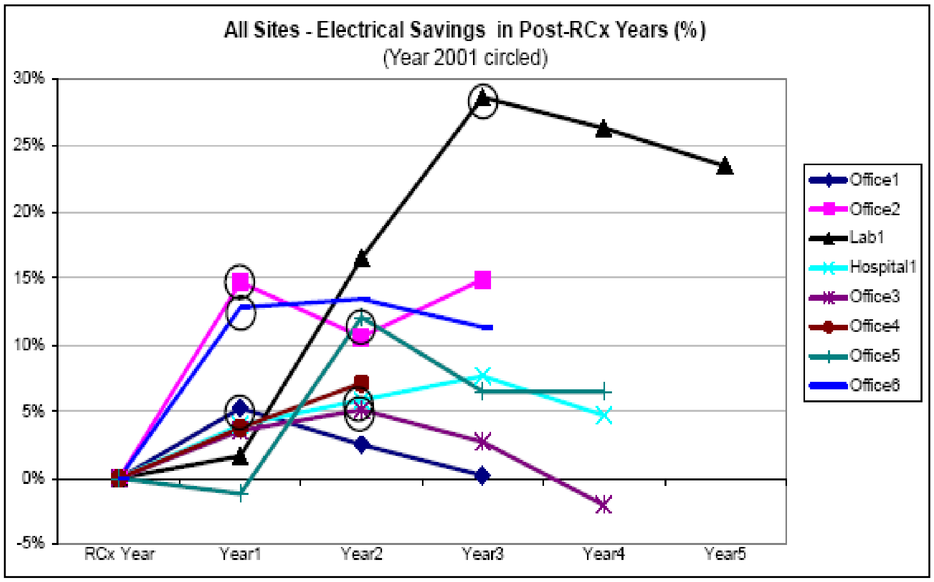


Figure 2 - 7. Electrical savings following retro-commissioning for each of the buildings (Bourassa et al. 2004).

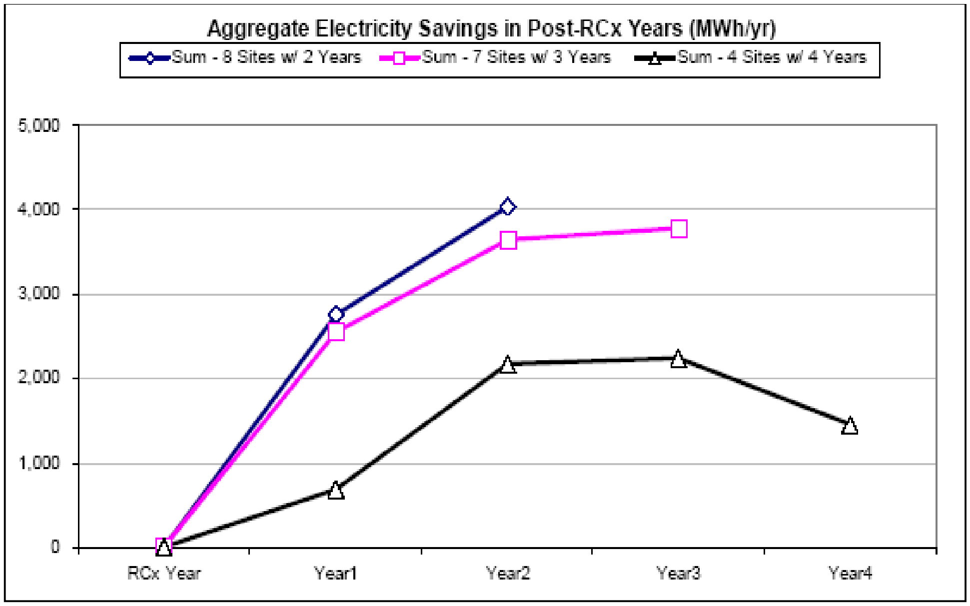


Figure 2 - 8. Plot of aggregate post-retro-commissioning electricity savings (Bourassa et al. 2004).

2.2.3.2 Measure Persistence Analysis

A series of interviews and site visits were used to determine the persistence in the retro-commissioning measures recommended. The eight retro-commissioning reports recommended a total of 81 corrective measures, of which 48 were implemented. Of these 48, it was found that 81% had persisted, in that they were still in that they were still in effect at the time of the study. It was discovered that four of the measures had been abandoned completely, all of which were air distribution component recommendations. Five of the measures had undergone evolution by the building engineers because the original measures had not resolved the problems.

Surveys were given at the sites to determine attitudes regarding the retro-commissioning process, as well as its benefits. All of the sites reported that retro-commissioning was a worthy process. Four of the sites listed training as the primary non-energy benefit from retro-commissioning. The most cited downside to retro-commissioning was the time intensive nature of the process. All of the sites came out of the retro-commissioning process with ideas on how to retain the commissioning benefits over time, the most common solutions being preventative maintenance plans. All of the sites would undertake retro-commissioning again, but only two had potential internal funding.

2.2.3.3 Conclusions

Some important retro-commissioning process factors that this study identified were:

- The commissioning authority is most effective when he is both an expert and a teacher.
- Building engineers prefer to evolve the settings on a recommendation that does not work, rather than revert to the previous condition.
- Retro-commissioning appears to raise energy efficiency awareness.
- Retro-commissioning funds are constrained within building management budgets.

The energy analysis results showed:

- Analyses should not emphasize first-year savings because savings typically take two to three years to fully manifest.
- Energy savings persist to four years or more, although some degradation begins in the third year.
- The retro-commissioning energy savings predictions were reasonably accurate.
- Building managers lack tools for tracking energy performance.
- Retro-commissioning cost pay back was shorter than the apparent savings persistence.
- Retro-commissioning focused mostly on electricity savings and some natural gas tradeoffs in the savings occurred.

On the whole, the two broad goals of the SMUD retro-commissioning program were met at the eight sites. Aggregate post-retro-commissioning savings were strong, peaking at approximately 4,420 MWh and the program helped educate site staff about energy efficiency and the role operations and maintenance plays.

2.2.4 Oregon Case Study

A study performed in Oregon in 2004 examined eight Intel buildings that had been retro-commissioned in 1999 and 2000 (Peterson 2005). The buildings were located on the Intel Jones Farm and Hawthorn Farms campuses. The retro-commissioning for these buildings was performed by Kaplan Engineering and PECI through funding from Portland General Electric (PGE). At the time retro-commissioning occurred, it was estimated that electricity savings of nearly 3.5 million kWh annually would result from the low cost energy efficiency measures (EEMs) proposed. The purpose of this study was to examine the energy usage of the buildings to determine what percentage of the original savings was still being achieved four years later. At the same time, it was desired to determine how many of the EEMs proposed were still being utilized.

Three of the buildings studied were located on the Hawthorn Farms Campus, and were designated HF1, 2, and 3. The buildings combined for a total of 640,000 square feet, and were served by a central chiller and boiler plant. HF1 had DDC control interfaced with pneumatic actuators, and the other two buildings were upgraded to DDC control in 2000. The remaining five buildings studied were located on the Jones Farm Campus, and were designated by JF. They combined for a total of 1.4 million square feet, with over 40 major air handling systems served by two central chiller plants and two hot water boiler plants. Most of the spaces on both campuses were served by variable air volume (VAV) systems.

Three reports generated at the time of retro-commissioning were examined to determine what measures had been implemented. The current status of these measures was determined through random sampling, with functional testing or trending being used as appropriate. For HF1, the terminal reheat units were serviced at the time of retro-commissioning to ensure proper damper motion. At the time of this study, random sampling discovered no noticeable damper movement from full cooling to full heating in 60% of the units. The savings for this measure did not persist, probably due to the aging pneumatic system. For HF 1, 2, and 3, retro-commissioning had modified outside air intake controls to allow for the economizing cycle to function. At the time of the study, random sampling revealed this measure to still be functioning. For the HF chillers, retro-commissioning had lowered the condenser water set point from 75°F to 70°F, while raising the chilled water set point from 42°F to 45°F. This measure was also found to be in operation at the time of this study.

For the JF buildings, air handling units and terminal boxes were scheduled at the time of retro-commissioning to reflect occupancy patterns, scheduling unoccupied hours as 6 PM to 6 AM on weekdays and all day on weekends. At the time of this study, JF3 was evaluated, and the control was found to be working fairly well, with only a couple of override issues. Additional savings opportunities for the JF buildings were also identified in this study, including air flow and scheduling opportunities and control overrides that needed adjustment. For the HF chillers, the leaving condenser water set point was lowered from 80°F to 67°F at the time of retro-commissioning. The current study found the set point to be at 71°F, still significantly lower than the original.

Overall at the Hawthorn Farms campus the ECMs were found to have been maintained, with the exception of the terminal unit reheat optimization in HF1. Of the original projected savings in the three buildings at Hawthorn Farms, 89% of the electric savings and 0% of the natural gas savings were still being achieved at the time of this study. In the five buildings at Jones Farm, the results were more mixed and less quantifiable. The recommended scheduling changes were still programmed at a high level, but it appeared that numerous control overrides at a zone or box level had been made. Some overrides may have been due to changes in space use (such as conversion to a lab), but in many instances conference and training rooms were maintaining occupied modes around the clock. The trending done on some of the variable speed air handlers showed little difference between day and nighttime airflow suggesting that terminal box scheduling was not having an impact on overall airflow.

2.2.4.1 Summary

Of the eight buildings retro-commissioned in Oregon in 1999 and 2000 quantitative findings were reported for three and qualitative findings for the other group of five buildings. For the three buildings on the Hawthorn Farms campus, totaling 645,000 ft^2 in floor area:

- 89% of the original electric savings were achieved in 2004.
- 0% of the natural gas savings were achieved in 2004.

For the five buildings on the Jones Farm campus with 1,400,000 ft^2 of floor area, the results were mixed and less quantifiable. It was found that:

- Scheduling changes were still programmed at a high level, but
- Numerous control overrides at a zone or box level had been made.

2.2.5 Office Building in Colorado

A study completed in 2005 evaluated the persistence of recommissioning savings in a large office building in Colorado (Selch and Bradford 2005). Of the studies of this kind done to date, this study appears to have chosen the largest window of time over which to look at persistence. The office building was recommissioned in 1995, which resulted in verified savings of 14% in electrical demand, 25% in electrical use, and 74% in gas use. In 2003, the building was again recommissioned, at which time the status of the energy conservation measures implemented in the initial recommissioning effort was evaluated.

The computation of savings was done in two ways. The overall energy use of the building for each year was obtained from utility bills. These data were then normalized to account for factors such as weather differences, changing occupancy patterns in the building, and added construction in the building. In this way the yearly energy use could be accurately compared to the baseline, pre-commissioned energy use. The other savings calculation method was an individual measure evaluation. Specific measures that impacted individual HVAC system components were examined. To perform the calculations, Options B & C of the International Performance Measurement and Verification Protocol (IPMVP 2001) were employed, Option B being used for individual measure evaluation, and Option C for whole building usage comparison.

Table 2-2 summarizes the results of the individual measures evaluation. The savings from the 2003 recommissioning effort are compared with the 1996 savings. To determine the persistence of savings, the percentage of 1996 savings achieved after recommissioning in 2003 was subtracted from 100%. This is because it was supposed that the difference in achieved savings between the two recommissioning efforts represented those savings that had persisted.

Table 2 - 2. Savings persistence summary (Selch and Bradford 2005).

	1996 Savings	2003
Electricity	20% (1,600,000 kWh)	83% Persistence (17% Savings) (1,330,000 kWh)
Demand	14% (219 kW)	86% Persistence 12% Savings (188 kW)
Gas	74%	Complete persistence

As noted in the table, it was calculated that 86% of the electrical demand savings had persisted, while 83% of the electrical use savings had persisted. There had been complete persistence of the large natural gas savings. The results of the whole building energy use comparison appear in Figures 2-9 and 2-10. The left chart in each figure represents the raw values, while the right chart displays adjusted, normalized values.

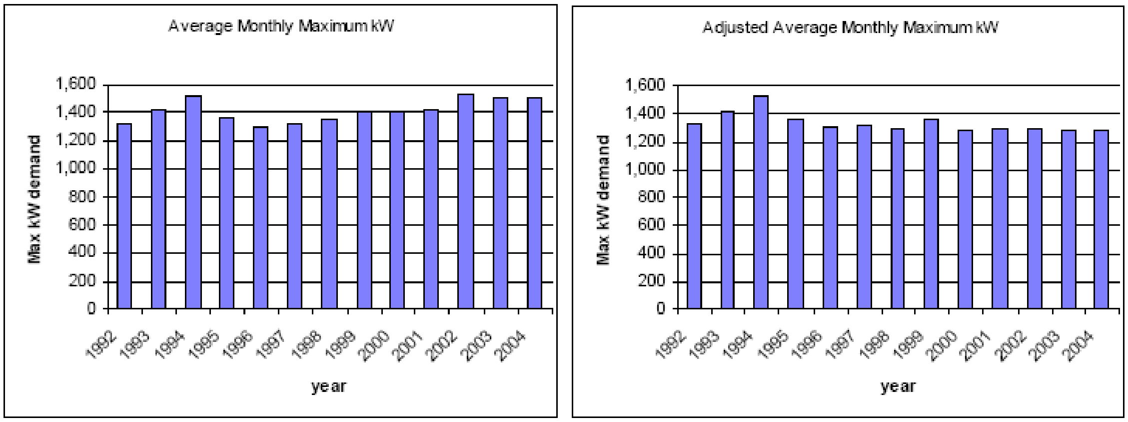


Figure 2 - 9. Annual electrical demand, raw and adjusted (Selch and Bradford 2005).

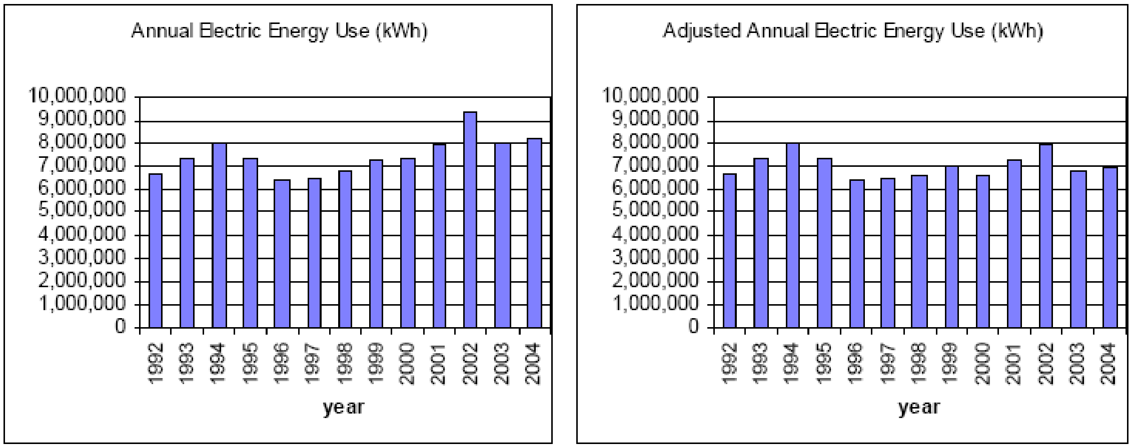


Figure 2 - 10. Annual electrical use, raw and adjusted (Selch and Bradford 2005).

The annual demand and consumption values that were adjusted to account for changing conditions indicated that the savings achieved from recommissioning had largely persisted. This was concluded with greater confidence due to the corroboration of the independent measure analysis.

The study reported that a large majority of the energy savings measures implemented in the original recommissioning effort had persisted, as had their resultant energy savings. This was in spite of changing conditions in the building, including a complete change in operation staff. It was concluded that ECMs of this nature can persist for at least eight years even with limited support from operators and staff. However, it was noted that continued, on-going support to the building staff as part of the original recommissioning effort probably would have resulted in complete persistence of the savings achieved.

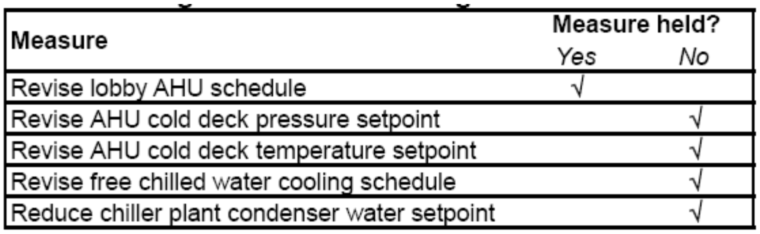
2.2.6 Two Buildings in Utility Retro-commissioning Program

A study was published in 2007 that applied a persistence tracking strategy to two office buildings that had undergone retro-commissioning (Eardley 2007). This study did not evaluate energy savings, but looked only at the persistence of implemented measures. The timeframe over which this was observed was very narrow, representing only a couple of months. However, this was done in order to test the persistence tracking system.

The tracking system was set up to retrieve building automation system (BAS) data from each building at five minute intervals. These data were sent through the internet to a remote server where they were stored. This was only done with the data points needed to verify the specific measures implemented. The persistence of the measures was then evaluated through inspection of the data.

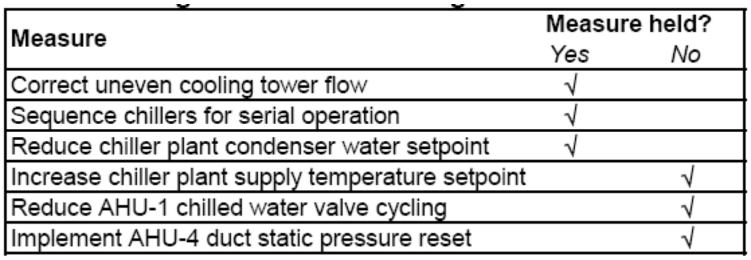
Despite initial setup problems, the system eventually became functional, and data was trended for the two month period. Tables 2-3 and 2-4 demonstrate which measures were found to persist and which were not.

Table 2 - 3. Building 1 measure tracking (Eardley 2007).



Measure	**Measure held?**	
	Yes	*No*
Revise lobby AHU schedule	√	
Revise AHU cold deck pressure setpoint		√
Revise AHU cold deck temperature setpoint		√
Revise free chilled water cooling schedule		√
Reduce chiller plant condenser water setpoint		√

Table 2 - 4. Building 2 measure tracking (Eardley 2007).



Measure	**Measure held?**	
	Yes	*No*
Correct uneven cooling tower flow	√	
Sequence chillers for serial operation	√	
Reduce chiller plant condenser water setpoint	√	
Increase chiller plant supply temperature setpoint		√
Reduce AHU-1 chilled water valve cycling		√
Implement AHU-4 duct static pressure reset		√

It was noted that the measures implemented did not have a high level of persistence, even over the short time frame observed. However, the persistence tracking system allowed the measures that did not persist to be pinpointed, so that further investigation could be performed as to why they did not persist. It was observed that this low level of persistence of measures might not be uncommon within the utility retro-commissioning program, making the persistence tracking system an important component of the program.

2.3 Persistence of Commissioning Measures in New Buildings

2.3.1 PECI PIER Study

In the summer of 2002, a study was completed that had begun in the fall of 2001 under a California Energy Commission Public Interest Energy Research (PIER) project (Friedman et al. 2002, 2003). The purpose of the study was to examine ten buildings that were commissioned at building start-up in order to address the persistence of benefits from the commissioning process. This study drew qualitative conclusions about the persistence of new building commissioning, focusing on three issues: how well the benefits of commissioning persisted, the reasons for declining performance, and the methods that can be used to improve the persistence of benefits achieved through commissioning. A quantitative assessment of persistence by measure ("this measure has an expected persistence of X years") was outside the scope of this project, since a large number of buildings would have been required to determine the figures for each measure.

To evaluate the persistence of commissioning benefits on new buildings, the buildings first had to be selected. To qualify for the study, the facility needed to have been commissioned as a new building or major retrofit between two and eight years prior to the study. Due to the difficulty in finding such buildings with adequate commissioning documentation in California, five buildings were selected in the Pacific Northwest, and five more in California. It was not feasible to limit the study to buildings that followed the full commissioning process, from pre-design through final acceptance and post-occupancy, as described in ASHRAE Guideline 1 (1996). The most completely commissioned and documented buildings were sought, but these typically did not include design-phase commissioning.

For each building, three to eight items were identified that were documented to have been fixed during commissioning. The changes and repairs made during commissioning generally fell into three categories: hardware, control system, and documentation improvements. Due to the focus on energy savings measures in the study, the hardware and control system changes with the greatest energy implications were of highest interest, as well as measures dealing with comfort and reliability. The amount of documentation available for each measure was also a driving force in measure selection. It was necessary to only evaluate those measures that had actually been implemented and documented. Routine maintenance issues or measures deemed static once corrected (such as equipment disconnected from the power supply) were not looked at. With the limited amount of time and funding for the study, it was necessary to focus on measures whose current status could easily be compared to the as-commissioned status and which would affect energy consumption. Because of the bias in selecting these measures, and the underestimation of savings persistence due to the limited number of measures considered, the results of the study were presented qualitatively.

For purposes of the study, it was decided that if the measure resulted in better performance than the pre-commissioning condition, then the measure was said to have persisted, even if it had been adapted to meet real operating conditions of the building. In some cases the persistence of a measure was somewhat subjective.

The people with the most knowledge about the control system at each site were interviewed. Some sites were identified for site visits, and for the others a second interview was conducted to discuss the current status of the commissioning measures. Six of the buildings were visited, during which the persistence of the selected commissioning measures was investigated, and the work environment and resources available to the operations staff were evaluated.

2.3.1.1 Results

It was found that the process of finding qualified buildings for the study in California was difficult. As mentioned above, qualified buildings were located more easily in Oregon, most likely because of the longer history of new building commissioning in the Pacific Northwest. California had numerous existing buildings involved in retro-commissioning projects, but new buildings having undergone commissioning at least two years earlier were sparse. For many of the commissioned buildings considered for the study, commissioning reports had not been written, so the information that could have been used by operations personnel to more efficiently operate the building essentially was lost. Often times in lieu of a report, the commissioning activities would simply be placed on a “punch list” for maintenance personnel to work on, who, when they had completed them usually did not document the changes. In other buildings the reports had been written, but were not readily available to the operations staff, having been filed away in storage and not easily accessible. In many cases where documentation did exist, it was not clear when or if the commissioning measures had been implemented, as they were noted as “recommendations” or “pending.” These issues led to the conclusion that the term “commissioning” had been applied to a variety of different activities, including troubleshooting items and checklists, indicating a lack of consistency in the way the term was being applied.

Table 2-5 summarizes the commissioning measures studied and their level of persistence. A light gray square indicates that the measure persisted, while a black square indicates that the measure did not persist. A square split in half horizontally indicates that more than one measure was investigated in the category.

Table 2 - 5. Persistence of equipment and controls fixed during commissioning (Friedman et al. 2003).

BUILDING (year commissioned)		DOCUMENTS			CENTRAL PLANT				AIR HANDLING AND DISTRIBUTION								PREFUNCTIONAL TEST					OTHER		
		Commissioning report on site	Commissioning report used	Control sequences available	Chiller control	Cooling tower control	Boiler control	Hydronic control	Economizer control algorithm	Discharge air temperature reset	Simultaneous heating and cooling	VFD modulation	Dessicant cooling	Duct static pressure	Space temperature control	Terminal units	Piping and fitting problems	Valve modification	Wiring and instrumentation	Sensor placement or addition	Sensor error or failure	Scheduling	Skylight louver operation	Occupancy sensor
California	Lab and Office 1 (1995)	no	-	yes	■	▨		▨							▨				▨			■		
	Office Building 1 (1996)	no	-	yes	▨	■		▨	▨	▨				▨					▨		▨			
	Office Building 2 (1996)	no	-	no				▨	■			▨		▨								▨		
	Office Building 3 (1994)	yes	yes	no								▨	■	■	▨ ▨		▨	▨						
	Office Buidling 4 (1994)	no	-																			■	■	▨
Pacific Northwest	Office Building 5 (1997)	no	-	yes	■		■	▨ ■	▨												■			
	Medical Facility 1 (1998)	yes	yes	yes	■													▨		▨	▨	▨		
	Medical Facility 2 (1998)	yes	yes	yes					▨	▨	▨					■ ▨		▨			▨	■		
	Lab and Office 2 (1997)	no	-	yes					▨	▨						■					■			
	Lab and Office 3 (2000)	no	-	no				▨			▨			▨								■		

Across the ten buildings studied, patterns about the types of commissioning fixes that persisted emerged. For the fifty-six commissioning fixes selected, well over half of the measures persisted. It was not surprising that hardware fixes, such as moving a sensor or adding a valve, persisted. Furthermore, when control algorithm changes were reprogrammed, these fixes often persisted, especially when comfort was not compromised. Many design phase fixes may have persisted in a similar way, but these were not able to be studied since only one building was commissioned in the design phase.

The types of measures that tended *not* to persist were the control strategies that could easily be changed, such as occupancy schedules, reset schedules, and chiller staging. Four out of six occupancy schedules did not persist. Chiller control strategies did not persist in three out of four cases, most likely due to the complex nature of control in chilled water systems. The study of sensor issues was limited to major sensor problems that were corrected during commissioning, such as sensor failure or excessively faulty readings. With this selection bias applied, two out of five sensor repairs did not persist.

Among the commissioning measures implemented, a few cases involved technologies that were new or different from normal practice. Due to lack of documentation, these measures were not included in this study, but it was observed during the investigation that these measures generally did not persist. This was attributed to a lack of operator training for the technologies.

2.3.1.2 Discussion

The study suggested three possible reasons for lack of persistence among some measures. The first was limited operator support and high operator turnover rates. Operators often did not receive the training necessary or they did not have sufficient time or guidance for assessing energy use, and the training given new operators who came in after the commissioning was usually inadequate. The second reason involved poor information transfer from the commissioning process. For nearly every case studied, the commissioning report was either difficult to locate, or was not even located on site, which reduced the ability of building operators to review commissioning measures implemented. The third reason for lack of persistence was a lack of systems to help track performance. Operators spent most of their time responding to complaints and troubleshooting problems, leaving little time to focus on assessing system efficiency. Aside from this, lack of information and knowledge impeded the efficiency assessment by building operators.

The persistence of commissioning benefits was found to be highly dependent on the working environment for building engineers and maintenance staff. A working environment that was supportive of persistence included adequate operator training, dedicated operations staff with the time to study and optimize building operation, and an administrative focus on building performance and energy costs. Trained operators were found to be knowledgeable about how the systems should run and, with adequate time and motivation to study the system operation, these operators evaluated and improved building performance. In five buildings, operators participated in the commissioning process and came away with a good understanding of their systems. In addition, good system documentation in the form of a system manual served as a troubleshooting resource for operators at two buildings. It was noted that administrative staff can help enable a supportive working environment by placing high priority on energy efficient systems and operator training. Only a few of the buildings studied seemed to operate in this environment, and the measures investigated at these facilities had the highest rate of persistence.

Some of the measures simply persisted by default – no maintenance being required to keep them operational. If comfort issues were not a factor, or the measure involved programming buried deep within code, the measures tended to persist.

The study recommended four methods for improving persistence. First, operators should be provided with training and support. Especially with high operator turnover, adequate training is needed for benefits to persist, and a working environment with energy efficiency as a high priority is also beneficial. Second, a complete systems manual should be provided at the end of the commissioning process. This will serve as a reference for building operators, and will allow the systems knowledge gained from the commissioning process to be available over the long term. Third, building performance should be tracked. New building commissioning efforts should help to implement mechanisms for performance tracking, including what information to track, how often to check it, and the magnitude of deviations to address. Fourth, commissioning should begin in the design phase to prevent nagging design problems. Changes made on paper before construction has begun tend to be more cost effective and have higher levels of persistence.

The study concluded with a recommendation that more in-depth, quantitative studies be performed to investigate the life of commissioning measures and carry out cost-benefit analyses for new building commissioning. It was further recommended that a manual of guidelines for improving persistence be developed to give guidance and direction to building operators with regard to energy efficiency.

2.4 Related Reports

2.4.1 2004 Commissioning Cost Benefit Study

A report was compiled in 2004 that evaluated the cost effectiveness of commissioning in new and existing buildings (Mills et al. 2004, 2005). The largest study of its kind to date, it examined the results of commissioning for 224 buildings across 21 states. Among the existing buildings commissioned, a median payback period for commissioning was reported to be 0.7 years. For new buildings, this value was found to be 4.8 years. Both of these figures excluded non-energy benefits, which would increase the savings experienced.

While persistence of savings was not the primary focus of the study, it was examined briefly since it plays a role in determining overall savings. Figure 2-11 shows the persistence of savings results for 20 of the buildings in the study, with a four year period following commissioning in each building. The savings are indexed by a comparison of the year's consumption to the pre-commissioning baseline consumption. The savings are compared by category: electricity, fuel, chilled water, and steam/hot water.

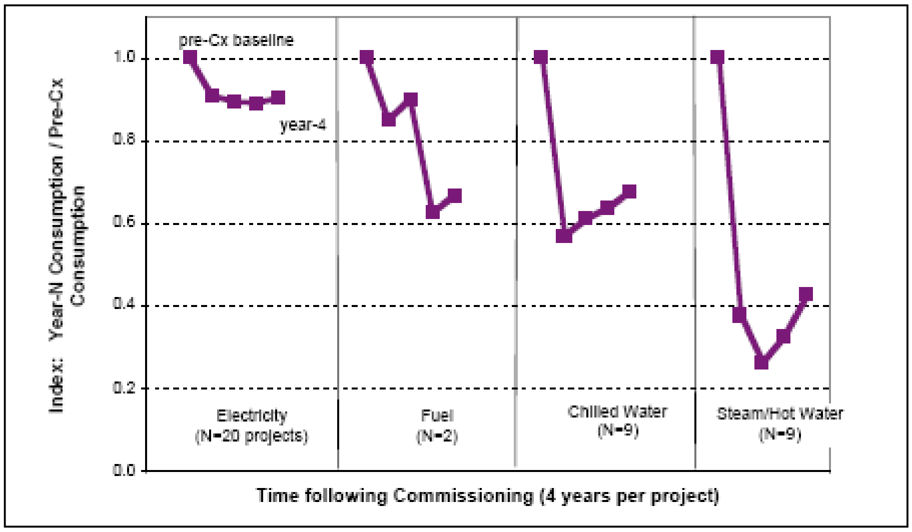


Figure 2 - 11. Emergence and persistence of energy savings (weather normalized) (Mills et al. 2004).

An important factor noted in the report was the fact that in many cases of commissioning, the recommended measures were implemented gradually, indicating that the first year after commissioning was not the best year for calculating savings. On the other hand, it was also observed that after time some of the savings began to degrade due to changing building conditions, operations, or aging. As seen in the figure, the maximum value for savings was reached and subsequently savings began to degrade. This effect was smallest for electricity, but much more noticeable for chilled and hot water and steam.

With regard to persistence of commissioning benefits, the report concluded that tracking energy consumption for evidence of significant consumption increases is the most important means of determining the need for follow-up commissioning, and that while controls changes by building operators account for a portion of savings degradation, hidden component failures are perhaps the greatest culprit in persistence problems.

2.4.2 2009 Commissioning Cost Benefit Study

A follow up to the 2004 report was published in 2009 (Mills 2009). This report also attempted to evaluate the cost effectiveness of commissioning new and existing buildings, but greatly expanded the data set of commissioning projects examined. The total number of buildings evaluated was 643, up from the 224 looked at in 2004. This totaled 100 million square feet of space. The study also took a closer look at some of the non-energy benefits associated with commissioning, such as greenhouse gas reductions and first-cost savings.

The study found that the median normalized cost to deliver commissioning was \$0.30/ft2 for existing buildings and \$1.16/ft2 for new construction. The median whole-building energy savings were 16% in existing buildings and 13% in new construction, resulting in payback periods of 1.1 years and 4.2 years, respectively. These findings along with findings relative to first-cost savings and carbon emissions reductions led the study to conclude that commissioning was arguably the most cost-effective strategy in reducing costs, energy, and greenhouse gas emissions in buildings.

The study also took a brief look at persistence of savings, using for data a sample of 36 buildings wherein up to five years of post-commissioning data were available. (All of these buildings have already been discussed in this Literature Review). The study generally concluded that energy savings tend to persist well over a three to five year period, but noted that data from longer periods were not typically available for evaluation. It was also concluded that on average buildings should be commissioned every five years.

Figure 2-12 summarizes the results of this study graphically.

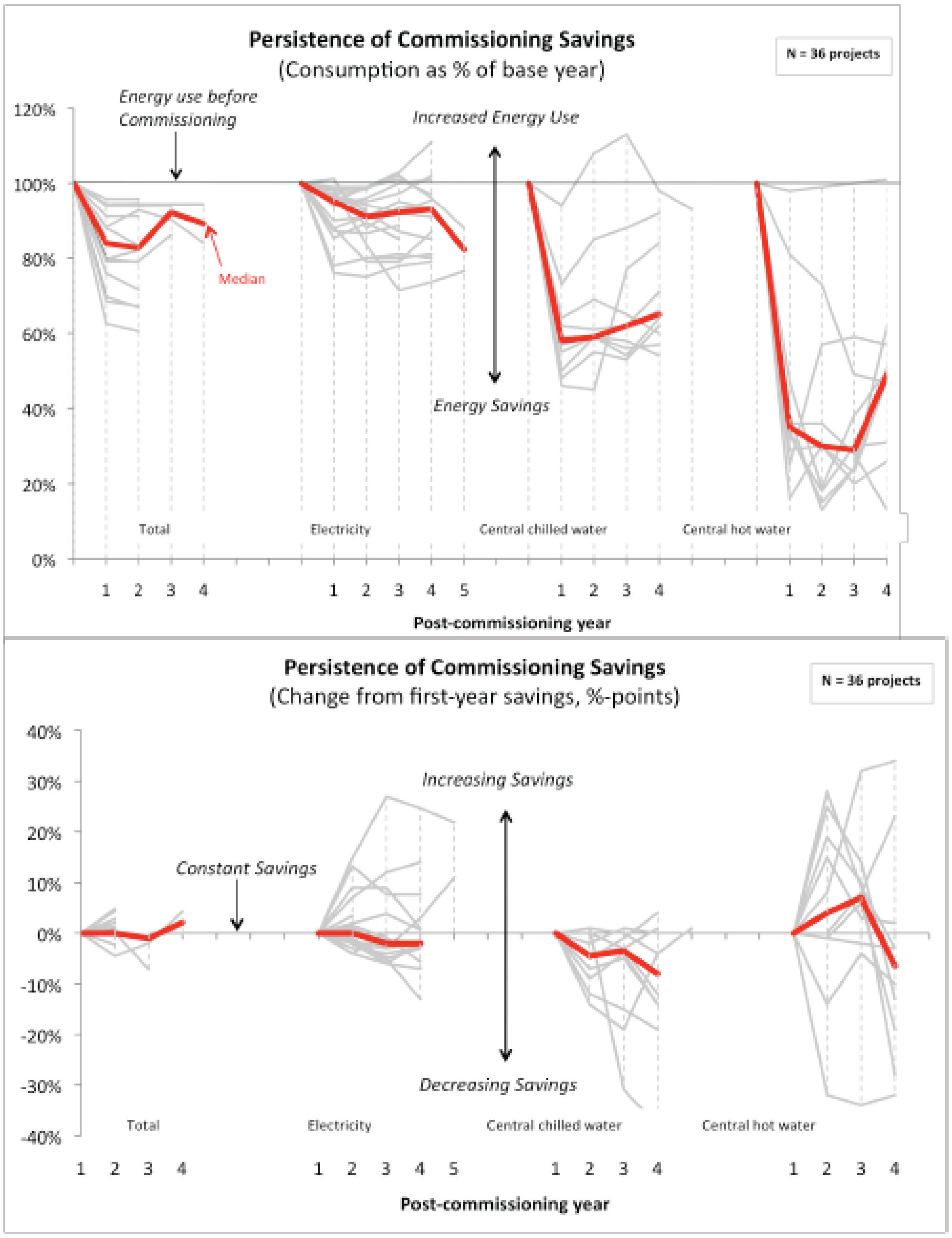


Figure 2 - 12. Two views of the persistence of commissioning energy savings: 36 projects (Mills 2009).

2.5 Methodologies for Determining Persistence of Commissioning Measures and Energy Benefits of Commissioning

The retro-commissioning studies that provided a quantitative evaluation of the persistence of energy benefits of commissioning used multiple approaches to evaluating the persistence of energy benefits.

The study of 10 Texas buildings (Turner et al. 2001) used a variation on Option C of the IPMVP that normalized for weather differences between years by selecting a “normal” year of weather data in the sequence available that most closely met long term norms. A suitable three-parameter or four-parameter regression model of the baseline year was created along with models of the performance of the building in each year evaluated. Then the annual consumption for each year was determined by running the appropriate model with the appropriate year of weather data.

The study of three Texas buildings (Engan 2007) also used Option C of the IPMVP to calculate savings, and normalized data based on a long-term average weather data as per the NAC weather normalization approach.

The study of eight SMUD buildings (Bourassa et al. 2004) used the same methodology, except that they used a long term average weather year instead of selecting one of the available years of weather data. The Colorado study (Selch and Bradford 2005) used a different approach, evaluating savings persistence with IPMVP Option C with baseline adjustments and IPMVP “Option B” was used to determine savings for specific measures in operation. The Oregon study did not specify how savings were evaluated.

The study of eight buildings in Oregon (Peterson 2005) and the Colorado building (Selch and Bradford 2005) used different approaches. These studies examined each of the measures that had been implemented and determined whether the measures were still in place and functioning. Peterson (3) found that in three of the buildings, she could quantify the savings associated with measures that had been disabled after four years. It was found that numerous measures implemented in the other five buildings were still in place, but there were also numerous overrides and changes that had occurred as well. It was not possible to quantify the degree of persistence in these buildings. Selch and Bradford (2005) found that they were able to quantify the savings associated with measures that had been disabled.

The study of two existing buildings in a utility retro-commissioning program did not quantify savings. Only data points from the BAS were monitored to identify which implemented measures had persisted.

The study of 10 new buildings that had been commissioned in Oregon and Washington (Friedman et al 2002) used a methodology that quantified the number of measures that were still in place, but it did not seem appropriate to try to quantify the energy savings associated with these measures. The four retro-commissioning studies all discussed the measures found to be still operating and those that had been changed. The Texas study used calibrated simulation to evaluate measures that had been changed. The other studies were not explicit in the methods used to evaluate the impact of measure changes.

2.6 Summary and Conclusions

The results of studies from seven projects related to commissioning, either in new or existing buildings, have been discussed, with the major conclusions drawn from each. These studies represent the extent of research that has been performed with regard to the persistence of commissioning benefits over time. These studies together provide a foundation for helping to understand how savings persist or degrade over time, and how to maintain savings. The current study builds upon the findings and information presented in these seven projects.

The savings in the buildings that were retro-commissioned generally showed some degradation with time, with specific findings as detailed below. For the ten buildings studied at Texas A&M, the cooling energy savings obtained from retro-commissioning degraded from 44.8% to 35.1% during the period from 1997 to 2000. The heating energy savings decreased 79.7% in 1998 to 49.7 % in year 2000. In spite of these decreases, cost savings from retro-commissioning in these 10 buildings were still $985,626/year compared with original savings of $1,192,884/year. As noted, 3/4 of the decrease was in two buildings in which component failures occurred. For the additional three buildings at Texas A&M, aggregate site savings increased with time. One building saw an increase from 6.9% savings the first year after commissioning to 15.6% the most recent year, another from 10.5% to 21.7%, and the third from 11.9% to 26.7%. For the eight buildings in California, peak aggregate savings occurred in years two and three with about 1/4 of the savings disappearing in year four for the four buildings for which that much data was available. 89% of the electric savings and none of the gas savings in three of the Oregon buildings persisted four years later. The persistence in the other five Oregon buildings was not quantified. The building in Colorado was still saving 86+% as much after seven years as after the initial retro-commissioning. Savings were also not quantified in the two utility retro-commissioning program office buildings, though less than 40% of the measures implemented persisted.

For the new buildings, well over half of the fifty-six commissioning fixes persisted. Hardware fixes, such as moving a sensor or adding a valve, and control algorithm changes that were reprogrammed generally persisted. Control strategies that could easily be changed, such as occupancy schedules, reset schedules, and chiller staging tended not to persist. It was also found that the extent to which persistence occurs is also related to operator training.

As is evident, the number of buildings studied in all of the papers described here represents a very small portion of commercial buildings that have undergone commissioning or retro-commissioning. Much more research is needed to verify the conclusions made in these studies, as well as to continue to provide practical solutions to building owners and operators as to how to best maintain commissioning savings, and how these methods may be better integrated in the commissioning process.

Useful work for the future would be to attempt to consolidate all the data and findings from each of these studies, along with the current study, to see what further conclusions, models, or correlations could be developed based on the entire set of data. Part of this would include presenting the results of each of these studies in a consistent format so that persistence of savings could be visually and mathematically compared more easily.

CHAPTER III
METHODOLOGY

3.1 Background

The development of procedures for calculating energy savings in buildings is directly linked to the development of procedures to measure and verify energy consumption. Haberl and Culp (2003) trace the history of energy consumption measurement and verification (M&V) from the earliest days of electricity consumption (circa 1890) to the 2003 industry standards for savings calculations. Table 3-1 below lists major events in this history beginning with the first energy simulations in the 1960s.

Table 3 - 1. History of M&V protocols (Haberl and Culp 2003).

2003 – IPMVP-2003 Volume III (new construction)
2002 – ASHRAE Guideline 14-2002
2001 - IPMVP-2001 Volume I & II (revised and expanded IPMVP)
1998 - Texas State Performance Contracting Guidelines
1997 - IPMVP (revised NEMVP)
1996 - FEMP Guidelines
1996 - NEMVP
1995 - ASHRAE Handbook - Ch. 37 “Building Energy Monitoring”
1994 - PG&E Power Saving Partner “Blue Book”
1993 - NAESCO M&V Protocols
1993 - New England AEE M&V Protocols
1992 - California CPUC M&V Protocols
1989 - Texas LoanSTAR Program
1988 - New Jersey M&V Protocols
1985 - First Utility Sponsored Large Scale Programs to Include M&V

The 1980s saw a surge in the number of programs designed to utilize measurement and verification, as the ability to monitor energy savings precisely became increasingly important. The early to mid 1990s witnessed the beginnings of state and federal guidelines for measurement. In 1996, the North American Energy Measurement and Verification Protocol (NEMVP) was published, and was later expanded and republished as the International Performance Measurement and Verification Protocols (IPMVP) in 1997 and again in 2001. Meanwhile, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) had been working simultaneously on the development of a guideline, although it was not published until 2002. This document is called ASHRAE Guideline 14-2002, Measurement of Energy and Demand Savings, and provided more technical basis for the procedures described in the IPMVP. The IPMVP was subsequently updated and revised, and republished in 2007. The 2007 IPMVP was used as the basis for savings analysis calculations performed in this study, although ASHRAE Guideline 14 also served as a valuable reference. One of the statistical tests required by Guideline 14, the mean bias test, could not be met with the data from this study. This test may be removed from the Guideline in future editions, but is currently not required by IPMVP 2007.

3.2 IPMVP 2007

The 2007 IPMVP explains that energy savings cannot be directly measured, but are determined by comparing measured consumption before and after an energy program has been implemented and making adjustments for changes in conditions. This is summarized in Equation 3.1 below:

$$Savings = \begin{pmatrix} Baseline\ Period\ Use\ or\ Demand - \\ Reporting\ Period\ Use\ or\ Demand \end{pmatrix} \pm Adjustments \tag{3.1}$$

In order to compute this, a measurement boundary must first be established in order to specify what level of energy savings need to be determined. This could be a specific group of equipment, the entire facility, or even a calibrated simulation of part or all of the facility. Then the measurement period must be carefully selected. The baseline period should represent all operating modes of the facility and should span all of the differing weather conditions. This should be the period immediately preceding commitment to undertake the retrofit or energy program, and should fairly represent all operating conditions. The reporting period should be determined by the user of the savings, and should include at least one normal operating cycle of the equipment or facility.

The adjustments referred to in Equation 1 arise from identifiable physical characteristics related to energy consumption in the measurement boundary. These are placed into one of two categories: routine adjustments and non-routine adjustments. Routine adjustments refer to energy governing factors expected to change routinely during the reporting period, such as weather or production volume. These adjustments may be made using multiple parameter regression models that correlate energy consumption with one or more independent variables. Non-routine adjustments must be made for any change that is not expected, such as changes in facility size, the type of occupants, or design and operation of installed equipment.

Savings can be determined based on conditions in the reporting period (called “avoided energy use”) or based on fixed or “normal” conditions (called “normalized savings”). The former method requires that the baseline energy be adjusted to the reporting period conditions, and is given by Equation 3.2 as follows:

$$\begin{pmatrix} \text{Avoided Energy} \\ \text{Use or Savings} \end{pmatrix} = \begin{pmatrix} \text{Baseline Energy Routine Adjustments} \\ \text{to reporting period conditions} \\ \pm \text{NonRoutine Adjustments to} \\ \text{reporting period conditions} \end{pmatrix} - \begin{pmatrix} \text{Reporting} \\ \text{Period} \\ \text{Energy} \end{pmatrix} \tag{3.2}$$

The latter method (normalized savings) requires that energy from the reported period and possibly also the baseline period be adjusted to another set of conditions called "normal," as expressed in Equation 3.3 below.

$$\begin{aligned} \mathit{Normalized\ Savings} = & \begin{pmatrix} \mathit{Baseline\ Energy} \\ \pm\ \mathit{Routine\ Adjustments\ to\ fixed\ conditions} \\ \pm \mathit{NonRoutine\ Adjustments\ to\ fixed\ conditions} \end{pmatrix} \\ & - \begin{pmatrix} \mathit{Reporting\ Period\ Energy} \\ \pm \mathit{Routine\ Adjustments\ to\ fixed\ conditions} \\ \pm \mathit{NonRoutine\ Adjustments\ to\ fixed\ conditions} \end{pmatrix} \end{aligned} \tag{3.3}$$

IPMVP provides four options for determining savings, labeled Options A, B, C, and D, respectively. Options A and B both involve retrofit isolation. This entails only consideration of the energy consumption affected by the particular retrofit or energy conservation measure. This requires measurement of energy at the level of the retrofit, which typically involves sub-metering in the facility.

3.2.1 Option A

Option A is specifically called "Key Parameter Measurement," and utilizes a combination of measurements of some parameters and estimates of others in order to determine energy usage. In order to decide which parameters may be estimated and which must be measured, an uncertainty analysis must be performed. Enough parameters must be measured so that the combined uncertainty of the estimates does not significantly affect the overall savings. It is likely that using Option A may not require routine or non-routine adjustments, depending on the selection of the measurement boundary, the length of the reporting period, or the amount of time between baseline and reporting period measurements. The savings calculated using Option A would then be given by Equation 3.4 below.

$$\text{Option A Savings} = \text{Estimated Value} \times \left(\begin{pmatrix} \text{Baseline Period,} \\ \text{measured parameter} \end{pmatrix} - \begin{pmatrix} \text{Reporting period,} \\ \text{measured parameter} \end{pmatrix} \right) \tag{3.4}$$

3.2.2 Option B

Option B also involves only energy usage expected to be affected by the retrofit or energy conservation measure. However, unlike Option A, Option B requires the measurement of all parameters needed to compute energy consumption. Like Option A, Option B may not require any routine or non-routine adjustments, in which case the savings formula would simplify to Equation 3.5 below.

$$\text{Option B Savings} = \text{Baseline Energy} - \text{Reporting Period Energy} \tag{3.5}$$

3.2.3 Option C

Option C involves whole facility energy use. Utility meters measure usage for the whole facility or a major section, and the interactive effects of the applied energy conservation measures are encompassed. Since the whole facility is measured, the effects of any changes to the facility not pertaining to the applied energy conservation measures also show up in the savings calculations. To use Option C, the expected savings from the project should be large in comparison to random or unexplained variations to energy usage that may occur at the whole facility level. Savings should typically exceed 10% of the baseline consumption in order to confidently ignore the effects of random variations in usage. Routine adjustments are typically made using linear regression models to correlate energy consumption to an independent variable such as outdoor air dry bulb temperature. Non-routine adjustments can be a major challenge, particularly when savings are tracked over a long period of time. These adjustments should be closely tracked and accounted for in the savings calculations.

3.2.4 Option D

Option D uses calibrated simulation to predict the energy consumption of the baseline period and/or the reporting period. Option D allows the evaluation of the effect of multiple energy conservation measures on the whole facility, as in Option C, or the effects on specific systems of individual energy conservation measures, as in Options A and B. Option D is useful when either baseline period or reporting period energy data are unavailable, where factors difficult to quantify have made data comparison unreliable, or when savings associated with individual energy conservation measures are desired but measurements are deemed too difficult or costly. The most difficult challenge in using Option D is in the calibration of the simulation. To do this properly, as much information about the facility as possible should be collected that would be useful in calibration. Other input parameters should be assumed and documented.

Where possible, actual weather data should be used in order to compare simulated data and metered data for calibration. Simulated data are then compared to metered data on an hourly or monthly basis, and necessary adjustments to the simulation model are made. Option D requires that the name of the software used to simulate be provided, as well as input/output data, measured data, and accuracy of the calibration. Savings using Option D are computed using either Equation 3.6 or Equation 3.7 below.

$$Savings=\left(\begin{matrix}\text{Baseline energy from the}\\ \text{calibrated model without ECMs}\end{matrix}\right)-\left(\begin{matrix}\text{Reporting period energy from}\\ \text{the calibrated model with ECMs}\end{matrix}\right) \tag{3.6}$$

$$Savings=\left(\begin{matrix}\text{Baseline energy}\\ \text{from the calibrated}\\ \text{model without ECMs}\end{matrix}\right)-\left(\begin{matrix}\text{Actual calibration}\\ \text{period energy}\\ \text{(with ECMs)}\end{matrix}\right)\pm\left(\begin{matrix}\text{Calibration error in}\\ \text{the corresponding}\\ \text{calibration reading}\end{matrix}\right) \tag{3.7}$$

3.3 Uncertainty

For any of the options chosen, it is important that an uncertainty analysis be performed and that uncertainty in the savings estimates be reported. Acceptable levels of uncertainty should be determined before beginning the project. Some factors that contribute to uncertainty include modeling error, sampling error, metering error, interactive effects not included in the measurement boundary, and estimation of parameters in Option A. To the extent feasible, these sources should be minimized.

Regression models are used to perform routine adjustments to energy data. Modeling error can be introduced in several ways, including: creating a model based on values outside the probable range of variables to be used, omitting relevant independent variables, including irrelevant independent variables, using inappropriate functional form, or creating a model based on insufficient or unrepresentative data.

To determine the accuracy of a model, the Coefficient of Determination (R^2) should first be determined. This is a measure of how well the regression model explains variations in the dependent variable from its mean value. It is given by Equation 3.8 below:

$$R^2 = \frac{\sum(\hat{Y}_i - \bar{Y})^2}{\sum(Y_i - \bar{Y})^2} \tag{3.8}$$

where:

$\hat{Y}_i$= model predicted *energy* value for a particular data point using the measured value of the *independent variable* (i.e., obtained by plugging the X values into the regression model)

$\bar{Y}$ = *mean* of the *n* measured *energy* values

Y_i= actual observed (e.g., using a meter) value of *energy*

The Coefficient of Determination can range in value from 0 to 1, with 1 indicating that the model explains 100% of the variations, and 0 meaning the model explains none of the variations.

The accuracy of an energy value prediction by a model is measured by the standard error of the estimate ($SE_{\hat{Y}}$), also commonly referred to as the root-mean squared error (RMSE). This is calculated using Equation 3.9 below:

$$SE_{\hat{Y}} = \sqrt{\frac{\sum(\hat{Y}_i - Y_i)^2}{n-p-1}} \qquad (3.9)$$

where p is the number of *independent variables* in the regression equation and $\hat{Y}$

is the predicted value of *energy* (Y) from the regression model.

Another useful index, called the coefficient of variation of the root-mean squared error, or CV(RMSE), is calculated by dividing the RMSE by the average energy use as shown in Equation 3.10 below.

$$CV(RMSE) = \frac{SE_{\hat{Y}}}{\bar{Y}} \qquad (3.10)$$

Sampling error is introduced when only a sample of units under study is measured, since some units would not be represented. When whole building energy meters are used along with an entire year of data, sampling error can be neglected.

Measurement equipment error is that error introduced by the equipment used in measuring energy consumption or demand. This error can be determined by equipment manufacturer information, or can be estimated using statistical techniques. ASHRAE Guideline 14 indicates that when a regression model is used to adjust a set of energy data, the modeling uncertainty computed will already include uncertainty resulting from measurement error. IPMVP 2007 corroborates this.

The individual components of uncertainty must be combined in order to determine the uncertainty in the savings. When savings is the sum or difference of independently determined components (i.e., $Savings=C_1 \pm C_2 \pm \ldots C_p$), then the standard error of the reported savings is given by Equation 3.11 below.

$$SE(Savings) = \sqrt{SE(C_1)^2 + SE(C_2)^2 + \ldots\ldots + SE(C_p)^2} \tag{3.11}$$

For the case in which normalized savings are determined by adjusting both the baseline and reporting period energy consumption to a common set of conditions using regression models, and where a full year of daily baseline and reporting period consumption and weather data are utilized, the total uncertainty in annual savings reported is given by Equation 3.12 below.

$$SE(Savings) = \sqrt{365 \times (SE_{\hat{Y}}(Adj.Baseline)^2 + SE_{\hat{Y}}(Adj.Reporting\ Period)^2)} \tag{3.12}$$

The absolute precision and relative precision of the savings estimate are then given by Equations 3.13 and 3.14.

$$Absolute\ Precision = t \times SE(Savings) \tag{3.13}$$

$$Relative\ Precision = \frac{t \times SE(Savings)}{Savings} \tag{3.14}$$

In these equations, t is the t-statistic determined by the desired confidence interval. The savings is then expressed as a range as shown in Equation 3.15.

$$Range = estimate \pm absolute\ precision \tag{3.15}$$

The range must state the appropriate confidence interval.

Both IPMVP and ASHRAE Guideline 14 indicate that the savings estimate needs to be larger than twice the standard error in order to be statistically significant (relative precision less than ±50% at a 68% confidence interval).

In order to report the uncertainty in the savings percentages presented, Equation 3.16 was used to determine the standard error of the savings percentage.

$$SE(Savings\%) = \frac{Savings}{Adj.Baseline} \times \sqrt{\left(\frac{SE(Savings)}{Savings}\right)^2 + \left(\frac{SE(Adj.Baseline)}{Adj.Baseline}\right)^2} \qquad (3.16)$$

3.4 Data Modeling Tools

Haberl and Cho (2004) trace the history of ASHRAE's Inverse Model Toolkit (IMT), a software program for calculating regression models. The Princeton Scorekeeping Method (PRISM) was one of the first methods developed for determining savings in residential buildings (Fels 1986). It used variable-based degree days to normalize energy consumption based on monthly data. This method was widely used in the utility industry, but did not always adequately model the characteristics of commercial buildings (Haberl and Ch, 2004).

Shrock and Claridge (1989) and Ruch and Claridge (1992) developed four-parameter change-point models to better model weather-normalized energy consumption data for commercial buildings with varying degrees of heating and cooling energy use. Kissock (1993 and 1994) then developed algorithms for determining change point parameters and created the EModel software as a statistical package for determining these models. With sponsorship by ASHRAE research project RP-1050, and under the guidance of Technical Committee 4.7, Energy Calculations, the Inverse Model Toolkit was then developed. This toolkit expanded upon the capabilities of EModel by also including change-point algorithms for multiple independent variables.

3.5 Data Quality Check

Shao and Claridge (2006) defined and described an Energy Balance parameter which was shown to be useful in identifying problematic patterns with metered energy consumption data. The Energy Balance parameter (E_{BL}) was defined by Equation 3.17 below.

$$E_{BL} = fWbele + Wbheat - Wbcool \tag{3.17}$$

In this equation, *Wbele* is the whole building electricity usage, with *f* representing the fraction of electricity that becomes part of the heat load in the building. *Wbheat* is the whole building heating usage, and *Wbcool* is the whole building cooling usage.

The Energy Balance parameter was shown to represent a relationship between measured consumption data that is independent of the type of HVAC system in the building. Baltazar (2007) showed how this parameter could be useful in identifying data quality and metering issues by applying the parameter to several institutional buildings. A three step procedure was utilized in this evaluation. First, all metered data were gathered for each building, and sorted into daily intervals over a yearly period. The data were then plotted on a consumption per square foot basis versus time and versus average daily outdoor air temperature, and the Energy Balance parameter was also plotted versus time and versus average daily outdoor air temperature. Finally, each data set was evaluated to identify any missing data, and where possible appropriate procedures were utilized to fill these data gaps (Baltazar and Claridge, 2002). Visual inspections of the graphs produced then allowed data quality problems to be identified, and follow up could occur. The results of this procedure were that for some buildings suspicious data were readily identified, and metering problems were able to be corrected, allowing energy managers and engineers to be able to more confidently assess building performance.

In the current study, a similar data inspection procedure was employed. While it was recognized that this procedure could not with certainty declare that a data set was reliable, it was noted that the procedure could be a useful tool in identifying some of the problematic areas with the measured data for each building.

3.6 Summary of Procedure

In this study, the methodology described in IPMVP 2007 was utilized to determine the level of energy savings for ten university buildings that underwent retro-commissioning in 1996 in each of the years following retro-commissioning for which reliable measured consumption data were available. The savings in each of the years from 1997 through 2000 were well documented in a previous study, using similar methodology (Cho 2002).

For the current study, Option C of the IPMVP was used for each of the buildings, and Option D was used for some of the comparisons in more recent years for one of the buildings that underwent a major renovation. In using Option C, the normalized savings approach was utilized. Both the baseline period data and reporting period data were adjusted to a common weather year. The common year selected was the 1995 daily average weather data for College Station, TX. This provided consistency with the previous study of these buildings.

In order to adjust each year of data to the selected conditions, three- and four-parameter change-point models were developed using Emodel, the statistical toolkit described previously. The models used average daily temperature as the independent variable, with daily hot water or chilled water consumption as the dependent variable. Once the models were generated, the average daily temperatures from the 1995 weather data were substituted to obtain normalized energy consumption data. The electricity consumption was found to have negligible dependence on weather data for the buildings studied since each of the buildings received chilled water and hot water from a central plant, the electricity consumption of which was not included in the metered building electricity consumption data. Therefore, the electricity consumption data were not normalized to a common weather year.

Once weather normalized consumption data had been obtained for all of the applicable years for which metered data were available, year by year comparisons of consumption were conducted for each of the buildings to determine to what level retro-commissioning savings had persisted. The percentage of energy savings as compared with the baseline year was calculated for chilled water, hot water, and electricity where available.

In one of the buildings, a major addition took place in 2002. The metered energy data after this year include the consumption for this addition combined with the original building. In order to quantify the effects of this added space so that the original building energy consumption could be appropriately compared with the consumption of previous years, a calibrated simulation of the building using a commercial simulation program was performed, in accordance with Option D of the IPMVP. The simulation model was calibrated to the most recent consumption data using procedures documented by Claridge et al. (2003). The HVAC systems modeled for the addition were then removed from the model and another simulation was performed, using 1995 weather data. The energy consumption from this simulation, representing the most recent data from the original building, was then compared with the adjusted baseline data for the building to determine the level of savings. Simulation details can be found in Appendix E.

For all savings estimates reported, an uncertainty analysis was performed according to guidelines given in IPMVP 2007, as previously explained. Each savings estimate was reported as a range with a calculated precision at the stated confidence interval.

In addition to the savings calculations performed, this study also compared the Energy Management Control System (EMCS) settings in each of the buildings during the baseline, post-CC, and most recent periods. In the previous study by Cho (2002), the building control settings for baseline, post-CC, and year 2000 periods were well documented, and changes in the settings in some cases were shown to have direct correlation with changes in the level of savings achieved. In the current study, the control settings in place in more recent years were compared with these other documented periods to determine how additional changes in control correlated with changes in energy consumption.

As mentioned, data quality checks were performed using the Energy Balance parameter on all data sets, and those data that were not found to be reliable were disqualified from the analysis.

CHAPTER IV

SAVINGS ANALYSIS RESULTS

4.1 Results of Previous Study

As noted earlier, the previous study of the ten buildings by Cho compared the normalized energy savings of each building over a period of four years following retro-commissioning. Table 4-1 details the results of this study, with the chilled water, hot water, and electricity consumption and savings shown on a yearly basis.

4.2 New Findings

The results of the previous study were expanded upon to include normalized consumption data and savings calculations for additional years following the completion of the original study. For eight of the buildings, reliable energy consumption data were available from as recently as 2008-2009. For the other two buildings, the last year of reliable consumption data was 2002 for one and 2004 for the other. Table 4-2 shows the combined results of the previous study with the additional years of data for each building. All data after 2004 (to the right of the double red line shown) were collected using a different metering system than what was previously in place in each building, as already noted.

Table 4-3 summarizes the estimated chilled water and hot water savings percentages for each year in each building, and reports the uncertainty associated with each estimate at the 90% confidence interval.

Table 4 - 1. Energy savings results for the years examined in the previous study (Cho 2001).

Building Name	Type	Baseline Use (MMBtu) (MWh) / yr	1997		1998		1999		2000	
			Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)
Blocker	CHW	22,955	16,723	**27**	19,530	**15**	20,164	**12**	21,083	** **8**
	HW	8,735	4,093	**53**	1,676	**81**	3,330	**62**	4,344	** **50**
	Elec	4,832	3,773	**22**	3,883	**20**	3,936	**19**	3,859	**20**
Eller O&M	CHW	30,625	18,846	**38**	18,660	**39**	19,012	**38**	20,360	**34**
	HW	7,584	2,578	**66**	1,154	**85**	1,831	**76**	4,712	**38**
	Elec	4,891	3,698	**24**	3,675	**25**	3,823	**22**	3,874	**21**
G.R.White Coliseum	CHW	18,872	8,717	**54**	8,511	**55**	14,548	**23**	15,858	**16**
	HW	21,155	6,091	**71**	549	**97**	4,923	**77**	10,111	**52**
	Elec	1,480	1,297	**12**	1,168	**21**	1,171	**21**	1,291	**13**
Harrington Tower	CHW	14,179	7,109	**50**	8,420	**41**	7,660	**46**	9,032	**36**
	HW	6,896	2,603	**62**	914	**87**	1,629	**76**	3,519	**49**
	Elec	1,666	1,297	**22**	1,336	**20**	1,341	**20**	1,353	**19**
Kleberg Building	CHW	59,271	34,864	**41**	34,969	**41**	36,731	**38**	41,965	**29**
	HW	40,812	6,523	**84**	1,215	**97**	8,030	**80**	10,591	**74**
	Elec	5,511	5,458	**1**	5,067	**8**	4,778	**13**	4,684	**15**
Koldus Building	CHW	* 21,964	12,177	**45**	12,988	**41**	12,740	**42**	11,804	**46**
	HW	2,103	704	**67**	399	**81**	634	**70**	649	**69**
	Elec	2,850	2,511	**12**	2,597	**9**	2,624	**8**	2,592	**9**
Rich. Petroleum	CHW	28,526	13,599	**52**	15,637	**45**	15,078	**47**	17,702	**38**
	HW	* 18,227	6,565	**64**	5,588	**69**	5,098	**72**	2,171	**88**
	Elec	1,933	1,898	**2**	1,914	**1**	1,991	**-3**	2,153	**-11**
VMC Addition	CHW	40,892	23,115	**43**	24,080	**41**	22,915	**44**	23,307	**43**
	HW	3,569	887	**75**	2,041	**43**	2,097	**41**	2,051	**43**
	Elec	4,186	3,996	**5**	4,140	**1**	4,236	**-1**	4,056	**3**
Wehner CBA	CHW	19,193	12,327	**36**	13,339	**31**	12,530	**35**	11,609	**40**
	HW	13,393	10,876	**19**	9,715	**27**	6,581	**51**	6,350	**53**
	Elec	2,555	2,410	**6**	2,446	**4**	2,552	**0**	2,581	**-1**
Zachry Engr. Center	CHW	40,824	16,737	**59**	17,377	**57**	18,148	**56**	20,225	**50**
	HW	7,676	1,630	**79**	3,230	**58**	2,226	**71**	4,271	**44**
	Elec	7,502	6,762	**10**	6,793	**9**	7,099	**5**	6,955	**7**
Type		*Total*	*Total*	***Average***	*Total*	***Average***	*Total*	***Average***	*Total*	***Average***
Chilled Water		297,298	164,215	**44.8**	173,509	**41.6**	179,527	**39.6**	192,946	**35.1**
Hot Water		130,149	42,549	**67.3**	26,482	**79.7**	36,380	**72.0**	48,768	**62.5**
Electricity		37,407	33,100	**11.5**	33,018	**11.7**	33,552	**10.3**	33,399	**10.7**

* The baseline energy use for these buildings was estimated from the average savings of the other buildings because insufficient data was available to create reliable baselines.

** The Blocker building had insufficient chilled water and hot water energy use data in 2000 to determine normalized annual consumption. So the savings were estimated from the average degradation that occurred between 1999 and 2000 in the other 9 buildings.

Table 4 - 2. Updated results of energy savings analysis, normalized to common weather year.

Building Name	Type	Baseline Use (MMBtu) (MWh) / yr	1997		1998		1999		2000		2001		2002		2003		2004		2005-2006		2006-2007		2007-2008		2008-2009	
			Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)	Use (MMBtu) (MWh) / yr	Saving (%)
Blocker	CHW	22,955	16,723	27	19,530	15	20,164	12			19,082	17	17,887	22	20,850	9					21,179	8	20,283	12	21,142	8
	HW	8,735	4,093	53	1,676	81	3,330	62			4,623	47	2,654	70	6,367	27			2,158	75	4,409	50				
	Elec	4,832	3,773	22	3,883	20	3,936	19	3,859	20	3,639	25	3,516	27	3,583	26			3,273	32	3,535	27	3,561	26	3,668	24
Eller O&M	CHW	30,625	18,846	38	18,660	39	19,012	38	20,360	34	24,002	22	21,120	31	19,948	35	21,805	29								
	HW	7,584	2,578	66	1,154	85	1,831	76	4,712	38	4,488	41														
	Elec	4,891	3,698	24	3,675	25	3,823	22	3,874	21	3,972	19	3,732	24	3,745	23	3,861	21								
G.R.White Coliseum	CHW	18,872	8,717	54	8,511	55	14,548	23	15,858	16									6,837	64	11,134	41	4,628	75	7,491	60
	HW	21,155	6,091	71	549	97	4,923	77	10,111	52									3,276	85	2,216	90	2,111	90	1,983	91
	Elec	1,480	1,297	12	1,168	21	1,171	21	1,291	13	1,102	26	1,028	31	1,015	31	1,109	25	1,028	31	956	35	986	33	979	34
Harrington Tower	CHW	14,179	7,109	50	8,420	41	7,660	46	9,032	36	8,380	41	9,267	35	8,614	39	7,817	45	7,103	50	6,927	51	8,789	38	6,905	51
	HW	6,896	2,603	62	914	87	1,629	76	3,519	49			3,921	43	3,538	49			2,966	57	2,807	59	3,559	48	2,400	65
	Elec	1,666	1,297	22	1,336	20	1,341	20	1,353	19	1,319	21	1,331	20	1,390	17			1,293	22	1,220	27	1,294	22	1,253	25
Kleberg Building	CHW	59,271	34,864	41	34,969	41	36,731	38	41,965	29	45,187	24	37,180	37	31,911	46	33,560	43			28,831	51	30,088	49	28,098	53
	HW	40,812	6,523	84	1,215	97	8,030	80	10,591	74											12,989	68	15,266	63	16,450	60
	Elec	5,511	5,458	1	5,067	8	4,778	13	4,684	15	4,539	18	4,564	17	4,832	12	4,666	15	3,320	40	3,533	36	3,828	31	3,662	34
Koldus Building	CHW	21,964	12,177	45	12,988	41	12,740	42	11,804	46	12,735	42									13,784	37	13,419	39	12,780	42
	HW	2,103	704	67	399	81	634	70	649	69	390	81									4,225	-101	4,429	-111	4,173	-98
	Elec	2,850	2,511	12	2,597	9	2,624	8	2,592	9	2,603	9	2,667	6			2,682	6	2,553	10	2,546	11	2,621	8	2,491	13
Rich. Petroleum	CHW	28,526	13,599	52	15,637	45	15,078	47	17,702	38	13,937	51	15,587	45	17,023	40	17,625	38							19,518	32
	HW	18,227	6,565	64	5,588	69	5,098	72	2,171	88	6,568	64	6,994	62	7,391	59	8,882	51							8,512	53
	Elec	1,933	1,898	2	1,914	1	1,991	-3	2,153	-11	2,039	-5	2,026	-5	2,110	-9	2,155	-11							2,031	-5
VMC Addition	CHW	40,892	23,115	43	24,080	41	22,915	44	23,307	43	24,380	40	25,849	37												
	HW	3,569	887	75	2,041	43	2,097	41	2,051	43	1,881	47														
	Elec	4,186	3,996	5	4,140	1	4,236	-1	4,056	3	4,219	-1	4,169	0												
Wehner CBA	CHW	19,193	12,327	36	13,339	31	12,530	35	11,609	40	13,490	30													15,474	19
	HW	13,393	10,876	19	9,715	27	6,581	51	6,350	53	7,309	45													1,237	91
	Elec	2,555	2,410	6	2,446	4	2,552	0	2,581	-1	2,529	1													2,247	12
Zachry Engr. Center	CHW	40,824	16,737	59	17,377	57	18,148	56	20,225	50	19,794	52									24,296	40	23,588	42	23,219	43
	HW	7,676	1,630	79	3,230	58	2,226	71	4,271	44	4,467	42							3,623	53	4,694	39	5,934	23	5,253	32
	Elec	7,502	6,762	10	6,793	9	7,099	5	6,955	7	6,597	12	6,516	13	6,456	14			4,377	42	4,662	38	4,793	36	4,871	35

Note: The consumption data used for the time period labeled "2005-2006" were from 7/25/2005 – 7/24/2006 for all of the buildings with data for this period. For the period labeled "2006-2007," the consumption data were from 7/25/2006 – 7/24/2007 for G.R. White, Harrington, and Kleberg, and were from 10/16/2006 – 10/15/2007 for Blocker and Zachry. For the period labeled "2007-2008," the consumption data were from 8/1/2007 – 7/31/2008 for G.R. White, Harrington, Kleberg, and Koldus, and were from 10/16/2007 – 10/15/2008 for Blocker and Zachry. For the period labeled "2008-2009," the consumption data were from 8/1/2008 – 7/31/2009 for G.R. White, Harrington, Kleberg, and Koldus, were from 10/16/2008 – 10/15/2009 for Blocker and Zachry, were from 11/1/2008 – 10/31/2009 for Richardson, and were from 6/1/2008 – 5/31/2009 for Wehner. These time periods were chosen due to the availability of reliable energy consumption data.

Table 4 - 3. Annual savings percentage estimates with uncertainty reported to the 90% confidence interval.

Building Name	Type	1997		1998		1999		2000		2001		2002		2003		2004		2005-2006		2006-2007		2007-2008		2008-2009	
		Saving (%)	+/-	Saving (%)	+/-	Saving (%)	+/-	Saving (%)	+/-	Saving (%)	+/-	Saving (%)	+/-	Saving (%)	+/-	Saving (%)	+/-	Saving (%)	+/-	Saving (%)	+/-	Saving (%)	+/-	Saving (%)	+/-
Blocker	CHW	27	3	15	3	12	3			17	2	22	2	9	2					8	2	12	2	8	3
	HW	53	5	81	5	62	5			47	4	70	5	27	4			75	5	50	6				
Eller O&M	CHW	38	3	39	3	38	3	34	3	22	3	31	3	35	3	29	3								
	HW	66	9	85	9	76	9	38	10	41	9														
G.R.White Coliseum	CHW	54	3	55	3	23	4	16	4									64	3	41	3	75	4	60	4
	HW	71	3	97	3	77	4	52	3									85	2	90	2	90	2	91	2
Harrington Tower	CHW	50	3	41	3	46	3	36	3	41	2	35	2	39	2	45	2	50	2	51	3	38	2	51	2
	HW	62	9	87	9	76	9	49	8			43	7	49	7			57	7	59	8	48	7	65	8
Kleberg Building	CHW	41	3	41	3	38	3	29	3	24	2	37	2	46	2	43	2			51	2	49	2	53	2
	HW	84	4	97	4	80	4	74	4											68	4	63	3	60	4
Koldus Building	CHW	45	1	41	1	42	1	46	1	42	1									37	1	39	1	42	1
	HW	67	5	81	5	70	5	69	5	81	5									-101	6	-111	6	-98	6
Rich. Petroleum	CHW	52	1	45	1	47	1	38	2	51	1	45	1	40	1	38	1							32	1
	HW	64	2	69	2	72	1	88	2	64	1	62	1	59	1	51	2							53	1
VMC Addition	CHW	43	3	41	3	44	3	43	3	40	2	37	2												
	HW	75	10	43	8	41	9	43	10	47	9														
Wehner CBA	CHW	36	2	31	2	35	2	40	2	30	2													19	2
	HW	19	4	27	4	51	2	53	2	45	2													91	2
Zachry Engr. Center	CHW	59	2	57	2	56	2	50	2	52	2									40	2	42	2	43	2
	HW	79	5	58	5	71	5	44	5	42	5							53	5	39	5	23	5	32	5

Note: The baseline consumptions reported by Cho (2002) for Koldus CHW and Richardson HHW were determined by average savings of the other buildings, due to insufficient baseline data. Since a model was not used, and uncertainty was not reported, it was assumed to be zero for these two cases when calculating the savings uncertainties in the subsequent years. While this is obviously not true, since the main focus of the current study is on persistence, assuming these values allows the savings estimates in the years following retro-commissioning to be compared with one another. Although little confidence can be placed in the actual savings amounts for these commodities in these two buildings, the savings estimates reported can at least be evaluated relative to one another.

The overall trends in chilled water, hot water, and electricity savings over the period sampled for the ten buildings are diagrammed in Figures 4-1, 4-2, and 4-3 that follow. Specifics about the savings patterns of each building are discussed thereafter.

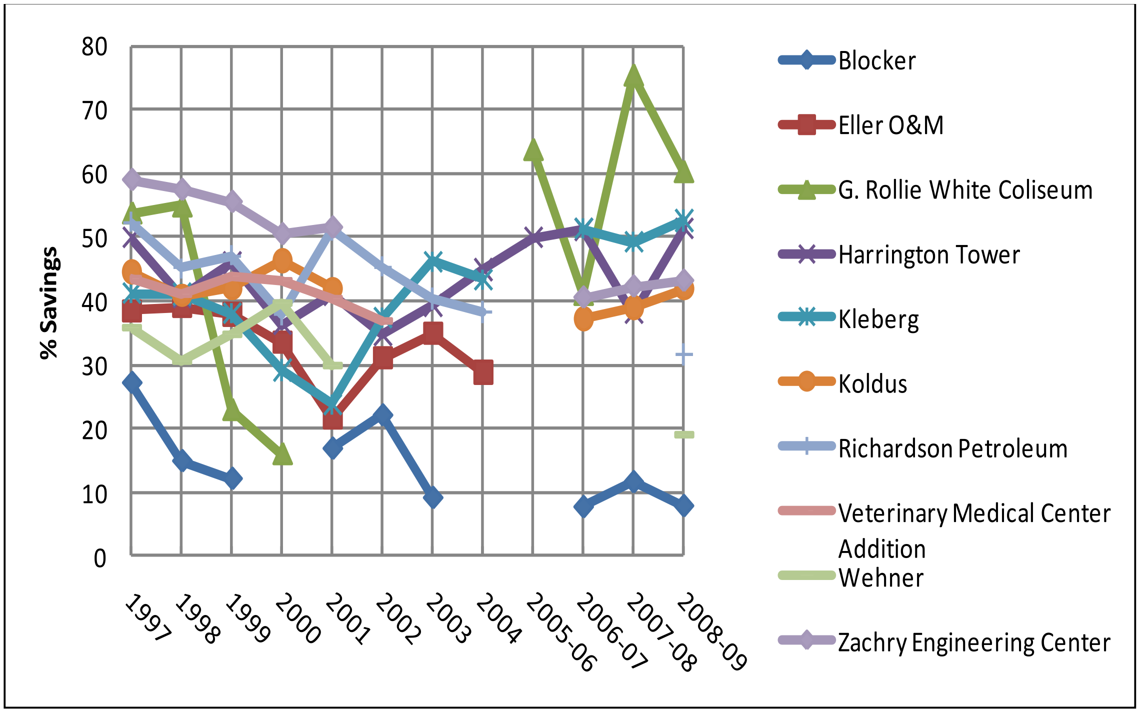


Figure 4 - 1. Chilled water savings trends over time for the ten buildings studied.

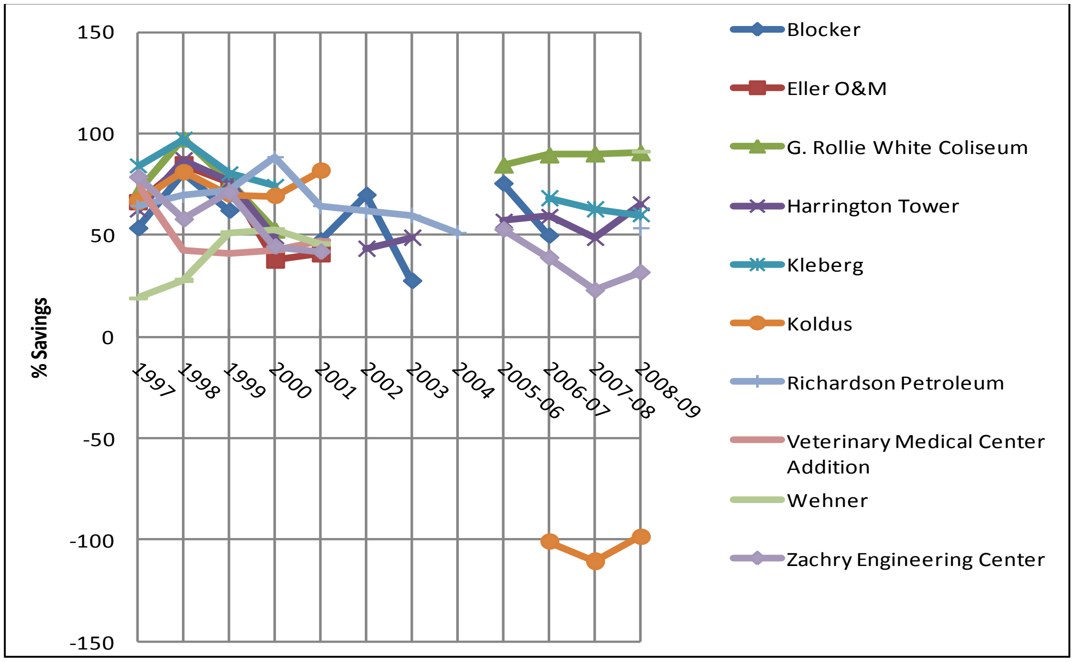


Figure 4 - 2. Hot water savings trends over time for the ten buildings studied.

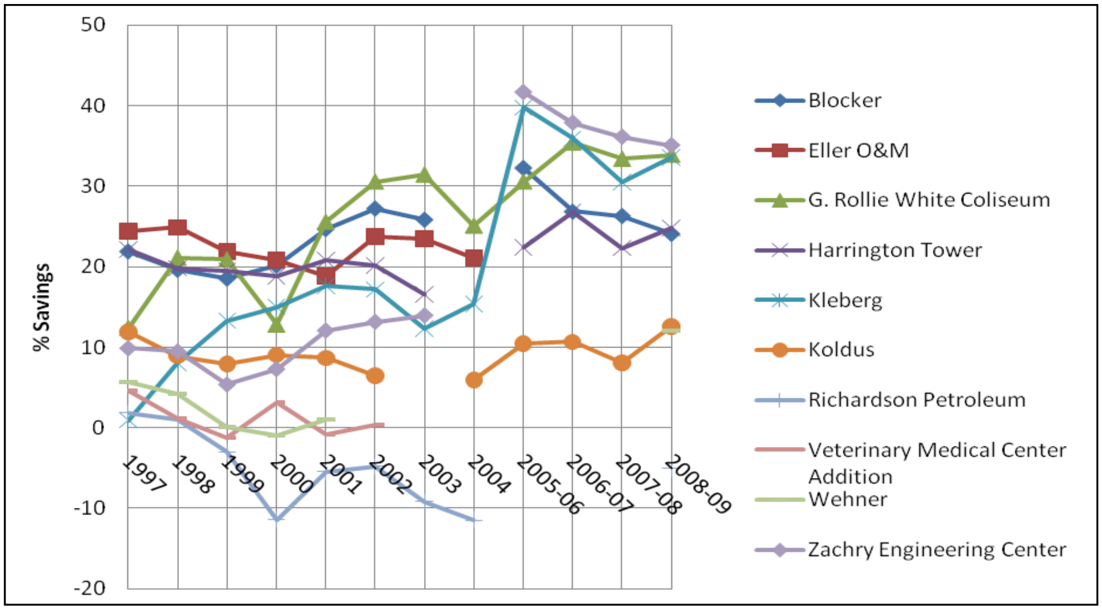


Figure 4 - 3. Electricity savings trends over time for the ten buildings studied.

4.2.1 Blocker

The savings trends for chilled water, hot water, and electricity consumption for the Blocker Building are shown in bar graph form in Figure 4-4.

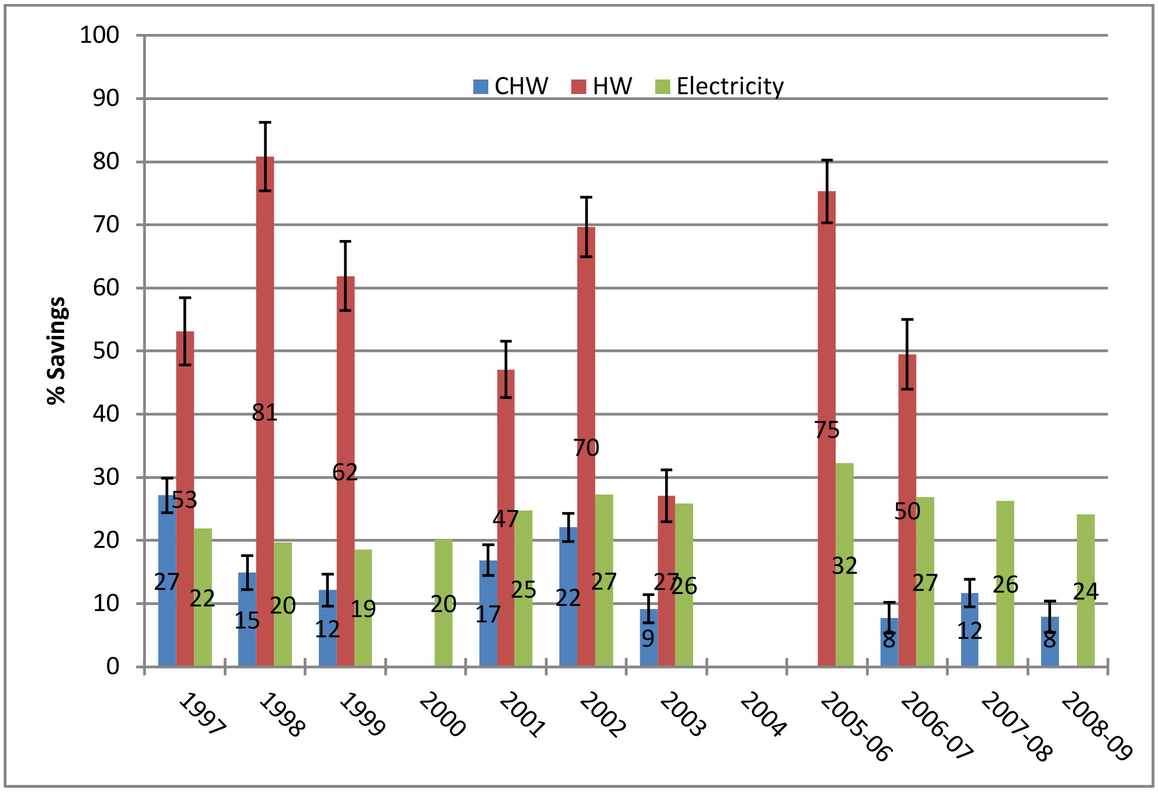


Figure 4 - 4. Normalized energy savings patterns for the Blocker Building.

The chilled water savings achieved in 1997 was 27%, but had degraded to 12% by 1999. It rose again from 2001 to 2002, but remained in the range of 8-12% from 2003 to 2009. The hot water savings achieved in 1997 was 53%, and in 2006-07 was a close 50%. During the years between, however, it rose as high as 81%, while dropping as low as 27%. The electricity savings remained fairly constant in the ten year period, even rising some from 22% in 1997 to a peak of 32% in 2005-06.

4.2.2 Eller O&M

The savings trends for chilled water, hot water, and electricity consumption for the Eller O&M Building are shown in bar graph form in Figure 4-5.

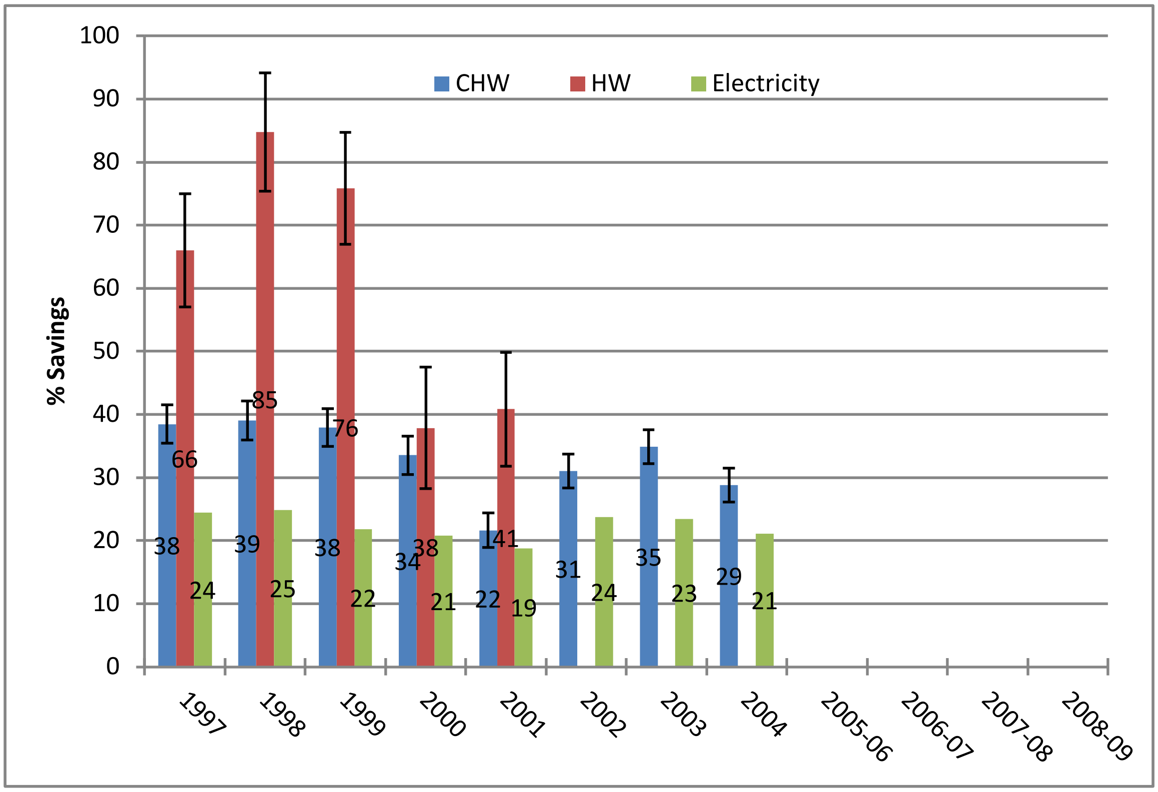


Figure 4 - 5. Normalized energy savings patterns for the Eller O&M Building.

The chilled water savings achieved in 1997 was 38%. By 2004, the last year of available data, the savings had degraded slightly to 29%. The hot water savings achieved in 1997 was 66%, increased to 85% the next year and 76% the next, and then declined sharply to 38% and 41% in the final two years of available data. The electricity savings remained fairly constant in the eight year period of available data, beginning at 24% in 1997 and falling slightly to 21% by 2004.

4.2.3 G. Rollie White Coliseum

The savings trends for chilled water, hot water, and electricity consumption for the G. Rollie White Coliseum are shown in bar graph form in Figure 4-6.

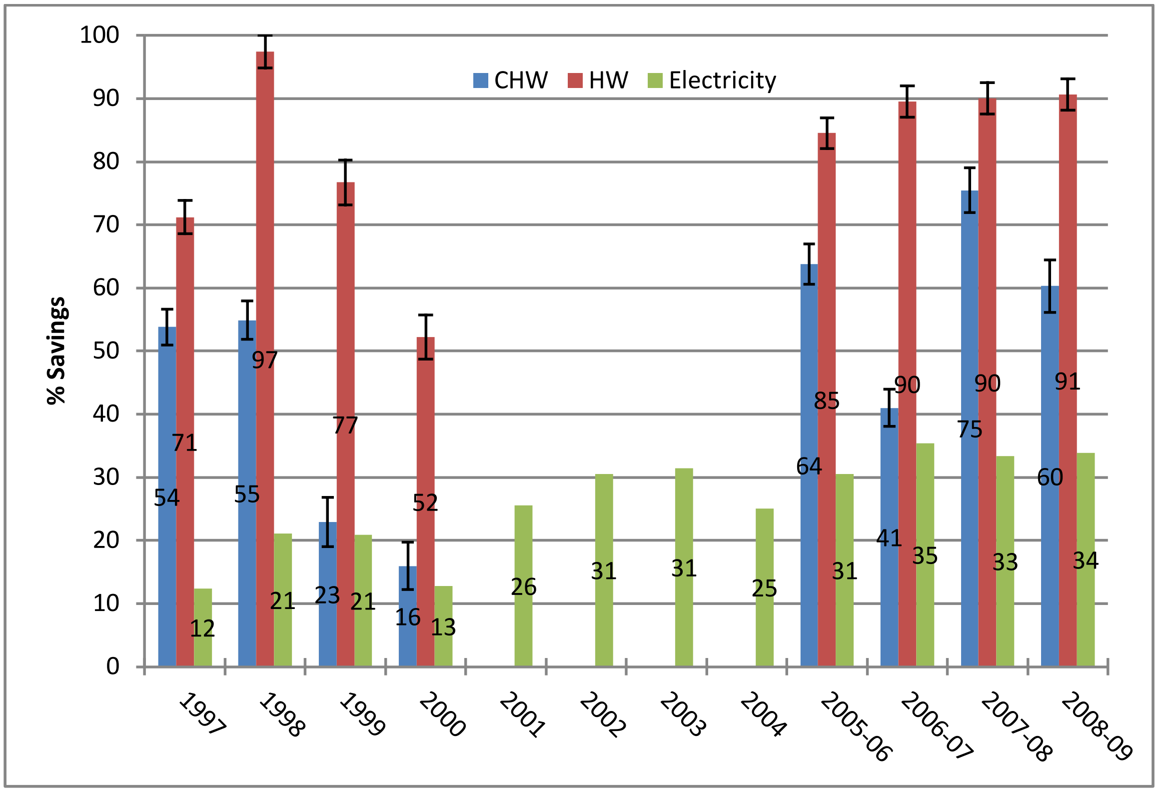


Figure 4 - 6. Normalized energy savings patterns for the G. Rollie White Coliseum.

The G. Rollie White Coliseum experienced some rather dramatic swings in the level of savings in both chilled water and hot water consumption, particularly in the first few years after retro-commissioning. However, by the later years (2005-2009), the level of savings for hot water was close to its post-retro-commissioning peak, and the level of chilled water savings in three of the last four years was higher than the 1997 and 1998 values. The electricity savings actually increased considerably from its initial value of 12% in 1997, and remained above 30% in six of the last seven years reported.

4.2.4 Harrington Tower

The savings trends for chilled water, hot water, and electricity consumption for the Harrington Tower are shown in bar graph form in Figure 4-7.

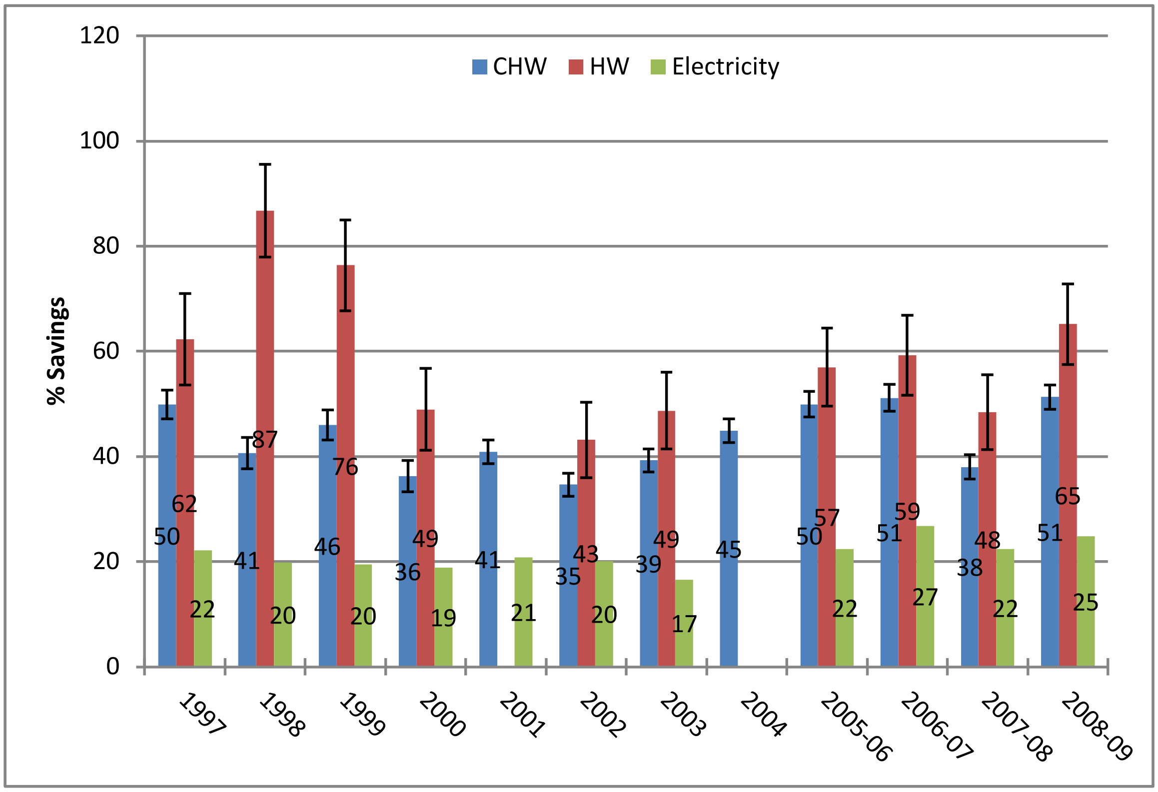


Figure 4 - 7. Normalized energy savings patterns for the Harrington Tower.

Harrington Tower demonstrated remarkable levels of savings persistence in both chilled water and electricity consumption, actually increasing slightly in the level of savings of each in a twelve year period. While the hot water savings ended up considerably lower than the peak level achieved (down to 65% from 87%), it had risen in later years, and ended just above the level achieved originally in 1997 (62%).

4.2.5 Kleberg

The savings trends for chilled water, hot water, and electricity consumption for the Kleberg Building are shown in bar graph form in Figure 4-8.

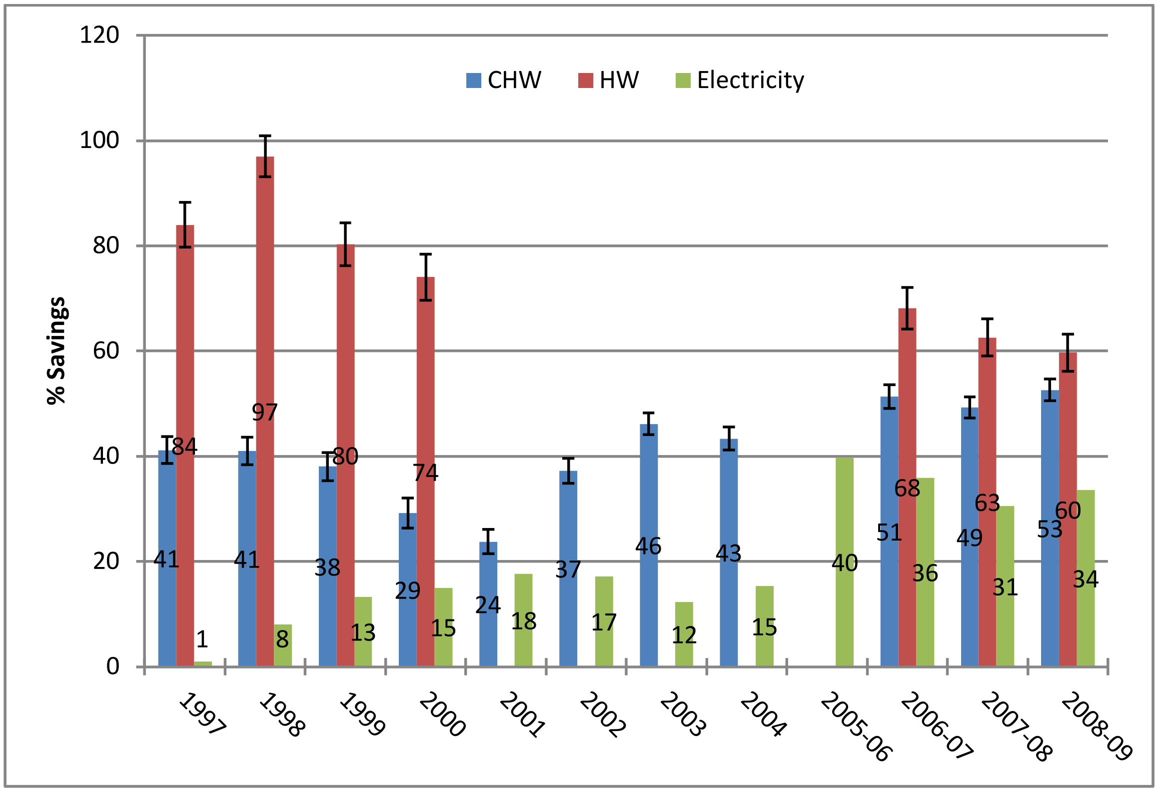


Figure 4 - 8. Normalized energy savings patterns for the Kleberg Building.

The level of hot water savings in Kleberg decreased from a peak of 97% in 1998 to 60% in 2008-09. However, the chilled water savings increased during the same period, rising from 41% in 1997 to its high of 53% in 2008-09. Electricity savings were higher in every subsequent year following 1997, reaching a peak of 40% in 2005-06, and ending at 34% in 2008-09.

4.2.6 Koldus

The savings trends for chilled water, hot water, and electricity consumption for the Koldus Building are shown in bar graph form in Figure 4-9.

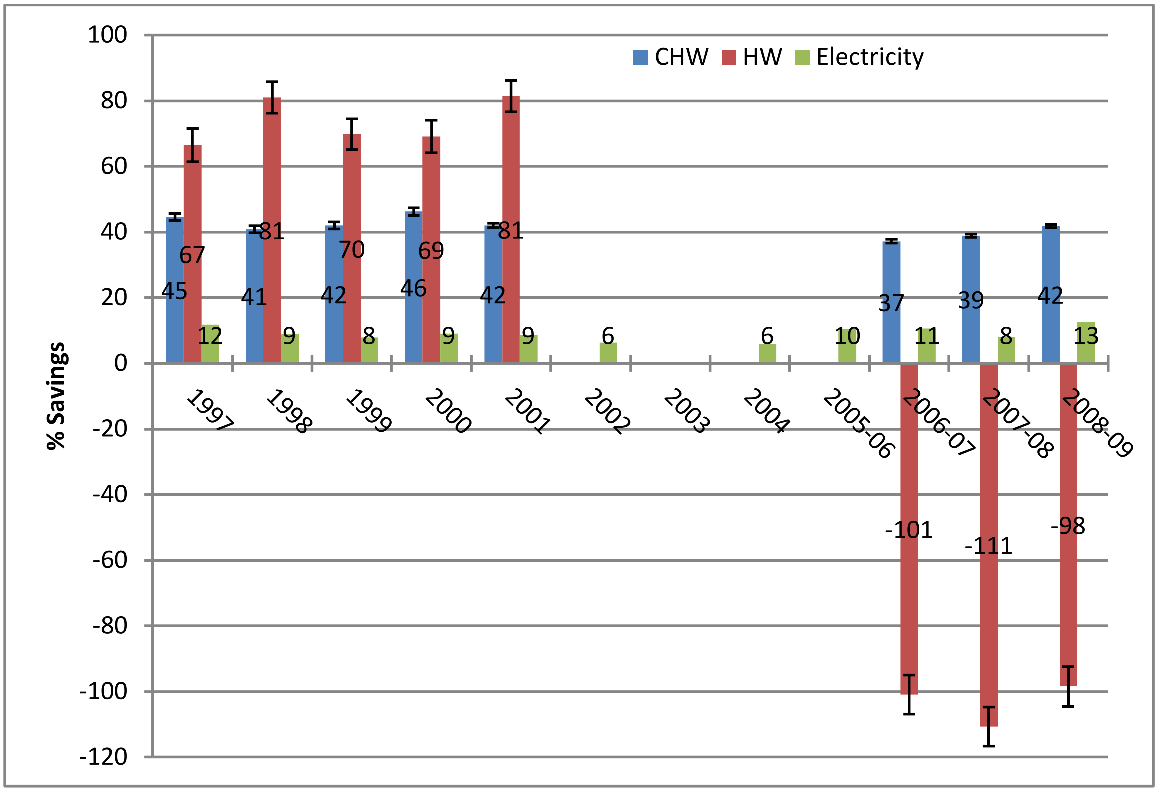


Figure 4 - 9. Normalized energy savings patterns for the Koldus Building.

The Koldus building demonstrated high levels of persistence in both chilled water and electricity savings over a twelve year period. However, it apparently also experienced a huge increase in hot water consumption in the most recent years, even doubling pre-retro-commissioning consumption levels. This would be by far the most significant example of savings degradation noted in the ten buildings during the period studied. However, as will be discussed later, follow up analysis revealed that the hot water consumption data prior to 2005 were not valid. Therefore, no meaningful hot water savings comparison can be made for this building, and savings estimates should be ignored, except only as a comparison between years when the metering was consistent.

4.2.7 Richardson Petroleum

The savings trends for chilled water, hot water, and electricity consumption for the Richardson Petroleum Building are shown in bar graph form in Figure 4-10.

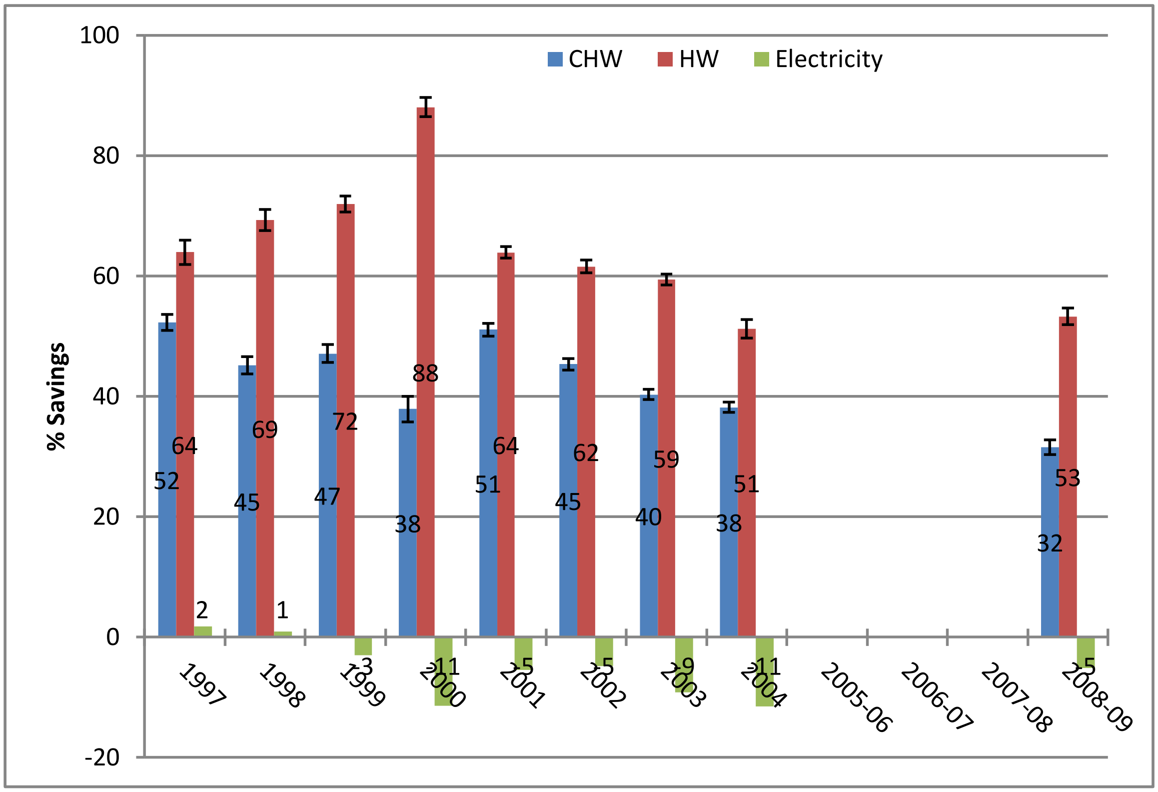


Figure 4 - 10. Normalized energy savings patterns for the Richardson Petroleum Building.

The chilled water savings for the Richardson Petroleum Building decreased over time from 1997 (52%) to 2000 (38%), rose again in 2001 (51%), then decreased over time again. The most recent data show a chilled water savings of 32%. The hot water savings increased in each of the first four years after retro-commissioning, peaking at

88%, but then fell in succeeding years to a level of 51% in 2004. The level in 2008-09 was very close to the 2004 level. Electricity savings had fallen to the negative range by the third year after commissioning, reaching -11% in 2000 and 2004, and ending at -5% in 2008-09.

4.2.8 Veterinary Medical Center Addition

The savings trends for chilled water, hot water, and electricity consumption for the Veterinary Medical Center Addition are shown in bar graph form in Figure 4-11.

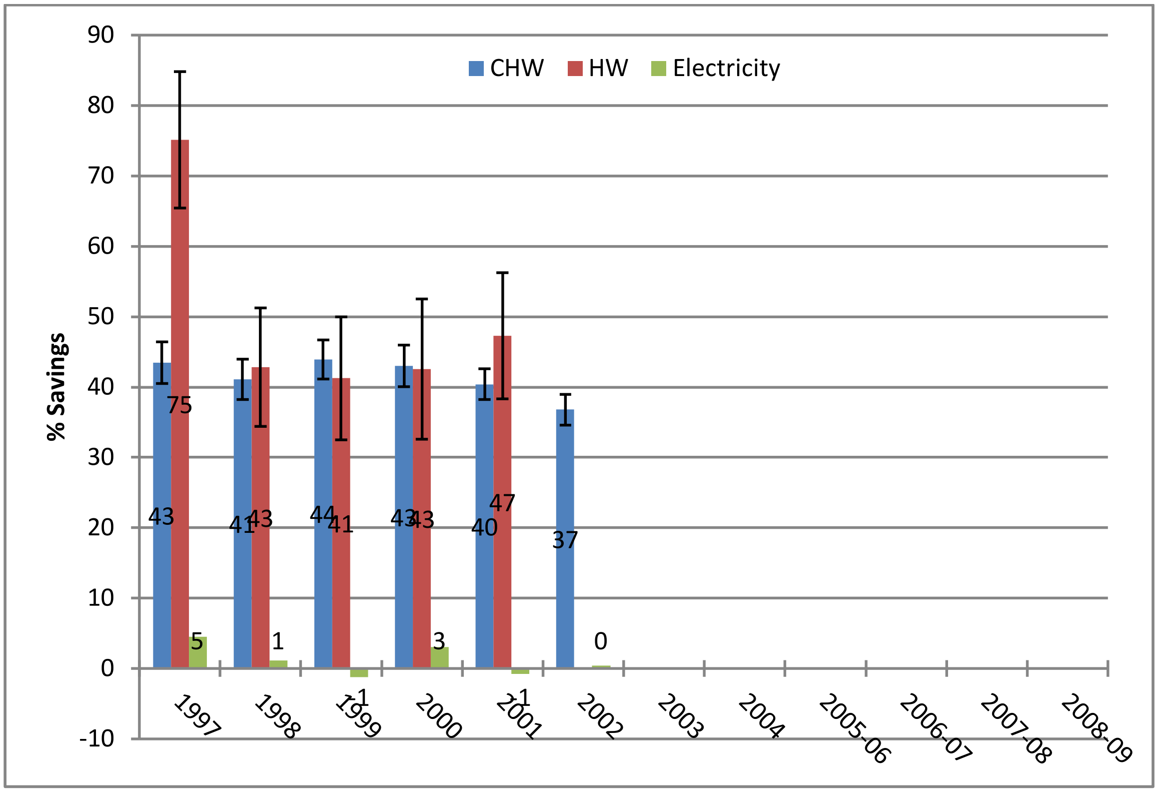


Figure 4 - 11. Normalized energy savings patterns for the Veterinary Medical Center Addition.

The Veterinary Medical Center Addition had the least amount of reliable energy data available, but a six year period following retro-commissioning was able to be examined.

During this time chilled water savings remained consistent, falling only to 37% in 2002 from 43% in 1997. Electricity savings essentially degraded to none after a 5% level initially. Hot water savings was 75% in 1997, fell sharply to 43% in 1998, and remained very close to that level for the next three years, ending at 47% in 2001.

4.2.9 Wehner

The savings trends for chilled water, hot water, and electricity consumption for the Wehner Building are shown in bar graph form in Figure 4-12.

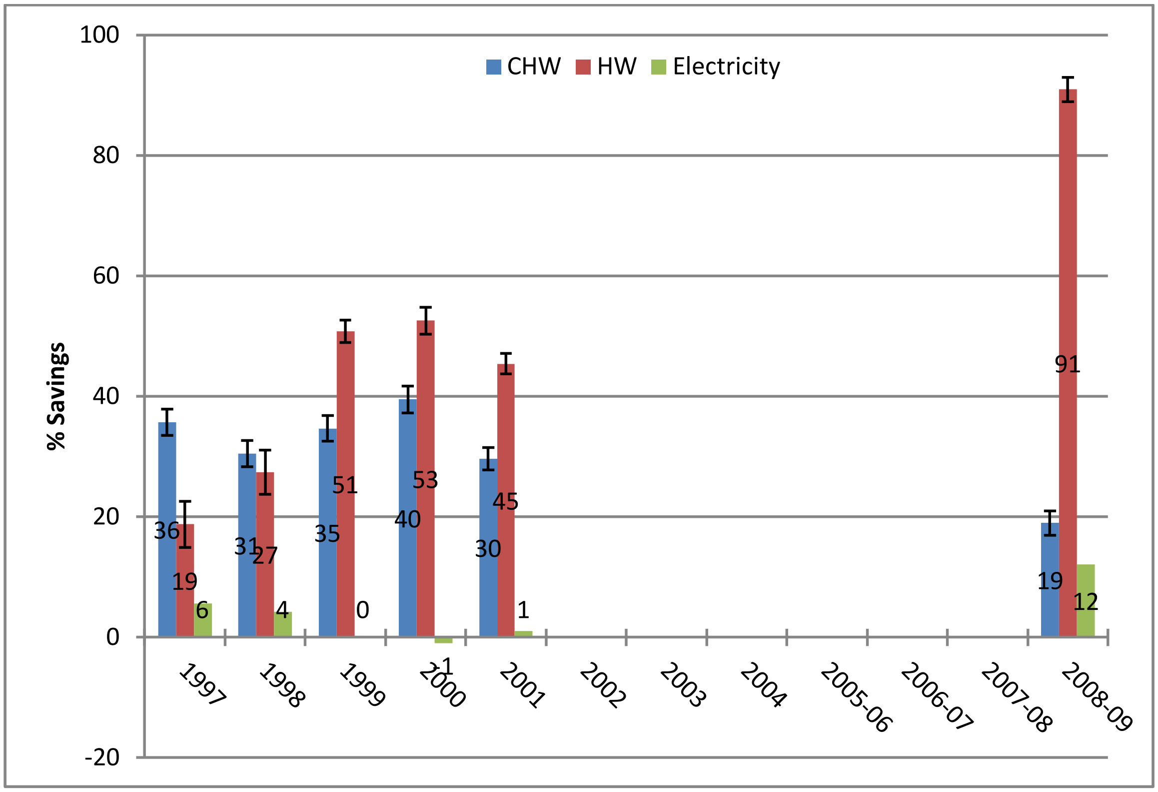


Figure 4 - 12. Normalized energy savings patterns for the Wehner Building.

The Wehner building experienced good persistence in chilled water savings over time. Hot water savings increased in the years following retro-commissioning. In the most recent year, the savings were enormous relative to initial levels, reaching an estimated 88% based on the calibrated simulation model used. Electricity savings degraded some in the years following commissioning, but increased back to a level double that of the 1997 level in the most recent data year, based on the calibrated simulation model.

4.2.10 Zachry Engineering Center

The savings trends for chilled water, hot water, and electricity consumption for the Zachry Engineering Center are shown in bar graph form in Figure 4-13.

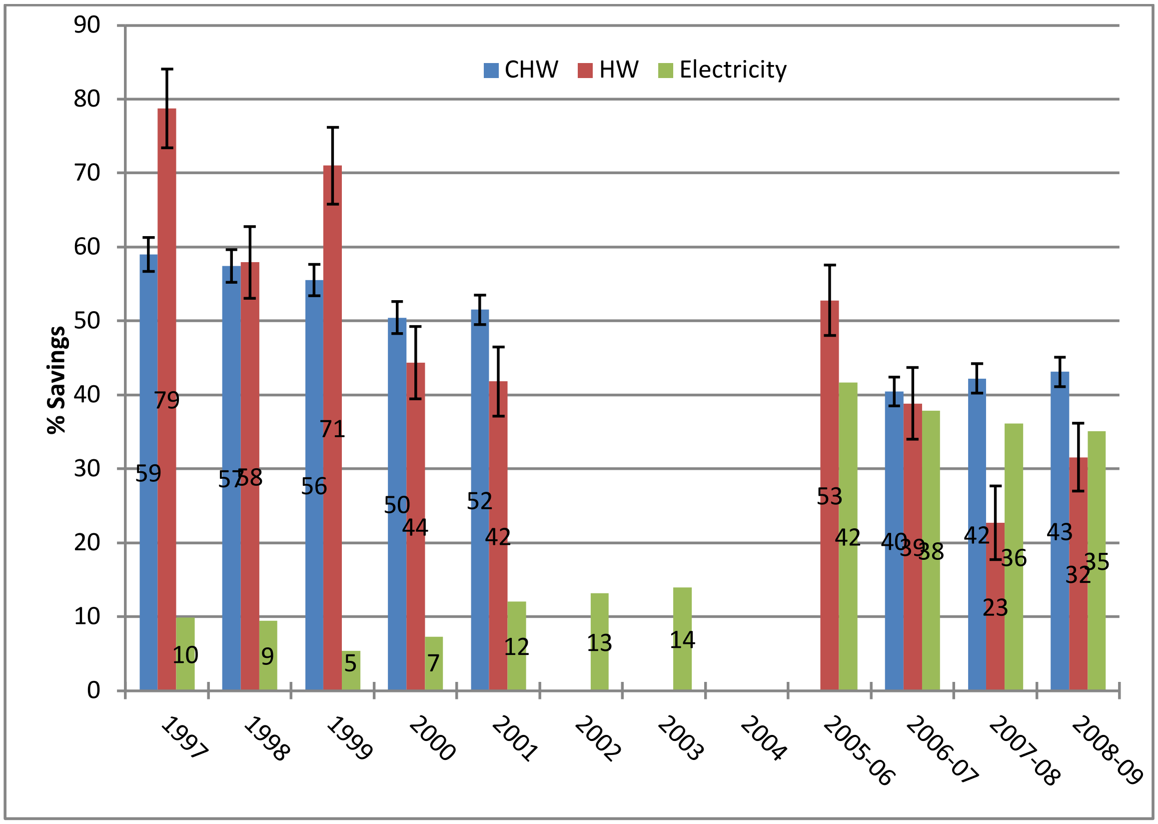


Figure 4 - 13. Normalized energy savings patterns for the Zachry Engineering Center.

The chilled water savings in the Zachry Engineering Center degraded from 59% in 1997 to levels of 40-43% from 2006 to 2009. The hot water savings fluctuated in the first few years after retro-commissioning. In 1997 it was at its highest level, 79%, but had degraded to 23% by 2007-08. It rose again slightly to 32% in the most recent year. Electricity consumption was a different story, however, beginning at 10% in 1997, holding fairly constant for several years thereafter, then jumping to 42% in 2005-06, and ending at 35% in the most recent year.

CHAPTER V

SUMMARY OF RETRO-COMMISSIONING WORK

This chapter describes the retro-commissioning work performed in each of the buildings during the period studied (1996-2009). A discussion of the potential impact of this work in each of the buildings is included. Control system settings and changes are described qualitatively. To see the details of the control system parameters mentioned, refer to Appendix A.

5.1 Blocker

The Blocker building was first commissioned in early 1997. Prior to commissioning, the AHU cold deck temperature set points were all a constant 52°F. The AHU hot deck temperature set points were on an outside air temperature based reset schedule. Each AHU also had a fixed static pressure set point. One AHU had a failed chilled water valve. All terminal boxes remained constantly in Day mode, and numerous mechanical and control problems were found with the terminal boxes. The chilled water differential pressure set point was reset with flow, and the chilled water pumps staged on and off with demand. The hot water pump ran continuously, and the hot water return temperature set point was reset with outside air temperature.

The first round of retro-commissioning resulted in some significant operational changes in the building. AHU cold deck temperature and hot deck temperature reset schedules were adjusted to promote better energy efficiency, although the reset schedules were still based on outside air temperature. A static pressure reset schedule was also implemented for each AHU based on outside air temperature, and further resets occurred at night. The operation of the preheat pump on each AHU was minimized. The terminal box problems and AHU valve problem identified were repaired. Most of the terminal boxes were set up with temperature dead bands and with Day and Night mode set points. Minimum airflow for each terminal box was set to zero at night.

In 2000, it was noted that building chilled water consumption had increased by approximately 9 MMBtu per day, and electricity consumption had increased by approximately 900 kWh per day over the levels observed shortly after retro-commissioning. A brief follow-up investigation was performed in an attempt to explain these problems. The investigation did little to pinpoint the specific causes of this increased consumption, noting only that both chilled water pumps were running near full speed, and recommending that this be corrected. Inspection of the available data from 2000 would now indicate that the observed increases in consumption were most likely due to meter problems, as the data do not show a significant increase over previous levels.

Sometime in 2005 or early 2006, facilities personnel modified the AHU cold deck and hot deck temperature reset schedules and static pressure reset schedules to allow them to reset based on feedback from the terminal boxes. This allowed AHU settings to track building demand, rather than just outside air temperature. The chilled water differential pressure reset schedule and hot water return temperature reset schedule had both been modified, but were still based on outside air temperature.

These changes in control settings produced very little noticeable change in the overall consumption levels in the building. The annual chilled water consumption in 2006 through 2009 and hot water consumption in 2005 through 2007 were very close to the levels seen in the years just following retro-commissioning. The most recent data for each commodity show consumption levels lower than the levels prior to initial retro-commissioning, but higher than the lowest consumption levels observed.

A building lighting retrofit occurred in June 2005.

Table 5-1 gives a summary of what has been done in the Blocker building relative to retro-commissioning. Figure 5-1 then shows the normalized consumption values over time of chilled water, hot water, and electricity for the Blocker building.

Table 5 - 1. Summary of retro-commissioning work in Blocker.

	Pre-RC (1/97)	**Post-RC (5/97)**	**2000 Follow-up**	**2006**
AHU Cold Deck Temperatures	Constant 52°F. One bad ChW valve.	Reset with outside air temperature.	Same as post-RC.	Reset based on average terminal box cooling demand.
AHU Hot Deck Temperatures	Reset with outside air temperature.	Reset with outside air temperature, but schedules modified.	Same as post-RC.	Reset based on average terminal box heating demand.
AHU Static Pressure Set Points	Constant.	Reset with outside air temperature.	Same as post-RC.	Reset based on average terminal box damper position.
Chilled Water System	Differential pressure reset with flow rate.	Differential pressure reset with flow rate, but modified from pre-RC. Pumps staged to run one at a time.	Both pumps running 99% speed.	Differential pressure reset with outside air temperature.
Hot Water System	Return temperature reset with outside air temperature. Pumps run continuously.	Return water temperature reset schedule modified, still based on outside air temperature. HW pumps come on and off based on outside air temperature.	Same as post-RC.	Return water temperature reset schedule modified, still based on outside air temperature.
Terminal Boxes	All boxes in Day mode at all times. Numerous mechanical problems.	Day/Night mode implemented for boxes. Minimum flow set to zero at night. Mechanical issues repaired.	Same as post-RC.	Night minimum flow no longer zero.

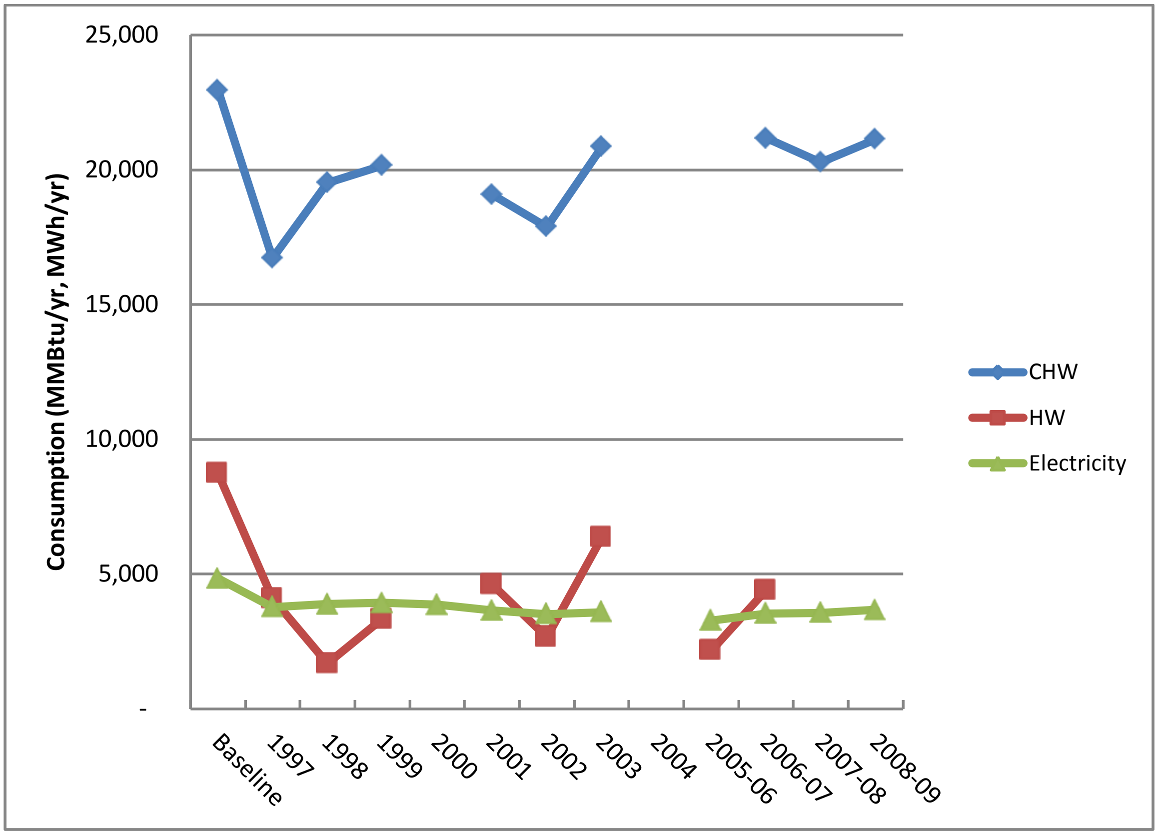


Figure 5 - 1. Normalized energy consumption over time for the Blocker building.

5.2 Eller O&M

The Eller O&M building first underwent retro-commissioning in early 1997. Prior to this, the AHU cold deck temperature set points were reset based on outside air temperature, as were the hot deck temperature set points. The AHU static pressure set points were constant for each AHU. The chilled water and hot water pump speeds were controlled based on the maximum AHU valve positions. No night set backs were in place.

During the first round of retro-commissioning, chilled water and hot water valve loops were tuned. Chilled water and hot water pump speeds were made to control based on average valve positions to avoid frequent speed cycling and valve hunting. Day temperature set points were set up with a heating and cooling dead band of four degrees, and night set points were given a dead band of twelve degrees. All terminal boxes were set to have a minimum flow of zero cfm at night. The AHU cold deck and hot deck temperature reset schedules were modified, but continued to be based on outside air temperature. The AHU static pressure set points were set up to reset based on outside air temperature, with an even lower set point at night. Non-functional outside air fans on the roof were identified, and it was recommended that they be repaired. It was recommended that AHU control valves on the fourteenth floor be relocated to improve loop control. These were relocated to the eleventh floor at a later time.

At some point after 2001 but before 2006, the control programming was changed significantly such that all of the air handling unit hot and cold deck temperature set points and static pressure set points would be reset between upper and lower limits based on a weighted average of terminal box demand, in place of the reset with outside air temperature that had previously been in place. It is unknown whether this change occurred prior to 2004, the last year of reliable energy data for the building. However, as noted in the previous chapter, the chilled water and electricity savings for this building degraded very little from 1997 to 2004. The hot water savings, however, degraded significantly in 2000 and 2001 as compared with previous years. If this degradation was a result of control programming changes, it would need to be found in changes implemented before 2000. The study by Cho reported that in the years between 1997 and 2000, the minimum hot deck temperature set point for the four dual duct air handling units was raised from 70°F to 80°F. Since this system utilizes hot deck air flow practically all of the year in order to maintain minimum air flow rates at each terminal box, this change in set point may help explain the increase in heating consumption that began in 2000. Unfortunately, reliable hot water consumption data for the years following 2001 were not available, so it is impossible to know if the drop in hot water savings has continued to the present.

A building lighting retrofit took place in June 2005, although the effects of this are not seen due to lack of data after 2004.

Figure 5-2 shows the normalized consumption values over time of chilled water, hot water, and electricity for the Eller O&M building.

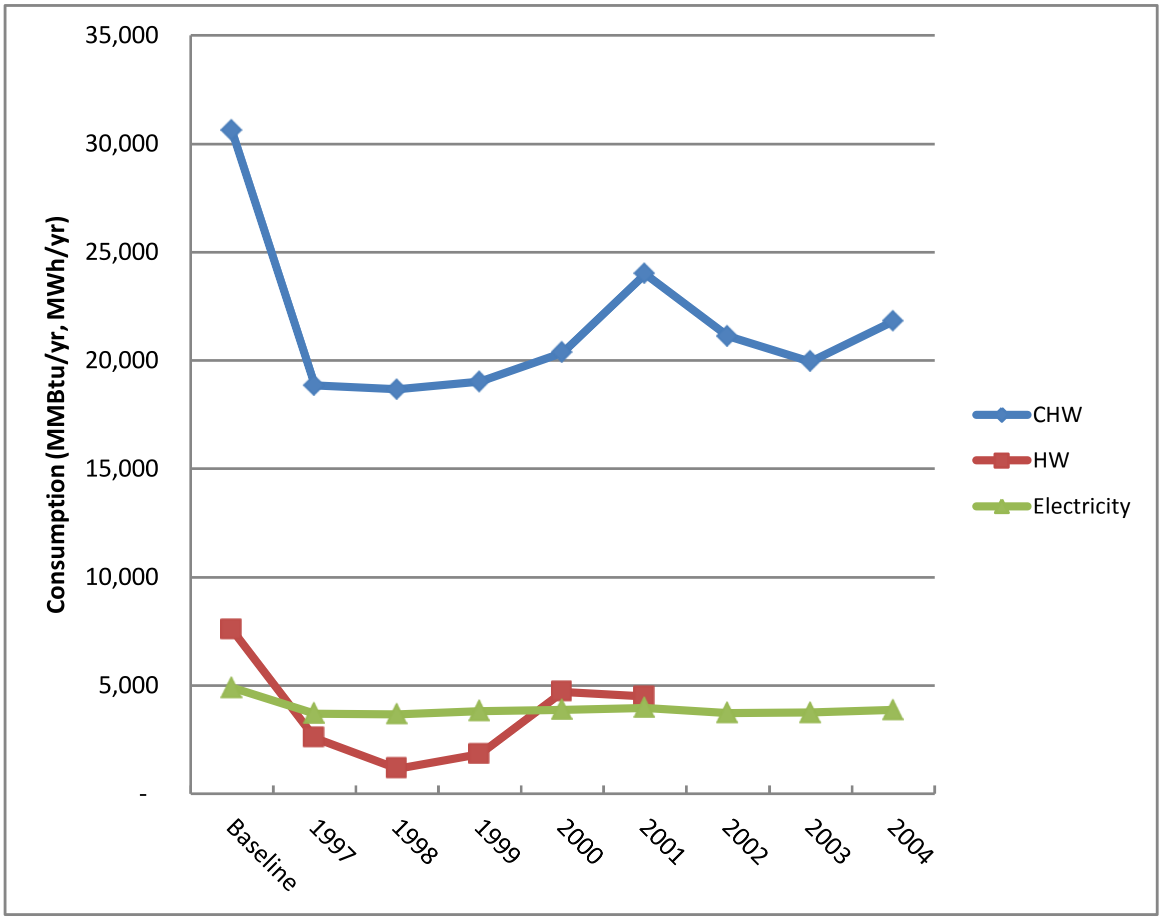


Figure 5 - 2. Normalized energy consumption over time for the Eller O&M building.

5.3 G. Rollie White Coliseum

The G. Rollie White Coliseum first underwent retro-commissioning in 1997. Prior to this, the chilled water differential pressure set point was reset with flow rate, but was allowed to reset to an excessively high set point (15 to 54 psi). The constant speed hot water pump ran all the time, resulting in excessive pressures in the loop at times. The outside air flow to FCUs 1 and 2 was higher than necessary. The chilled water valve on FCU 3 was wide open due to a faulty control signal. The cold deck temperatures on some AHUs were much colder than needed. One AHU had a hot deck temperature that was much higher than needed. Air balance problems were also discovered.

During the first round of retro-commissioning, the chilled water differential pressure set point was set to reset with flow rate, but with a much lower range (5 to 17 psi). The hot water pump was shut off. Cold deck temperatures on all AHUs were adjusted to between 55 and 57°F. The outside air flow to FCUs 1 and 2 was adjusted to meet the minimum needed. Zone airflows were reduced in order to minimize simultaneous heating and cooling.

Observed savings degradation led to a follow up investigation in 2001. This investigation revealed that the heating and cooling set points that had been established for the 13 arena units had been overridden. Instead of a heating set point of 68°F and a cooling set point of 74°F, these units now had a heating set point of 74°F and a cooling set point of 68°F, resulting in constant simultaneous heating and cooling. It was also found that the valve action on AHU 13 was reversed on both of the valves. The hot water pump on and off commands were reversed in the PPCL. The chilled water differential pressure set point was found to be high (49 psi) due to a faulty chilled water flow reading. In addition to these problems, a number of maintenance issues were also identified. The problems found were corrected as part of the follow up activities, and immediately energy savings began to occur. In fact, more savings were achieved after this follow up than had originally been obtained from retro-commissioning in 1997. These new levels of savings appear to have persisted well to the present time.

A second round of retro-commissioning was performed in 2006. It was found that 10 arena area AHUs had non-functional outside air dampers that were stuck closed. The office and corridor chilled water loop had high differential pressure readings (as high as

50 psi recorded) well outside the set point range (5 to 17 psi). Five office and corridor AHUs had non-functional outside air systems. Maintenance issues on the classroom and office units caused simultaneous heating and cooling. Approximately 70% of the classroom and office FCUs had significant operating deficiencies. Three AHUs still used bypass valves for chilled water. As part of the second round, the chilled water bypass piping for these three units was blanked off. The reset schedules for both the arena and office chilled water loops were also adjusted to decrease the set point ranges.

Figure 5-3 shows the normalized consumption values over time of chilled water, hot water, and electricity for the G. Rollie White Coliseum.

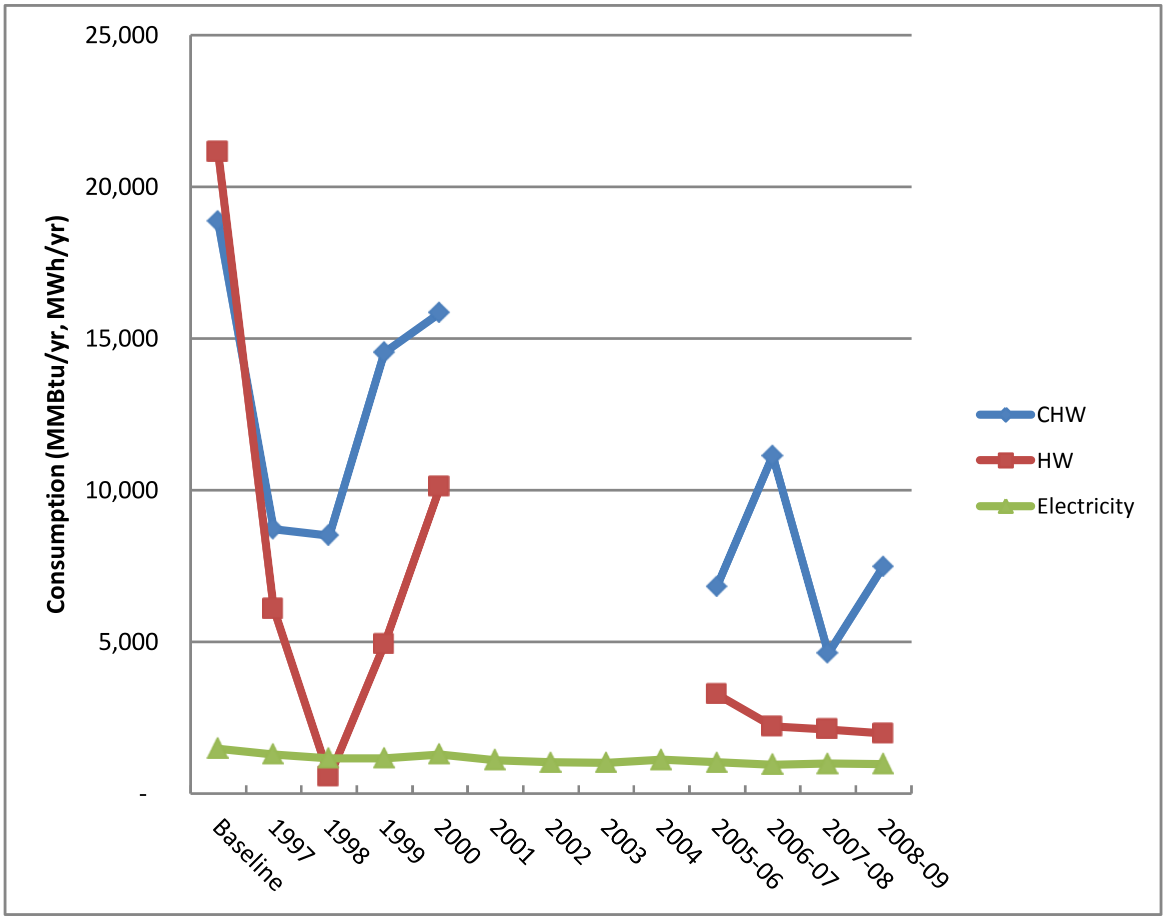


Figure 5 - 3. Normalized energy consumption over time for the G. Rollie White Coliseum.

5.4 Harrington Tower

Harrington Tower first underwent retro-commissioning in 1996. Prior to this, the building was slightly negatively pressurized. Two relief fans were running when not needed. The AHU static pressure set point was constant, the cold deck temperature was constant, and the hot deck temperature was reset with outside air temperature. Occupants on the top floor complained of being too cold even during very warm outside air conditions. Maximum air flow for some terminal boxes exceeded two cfm per square foot.

During retro-commissioning, the outside air dampers were adjusted to bring in a minimum of eight percent outside air. The AHU cold deck temperature set point was left at the same constant value. The AHU static pressure set point was lowered considerably, but also left constant, except during night time operation, when it was lowered further. The maximum flow for each terminal box was set at one cfm per square foot, while the minimum was set at 75 cfm. The chilled water and hot water pumping control was altered to allow pumps to shut off when not needed.

Sometime between 2001 and 2006, the AHU cold deck temperature was set up with an outside air temperature based reset schedule. The chilled water, hot water, and electricity savings observed in 2005-06 and 2006-07 were slightly higher than in the years 2000-2004.

Another round of retro-commissioning was performed in 2006, but the majority of the recommendations were not implemented until July 2007. The major changes involved setting up reset schedules for the AHU cold deck temperature, hot deck temperature, and static pressure set points based on demand.

A building lighting retrofit was completed in October 2008.

Figure 5-4 shows the normalized consumption values over time of chilled water, hot water, and electricity for Harrington Tower.

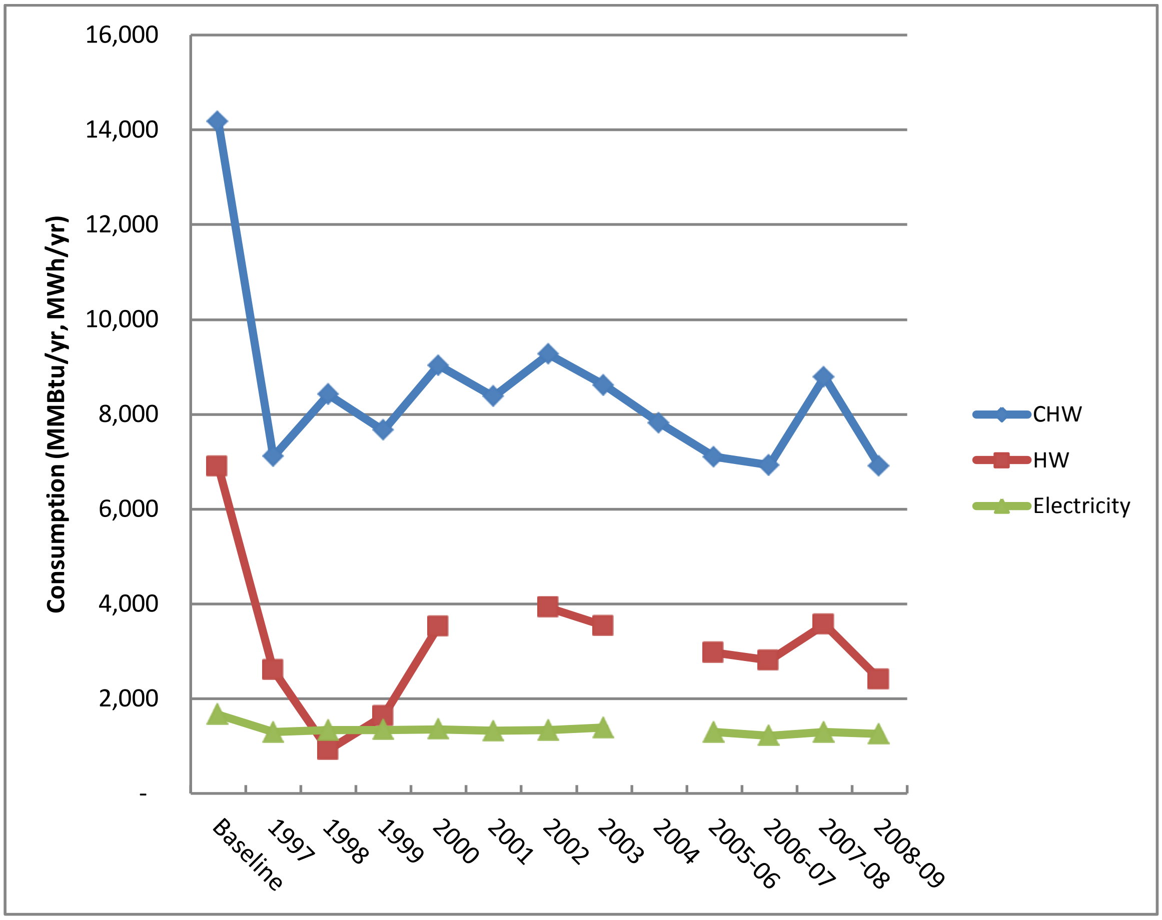


Figure 5 - 4. Normalized energy consumption over time for Harrington Tower.

5.5 Kleberg

The Kleberg building first underwent retro-commissioning in 1996. Prior to this, a faulty building pressure sensor caused nearly 100% outside air to enter the building. One exception was that a faulty carbon dioxide sensor on one AHU caused its outside air damper to remain fully closed at all times. The hot water control sequence in place for two of the AHUs caused simultaneous heating and cooling. All AHU cold deck temperature set points were a constant value.

During the first round of retro-commissioning, some programming changes were implemented in order to ignore the faulty building pressure sensor, and instead use two other sensors with calibrated output in order to regulate outside air intake. The building pressure set point was also lowered at this time. The faulty carbon dioxide sensor on one AHU was replaced. The hot water sequence on two AHUs was modified to eliminate simultaneous heating and cooling, and a dead band between operation of the valves was established. The cold deck temperature set point for all AHUs was changed to reset with outside air temperature. The economizer mode was made to operate when outside air dry bulb temperature was below 60°F, attempting to maintain a 57°F cold deck temperature. The chilled water pumps were programmed to stage on one at a time according to demand. A night setback was implemented to lower the AHU static pressure set point and raise the cold deck temperature set point.

After the first round of retro-commissioning in 1996, some follow up work was performed in the period between June 1998 and April 1999. This focused on air balance in laboratories, terminal box calibration, and improved exhaust control. Temperature sensors, static pressure sensors, and AHU VFD outputs were calibrated. The cold deck temperature reset schedule was modified slightly, although it continued to be based on outside air temperature. Thermostats and controllers were repaired, and the control program for laboratories and offices was modified. The static pressure set point in the exhaust duct was set much lower than it had been, and the pressure sensor was calibrated. The result of this follow up work was a slight increase in electricity savings.

Hot and cold complaints in 2000 and 2001 in the building resulted in additional commissioning follow up work being performed. This further investigation found a combination of changed control parameters and maintenance problems that were causing excessive energy consumption and comfort problems. For one of the air handling units, chilled water valves would not fully close, creating colder than desired discharge air temperatures, and in turn causing the preheat valve to operate unnecessarily due to the way in which it was programmed to control. Failed CO_2 sensors and a failed building pressure sensor caused the outside air dampers on some of the air handling units to remain fully open at all times. The chilled water pumps, which had been programmed to stage on and off as needed, were in bypass mode and remained on at full speed at all times, resulting in excessively high loop differential pressures. These problems and others were identified and corrected. (Chen, 2002)

Since only minor programming changes occurred between 2000 and 2009, the resultant increase in chilled water savings during that time period can most likely be attributed to the follow up work already described. This allowed savings to even exceed what had been achieved originally by retro-commissioning. Hot water consumption continued to climb, however, noted in more recent years when metering was again installed. Electricity savings increased in recent years, most likely due in part to a building lighting retrofit that took place in March 2005.

Some follow up investigation was performed in 2007. At this time, numerous maintenance problems were identified in the building. The two large AHUs were both found to be operating as constant volume units because their fan blade pitch control mechanisms were stuck in one position. These units also had problems with return air and relief air damper operation, and their return air fans were therefore turned off. Only one chilled water pump was operating, but it had been commanded to remain at full speed. Only one of the three hot water pumps was operable. A sampling of terminal boxes in the building revealed that the majority sampled did not have operable fan motors. Numerous other problems were discovered as well, including dirty coils and a few leaking hot water valves. The decision was made by management to suspend retro-commissioning activities and instead invest in retrofits of the equipment.

Figure 5-5 shows the normalized consumption values over time of chilled water, hot water, and electricity for the Kleberg building.

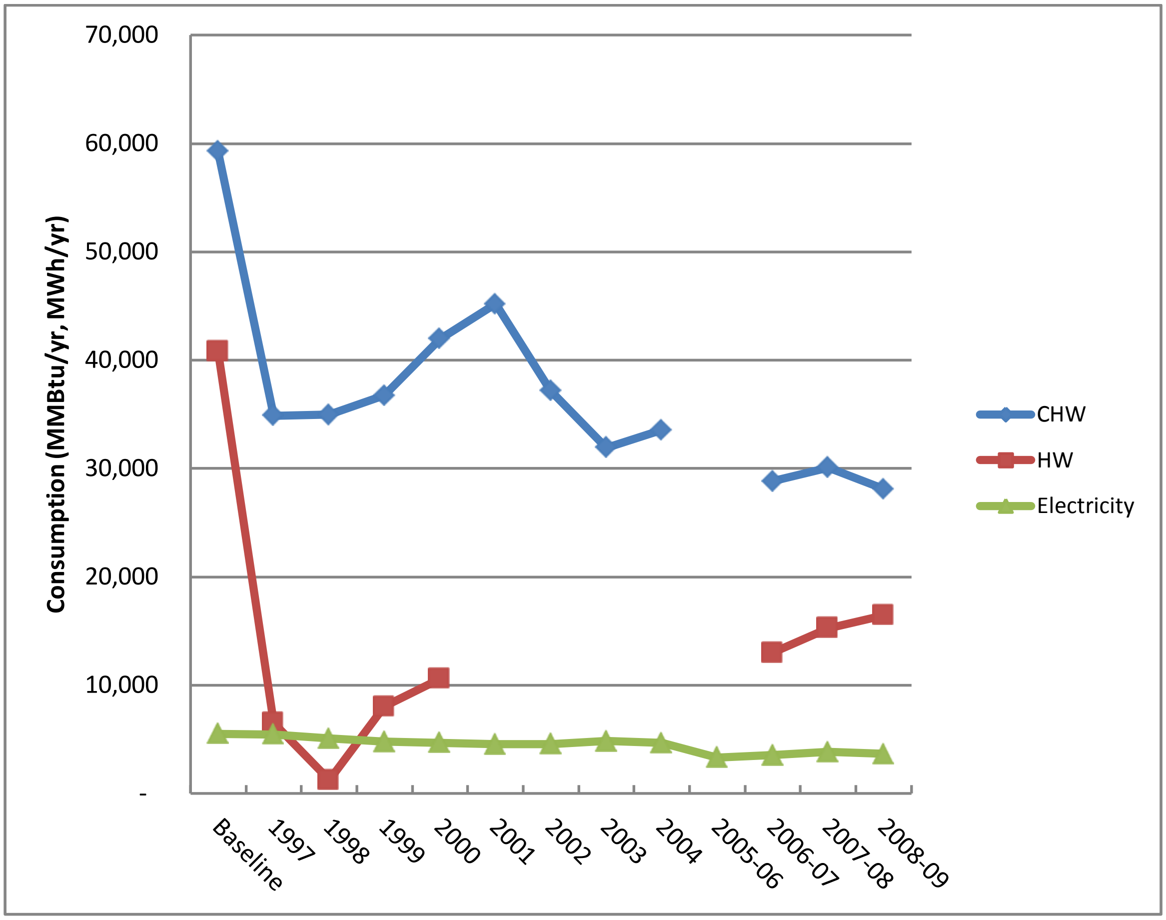


Figure 5 - 5. Normalized energy consumption over time for the Kleberg building.

5.6 Koldus

The Koldus building first underwent retro-commissioning in early 1997. Prior to this, both the chilled water and hot water systems had constant differential pressure set points. However, both pumps were in manual control resulting in excessively high pressures in the two loops. The AHUs each had constant discharge air temperature and static pressure set points. The economizer mode on the AHUs was enabled at outside air temperatures less than 55°F and maintained a mixed air temperature of 55°F. During non-economizer mode, outside air intake was found to be higher than needed. AHU return fans were found to run continuously during occupied periods. Four of five AHUs already shut down each night from midnight to 5:00 AM. One AHU was commanded in manual override to a constant speed. Some hallways and other rooms were found to be colder than desired. Hallway thermostats were found to set in the mid to low sixties.

During retro-commissioning, the chilled water and hot water differential pressure set points were set to reset based on flow rates. The chilled water and hot water pumps were set up to turn off and on based on outside air temperature. The discharge air temperature and static pressure set points for each AHU were set up with an outside air temperature based reset schedule. The return fans were given flow set points five to ten percent less than the supply air during normal operation, and 1,000 cfm less than supply air during economizer operation. Air leakage was measured to be high through the closed outside air dampers on the AHUs, so the outside air dampers were set to remain closed during normal operation. The AHU shutdown schedule was extended to 10 PM to 6 AM on weekdays and 9 PM to 7 AM on weekends. All thermostats were set to 73°F for cooling and 69°F for heating.

Another round of retro-commissioning was performed in 2001. At that time the differential pressure set points for both the chilled water and hot water loops were altered to utilize an outside air temperature based reset schedule. The static pressure reset schedule for five of the AHUs was altered to utilize slightly lower values than had been implemented during the initial retro-commissioning. Some mechanical issues were identified during this round of retro-commissioning, but it was unknown if they were ever repaired.

A building lighting retrofit occurred in March 2005.

A follow up investigation was performed in 2008. It was found that both the chilled water and hot water loop differential pressure set points were reset based on outside air temperature, but the limits were slightly different than what was implemented in 2001. The second chilled water pump and the second hot water pump were both inoperable. AHU static pressure and discharge air temperature reset schedules were still based on outside air temperature, but were altered slightly from the 2001 values. The economizer cycle for the AHUs was activated when outside air temperature was three degrees or more below the return air temperature. All AHUs were found to run continuously. Numerous mechanical problems with terminal boxes were found, including bad flow controllers and some boxes without reheat valves.

The chilled water and electricity savings in the most recent years were very close to those achieved in the years immediately following the first round of retro-commissioning, while hot water consumption had increased to a level more than twice the value before initial retro-commissioning. This was very suspicious, especially considering the lack of changes in control programming and in chilled water and electricity consumption over time. A metering problem was suspected. The 2008 investigation had confirmed that the metering at that time was accurate, and consumption values were believable. Energy balance plots from the data from both metering systems appeared feasible, though they were obviously different. Guanjing Lin, a Ph.D. candidate in mechanical engineering, studied the data further using a simplified energy analysis procedure. From this procedure, she was able to conclude that the hot water data from the previous metering system was inaccurate, since models of the building would not produce the hot water levels recorded at that time. Hot water levels recorded from the newer metering system were determined to be feasible based on the simplified energy analysis procedure. Therefore, it was concluded that no comparison of savings for hot water consumption could be accurately be performed for this building.

Figure 5-6 shows the normalized consumption values over time of chilled water and electricity for the Koldus building, as well as the hot water consumption since the new metering was installed.

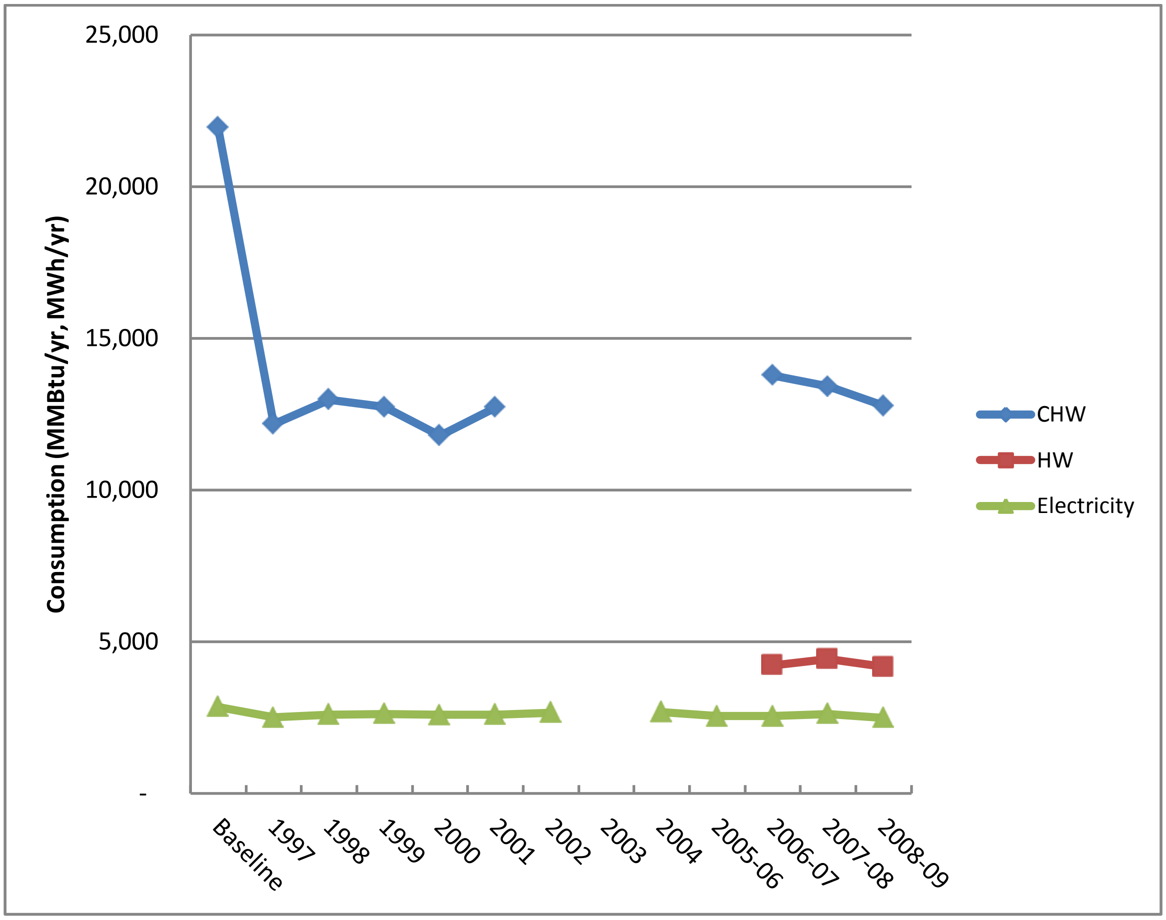


Figure 5 - 6. Normalized energy consumption over time for the Koldus building.

5.7 Richardson Petroleum

The Richardson building first underwent retro-commissioning in late 1996. Prior to this, minimum outside air dampers remained fully open, resulting in more outside air intake than needed. Faulty flow sensors caused return air dampers to fully close. The chilled water valves on three AHUs were not functioning properly. The building outside air temperature sensor was also not functioning properly.

During the first round of retro-commissioning, minimum outside air dampers were programmed to remain closed, relying on air leakage through the dampers to provide sufficient outside air flow. The return air dampers were programmed to remain open.

The maximum outside air dampers were programmed to modulate during economizer mode, when outside air temperature fell below 60°F. AHU discharge air temperature and static pressure set points were set up to reset based on fan speed. The building hot water loop temperature set point was programmed to reset based on outside air temperature, and the hot water pump was programmed to shut off at low speed signals. The AHU preheat control sequence was also improved.

In late 1997, approximately one year after implementation of the first round of retro-commissioning, some follow up work was performed in the building. It was found that the outside air intake was insufficient to account for the large amount of building exhaust, resulting in negative building pressurization. The minimum outside air dampers were once again programmed to remain open when the AHUs were running. The return air dampers were again allowed to modulate in order to maintain desired outside air flow at each unit. It was also found that the chilled water valves on four AHUs were not functional (three of which had been identified during retro-commissioning).

Another round of retro-commissioning was performed in 2001. During this time some changes were made to the operation of the building, including improving operation of the economizers, decreasing the amount of minimum outside air intake to the air handling units, modifying the cold deck discharge temperatures to vary according to outside air temperature instead of fan speed, and setting up outside air temperature reset schedules for the chilled water and hot water differential pressure set points. These measures may have helped restore chilled water savings in 2001 back to a level close to that achieved in 1997, however, hot water savings fell from a peak of 88% in 2000 back down to 64% in 2001, essentially the same level as achieved in 1997.

A third round of retro-commissioning took place beginning in late 2007. It was found that some laboratories had been converted to offices but still maintained air flow rates required for laboratory ventilation. The maximum outside air damper control for four AHUs was based on outside air temperature, for three AHUs it was based on enthalpy, and for one AHU it was based on measured carbon dioxide levels. The minimum outside air dampers remained open during occupied modes for all AHUs, but closed during the unoccupied mode for seven AHUs. The discharge air temperature set point for three AHUs was based on supply fan speed, for one AHU it was based on outside air temperature, for two AHUs it was based on a combination of fan speed and outside air temperature, and for one AHU it was based on mixed air temperature. The static pressure set point for all but one of the variable air volume AHUs was based on fan speed, while for the one it was constant. It was found that the chilled water loop differential pressure set point overridden to 8 psi. The hot water loop differential pressure set point was reset based on outside air temperature, with the sensors located in the pump room. Previously these sensors had been located at the top of the loop. The preheat temperature set point for three AHUs was constant, for three others it was reset based on outside air temperature, and for one AHU it was reset based on mixed air temperature.

A building lighting retrofit took place in October 2008.

Recently installed metering has allowed one additional year of consumption data to be obtained. The normalized chilled water usage during this year was higher than in any of the years since retro-commissioning, but was still considerably lower than the level before retro-commissioning. Hot water consumption in the most recent year was just slightly below that of 2004, and both were higher than any of the other years since retro-commissioning. Consumption was still much lower than the baseline value.

Figure 5-7 shows the normalized consumption values over time of chilled water, hot water, and electricity for the Richardson building.

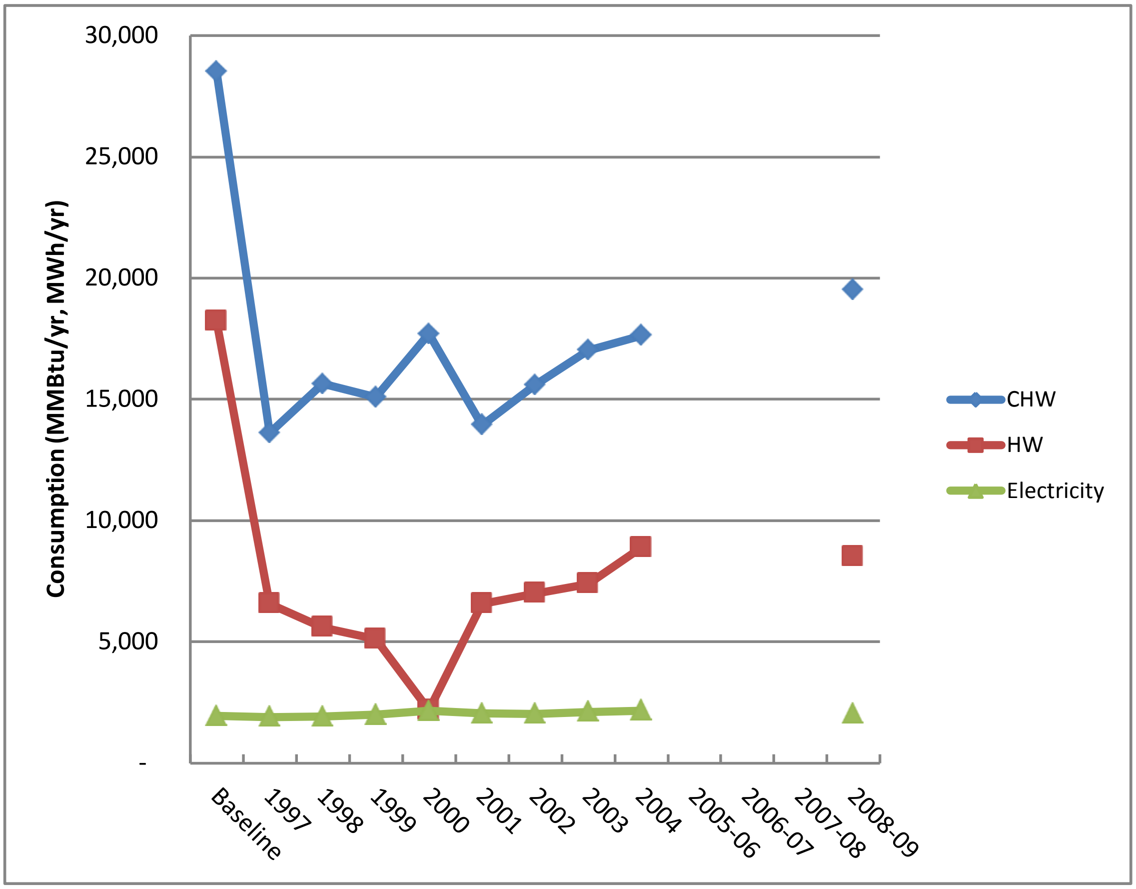


Figure 5 - 7. Normalized energy consumption over time for the Richardson building.

5.8 Veterinary Medical Center Addition

The Veterinary Medical Center Addition first underwent retro-commissioning in late 1996. Prior to this, the discharge air temperature set point on all of the AHUs was a constant value. Preheat control at the AHUs caused fighting between preheat valves and chilled water valves, resulting in simultaneous heating and cooling.

During retro-commissioning, the discharge air temperature set point for each AHU was set up to reset with outside air temperature. The heat recovery system was programmed to operate during a broad range of outside air temperatures. Preheat control was modified to prevent simultaneous heating and cooling at the AHU level. The speed control on the building pumps was modified to control to a return water temperature set point that was made to reset based on outside air temperature.

Between 2001 and 2006, some minor changes in cold deck temperature set point schedules and static pressure reset limits took place, but were not dramatic, and should not have had major impact on consumption. Besides an increase in hot water consumption between 1997 and 1998, the available data years for this building show very close levels of consumption from year to year for each commodity. A lighting retrofit took place in June 2005, but would not show up in the available data.

Figure 5-8 shows the normalized consumption values over time of chilled water, hot water, and electricity for the Veterinary Medical Center Addition.

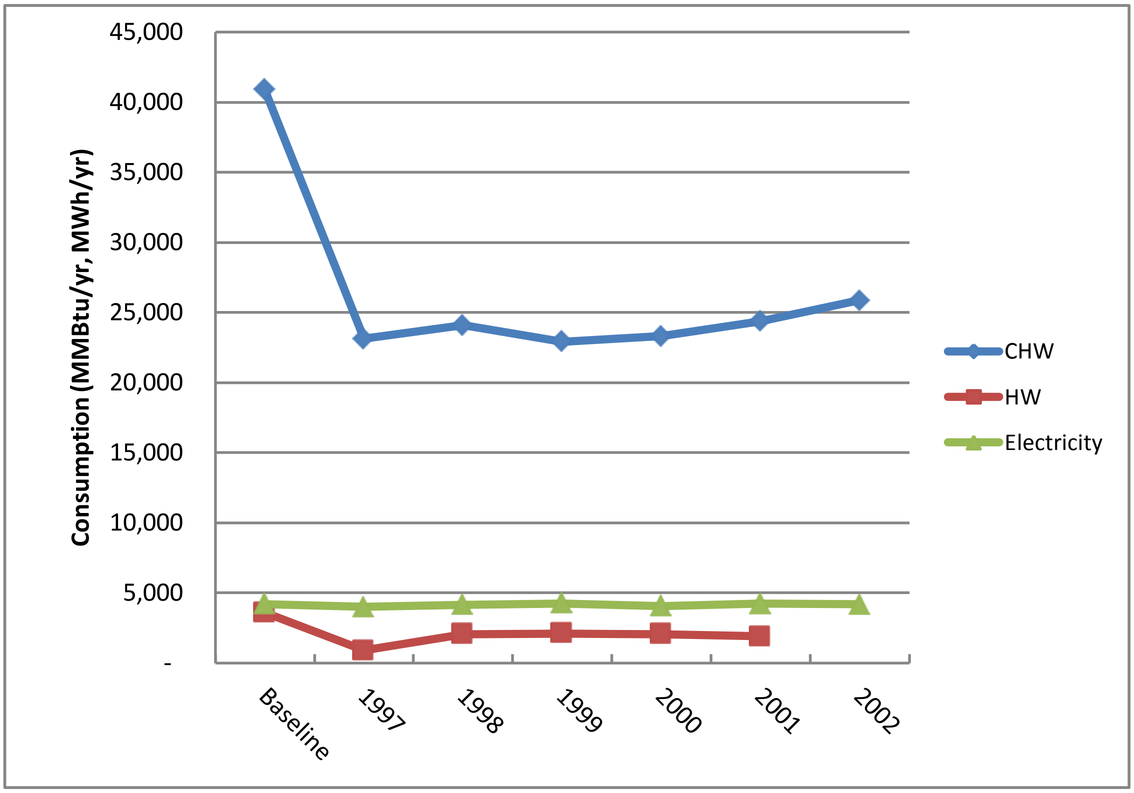


Figure 5 - 8. Normalized energy consumption over time for the Veterinary Medical Center Addition.

5.9 Wehner

The Wehner building first underwent retro-commissioning in late 1996. Prior to this, preheat valve control for the two single duct variable air volume AHUs caused fighting between preheat valves and chilled water valves, resulting in simultaneous heating and cooling. Several variable air volume terminal boxes were found to be in critical mode due to higher than desired humidity levels in the spaces served, which resulted in 100% primary air being supplied to the rooms. However, the humidity sensors were found to be out of calibration, and very low humidity levels were actually measured. The dual duct AHUs had a constant set point for cold deck temperature, and the set point for hot deck temperature was reset with outside air temperature. AHU static pressure set points were constant. High minimum supply air set points were in place for the terminal boxes.

During the first round of retro-commissioning, the AHU cold deck temperature set points were modified so that they would reset with outside air temperature. The hot deck temperature set point reset schedules were also modified, but continued to reset with outside air temperature. The preheat control on the single duct variable air volume AHUs was modified to avoid simultaneous heating and cooling at the AHU level. The AHU static pressure set points were all lowered, but remained constant values. The minimum flow settings for the terminal boxes were lowered throughout the facility. Room temperature set points were changed to 73ºF cooling and 70ºF heating. Night set points were set at 82 ºF cooling and 65 ºF heating. Lab areas maintained a constant 70 ºF cooling and 68 ºF heating.

A major addition to the building occurred in 2001, which completely changed the metered consumption data, since both the addition and the original building were metered together. Another round of retro-commissioning was performed in 2002, shortly after completion of the new addition. Some of the measures performed at this time included implementing static pressure set point and hot and cold deck temperature set point reset schedules based on outside air temperature for the air handling units, implementing differential pressure set point reset schedules for hot and cold water loops based on outside air temperature, and removing shut down schedules for several air handling units due to computer laboratories being added in the areas served by these units. This last measure would have served to increase overall energy consumption.

At some point after 2002 but before 2006 the control programming for this building was rewritten so that cold deck static pressure and temperature reset schedules that had been based on outside air temperature would instead be based on average building demand, as measured at the terminal boxes. In 2006, additional work was done in the building as a result of comfort complaints. This work mostly addressed maintenance issues and local terminal controller issues, however, and did not represent a full round of retro-commissioning.

A building lighting retrofit was completed in December 2008.

The most recent data show a dramatic drop in hot water consumption from previous years, with some increase in chilled water consumption and little change in electricity consumption.

Figure 5-9 shows the normalized consumption values over time of chilled water, hot water, and electricity for the Wehner building.

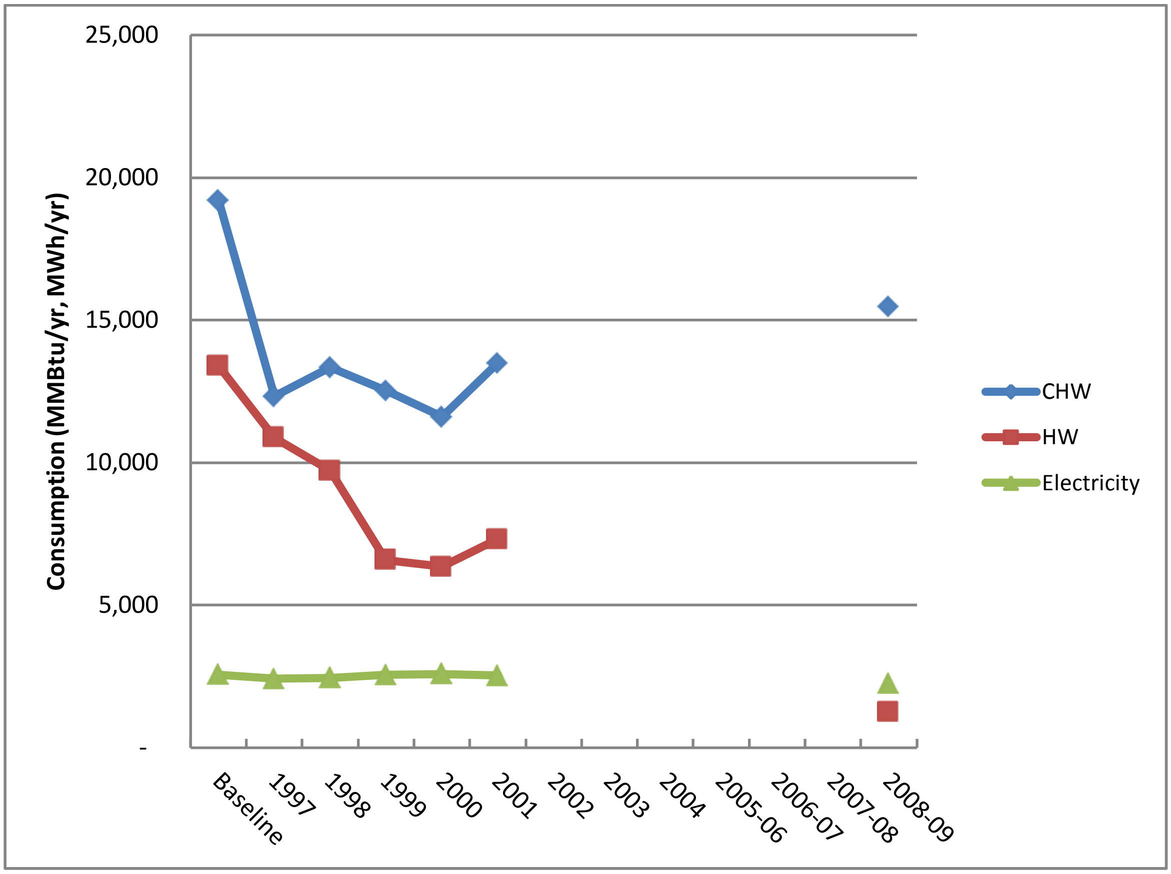


Figure 5 - 9. Normalized energy consumption over time for the Wehner building.

5.10 Zachry Engineering Center

The Zachry building first underwent retro-commissioning in 1997. Prior to this, all of the AHU static pressure set points were constant. The set points were high, causing problems with blown ductwork in some areas. The cold deck temperature and hot deck temperature set points for all of the AHUs were also constant values. AHU chilled water and hot water valves had severe hunting problems, creating wide ranges in both cold and hot deck temperatures that varied frequently. Two AHUs had bypassed variable frequency drives waiting on repairs. The chilled water loop differential pressure set point was a constant value. The chilled water pump was staged on and off according to the proximity of the differential pressure to its set point. The hot water pump was constant speed and ran continuously. The building chilled water supply valve was partially closed. Approximately 15 different day/night schedules for terminal boxes were in place in the building, creating some confusion.

During the first round of retro-commissioning, the AHU static pressure set points were set up to reset based on outside air temperature. The AHU cold deck and hot deck temperature set points were also made to reset with outside air temperature. The control loops for AHU valves were tuned to reduce hunting problems. The chilled water loop differential pressure set point was programmed to reset based on chilled water flow. The hot water pump was programmed to turn on and off based on outside air temperature. The building chilled water supply valve was fully opened. Three day/night schedules were set up to include all building terminal boxes. Terminal box minimum flow was set to go to zero during night mode. The day mode terminal box minimum and maximum flow set points were adjusted, and numerous mechanical problems with the boxes were repaired. Space temperature set points were adjusted so that the day heating set point would be 68ºF, the day cooling set point would be 73ºF, the night heating set point would be 65ºF, and the night cooling set point would be 76ºF.

Between 2001 and 2006, some changes in hot and cold deck temperature set point reset limits were implemented in the control programming, but the reset schedules were still based on outside air temperature. Static pressure set point reset limits were also increased. At some point during this time period, a large mainframe computer was removed from the building, which may explain some of the increases in electricity savings seen in most recent years. A building lighting retrofit was performed in June 2005, which also would help explain electricity savings in recent years.

Retro-commissioning was again performed in 2006. As part of this, the AHU static pressure, cold deck temperature, and hot deck temperature set points were modified to be based on average terminal box flow, heating, and cooling demands, instead of outside air temperature. Some chilled water and hot water valve problems identified were also corrected. A bypass damper on one AHU was found to be opened, and it was closed. These were the primary results of this retro-commissioning investigation.

Figure 5-10 shows the normalized consumption values over time of chilled water, hot water, and electricity for the Zachry building.

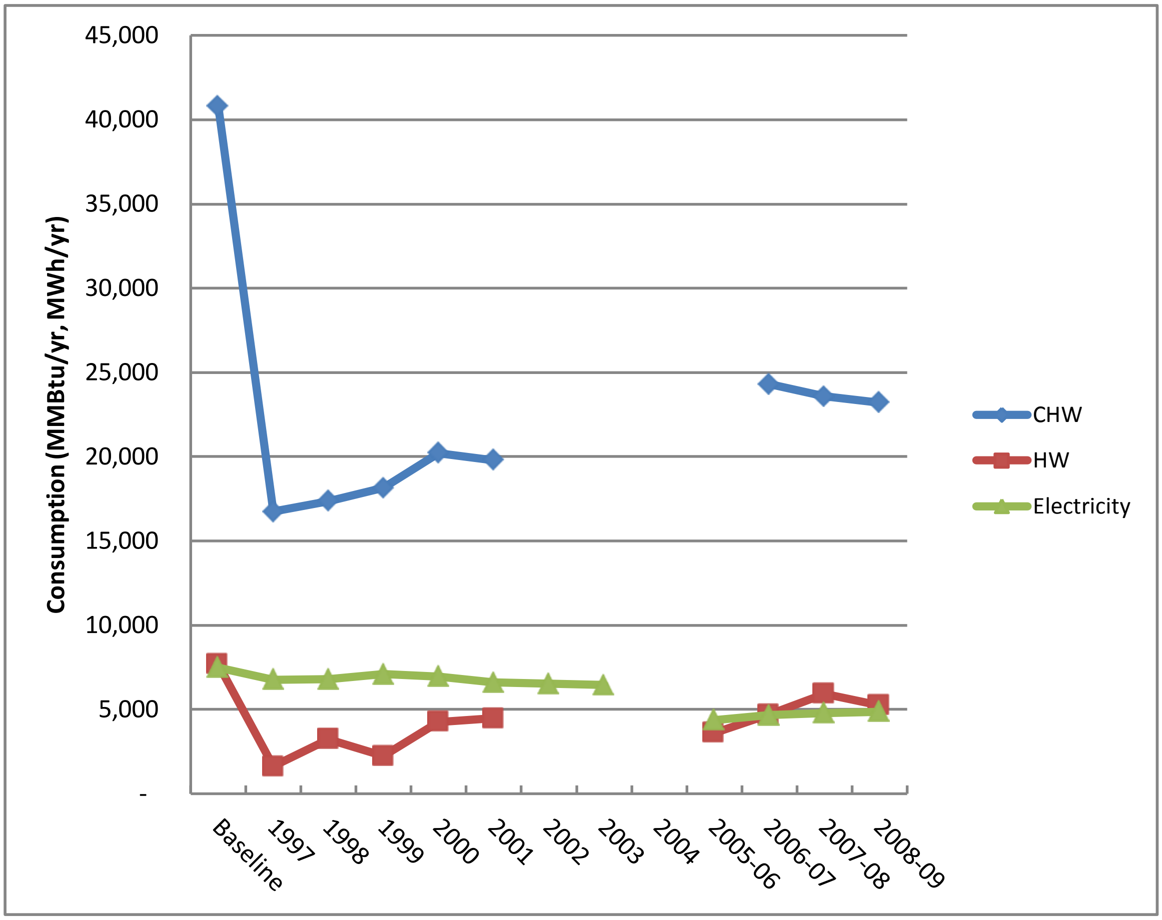


Figure 5 - 10. Normalized energy consumption over time for the Zachry building.

CHAPTER VI

CONCLUSIONS

Ten university buildings underwent retro-commissioning in 1996 or 1997, and were shown to have significant levels of energy savings directly following this event. Normalized energy consumption levels for each of the ten buildings have been tracked to the extent possible from that time until 2009. This has been done to evaluate how well initial savings have persisted over time, as well as to attempt to draw conclusions about some of the causes of persistence or the lack of persistence of retro-commissioning savings in a facility.

Table 6-1 gives percentages for the total savings achieved for all ten buildings during the first year after retro-commissioning (1997), then again using the total of the consumption data for each building in its most recent available data year. For chilled water, the most recent year for each building is 2008-09, except for Eller (2004) and VMCA (2002). For hot water, the most recent year for each building is 2008-09, except for Blocker (2006-07), Eller (2001), and VMCA (2001). The hot water data for Koldus were completely excluded due to the meter problems already described. For electricity, the most recent year for each building is 2008-09, except for Eller (2004) and VMCA (2002).

Table 6 - 1. Total cumulative savings percentage in 1997 and in most recent data year (90% confidence interval reported).

Year	CHW	HW	Electricity
1997	45(±2)%	67(±2)%	12%
Most recent data year	39(±1)%	64(±2)%	22%

Using this metric, it is apparent that most of the savings present in 1997 for chilled water and hot water persisted through the most recent year of available data. For electricity, the amount of cumulative savings dramatically increased.

To look at this more closely, Table 6-2 below is a summary of the chilled water, hot water, and electricity savings percentages for each of the ten buildings in the year just following the first round of retro-commissioning, in the year when maximum savings were observed, and in the most recent year that reliable metered data were available for the building.

In order to better examine the trends in persistence of savings from the data accumulated, the overall trends are presented in four different formats below. First, the average savings percentages for each year, calculated by taking a simple average of the savings percentages of each building with valid metered data for each year, are presented. Second, the cumulative savings for each year based on the total number of buildings with valid metered data are presented. For the third and fourth formats, the data were redistributed based on when significant follow up retro-commissioning work was performed, or when metering changes occurred or other changes to the building that would be expected to impact energy usage. In these cases, the year of data following the change or follow up was assigned as year zero, and years following were years one, two, etc. The year 1997 was also assigned as year zero for every building, since it represented the data just after retro-commissioning. This meant that for most buildings there was more than one data set per year after retro-commissioning. This shortened the overall time after retro-commissioning that would be evaluated for persistence, but greatly increased the data in the first few years after retro-commissioning or major follow up. For the third format, the average savings percentages of each year were again calculated, but this time with all year zero percentages averaged, all year one percentages averaged, etc. The fourth format did the same thing, but with cumulative savings instead of average savings, thus weighting larger energy users more heavily.

Table 6-3 shows these average savings and Figure 6-1 presents them graphically.

Table 6 - 2. Savings comparison for ten buildings in first year, maximum year, and most recent year.

Building	Utility	Savings 1997	Max Savings Achieved	Max Savings Year	Savings Most Recent Year	Most Recent Year
Blocker	CHW	27	27	1997	8	2008-09
	HW	53	81	1998	50	2006-07
	Elec	22	32	2006-07	24	2008-09
Eller	CHW	38	39	1998	29	2004
	HW	66	85	1998	41	2001
	Elec	24	25	1998	21	2004
G. Rollie White	CHW	54	75	2007-08	60	2008-09
	HW	71	97	1998	91	2008-09
	Elec	12	35	2006-07	34	2008-09
Harrington Tower	CHW	50	51	2006-07	51	2008-09
	HW	62	87	1998	65	2008-09
	Elec	22	27	2006-07	25	2008-09
Kleberg	CHW	41	53	2008-09	53	2008-09
	HW	84	97	1998	60	2008-09
	Elec	1	40	2005-06	34	2008-09
Koldus	CHW	45	46	2000	42	2008-09
	HW	NA	NA	NA	NA	NA
	Elec	12	13	2008-09	13	2008-09
Richardson	CHW	52	52	1997	32	2008-09
	HW	64	88	2000	53	2008-09
	Elec	2	2	1997	-5	2008-09
VMCA	CHW	43	44	1999	37	2002
	HW	75	75	1997	47	2001
	Elec	5	5	1997	0	2002
Wehner	CHW	36	40	2000	19	2008-09
	HW	19	88	2008-09	91	2008-09
	Elec	6	12	2008-09	12	2008-09
Zachry	CHW	59	59	1997	43	2008-09
	HW	79	79	1997	32	2008-09
	Elec	10	42	2005-06	35	2008-09

Table 6 - 3. Average savings by year for buildings with valid metered data.

Year	CHW		HW		Electricity	
	Savings	# of bldgs.	Savings	# of bldgs.	Savings	# of bldgs.
1997	45%	10	64%	9	12%	10
1998	41%	10	72%	9	12%	10
1999	38%	10	67%	9	10%	10
2000	37%	9	55%	8	9%	10
2001	35%	9	48%	6	12%	10
2002	35%	6	58%	3	15%	9
2003	34%	5	45%	3	16%	7
2004	39%	4	51%	1	11%	5
2005-06	57%	2	67%	4	30%	6
2006-07	38%	6	61%	5	29%	6
2007-08	43%	6	56%	4	26%	6
2008-09	38%	8	65%	6	21%	8

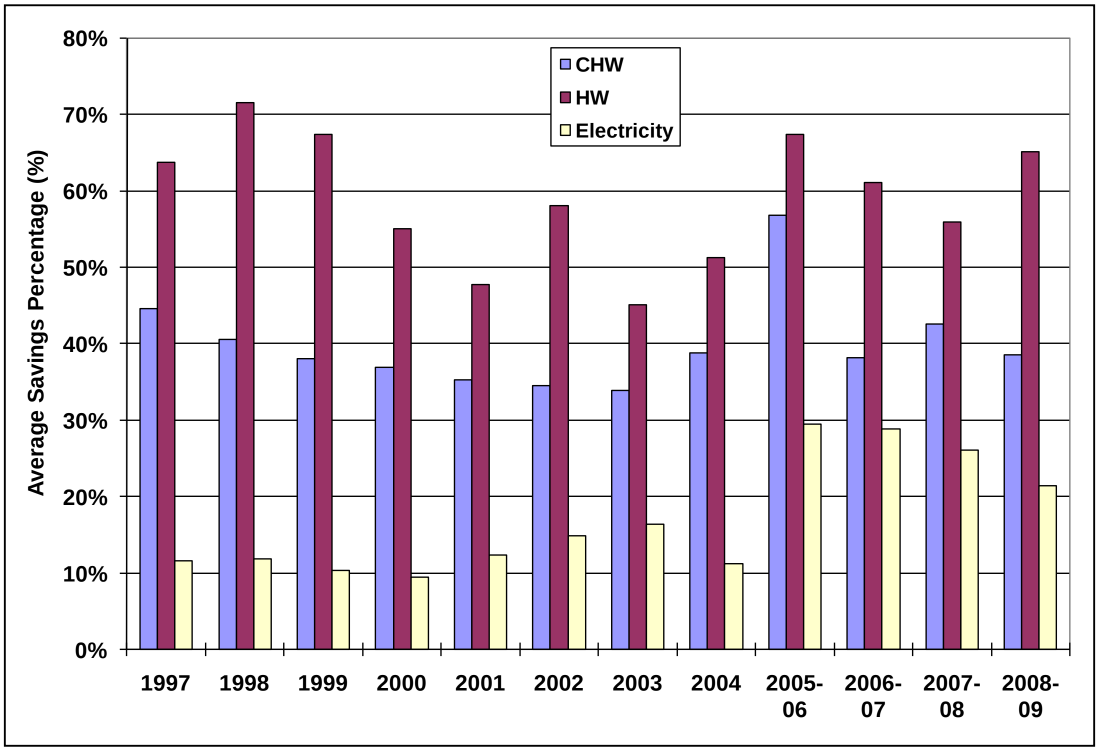


Figure 6 - 1. Average savings by utility by year for buildings with valid metered data.

The average chilled water savings for each year display a trend of slight degradation over several years, followed by a small rise in 2004, then a large rise in 2005-2006. Further degradation then occurs. The average hot water savings display at least three periods of degradation followed by increase. The average electricity savings demonstrate degradation and increase, followed by a large increase in 2005-2006, and then further degradation. The year 2005-2006 marked the first year after the new metering system was installed, as well as major lighting retrofits in several of the buildings, and a significant difference in average savings is noticeable for all three utilities over the previous year.

Table 6-4 shows the cumulative savings for each year for the buildings, and Figure 6-2 then shows these values graphically.

Table 6 - 4. Cumulative savings by year for buildings with valid metered data.

Year	**CHW**		**HW**		**Electricity**	
	Savings	**# of bldgs.**	**Savings**	**# of bldgs.**	**Savings**	**# of bldgs.**
1997	45%	10	67%	9	12%	10
1998	42%	10	80%	9	12%	10
1999	40%	10	72%	9	10%	10
2000	37%	9	63%	8	11%	10
2001	35%	9	50%	6	13%	10
2002	35%	6	60%	3	15%	9
2003	37%	5	49%	3	17%	7
2004	39%	4	51%	1	13%	5
2005-06	58%	2	81%	4	34%	6
2006-07	40%	6	68%	5	31%	6
2007-08	43%	6	65%	4	28%	6
2008-09	40%	8	67%	6	25%	8

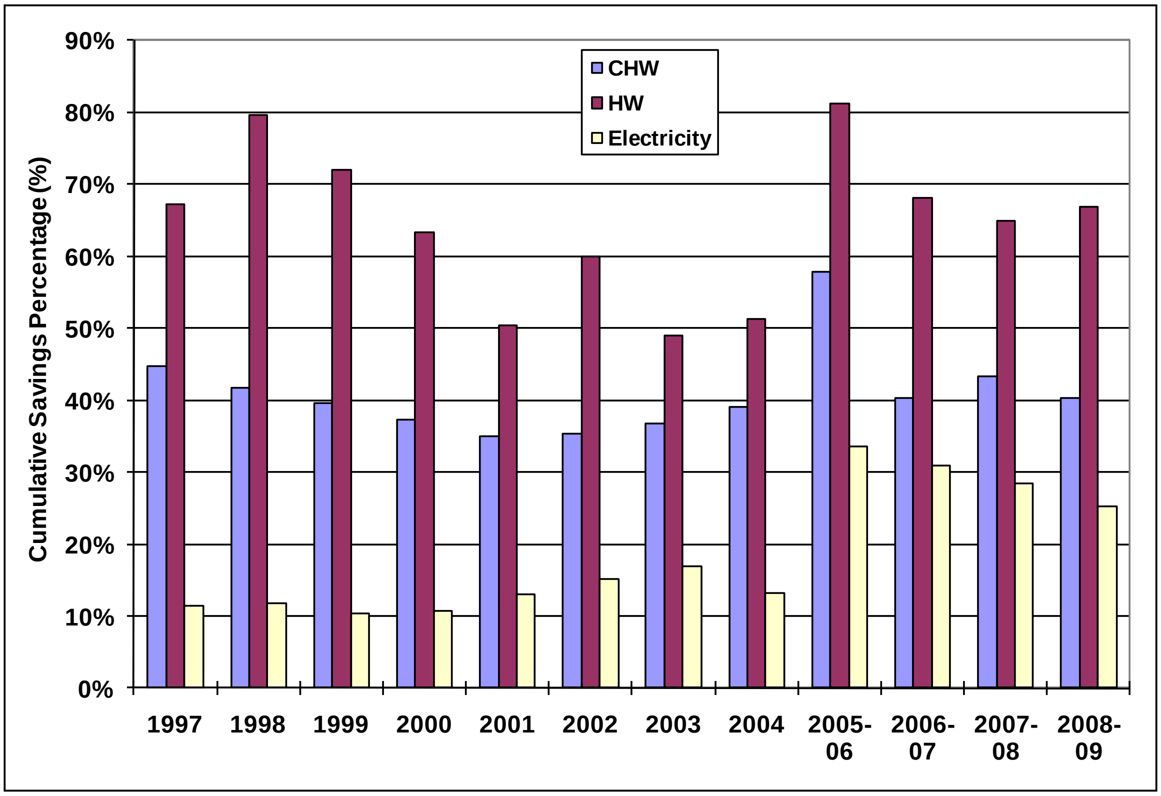


Figure 6 - 2. Cumulative savings by utility by year for buildings with valid metered data.

The trends for cumulative savings by year are very similar to those seen in the average savings trends. The large increase in savings is also noted for all three utilities in 2005-2006.

Table 6-5 shows the average savings adjusted for years with major changes or follow up, and Figure 6-3 presents them graphically.

Table 6 - 5. Average savings by year, years adjusted for major changes.

Years after RC or Follow Up	CHW		HW		Electricity	
	Savings	# of data years	Savings	# of data years	Savings	# of data years
0	43%	18	67%	26	16%	24
1	41%	19	65%	16	18%	20
2	40%	17	56%	12	15%	19
3	38%	14	51%	9	15%	16
4	33%	8	56%	2	13%	8
5	31%	4	38%	2	17%	5
6	28%	3			20%	4
7	37%	2			21%	1

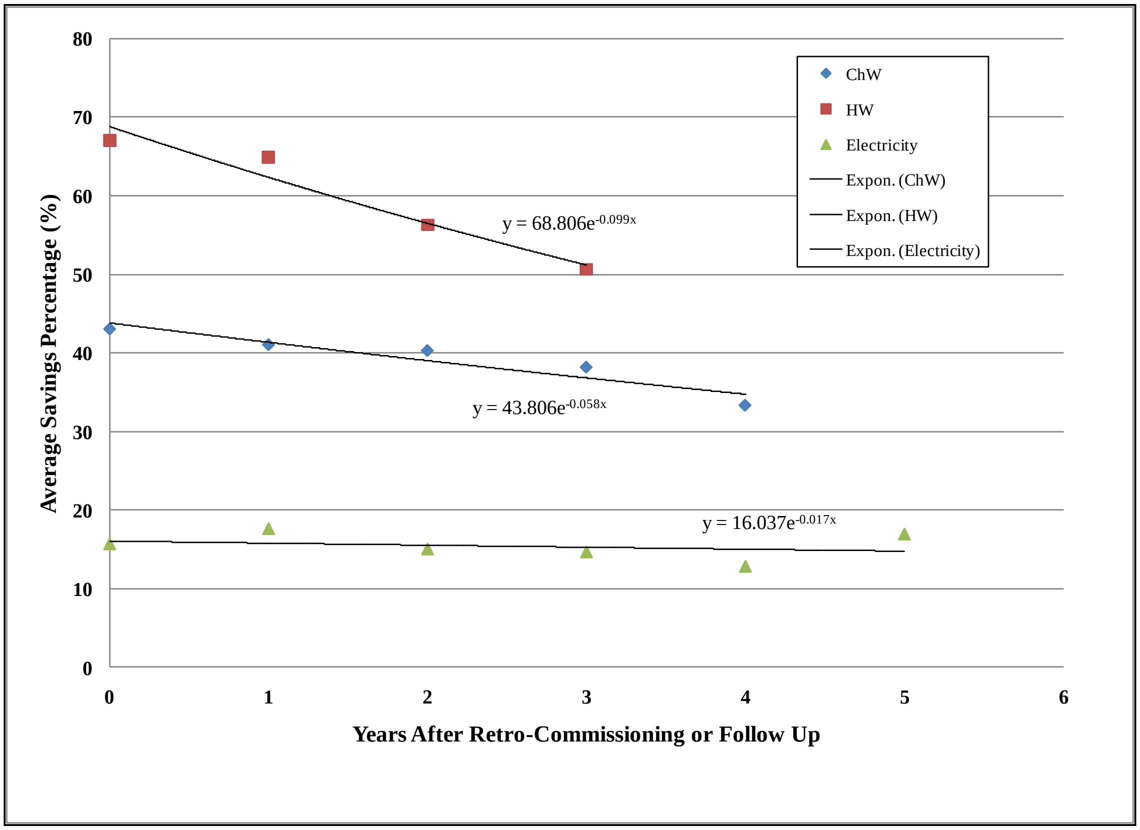


Figure 6 - 3. Average savings by utility versus number of years after major change.

When the years following major follow up work or building changes are treated the same as and grouped together with the years following initial retro-commissioning, more consistent data patterns begin to emerge. In Figure 6-3, the savings percentage points are plotted for years after retro-commissioning or follow up with at least five data sets. This allowed exponential curves to be fitted to the data to further describe the decay of savings noted in the average.

Table 6-6 shows the cumulative savings adjusted for years with major changes or follow up, and Figure 6-4 presents them graphically.

Table 6 - 6. Cumulative savings by year, years adjusted for major changes.

Years after RC or Follow Up	**CHW**		**HW**		**Electricity**	
	Savings	**# of data years**	**Savings**	**# of data years**	**Savings**	**# of data years**
0	43%	18	72%	26	16%	18%
1	42%	19	70%	16	18%	18%
2	41%	17	64%	12	15%	16%
3	39%	14	57%	9	15%	17%
4	33%	8	58%	2	13%	13%
5	32%	4	37%	2	17%	17%
6	27%	3			20%	20%
7	34%	2			21%	21%

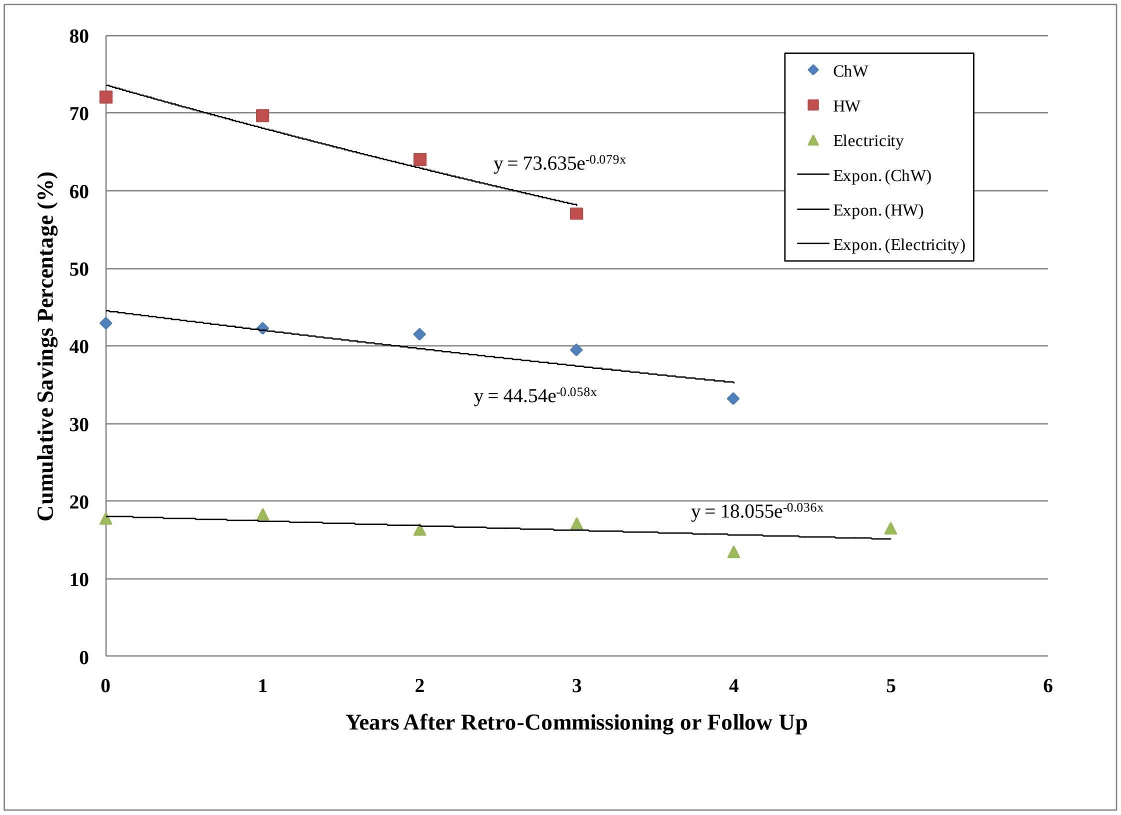


Figure 6 - 4. Cumulative savings by utility versus number of years after major change.

The cumulative savings with follow up years also treated as year zero demonstrated degradation trends very similar to those seen in the average savings graph treated in the same manner. Exponential curves were also fitted to the data points, with only those years with at least five valid data sets being included.

All of this information together shows that cumulative and average savings up to 11 years after the initial retro-commissioning still maintained levels close to, or even higher than initial savings. However, taking into consideration the follow up work that occurred in many of the buildings, the metering changes that occurred, the lighting retrofits and other major changes, the picture emerges that initial savings after a major event do degrade with time, in a way that can even be modeled exponentially.

From this study, some conclusions can be drawn about retro-commissioning savings persistence. In two of the buildings (G. Rollie White and Kleberg), major mechanical problems and significant control parameter changes led to dramatic reductions in savings in years after retro-commissioning. However, these increases were noticed by energy management personnel, and follow-up retro-commissioning work was able to be performed, after which savings improved significantly. From these examples it can be concluded that continuous monitoring and comparison of energy consumption in a facility is critical for identifying when follow up work might be needed due to unexpected changes in consumption.

This study found two of the buildings, the Eller O&M building and the Veterinary Medical Center Addition, which did not have any follow up retro-commissioning work performed after the initial round of retro-commissioning, at least during the years when valid metered data were available (the Eller O&M underwent retro-commissioning again in 2008, but no metered data were available after 2004). These two buildings experienced little degradation in chilled water or electricity savings, but both had some degradation in hot water savings.

The remaining eight buildings had some sort of retro-commissioning follow up work performed after the initial round of retro-commissioning. For some, this was just selected follow up that was a result of comfort complaints or unusual energy patterns, but for several of the buildings full rounds of retro-commissioning were performed again, sometimes even a third time. These appeared to be effective insofar as recommended measures were implemented, though they appear to have had less effect than the initial round of retro-commissioning, since much of the savings potential had already been recovered the first time. The implementation of recommended measures during this time was also not as complete as in the initial retro-commissioning.

One thing that was common for all of the facilities was that control parameter changes were made in all of the facilities over the years evaluated, and in most cases at least some changes were made outside of what was recommended during retro-commissioning work. This phenomenon demonstrates that energy management personnel felt the need to occasionally make changes to parameters set during retro-commissioning. In some cases this was done to further energy efficiency, such as implementing demand based AHU reset schedules in place of those based only on outside air temperature. But more often than not the parameter changes were most likely based on complaints from occupants or from changes in building usage that required changes.

From this set of buildings evaluated over a lengthy period of time, it can be concluded that even without retro-commissioning follow up work, some buildings will demonstrate a reasonably good level of savings persistence, while others will degrade significantly. As a whole, however, it can be concluded that on average savings will degrade over time after retro-commissioning or follow up work is performed, and this can even be modeled exponentially. Therefore, follow up retro-commissioning work is a good idea in order to maintain savings levels. Through this follow up work, maintenance problems contributing to savings degradation can be identified, and building usage changes can be optimally dealt with for maximum efficiency. Improving retro-commissioning knowledge and technology also opens the door to improving savings levels beyond what was originally achieved, such as in the cases of implementing demand based reset schedules over those just based on outside air temperature.

The frequency with which retro-commissioning follow up should be performed in a facility largely depends on the facility. Its level of maintenance is a good indicator of how often follow up might be needed. Also, major changes in usage generally present appropriate opportunities for follow up. The best method for determining when follow up is needed is through energy monitoring, to identify unusual consumption patterns. This study also provided some exponential fit curves modeling average savings degradation over a five to seven year period. While every facility is different, these models have the potential to be useful in helping a facility owner determine how often to pursue retro-commissioning follow up, since degradation levels could be predicted.

More work is needed in order to determine how to apply the findings from this study to future real world commissioning projects. Something that may be considered for future work would be to consolidate the findings from all of the work done thus far on persistence of commissioning and retro-commissioning savings, including the current study, and determine if a general exponential decay model can be determined that would describe the degradation in savings that could be expected over time. As more data become available regarding persistence of savings, this model could become more and more useful for assisting building owners in determining the frequency with which retro-commissioning should be performed. It may also be beneficial in the future to look at the same analysis using monthly data.

REFERENCES

ASHRAE, 2002, ASHRAE Guideline 14-2002, Measurement of Energy and Demand Savings, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE, 2005, ASHRAE Guideline 0, The Commissioning Process, Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Baltazar, J. and D. Claridge. 2006. Study of cubic splines and fourier series as interpolation techniques for filling in short periods of missing building energy use and weather data. *ASME Journal of Solar Energy Engineering*, Vol. 128, May, pp. 226-230.

Baltazar, J., Y. Sakurai, H. Masuda, D. Feinauer, J. Liu, J. Ji, D. Claridge, S. Deng, and H. Bruner. Experiences on the implementation of the 'energy balance' methodology as a data quality control tool: application to the building energy consumption of a large university campus. *Proceedings of the 2007 International Conference for Enhanced Building Operations*, 31 Oct. 2007, Energy Systems Laboratory. College Station, Texas: Texas A&M University, 2007.

Bourassa, N.J., M.A. Piette, N. Motegi. 2004. Evaluation of persistence of savings from SMUD Retro-commissioning Program - Final Report. Lawrence Berkeley National Laboratory, LBNL-54984.

Chen, Hui, Song Deng, Homer Bruner, David Claridge and W.D. Turner. 2002. Continuous commissioning^{SM} results verification and follow-up for an institutional building - A case study. *Proc. 13th Symposium on Improving Building Systems in Hot and Humid Climates* 87-95.

Cho, Sool Yeon. 2002. The persistence of savings obtained from commissioning of existing buildings. M.S. Thesis, Mechanical Engineering Department, Texas A&M University, ESL-TR-02-05-01, 347 pp.

Claridge, D.E., W.D. Turner, M. Liu, S. Deng, G. Wei, C. Culp, H. Chen and S.Y. Cho. 2002. Is commissioning once enough? *Solutions for Energy Security & Facility Management Challenges: Proc. of the 25th WEEC* 29-36.

Claridge, D.E., W.D. Turner, M. Liu, S. Deng, G. Wei, C. Culp, H. Chen and S.Y. Cho. 2004. Is commissioning once enough? *Energy Engineering* 101(4):7-19.

Claridge, D.E., N. Bensouda, S.U. Lee, G. Wei, K. Heinemeir and M. Liu. 2003. Manual of Procedures for Calibrating Simulations of Building Systems, 81 pp.

Continuous Commissioning® Guidebook for Federal Energy Managers

Eardley, Mike. 2007. Persistence tracking in a retro-commissioning program. *Proceedings of the 2007 National Conference on Building Commissioning.*

Engan, Kenneth. 2007. A comparison of commissioning savings determination methodologies and the persistence of commissioning savings in three buildings. M.S. Thesis. Mechanical Engineering Department, Texas A&M University.

Fels, M. 1986. PRISM: an introduction. *Energy and Buildings*, Vol. 9, pp. 5-18.

Friedman, H., A. Potter, T. Haasl and D. Claridge. 2002. Persistence of benefits from new building commissioning. *Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings* 3.129 – 3.140.

Friedman, H., A. Potter, T. Haasl, D. Claridge and S. Cho. 2003. Persistence of benefits from new building commissioning. *Proc. of 11th National Conference on Building Commissioning* 15 pp.

Friedman, H., A. Potter, T. Haasl, and D. Claridge. 2003. Report on strategies for improving persistence of commissioning benefits - final report. 47 pp.

Haberl, J. and C. Culp. 2003. Review of Methods for Measuring and Verifying Savings from Energy Conservation Retrofits to Existing Buildings. ESL-TR-03-09-01.

Haberl, J. and S. Cho. 2004. Literature review of uncertainty of analysis methods (inverse model toolkit). Report to the Texas Commission on Environmental Quality. ESL-TR-04-10-03.

IPMVP 2001. IPMVP Committee. *International performance measurement & verification protocol: concepts and options for determining energy and water savings*, Vol. 1, U.S. Dept. of Energy, DOE/GO-102001-1187, 86 pp.

IPMVP 2007. IPMVP Committee. *International performance measurement & verification protocol: concepts and options for determining energy and water savings*, Vol. 1, April 2007, Efficiency Valuation Organization, EVO 10000-1.2007, 123 pp.

Kissock, J.K. 1993. A methodology to measure energy savings in commercial buildings. Ph.D. Dissertation, Mechanical Engineering Department, Texas A&M University, College Station, TX, December.

Kissock, J.K. 1994. Modeling commercial building energy use with artificial neural networks. *Proceedings of the 29th Intersociety Energy Conversion Engineering Conference*, Vol. 3, pp. 1290-1295, Monterey, CA, August.

Liu, C., W.D. Turner, D. Claridge, S. Deng and H.L. Bruner. 2002. Results of CC follow-up in the G. Rollie White Building. *Proc. 13th Symposium on Improving Building Systems in Hot and Humid Climates* 96-102.

Mills, E., H. Friedman, T. Powell, N. Bourassa, D. Claridge, T. Haasl and M. Piette. 2004. The cost-effectiveness of commercial buildings commissioning: A metaanalysis of energy and non-energy impacts in existing buildings and new construction in the United States. LBNL-56637.

Mills, E., N. Bourassa, M.A. Piette, H. Friedman, T. Haasl, T. Powell and D. Claridge. 2005. The Cost-effectiveness of commissioning new and existing commercial buildings: Lessons from 224 buildings. *Proceedings of the 2005 National Conference on Building Commissioning*.

Mills, Evan. 2009. Building commissioning: A golden opportunity for reducing energy costs and greenhouse gas emissions. Report prepared for California Energy Commission Public Interest Energy Research (PIER). 59 pp.

Peterson, Janice. 2005. Evaluation of retro-commissioning results after four years: A case study. *Proceedings of the 2005 National Conference on Building Commissioning*.

Portland Energy Conservation, Inc. (PECI), 2001, Retrocommissioning Handbook for Facility Managers, Oregon Office of Energy, 55 pp.

Ruch, D. and D. Claridge. 1992. A four-parameter change-point model for predicting energy consumption in commercial buildings. *ASME Journal of Solar Energy Engineering*, Vol. 114, No. 2, pp. 77 -83.

Schrock, D. and D. Claridge. 1989. Predicting energy usage in a supermarket. *Proceedings of the Sixth Symposium on Improving Building Systems in Hot and Humid Climates.* pp. 44 – 54.

Selch, M. and J. Bradford. 2005. Recommissioning energy savings persistence. *Proceedings of the 2005 National Conference on Building Commissioning.*

Shao, X. and D. Claridge. 2006. Use of first law energy balance as a screening tool for building energy data, part I – methodology. *ASHRAE Transactions – Research*, Vol. 112, Part 2, QC-06-068.

Turner, W.D., D.E. Claridge, S. Deng, S. Cho, M. Liu, T. Hagge, C. Darnell, Jr. and H. Bruner, Jr. 2001. Persistence of savings obtained from continuous commissioning^{SM}. *Proc. of 9th National Conference on Building Commissioning* 20(1):1-13.

Vine, Edward L. 1992. Persistence of Energy Savings: What Do We Know And How Can It Be Ensured? *Energy* 17(11):1073-1084.

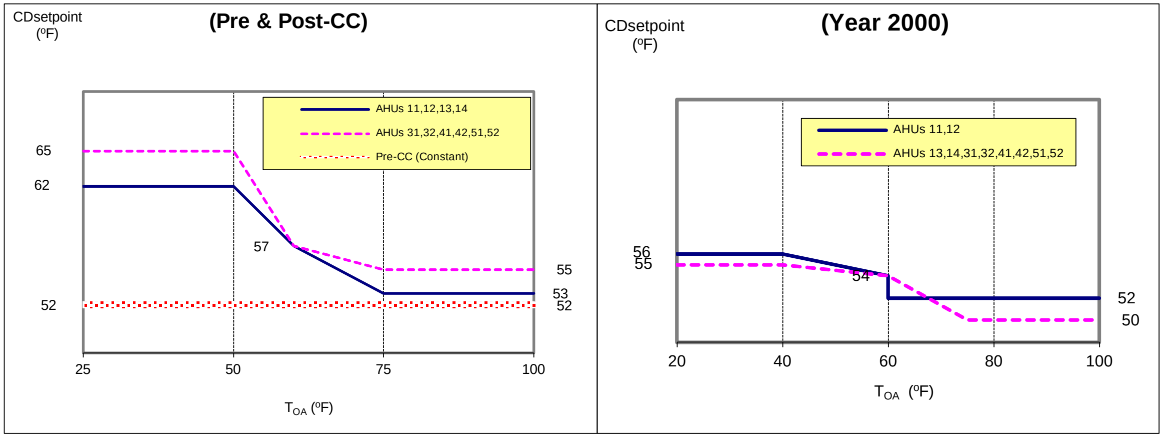
APPENDIX A

CONTROL SETTINGS

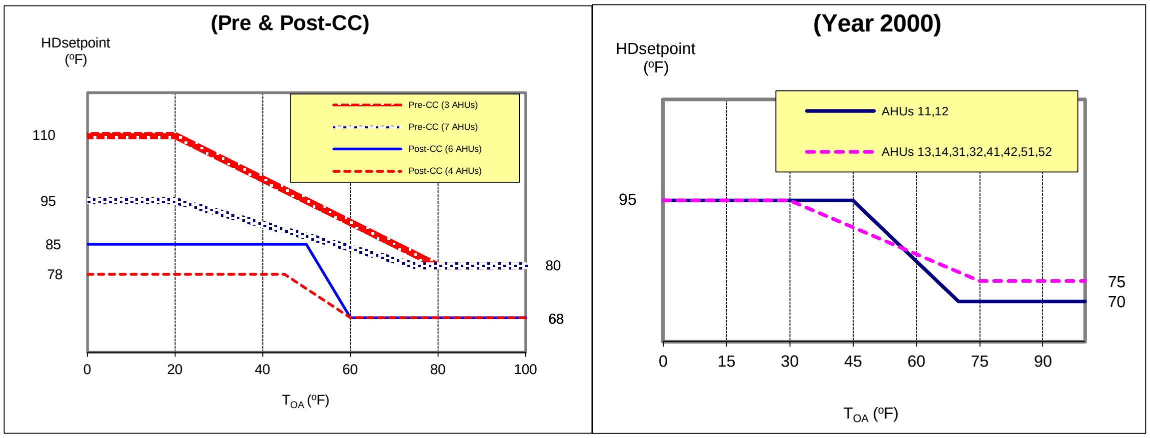
This appendix describes the control system settings in each of the buildings at different points throughout this study. The documentation of settings from pre-retro-commissioning periods to 2000 was done by Cho (2002) and is included as well for comparison.

Blocker

Cold Deck Settings



Hot Deck Settings



Static Pressure Settings

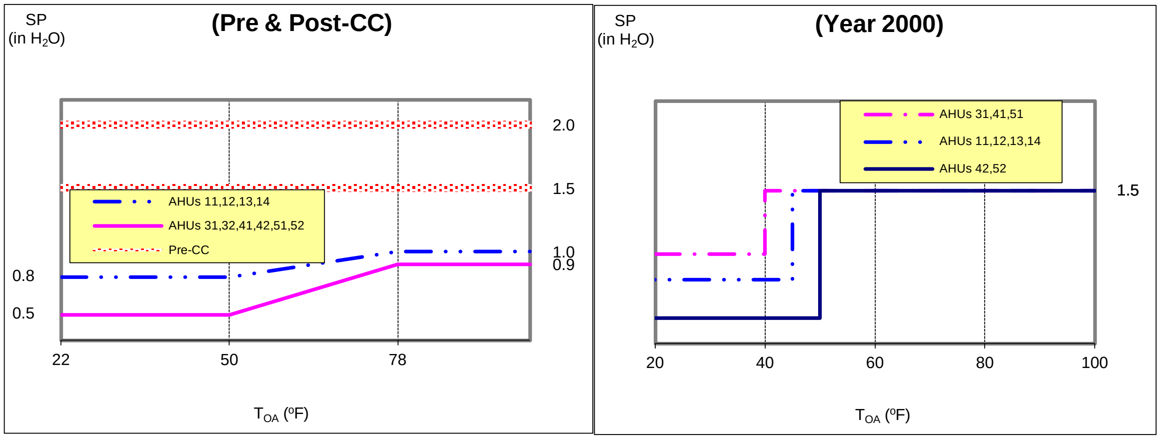


Figure A - 1. Control changes of cold deck, hot deck and static pressure for the Blocker building as a function of outside air temperature for the pre-CC, post-CC and year 2000 periods (Cho 2002).

Blocker 2006-2009 settings:

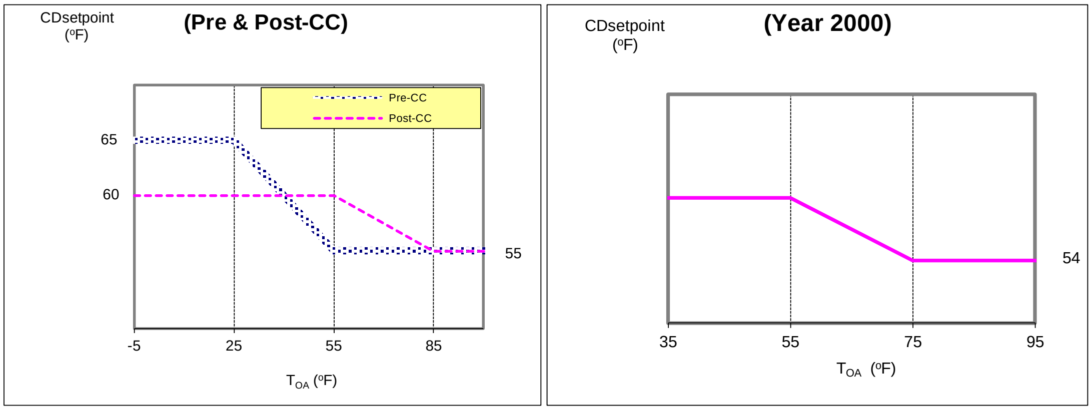
Cold deck temperature varies from 48°F to 58°F based on a weighted average of terminal box cooling demand for the terminal boxes served by each AHU.

Hot deck temperature set point varies from 72°F to 95°F based on a weighted average of the terminal box heating demand for the terminal boxes served by each AHU.

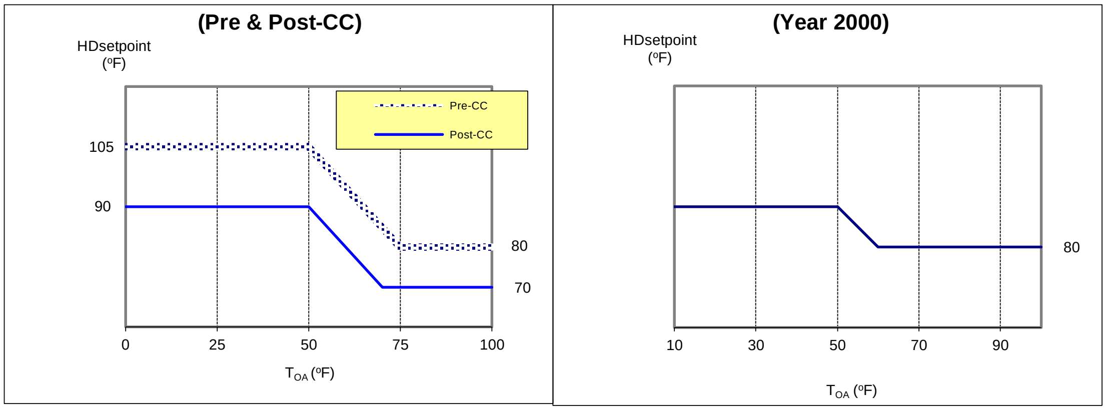
Static pressure set point varies from 0.5 to 2.0 in. W.G. based on a weighted average of the terminal box damper positions for the terminal boxes served by each AHU.

Eller

Cold Deck Settings



Hot Deck Settings



Static Pressure Settings

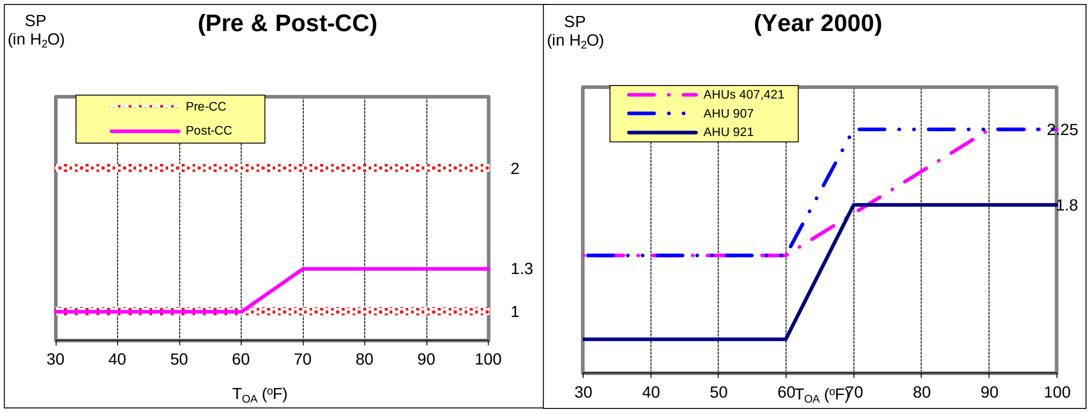


Figure A - 2. Control changes of cold deck, hot deck and static pressure for the Eller building as a function of outside air temperature for the pre-CC, post-CC and year 2000 periods (Cho 2002).

Eller 2006 settings:

Cold deck temperature varies from 52°F to a maximum temperature based on a weighted average of terminal box cooling demand for the terminal boxes served by each AHU. The maximum temperature is determined by outside air enthalpy according to the following table statement: Table(h_OA,max,26,60,29,56,31,54).

Hot deck temperature set point varies from 74°F to 110°F based on a weighted average of the terminal box heating demand for the terminal boxes served by each AHU.

Static pressure set point varies from 0.5 to 2.45 in. W.G. based on a weighted average of the terminal box damper positions for the terminal boxes served by each AHU.

G. Rollie White

Cold Deck Settings

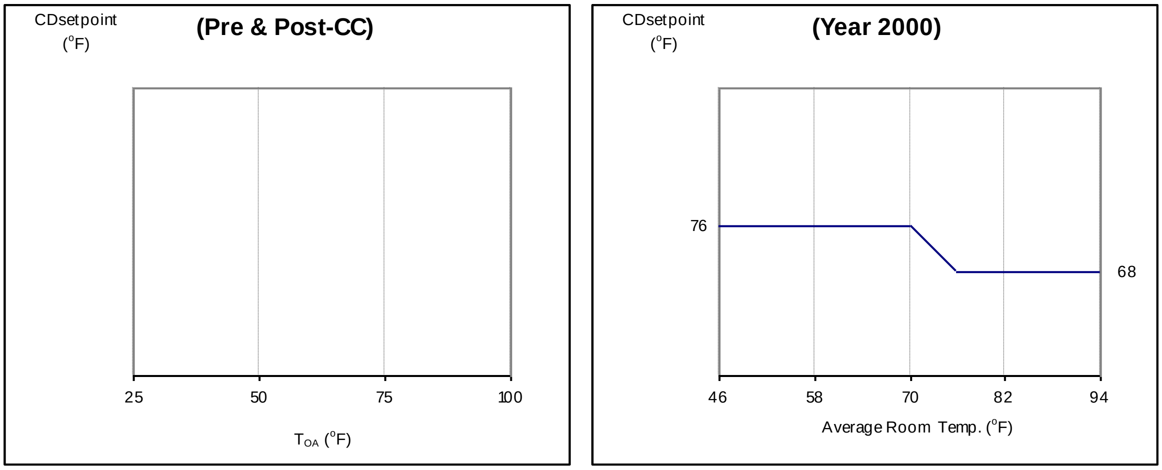


Figure A - 3. Control changes of cold deck for the G.R. White Coliseum as a function of average room air temperature for the pre-CC, post-CC and year 2000 periods (Cho 2002).

Control Schedules were not available for the pre-CC and post-CC Periods.

G. Rollie White 2006 settings:

AHUs control to space temperature only, and valves control to maintain space temperature at its setpoint. AHU discharge air temperature is not considered in the programming.

Harrington

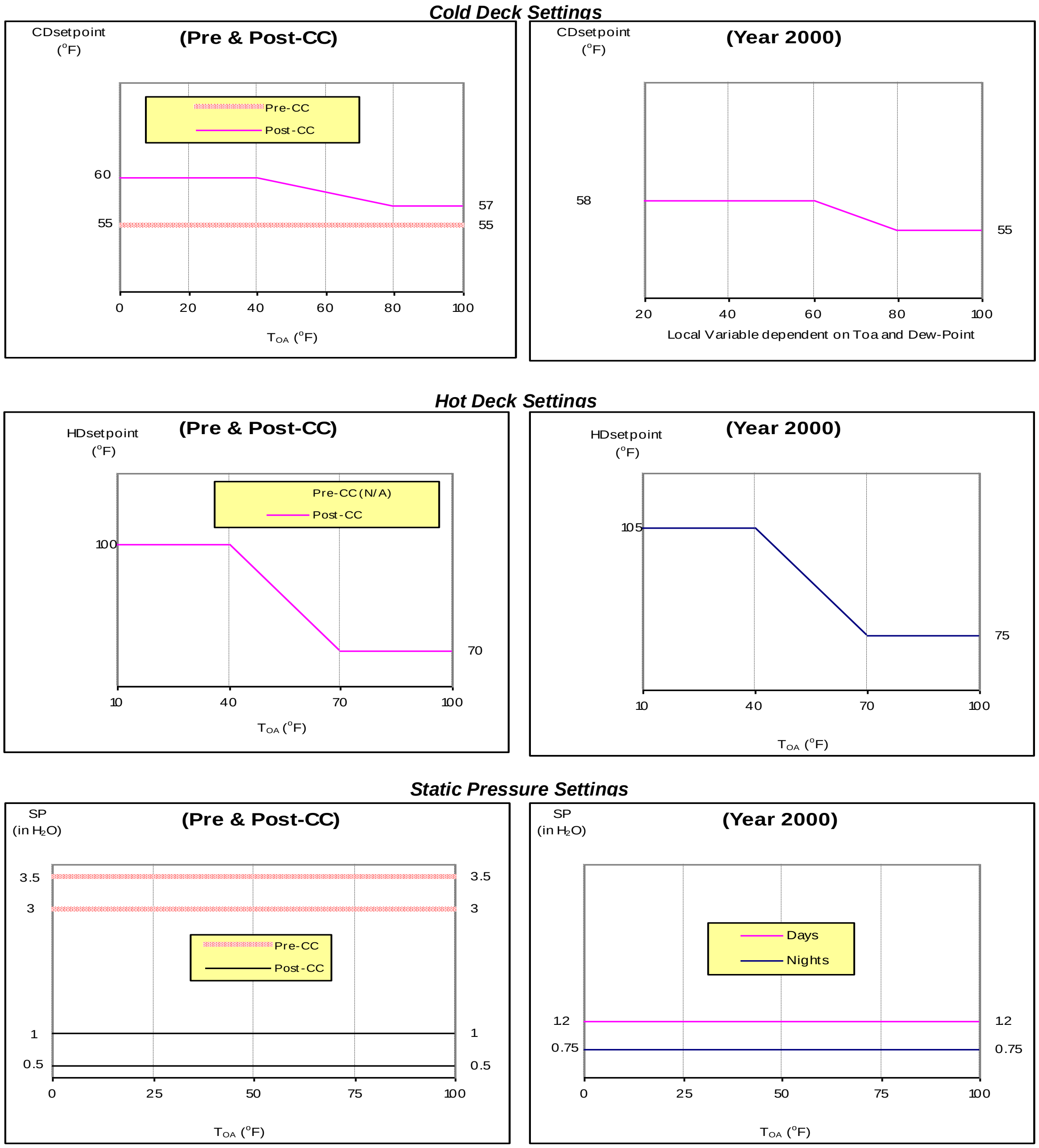


Figure A - 4. Control changes of cold deck, hot deck and static pressure for the Harrington Tower as a function of outside air temperature for the pre-CC, post-CC and year 2000 periods (Cho 2002).

Harrington 2006 settings:

Cold deck temperature set point varies with outside air temperature according to the following table statement: Table(T_OA,CDT,40,60,80,57,90,55).

Hot deck temperature set point varies with outside air temperature according to the following table statement: Table(T_OA,HDT,40,100,70,80).

Static pressure set point is a constant 1.2 in. W.G. during the day, and 0.75 in. W.G. at night.

Harrington 2009 settings:

Cold deck temperature varies from 50°F to 60°F based on a weighted average of terminal box cooling demand for the terminal boxes served by each AHU.

Hot deck temperature set point varies from 73°F to 115°F based on a weighted average of the terminal box heating demand for the terminal boxes served by each AHU.

Static pressure set point varies from 0.5 to 3.5 in. W.G. based on a weighted average of the terminal box damper positions for the terminal boxes served by each AHU.

Kleberg

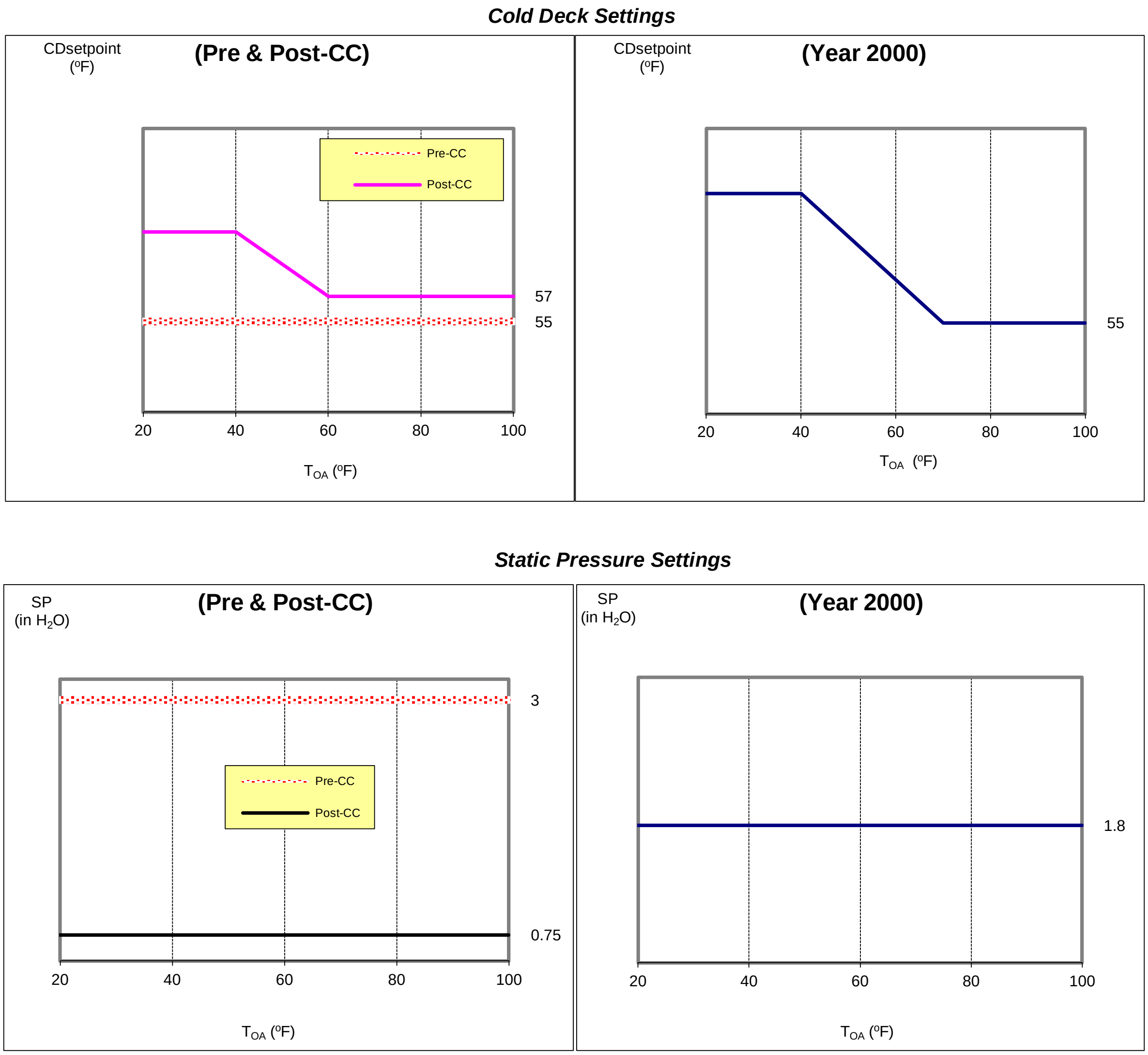


Figure A - 5. Control changes of cold deck and static pressure for the Kleberg building as a function of outside air temperature for the pre-CC, post-CC and year 2000 periods (Cho 2002).

Kleberg 2006 settings:

All are the same as the 2000 settings.

Kleberg 2009 settings:

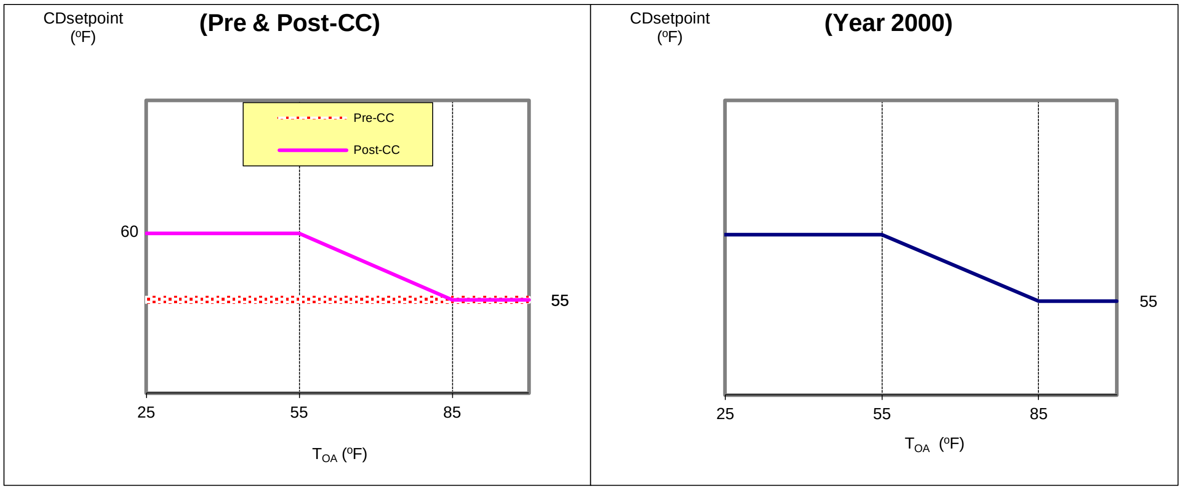
Static pressure settings are the same as 2000 settings.

Cold deck temperature varies with outside air according to the following table statement:

Table (OAT,CDT,40,65,70,60,80,58,100,55).

Koldus

Cold Deck Settings



Static Pressure Settings

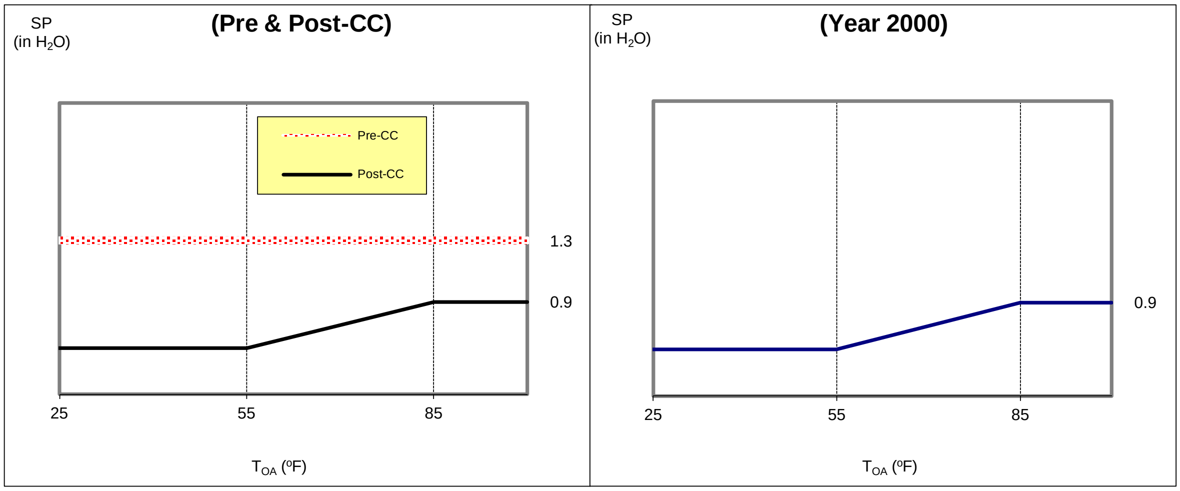


Figure A - 6. Control changes of cold deck and static pressure for the Koldus building as a function of outside air temperature for the pre-CC, post-CC and year 2000 periods (Cho 2002).

Koldus 2006-2009 settings:

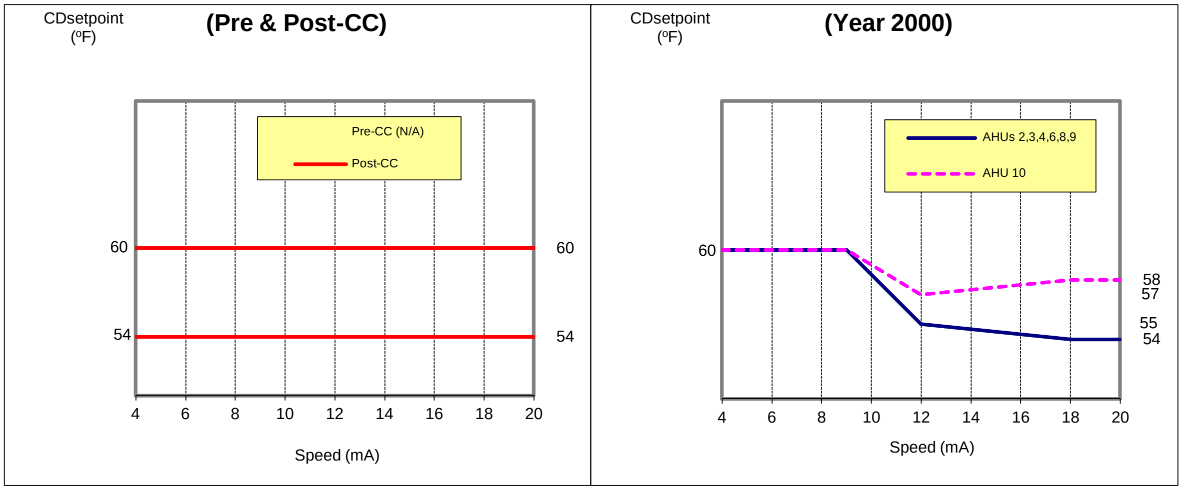
Cold deck temperature varies with outside air according to the following table statement:

Table (OAT,CDT,55,62,85,55).

Static pressure set point varies with outside air according to the following table statement: Table (OAT,SP,55,0.5,85,0.7).

Richardson

Cold Deck Settings



Static Pressure Settings

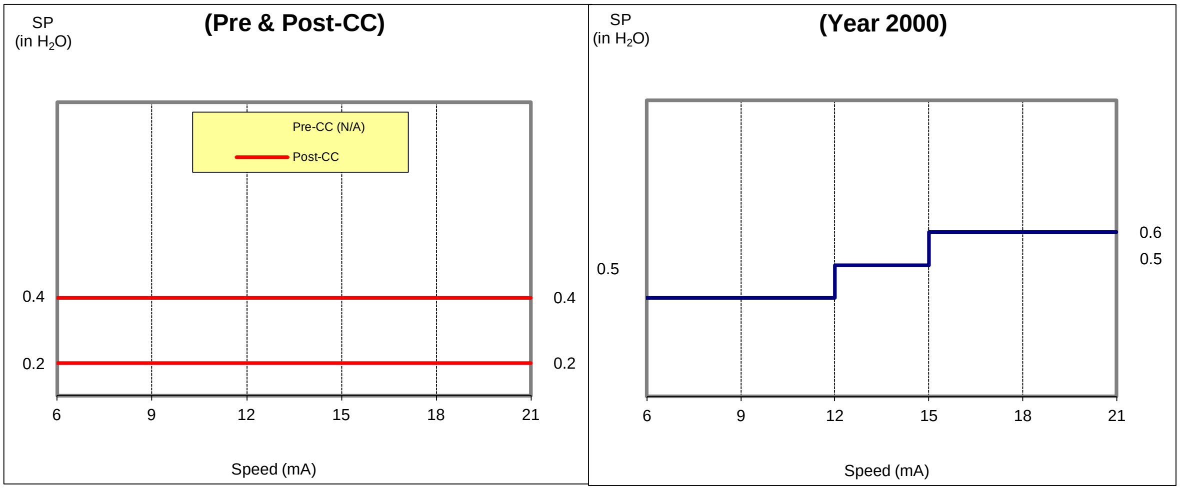


Figure A - 7. Control changes of cold deck and static pressure for the Richardson Petroleum building as a function of outside air temperature for the pre-CC, post-CC and year 2000 periods (Cho 2002).

Richardson 2006 settings:

Cold deck temperature set point varies with AHU fan speed (4 to 20 mA) or with outside air temperature according to the following table statements:

AHUs 2, 3, 4: Table(Speed,CDT,9,58,12,55,17,53)

AHUs 6, 9: Table(Speed,CDT,9,60,12,55,18,54)

AHUs 8, 10: Table(OAT,CDT,40,60,60,58,73,55)

Static pressure set point varies with AHU fan speed (4 to 20 mA) according to the following table statements:

AHU 2: Table(Speed,SP,12,0.6,15,0.8)

AHUs 3, 4: Table(Speed,SP,12,0.4,15,0.6)

AHU 6: Table(Speed,SP,12,0.4,13.5,0.5,15,0.6)

AHUs 8,9: Table(Speed,SP,12,0.3,13.5,0.4,15,0.5)

AHU 10: Table(Speed,SP,12,0.4,13.5,0.5,15,0.7)

Richardson 2009 settings:

Cold deck temperature set point varies from 57°F to 70°F with AHU fan speed when outside air dew point temperature is less than or equal to 55°F. When outside air dew point temperature is greater than 55°F, cold deck temperature set point remains at 57°F.

Static pressure set point varies with AHU fan speed (4 to 20 mA) according to the following table statements:

AHU 2: Table(Speed,SP,12,0.6,15,0.8)

AHU 3: Table(Speed,SP,12,0.4,15,0.6)

AHUs 4, 6: Constant 0.4

AHUs 8, 9: Table(Speed,SP,12,0.3,13.5,0.4,15,0.5)

AHU 10: Table(Speed,SP,12,0.4,13.5,0.5,15,0.7)

VMCA

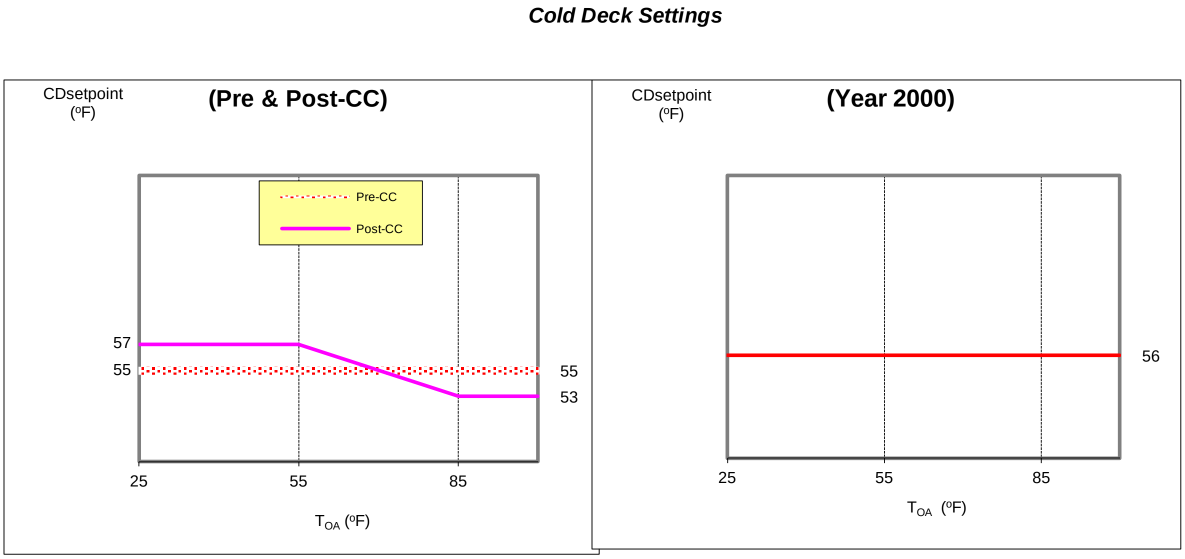


Figure A - 8. Control changes of cold deck for the VMC Addition as a function of outside air temperature for the pre-CC, post-CC and year 2000 periods (Cho 2002).

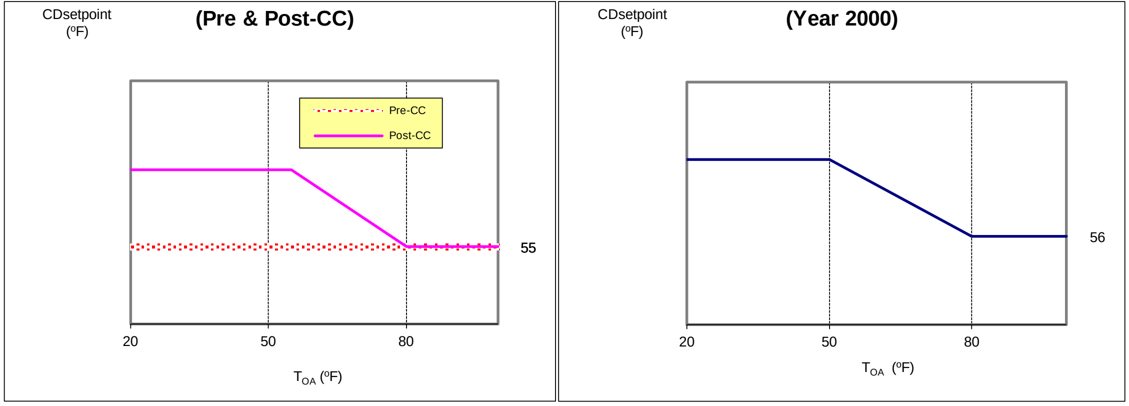
VMCA 2006 settings:

Cold deck temperature set point varies with outside air temperature according to the following table statement: Table(T_OA,CDT,55,62,85,55).

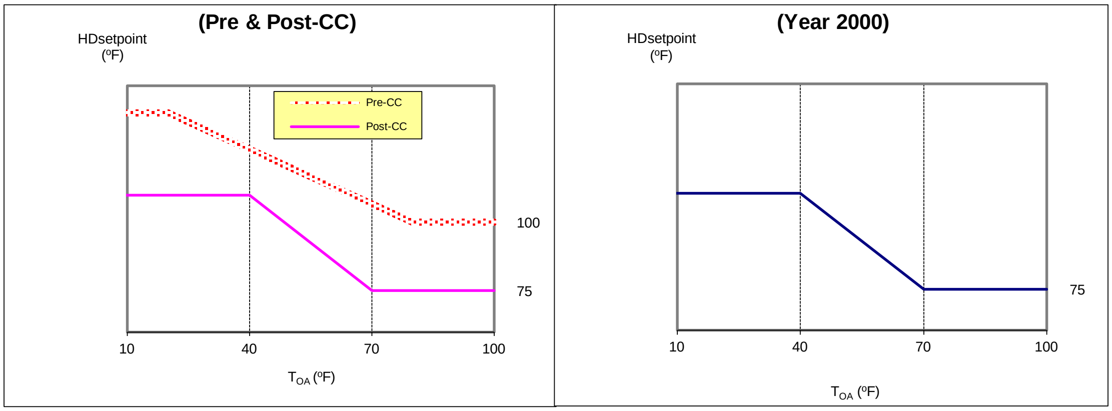
Static pressure set point is a constant 1.6 in. W.G.

Wehner

Cold Deck Settings



Hot Deck Settings



Static Pressure Settings

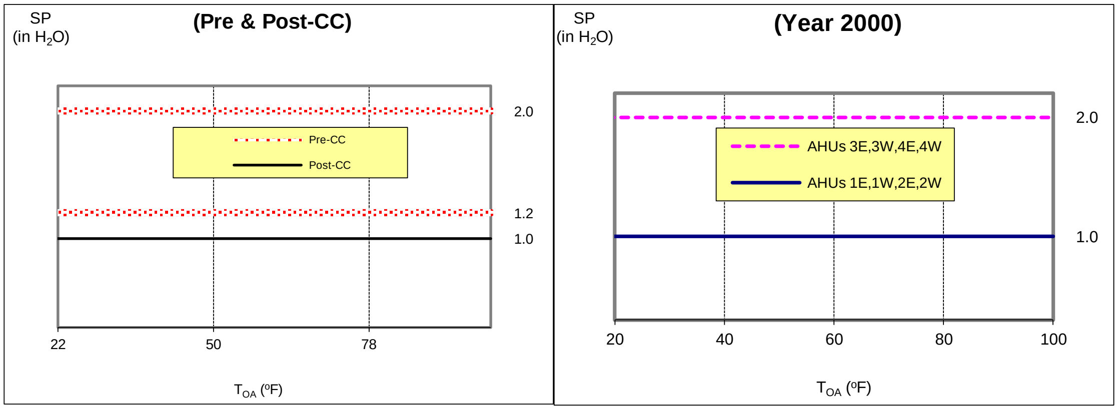


Figure A - 9. Control changes of cold deck, hot deck and static pressure for the Wehner building as a function of outside air temperature for the pre-CC, post-CC and year 2000 periods (Cho 2002).

Wehner 2009 settings:

Cold deck temperature varies from 54°F to 57°F based on a weighted average of terminal box cooling demand for the terminal boxes served by each AHU.

Hot deck temperature set point varies from 72°F to 110°F based on a weighted average of the terminal box heating demand for the terminal boxes served by each AHU.

Static pressure set point varies from 0.3 to 1.75 in. W.G. based on a weighted average of the terminal box damper positions for the terminal boxes served by each AHU.

Zachry

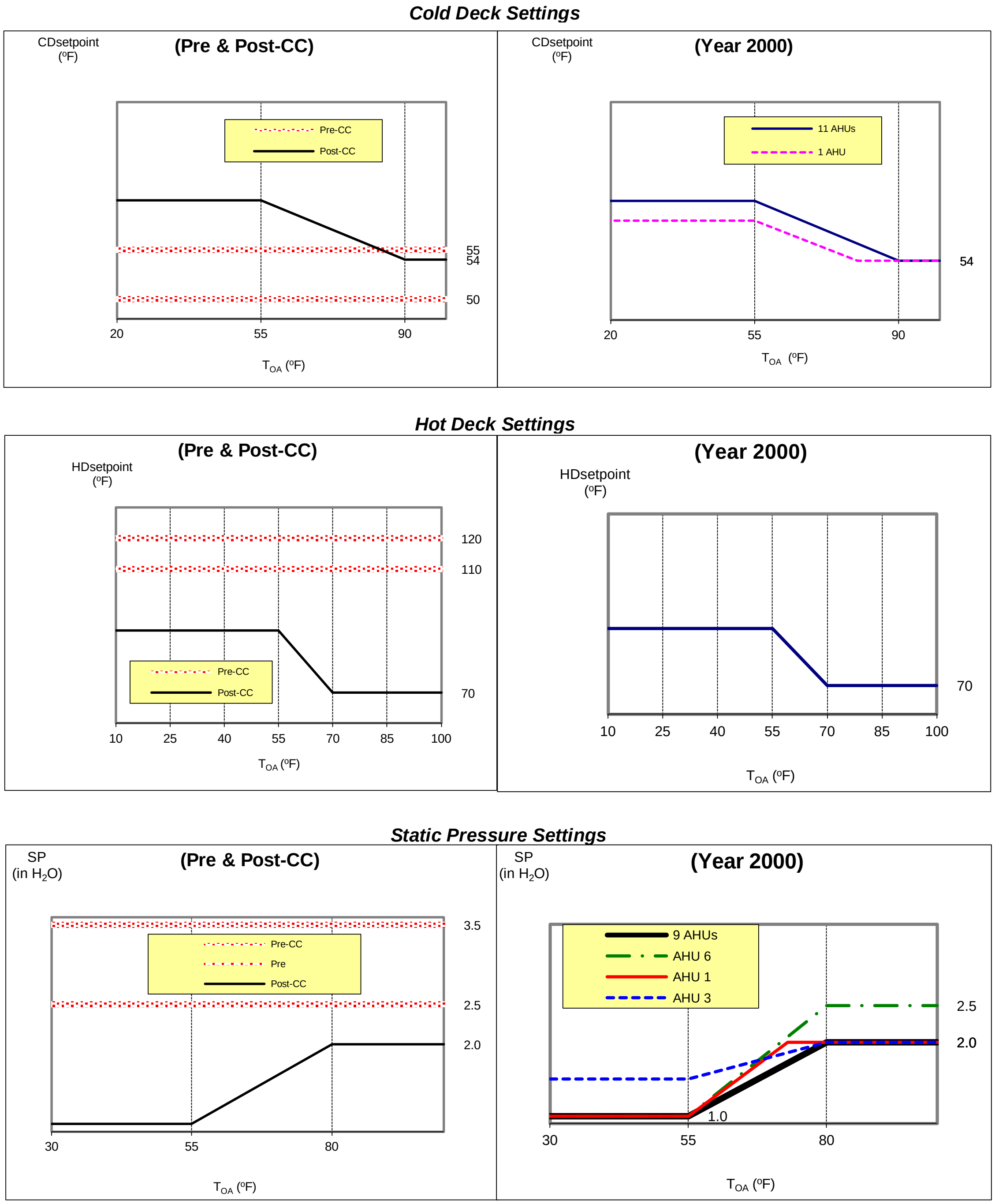


Figure A - 10. Control changes of cold deck, hot deck and static pressure for the Zachry building as a function of outside air temperature for the pre-CC, post-CC and year 2000 periods (Cho 2002).

Zachry 2006-2009 Settings:

Cold deck temperature set point varies with outside air temperature according to the following table statement: Table(T_OA,CDT,50,58,100,53).

Hot deck temperature set point varies with outside air temperature according to the following table statement: Table(T_OA,HDT,50,90,70,Mixed Air Temperature).

Static pressure set point varies with outside air temperature according to the following table statement: Table(T_OA,SP,60,1.5,90,2.25).

APPENDIX B

ABSOLUTE PRECISIONS

Figure B-1 shows the consumption estimate for each commodity, building, and year that data were available, along with the absolute precision of each estimate at the 90% confidence interval. Note that the uncertainty in the electricity data is assumed to be zero since it is a utility meter with an entire year of hourly/daily observations. Also the electricity consumption data were not adjusted to any other set of conditions, as they did not display dependency on an independent variable.

Table B-1. Consumption estimate for each commodity with calculated precision reported at the 90% confidence interval.

Building Name	Type	Baseline		1997		1998		1999		2000		2001		2002		2003		2004		2005-2006		2006-2007		2007-2008		2008-2009	
		Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr	Use (MMBtu) (MWh) / yr	+/- (MMBtu) (MWh) / yr
Blocker	CHW	22,955	458	16,723	402	19,530	420	20,164	357			19,082	298	17,887	213	20,850	212		197			21,179	309	20,283	205	21,142	344
	HW	8,735	309	4,093	310	1,676	257	3,330	310			4,623	188	2,654	168	6,367	161			2,158	106	4,409	338		181		159
	Elec	4,832		3,773		3,883		3,936		3,859		3,639		3,516		3,583				3,273		3,535		3,561		3,668	
Eller O&M	CHW	30,625	759	18,846	470	18,660	469	19,012	436	20,360	470	24,002	295	21,120	224	19,948	168	21,805	199								
	HW	7,584	509	2,578	297	1,154	252	1,831	218	4,712	483	4,488	409					NA									
	Elec	4,891		3,698		3,675		3,823		3,874		3,972		3,732		3,745		3,861									
G.R.White Coliseum	CHW	18,872	409	8,717	255	8,511	333	14,548	604	15,858	567									6,837	359	11,134	331	4,628	427	7,491	626
	HW	21,155	379	6,091	302	549	136	4,923	578	10,111	599									3,276	170	2,216	128	2,111	94	1,983	120
	Elec	1,480		1,297		1,168		1,171		1,291		1,102		1,028		1,015		1,109		1,028		956		986		979	
Harrington Tower	CHW	14,179	276	7,109	235	8,420	293	7,660	267	9,032	302	8,380	113	9,267	118	8,614	98	7,817	105	7,103	154	6,927	187	8,789	135	6,905	119
	HW	6,896	439	2,603	302	914	176	1,629	226	3,519	219			3,921	119	3,538	116			2,966	62	2,807	124	3,559	58	2,400	77
	Elec	1,666		1,297		1,336		1,341		1,353		1,319		1,331		1,390				1,293		1,220		1,294		1,253	
Kleberg Building	CHW	59,271	998	34,864	1086	34,969	1141	36,731	1166	41,965	1332	45,187	901	37,180	916	31,911	526	33,560	682		318	28,831	711	30,088	410	28,098	492
	HW	40,812	1144	6,523	871	1,215	165	8,030	817	10,591	1080										366	12,989	838	15,266	466	16,450	529
	Elec	5,511		5,458		5,067		4,778		4,684		4,539		4,564		4,832		4,666		3,320		3,533		3,828		3,662	
Koldus Building	CHW	21,964	NA	12,177	237	12,988	229	12,740	235	11,804	248	12,735	156								176	13,784	120	13,419	124	12,780	115
	HW	2,103	71	704	65	399	40	634	50	649	56	390	40								74	4,225	74	4,429	67	4,173	66
	Elec	2,850		2,511		2,597		2,624		2,592		2,603		2,667				2,682		2,553		2,546		2,621		2,491	
Rich. Petroleum	CHW	28,526	144	13,599	338	15,637	377	15,078	388	17,702	590	13,937	254	15,587	207	17,023	178	17,625	192							19,518	313
	HW	18,227	NA	6,565	369	5,588	317	5,098	244	2,171	288	6,568	171	6,994	202	7,391	174	8,882	282							8,512	252
	Elec	1,933		1,898		1,914		1,991		2,153		2,039		2,026		2,110		2,155								2,031	
VMC Addition	CHW	40,892	760	23,115	889	24,080	837	22,915	774	23,307	900	24,380	354	25,849	377												
	HW	3,569	254	887	138	2,041	117	2,097	148	2,051	226	1,881	154		245												
	Elec	4,186		3,996		4,140		4,236		4,056		4,219		4,169													
Wehner CBA	CHW	19,193	290	12,327	283	13,339	299	12,530	271	11,609	292	13,490	189													15,474	470
	HW	13,393	143	10,876	491	9,715	466	6,581	194	6,350	258	7,309	162													1,237	196
	Elec	2,555		2,410		2,446		2,552		2,581		2,529														2,247	
Zachry Engr. Center	CHW	40,824	707	16,737	464	17,377	381	18,148	337	20,225	411	19,794	170								418	24,296	225	23,588	297	23,219	279
	HW	7,676	310	1,630	113	3,230	99	2,226	122	4,271	158	4,467	128							3,623	99	4,694	164	5,934	215	5,253	132
	Elec	7,502		6,762		6,793		7,099		6,955		6,597		6,516		6,456				4,377		4,662		4,793		4,871	

APPENDIX C

MODELS

In order to determine savings, measured chilled water and hot water consumption for each year had to be adjusted to a “normal” set of conditions for comparison. In order to make the adjustments, three and four parameter change point models (3P-CP and 4P-CP) were developed using EModel, a statistical software package. Table C-1 lists the models that were used to adjust the data sets. The figures that follow show the models fit to the data for each year. Only the models developed from the years 2001 through 2008-09 are included as figures, as those prior to that date were developed by Cho (2002).

Table C - 1. Change point model parameters used to adjust consumption data.

Building Name	Energy Type	Model Type	Year	Ycp	LS	RS	Xcp	R^2	RMSE	CV RMSE
Blocker	CHW	4P-CP	Baseline	63.0061	0.6980	2.1238	75.3820	0.54	14.5412	24.2%
			1997	40.0913	0.3125	1.6082	71.0380	0.44	12.7551	25.2%
			1998	46.3349	0.6078	1.5567	67.7640	0.54	13.3120	24.1%
			1999	51.0292	0.4829	1.1565	68.8660	0.49	11.3215	20.5%
			2000	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			2001	59.4927	0.7710	1.0478	79.1583	0.596	9.4439	18.4%
			2002	29.6774	0.2910	0.9183	48.5433	0.7645	6.7684	14.2%
			2003	53.4566	0.6252	1.0778	68.0417	0.7319	6.7229	11.7%
			2004	47.2027	0.6678	1.1552	67.8400	0.7844	6.2551	12.2%
			2006-2007	41.8809	0.0000	0.6139	43.0658	0.4081	9.8094	17.1%
			2007-2008	34.6190	0.0000	0.6717	38.0600	0.6721	6.5056	11.6%
			2008-2009	48.2232	0.4124	1.09	62.2800	0.5869	10.9023	18.3%
	HW	3P-CP	Baseline	20.7566	-0.1655		88.4140	0.06	9.8100	40.1%
			1997	0.0000	-1.0047		78.6400	0.43	9.8400	168.8%
			1998	2.6400	-0.8757		58.8720	0.17	8.1500	200.7%
			1999	1.0332	-0.4462		87.3280	0.28	9.8300	108.1%
			2000	n/a	n/a	n/a	n/a	n/a	n/a	n/a
			2001	2.2144	-0.6985		83.7917	0.7234	5.9760	44.4%
			2002	1.1702	-0.6459		75.9833	0.6828	5.3282	67.0%
			2003	11.9701	-0.6693		73.8750	0.6754	5.0935	30.2%
			2005-2006	2.7139	-1.0335		62.1600	0.7502	3.3689	60.8%
			2006-2007	4.4254	-0.8398		75.4433	0.4646	10.7179	85.7%
			2007-2008	1.5465	-0.2483		88.9400	0.2647	5.7382	91.7%
			2008-2009	2.5268	-0.1079		80.5800	0.064	5.0476	132.5%
Eller O&M	CHW	4P-CP	Baseline	70.0160	0.7716	1.9658	64.5220	0.42	24.0906	28.8%
			1997	42.6854	0.4331	2.4375	71.0380	0.57	14.9012	26.6%
			1998	37.2655	0.6276	2.428	67.1560	0.68	14.8923	28.6%
			1999	43.9494	0.6145	2.2005	69.9520	0.61	13.8436	27.6%
			2000	41.1108	0.2551	1.9936	65.6080	0.58	14.9134	26.7%
			2001	43.6703	0.9603	2.1866	60.6250	0.88	9.3583	14.7%
			2002	46.0906	1.0632	2.351	66.8367	0.92	7.0947	13.0%
			2003	39.2816	0.8677	2.4207	65.6383	0.94	5.3448	10.7%
			2004	48.7953	0.8663	3.0525	70.0800	0.9321	6.3129	10.6%
	HW	3P-CP	Baseline	3.5820	-0.8960		88.4140	0.34	16.1600	87.2%

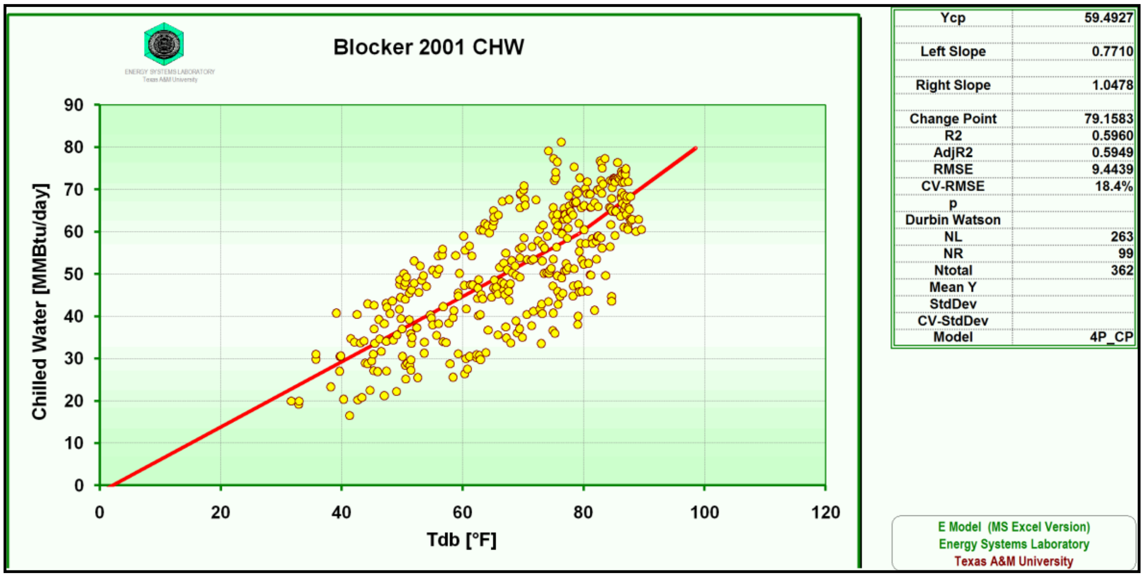
Building Name	Energy Type	Model Type	Year	Ycp	LS	RS	Xcp	R^2	RMSE	CV RMSE
			1997	0.0000	-0.3895		87.3280	0.21	9.4100	160.4%
			1998	0.5225	-0.6505		65.0280	0.23	7.9800	270.0%
			1999	0.0000	-0.3302		84.0700	0.29	6.9000	131.4%
			2000	0.0728	-0.7960		85.1560	0.33	15.3200	118.3%
			2001	0.8681	-1.0644		78.0000	0.5	12.9600	96.6%
G.R. White	CHW	3P-CP	Baseline	38.8635		0.7286	52.6200	0.21	12.9600	27.4%
			1997	16.4654		1.1226	67.7800	0.56	8.1000	30.8%
			1998	13.5198		1.2391	65.6080	0.48	10.5500	44.8%
			1999	44.7645		-0.293	53.6620	0.03	19.1500	48.0%
			2000	44.4863		-0.4304	76.7320	0.01	17.9800	41.5%
			2005-2006	2.2689		1.752	63.2800	0.66	11.3900	55.8%
			2006-2007	4.8354		1.3285	50.6650	0.6912	10.4862	36.0%
			2007-2008	5.5408		2.2602	74.8000	0.4004	13.5495	94.0%
			2008-2009	7.4331		2.5494	70.4800	0.4278	19.8452	85.3%
	HW	3P-CP	Baseline	54.4475	-0.4630		72.8080	0.12	12.0300	20.4%
			1997	8.0351	-0.4508		88.4140	0.3	9.5800	63.0%
			1998	0.5709	-0.4099		59.0920	0.19	4.3300	288.8%
			1999	2.3353	-0.5812		88.4140	0.16	18.3300	135.6%
			2000	10.0806	-0.9172		88.4360	0.29	19.0100	74.1%
			2005-2006	4.1756	-0.8061		69.5800	0.6137	5.3783	62.9%
			2006-2007	0.9963	-0.2930		86.4700	0.4963	4.0599	63.0%
			2007-2008	1.9868	-0.2046		87.7600	0.4846	2.9705	53.7%
			2008-2009	5.1174	-0.2660		53.7400	0.0427	3.8096	70.7%
Harrington Tower	CHW	4P-CP	Baseline	18.4888	0.0556	1.1712	52.8460	0.7	8.7469	25.2%
			1997	13.8290	0.3095	1.0962	67.7800	0.63	7.4702	38.6%
			1998	16.8813	0.5158	1.2493	67.1560	0.64	9.2989	39.6%
			1999	17.1942	0.2715	1.5437	73.2100	0.59	8.4634	40.0%
			2000	16.4897	0.2716	1.5009	68.0458	0.62	9.5762	37.9%
			2001	11.6663	0.2306	0.9041	58.3083	0.8928	3.5689	16.0%
			2002	22.5378	0.5064	1.1495	70.2667	0.8796	3.7402	15.2%
			2003	16.6497	0.4873	1.2996	66.8750	0.9322	3.1120	13.8%
			2004	13.7287	0.4518	1.2764	66.1000	0.9261	3.3230	15.8%
			2005-2006	17.6455	0.3290	1.4392	74.6200	0.79	4.8952	23.6%
			2006-2007	12.3729	0.2310	0.9665	65.6800	0.6552	5.9325	32.9%
			2007-2008	16.4489	0.4859	0.9354	62.6302	0.8583	4.2859	17.4%
			2008-2009	14.7625	0.3377	0.8335	67.1600	0.8444	3.7741	19.2%
	HW	3P-CP	Baseline	4.9804	-0.9599		83.2120	0.41	13.9300	75.6%
			1997	0.4346	-0.3489		88.4140	0.2	9.5700	133.4%
			1998	1.3976	-0.5710		57.5800	0.17	5.5700	227.6%

Building Name	Energy Type	Model Type	Year	Ycp	LS	RS	Xcp	R^2	RMSE	CV RMSE
			1999	3.0145	-1.4737		52.5760	0.29	7.1700	153.0%
			2000	6.6921	-1.7171		56.5417	0.75	6.9600	37.7%
			2002	3.1265	-0.7806		76.4808	0.8264	3.7788	39.0%
			2003	3.7828	-1.0222		69.2083	0.8652	3.6708	36.7%
			2005-2006	2.2383	-0.7464		73.3600	0.93	1.9600	26.3%
			2006-2007	3.5457	-0.5107		73.7650	0.6763	3.9493	49.5%
			2007-2008	4.2489	-0.3056		87.1880	0.8335	1.8454	19.4%
			2008-2009	2.5109	-0.4763		74.4800	0.7972	2.4432	38.5%
Kleberg	CHW	3P-CP	Baseline	129.7029		1.5598	48.8320	0.15	31.6500	21.8%
			1997	80.5380		3.4612	72.1240	0.24	34.4400	36.0%
			1998	76.2818		3.7286	70.2840	0.32	36.1900	36.3%
			1999	71.1613		4.4607	67.7800	0.44	37.0000	33.2%
			2000	83.4304		2.5394	59.0920	0.28	42.2400	36.7%
			2001	81.8884		4.3299	62.8633	0.6094	28.5675	24.5%
			2002	31.1663		2.6652	42.8267	0.6121	29.0423	29.7%
			2003	19.1446		4.4129	55.2083	0.8909	16.6724	20.1%
			2004	27.6732		5.4769	60.0000	0.8536	21.6415	23.6%
			2005-2006	21.5507		3.7795	62.0200	0.93	10.0783	14.9%
			2006-2007	45.8269		3.8637	64.5250	0.6265	22.5503	29.7%
			2007-2008	55.5637		3.7713	66.9011	0.8305	12.9996	15.4%
			2008-2009	51.7179		2.9867	64.7200	0.7645	15.5917	19.5%
	HW	3P-CP	Baseline	104.7819	-0.9946		71.8360	0.07	36.2800	30.4%
			1997	0.1576	-1.0359		86.2420	0.21	27.6400	155.2%
			1998	4.5778	0.1977		71.3460	0.11	5.2400	155.9%
			1999	11.3633	-4.6660		59.0920	0.35	25.9300	149.2%
			2000	5.5329	-1.2237		88.4140	0.2	34.2500	117.8%
			2005-2006	8.3183	-0.9424		80.9200	0.44	11.6100	67.6%
			2006-2007	11.3521	-1.9257		80.6950	0.4736	26.5724	71.4%
			2007-2008	22.9039	-2.8136		71.1720	0.7527	14.7919	36.2%
			2008-2009	21.0255	-2.5936		75.7000	0.7257	16.7783	38.6%
Koldus	CHW	4P-CP	Baseline							
			1997	23.6651	0.1321	0.9319	61.2640	0.59	7.5280	20.6%
			1998	24.1391	0.1612	1.2409	62.9000	0.74	7.2738	20.0%
			1999	29.3635	0.3226	1.2273	68.8660	0.66	7.4427	21.4%
			2000	23.9536	0.1915	0.7649	60.1780	0.53	7.8763	24.3%
			2001	14.4283	0.4605	0.9981	49.0417	0.876	4.9537	14.3%
			2005-2006	20.9720	0.4082	1.1336	59.0000	0.84	5.5739	15.4%
			2006-2007	13.4813	0.4680	1.2079	49.5100	0.9416	3.8190	10.5%
			2007-2008	11.4703	0.5456	1.1092	46.6120	0.9342	3.9339	10.5%

Building Name	**Energy Type**	**Model Type**	**Year**	**Ycp**	**LS**	**RS**	**Xcp**	**R^2**	**RMSE**	**CV RMSE**
			2008-2009	15.4747	0.4642	0.9459	48.8600	0.9274	3.6533	10.2%
	HW	3P-CP	Baseline	5.6277	-0.0386		63.2840	0.02	2.2400	37.4%
			1997	-0.0181	-0.1621		79.7260	0.44	2.0600	103.9%
			1998	0.0319	-0.0938		78.8600	0.43	1.2600	125.4%
			1999	0.1004	-0.0853		88.4140	0.35	1.6000	87.2%
			2000	0.1062	-0.0871		88.4140	0.31	1.7900	100.6%
			2001	0.3554	-0.1409		67.5750	0.4536	1.2755	120.6%
			2005-2006	5.2705	-0.2194		88.7600	0.59	2.3500	26.0%
			2006-2007	8.5394	-0.1753		86.4700	0.5167	2.3318	19.8%
			2007-2008	9.5937	-0.1584		85.0600	0.5009	2.1259	17.7%
			2008-2009	6.6982	-0.2121		91.5600	0.6736	2.0931	18.7%
Rich. Petroleum	CHW	3P-CP	Baseline	77.4038		0.223	74.3100	0.02	4.5800	5.7%
			1997	25.1161		1.8736	67.7800	0.62	10.7300	27.9%
			1998	23.1531		1.7634	60.7720	0.68	11.9500	27.5%
			1999	21.6462		1.9596	62.3500	0.69	12.3200	29.2%
			2000	27.3230		1.8251	60.1780	0.45	18.7100	33.8%
			2001	19.6666		1.7512	61.5900	0.7866	8.0505	18.8%
			2002	25.4177		2.0178	64.5500	0.8554	6.5576	15.9%
			2003	25.3428		2.1014	62.2083	0.9084	5.6493	12.6%
			2004	31.3538		2.1403	65.6000	0.8765	6.0952	12.7%
			2009	42.0900		1.4776	65.9400	0.6593	9.9428	18.0%
	HW	3P-CP	Baseline							
			1997	8.1443	-0.7304		81.8980	0.38	11.6900	73.1%
			1998	7.1159	-0.6807		79.9240	0.4	10.0500	66.9%
			1999	8.5638	-0.3775		82.9840	0.28	7.7500	56.7%
			2000	7.5316	0.3074		67.7800	0.03	9.1400	132.3%
			2001	10.0415	-2.7150		61.5900	0.8288	5.4313	38.7%
			2002	9.5251	-1.6779		69.1233	0.8624	6.3979	30.3%
			2003	9.4983	-1.2119		75.0417	0.8664	5.5139	26.3%
			2004	11.8618	-1.7037		72.3200	0.7807	8.9504	37.2%
			2009	10.5543	-1.0270		80.4800	0.5815	7.9933	44.7%
VMC Addition	CHW	3P-CP	Baseline	100.0292		1.8944	68.2480	0.17	24.1200	19.3%
			1997	21.9141		4.1272	62.3500	0.65	28.1900	44.4%
			1998	21.7759		3.8092	60.1780	0.67	26.5500	39.7%
			1999	28.4349		4.7382	66.6940	0.69	24.5600	39.4%
			2000	24.5845		3.6338	61.2640	0.6	28.5600	44.7%
			2001	7.7813		4.2366	57.1500	0.9437	11.2146	17.5%
			2002	13.4721		4.5441	58.8333	0.9364	11.9570	18.3%
	HW	3P-CP	Baseline	4.5874	-0.2645		88.8560	0.04	8.0600	122.0%

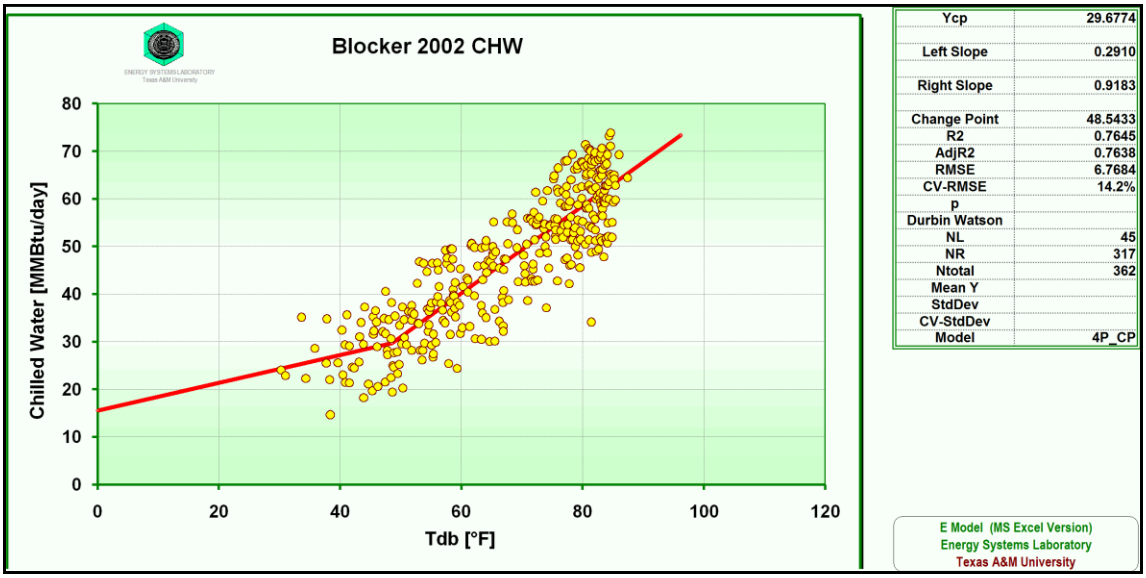
Building Name	Energy Type	Model Type	Year	Ycp	LS	RS	Xcp	R^2	RMSE	CV RMSE
			1997	0.1557	-0.1689		81.8980	0.2	4.3700	179.7%
			1998	1.8335	-0.2966		80.8120	0.51	3.7000	66.8%
			1999	0.4659	-0.3122		81.8980	0.42	4.7100	99.3%
			2000	0.3392	-0.3918		81.8980	0.33	7.1800	127.2%
			2001	0.7074	-0.4802		75.6833	0.569	4.8900	88.5%
			2002	5.0931	-0.2148		86.2733	0.1342	7.7583	84.7%
Wehner	CHW	3P-CP	Baseline	40.9478		0.7765	55.8160	0.37	9.2000	15.9%
			1997	20.8922		1.2837	62.3500	0.64	8.9700	26.6%
			1998	27.2346		1.1774	65.6080	0.51	9.5000	25.8%
			1999	23.3629		1.0929	62.3500	0.59	8.5900	25.1%
			2000	20.1977		0.9345	59.0920	0.52	9.2500	29.1%
			2001	16.1458		1.1752	52.5167	0.8515	5.9926	16.7%
			2005-2006	27.1929		1.7631	60.7600	0.7726	9.5703	19.5%
			2008-2009						12.5173	22.9%
	HW	3P-CP	Baseline	56.6959	-0.2475		64.9500	0.07	4.5400	12.3%
			1997	20.4127	-0.6176		84.0700	0.22	15.5800	52.3%
			1998	11.4917	-1.1939		80.8120	0.51	14.7800	56.0%
			1999	9.2251	-0.4588		88.4140	0.52	6.1400	33.8%
			2000	13.9109	-0.2930		79.7260	0.16	8.1700	46.9%
			2001	16.8786	-0.7586		65.2583	0.5764	5.1402	25.0%
			2004	25.6398	-0.5880		70.0800	0.2323	9.7102	33.3%
			2005-2006	9.8061	-0.3771		72.1000	0.3802	4.4776	36.6%
			2008-2009						4.3994	59.8%
Zachry	CHW	4P-CP	Baseline	94.9024	1.0723	3.034	66.6940	0.62	22.4356	19.5%
			1997	36.0696	0.6688	2.0027	67.7800	0.59	14.7215	28.9%
			1998	30.6003	0.5138	1.5272	59.7080	0.67	12.0879	25.1%
			1999	42.0505	0.4535	2.0523	71.0380	0.68	10.6968	21.8%
			2000	38.3887	0.2411	1.7721	62.3500	0.64	13.0535	23.6%
			2001	35.8891	0.5922	1.5036	58.3083	0.9164	5.3984	10.2%
			2005-2006	36.2282	0.8586	2.6947	64.5400	0.81	13.2724	22.6%
			2006-2007	43.8836	0.7368	2.4728	62.2533	0.8487	7.1308	8.9%
			2007-2008	53.1617	0.9291	1.9551	65.6200	0.8365	9.4062	14.3%
			2008-2009	45.7725	0.8125	2.2377	63.5000	0.8951	8.8511	13.3%
	HW	3P-CP	Baseline	19.6515	-0.9978		54.8500	0.29	9.8200	39.5%
			1997	1.4296	-0.3453		74.9200	0.4	3.5700	106.3%
			1998	5.8820	-0.2793		77.8360	0.49	3.1500	36.9%
			1999	0.7656	-0.4230		80.7280	0.65	3.8800	62.7%
			2000	7.3709	-0.2923		83.5720	0.36	5.0200	43.1%
			2001	6.6074	-0.3763		83.7917	0.6219	4.0632	31.6%

Building Name	**Energy Type**	**Model Type**	**Year**	**Ycp**	**LS**	**RS**	**Xcp**	**R^2**	**RMSE**	**CV RMSE**
			2005-2006	5.8123	-0.4042		77.1400	0.68	3.1400	32.9%
			2006-2007	8.7701	-0.4488		75.4433	0.5102	5.2106	39.7%
			2007-2008	8.8448	-0.5296		82.5800	0.5025	6.8297	42.7%
			2008-2009	8.7170	-0.4874		79.3600	0.6537	4.1907	29.7%



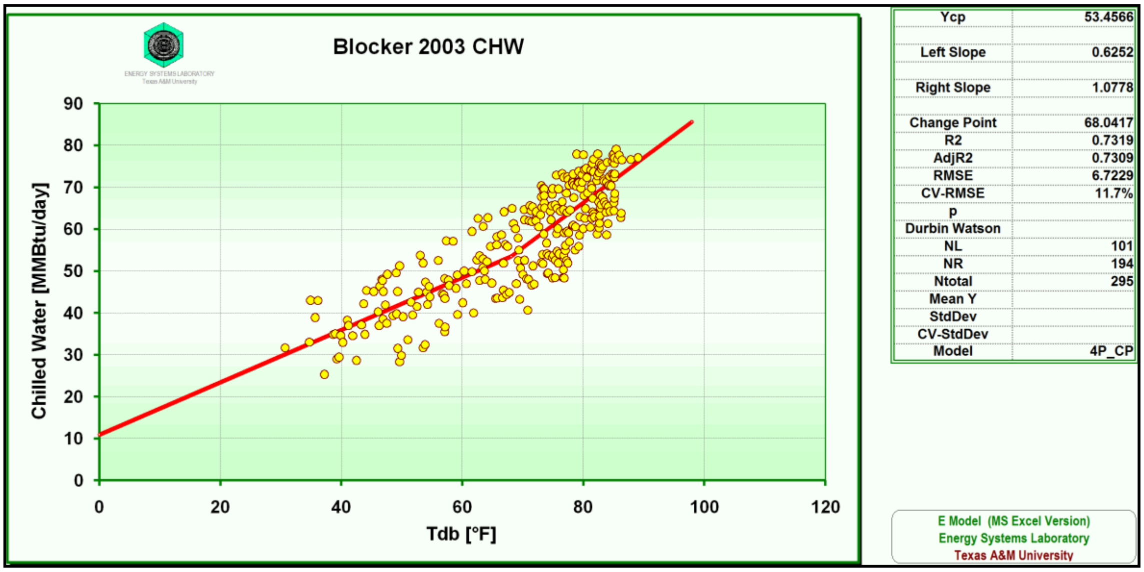
Ycp	59.4927
Left Slope	0.7710
Right Slope	1.0478
Change Point	79.1583
R2	0.5960
AdjR2	0.5949
RMSE	9.4439
CV-RMSE	18.4%
p	
Durbin Watson	
NL	263
NR	99
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 1. Change point model for Blocker 2001 chilled water data.



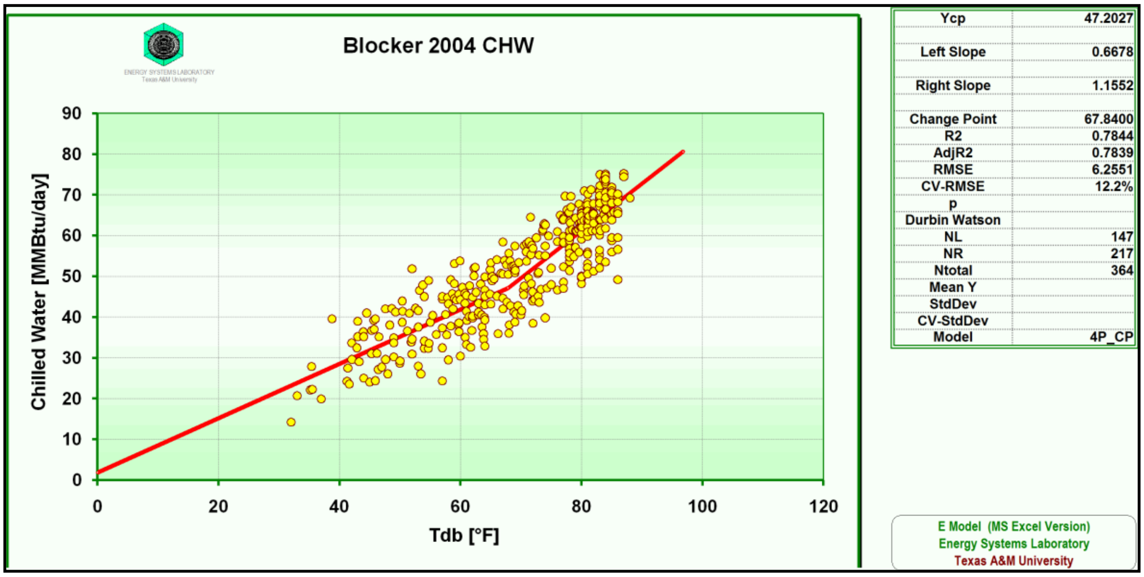
Ycp	29.6774
Left Slope	0.2910
Right Slope	0.9183
Change Point	48.5433
R2	0.7645
AdjR2	0.7638
RMSE	6.7684
CV-RMSE	14.2%
p	
Durbin Watson	
NL	45
NR	317
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 2. Change point model for Blocker 2002 chilled water data.



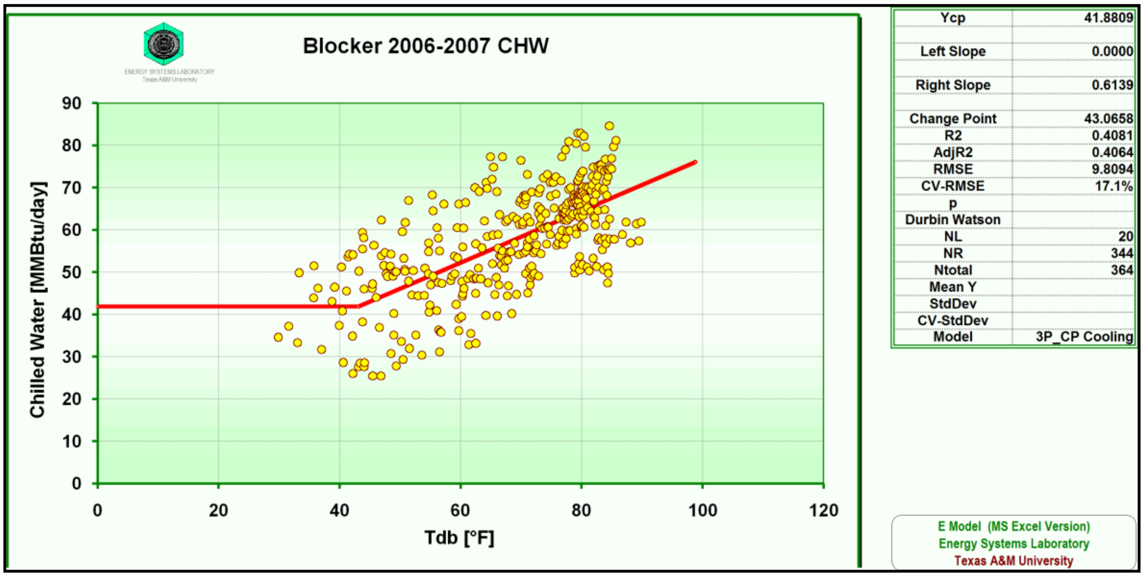
Ycp	53.4566
Left Slope	0.6252
Right Slope	1.0778
Change Point	68.0417
R2	0.7319
AdjR2	0.7309
RMSE	6.7229
CV-RMSE	11.7%
p	
Durbin Watson	
NL	101
NR	194
Ntotal	295
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 3. Change point model for Blocker 2003 chilled water data.



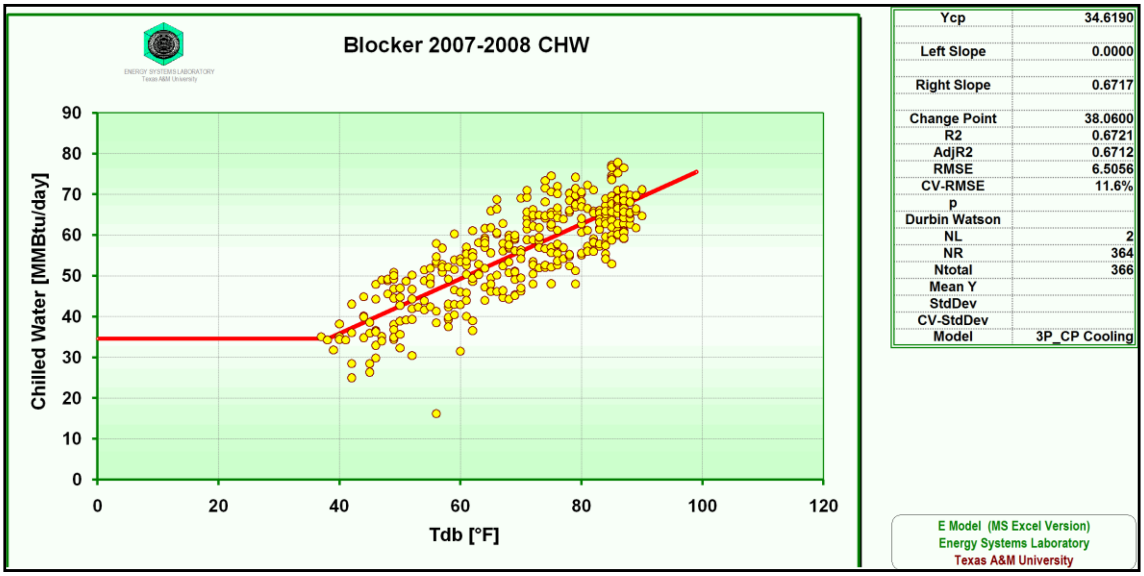
Ycp	47.2027
Left Slope	0.6678
Right Slope	1.1552
Change Point	67.8400
R2	0.7844
AdjR2	0.7839
RMSE	6.2551
CV-RMSE	12.2%
p	
Durbin Watson	
NL	147
NR	217
Ntotal	364
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 4. Change point model for Blocker 2004 chilled water data.



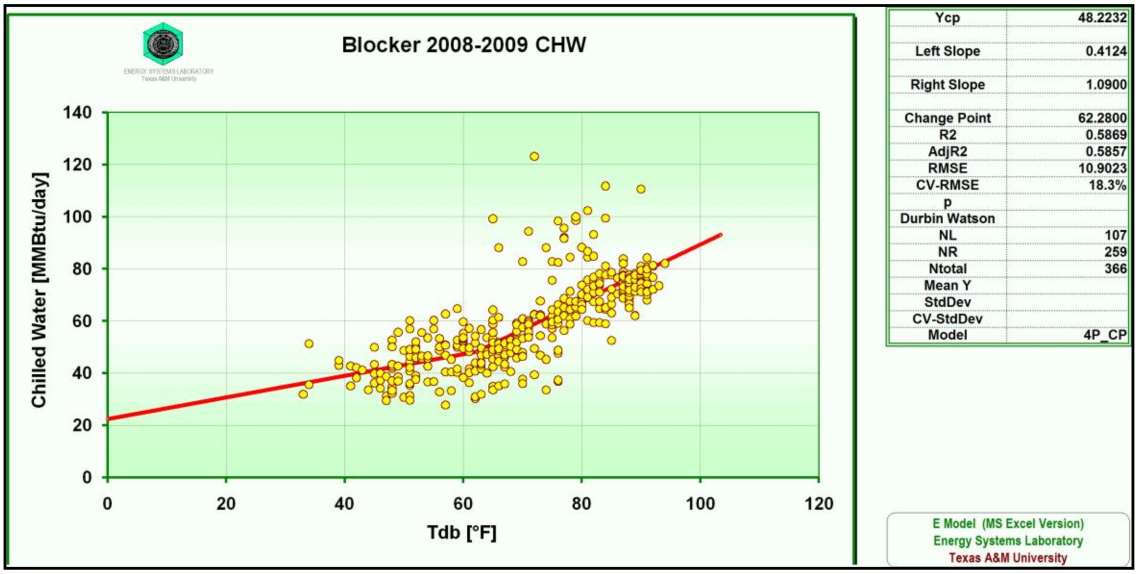
Ycp	41.8809
Left Slope	0.0000
Right Slope	0.6139
Change Point	43.0658
R2	0.4081
AdjR2	0.4064
RMSE	9.8094
CV-RMSE	17.1%
p	
Durbin Watson	
NL	20
NR	344
Ntotal	364
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 5. Change point model for Blocker 2006-07 chilled water data.



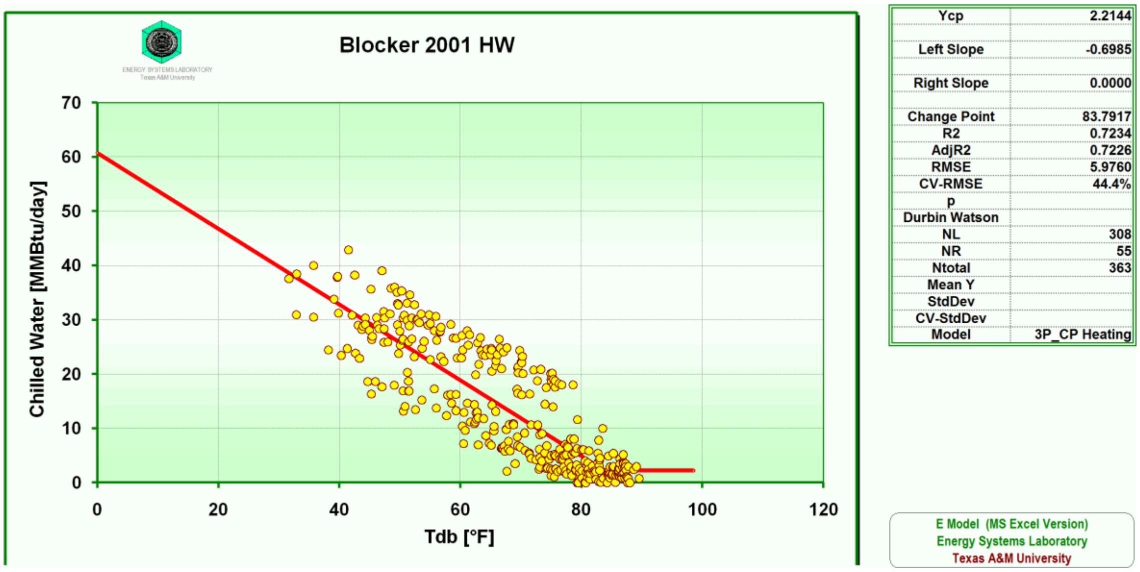
Ycp	34.6190
Left Slope	0.0000
Right Slope	0.6717
Change Point	38.0600
R2	0.6721
AdjR2	0.6712
RMSE	6.5056
CV-RMSE	11.6%
p	
Durbin Watson	
NL	2
NR	364
Ntotal	366
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 6. Change point model for Blocker 2007-08 chilled water data.



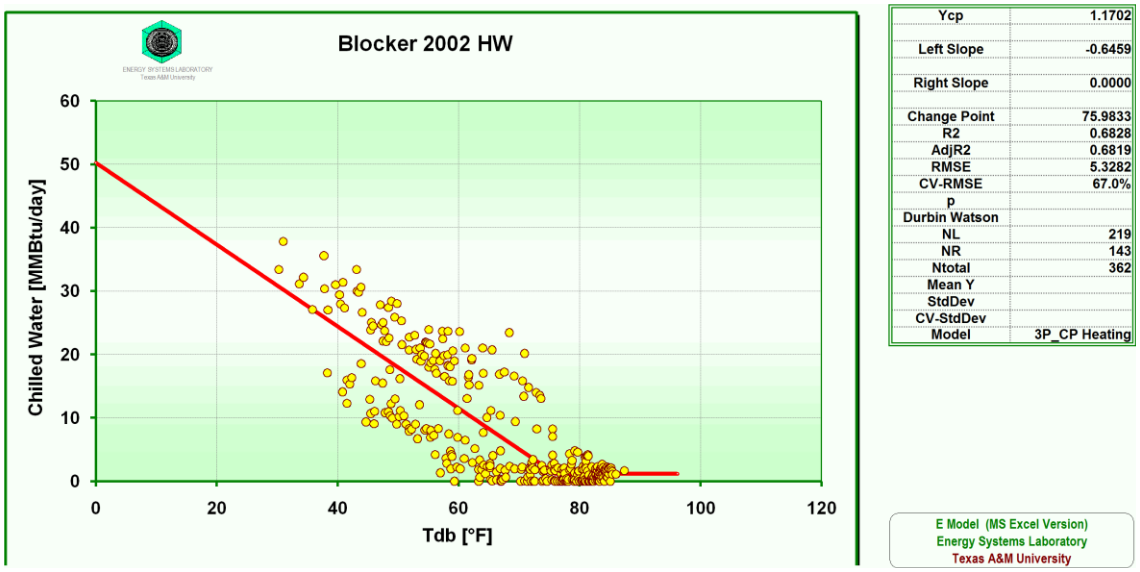
Ycp	48.2232
Left Slope	0.4124
Right Slope	1.0900
Change Point	62.2800
R2	0.5869
AdjR2	0.5857
RMSE	10.9023
CV-RMSE	18.3%
p	
Durbin Watson	
NL	107
NR	259
Ntotal	366
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 7. Change point model for Blocker 2008-09 chilled water data.



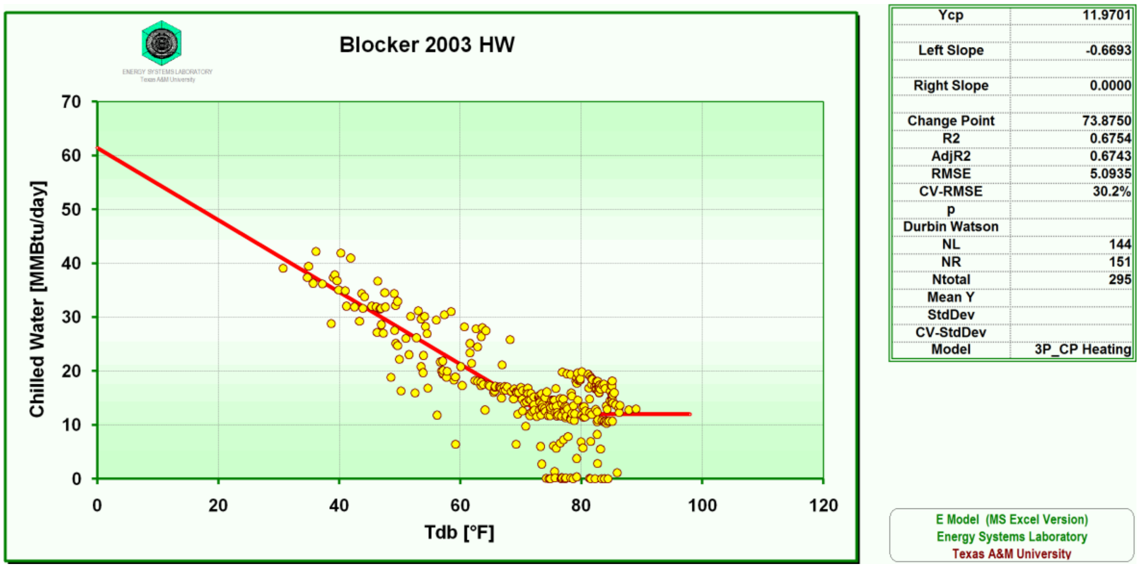
Ycp	2.2144
Left Slope	-0.6985
Right Slope	0.0000
Change Point	83.7917
R2	0.7234
AdjR2	0.7226
RMSE	5.9760
CV-RMSE	44.4%
p	
Durbin Watson	
NL	308
NR	55
Ntotal	363
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 8. Change point model for Blocker 2001 hot water data.



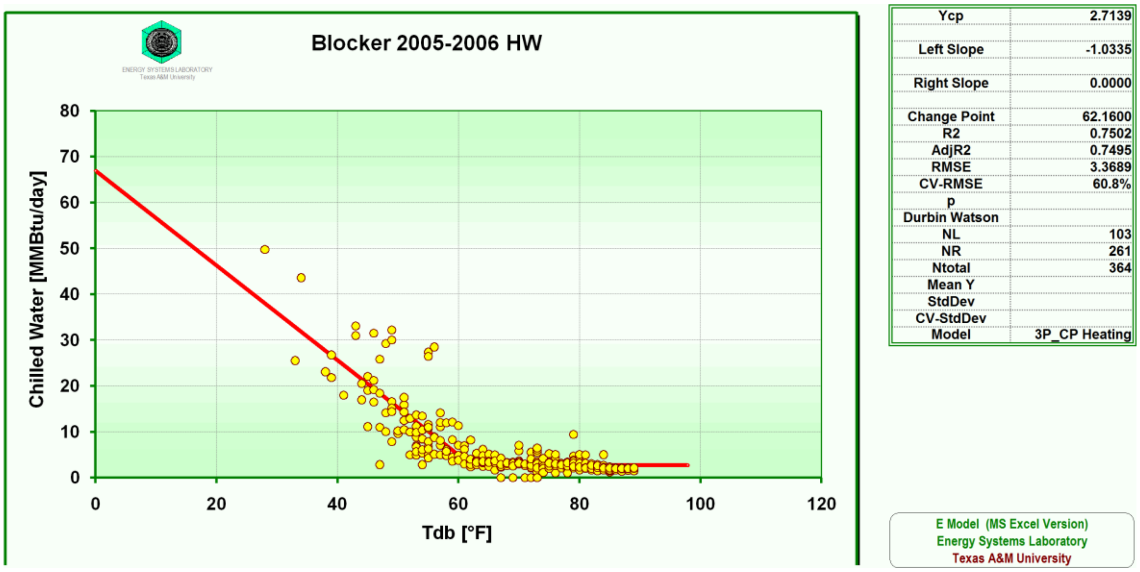
Ycp	1.1702
Left Slope	-0.6459
Right Slope	0.0000
Change Point	75.9833
R2	0.6828
AdjR2	0.6819
RMSE	5.3282
CV-RMSE	67.0%
p	
Durbin Watson	
NL	219
NR	143
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 9. Change point model for Blocker 2002 hot water data.



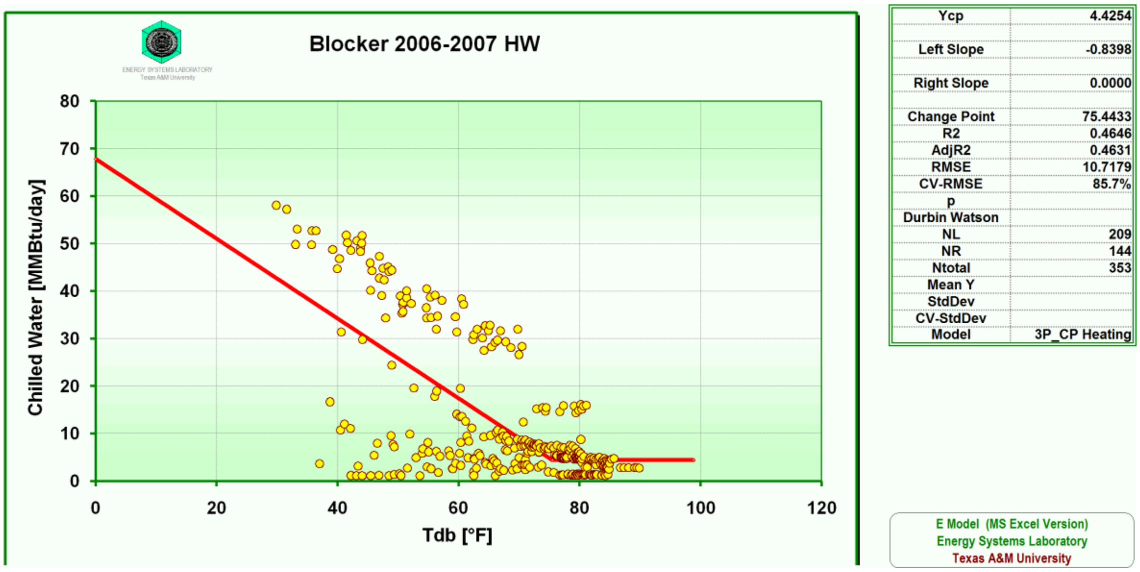
Ycp	11.9701
Left Slope	-0.6693
Right Slope	0.0000
Change Point	73.8750
R2	0.6754
AdjR2	0.6743
RMSE	5.0935
CV-RMSE	30.2%
p	
Durbin Watson	
NL	144
NR	151
Ntotal	295
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 10. Change point model for Blocker 2003 hot water data.



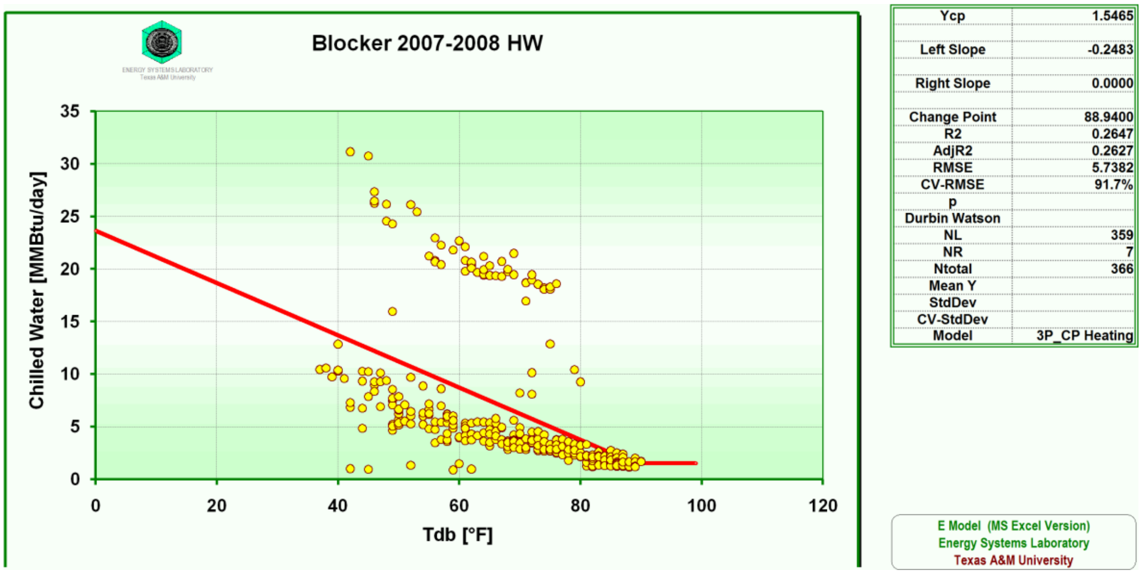
Ycp	2.7139
Left Slope	-1.0335
Right Slope	0.0000
Change Point	62.1600
R2	0.7502
AdjR2	0.7495
RMSE	3.3689
CV-RMSE	60.8%
p	
Durbin Watson	
NL	103
NR	261
Ntotal	364
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 11. Change point model for Blocker 2005-06 hot water data.



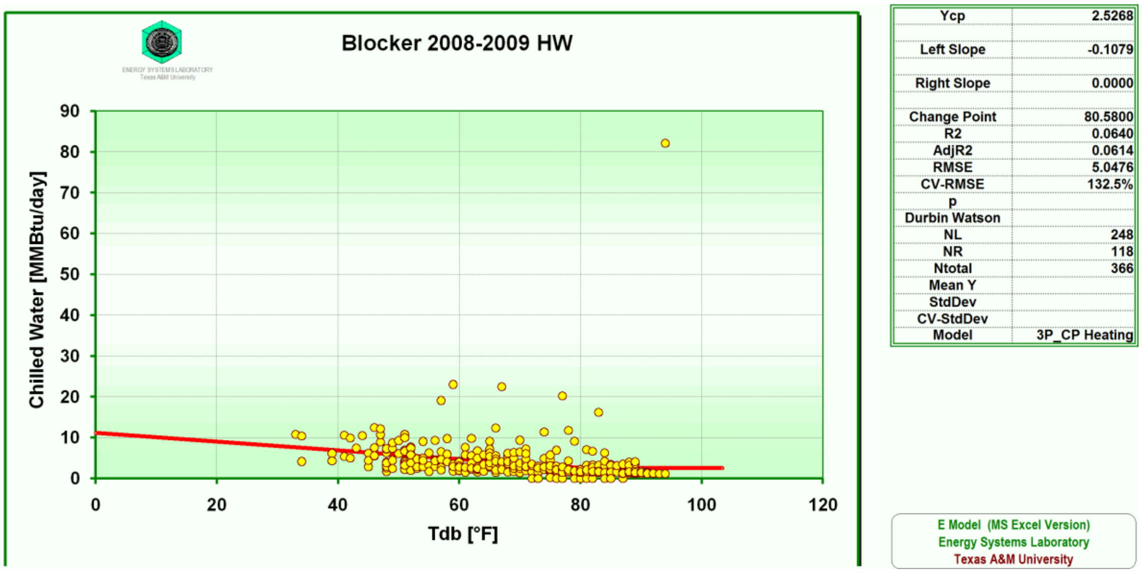
Ycp	4.4254
Left Slope	-0.8398
Right Slope	0.0000
Change Point	75.4433
R2	0.4646
AdjR2	0.4631
RMSE	10.7179
CV-RMSE	85.7%
p	
Durbin Watson	
NL	209
NR	144
Ntotal	353
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 12. Change point model for Blocker 2006-07 hot water data.



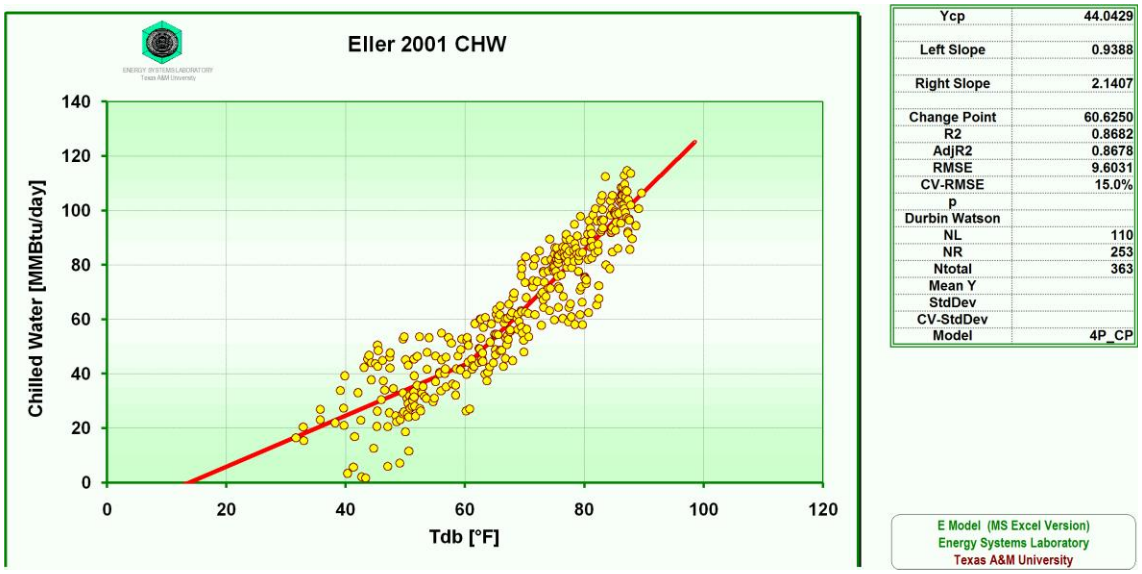
Ycp	1.5465
Left Slope	-0.2483
Right Slope	0.0000
Change Point	88.9400
R2	0.2647
AdjR2	0.2627
RMSE	5.7382
CV-RMSE	91.7%
p	
Durbin Watson	
NL	359
NR	7
Ntotal	366
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 13. Change point model for Blocker 2007-08 hot water data.



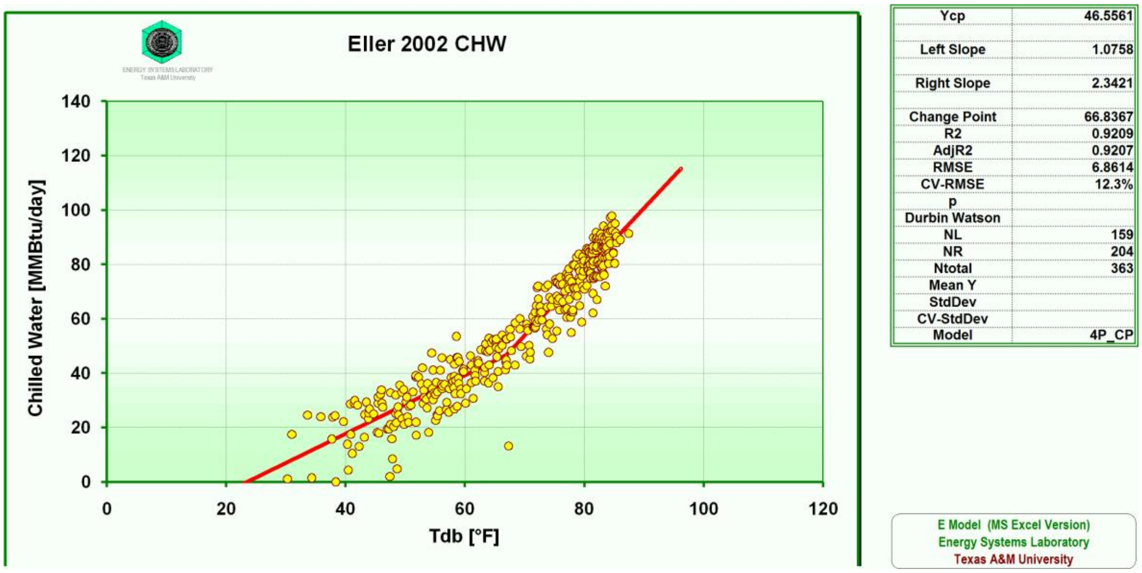
Ycp	2.5268
Left Slope	-0.1079
Right Slope	0.0000
Change Point	80.5800
R2	0.0640
AdjR2	0.0614
RMSE	5.0476
CV-RMSE	132.5%
p	
Durbin Watson	
NL	248
NR	118
Ntotal	366
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 14. Change point model for Blocker 2008-09 hot water data.



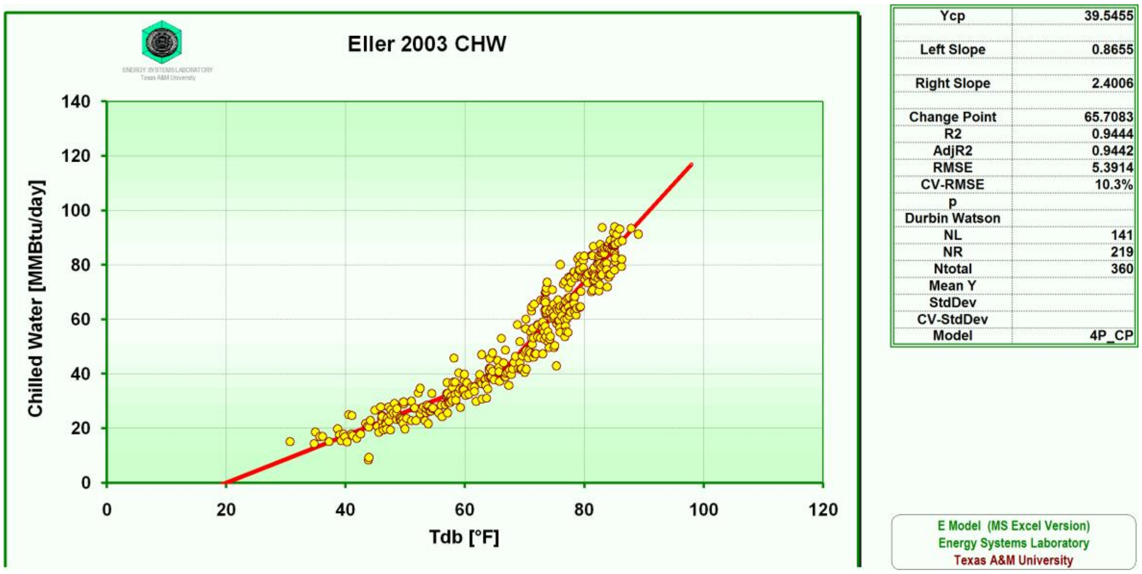
Ycp	44.0429
Left Slope	0.9388
Right Slope	2.1407
Change Point	60.6250
R2	0.8682
AdjR2	0.8678
RMSE	9.6031
CV-RMSE	15.0%
p	
Durbin Watson	
NL	110
NR	253
Ntotal	363
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 15. Change point model for Eller 2001 chilled water data.



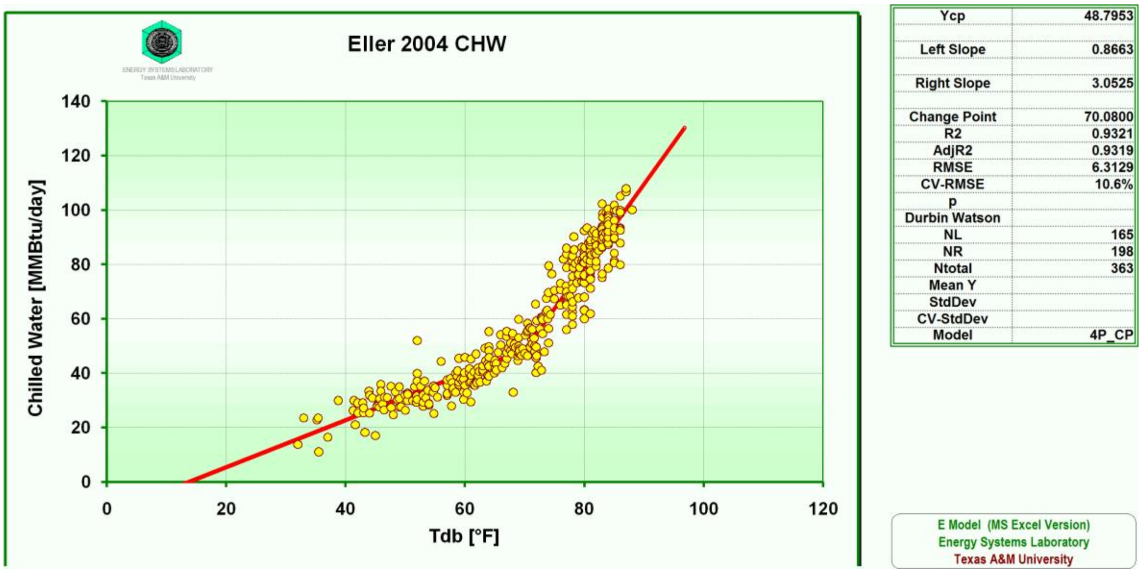
Ycp	46.5561
Left Slope	1.0758
Right Slope	2.3421
Change Point	66.8367
R2	0.9209
AdjR2	0.9207
RMSE	6.8614
CV-RMSE	12.3%
p	
Durbin Watson	
NL	159
NR	204
Ntotal	363
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 16. Change point model for Eller 2002 chilled water data.



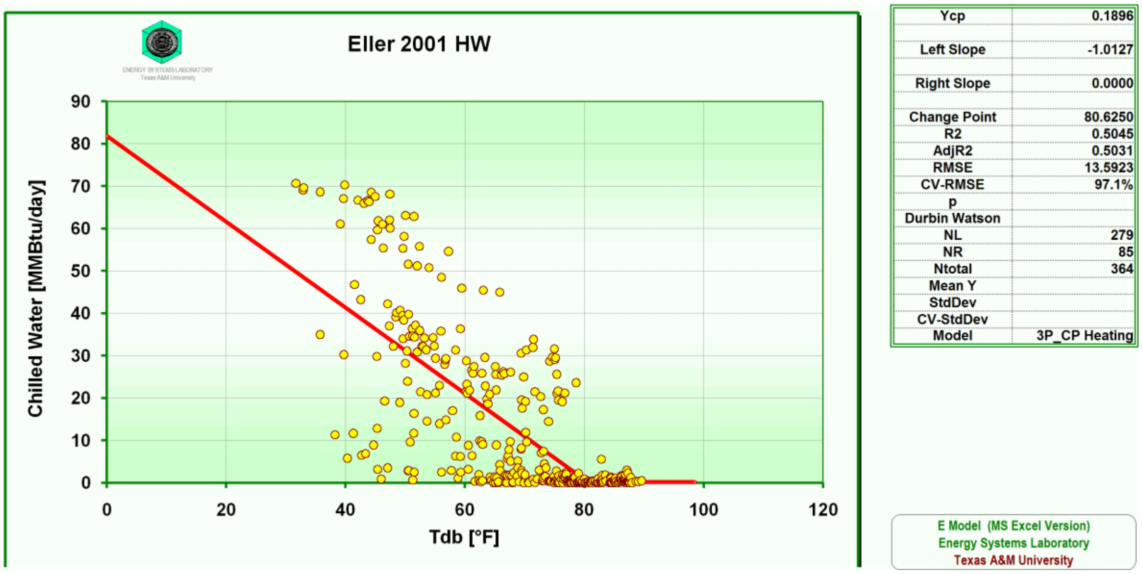
Ycp	39.5455
Left Slope	0.8655
Right Slope	2.4006
Change Point	65.7083
R2	0.9444
AdjR2	0.9442
RMSE	5.3914
CV-RMSE	10.3%
p	
Durbin Watson	
NL	141
NR	219
Ntotal	360
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 17. Change point model for Eller 2003 chilled water data.



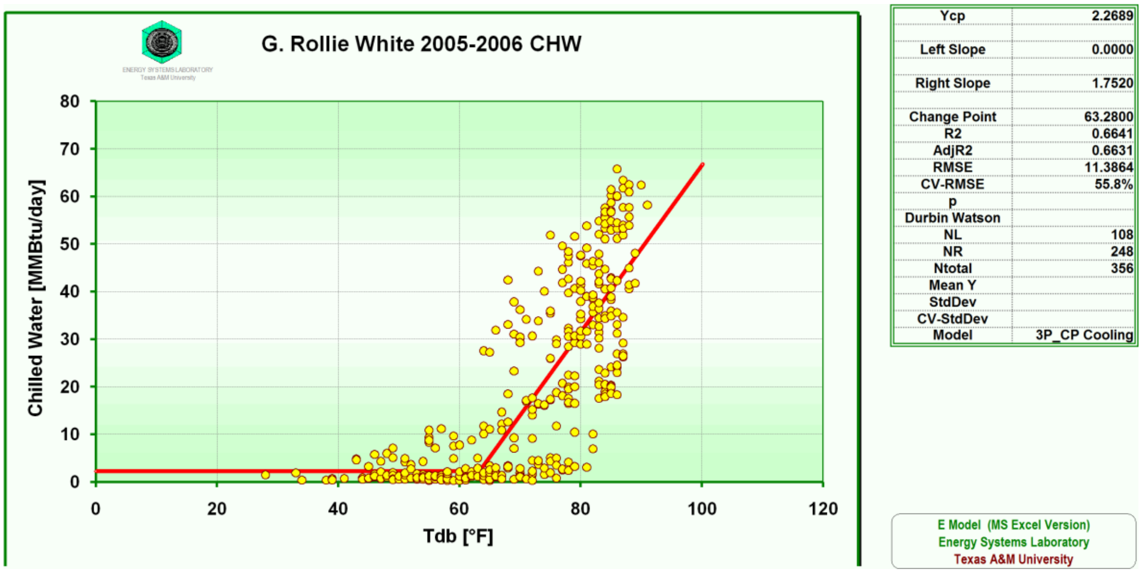
Ycp	48.7953
Left Slope	0.8663
Right Slope	3.0525
Change Point	70.0800
R2	0.9321
AdjR2	0.9319
RMSE	6.3129
CV-RMSE	10.6%
p	
Durbin Watson	
NL	165
NR	198
Ntotal	363
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 18. Change point model for Eller 2004 chilled water data.



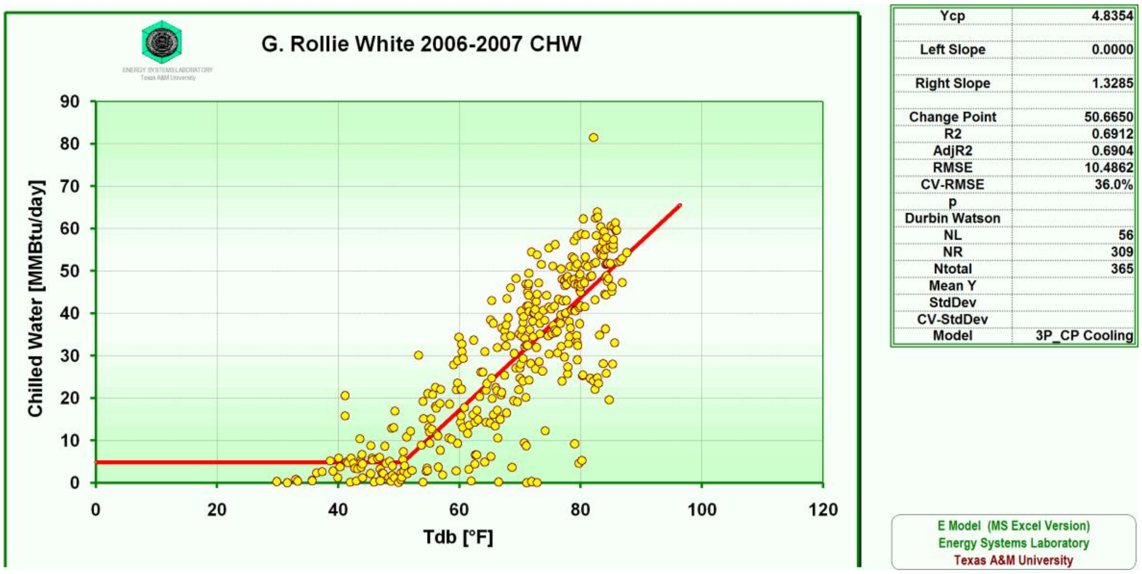
Ycp	0.1896
Left Slope	-1.0127
Right Slope	0.0000
Change Point	80.6250
R2	0.5045
AdjR2	0.5031
RMSE	13.5923
CV-RMSE	97.1%
p	
Durbin Watson	
NL	279
NR	85
Ntotal	364
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 19. Change point model for Eller 2001 hot water data.



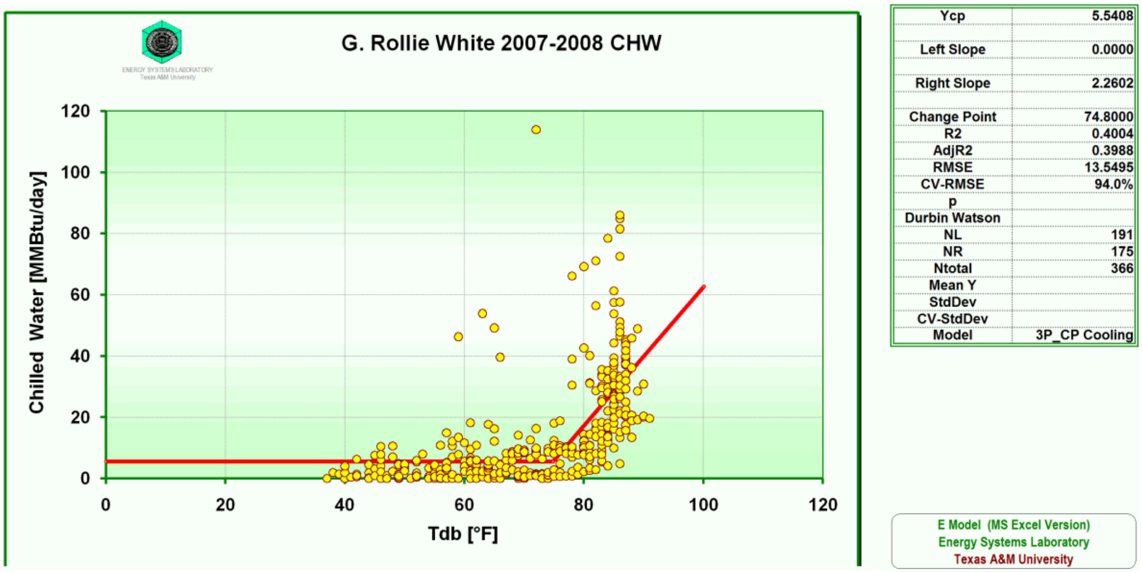
Ycp	2.2689
Left Slope	0.0000
Right Slope	1.7520
Change Point	63.2800
R2	0.6641
AdjR2	0.6631
RMSE	11.3864
CV-RMSE	55.8%
p	
Durbin Watson	
NL	108
NR	248
Ntotal	356
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 20. Change point model for G. Rollie White 2005-06 chilled water data.



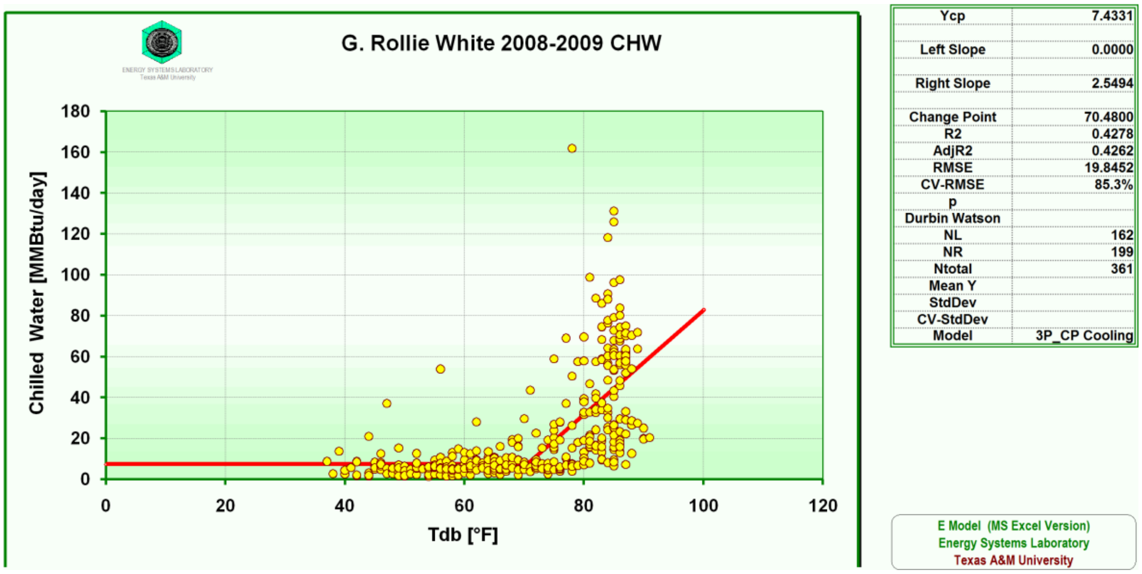
Ycp	4.8354
Left Slope	0.0000
Right Slope	1.3285
Change Point	50.6650
R2	0.6912
AdjR2	0.6904
RMSE	10.4862
CV-RMSE	36.0%
p	
Durbin Watson	
NL	56
NR	309
Ntotal	365
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 21. Change point model for G. Rollie White 2006-07 chilled water data.



Ycp	5.5408
Left Slope	0.0000
Right Slope	2.2602
Change Point	74.8000
R2	0.4004
AdjR2	0.3988
RMSE	13.5495
CV-RMSE	94.0%
p	
Durbin Watson	
NL	191
NR	175
Ntotal	366
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 22. Change point model for G. Rollie White 2007-08 chilled water data.



Ycp	7.4331
Left Slope	0.0000
Right Slope	2.5494
Change Point	70.4800
R2	0.4278
AdjR2	0.4262
RMSE	19.8452
CV-RMSE	85.3%
p	
Durbin Watson	
NL	162
NR	199
Ntotal	361
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

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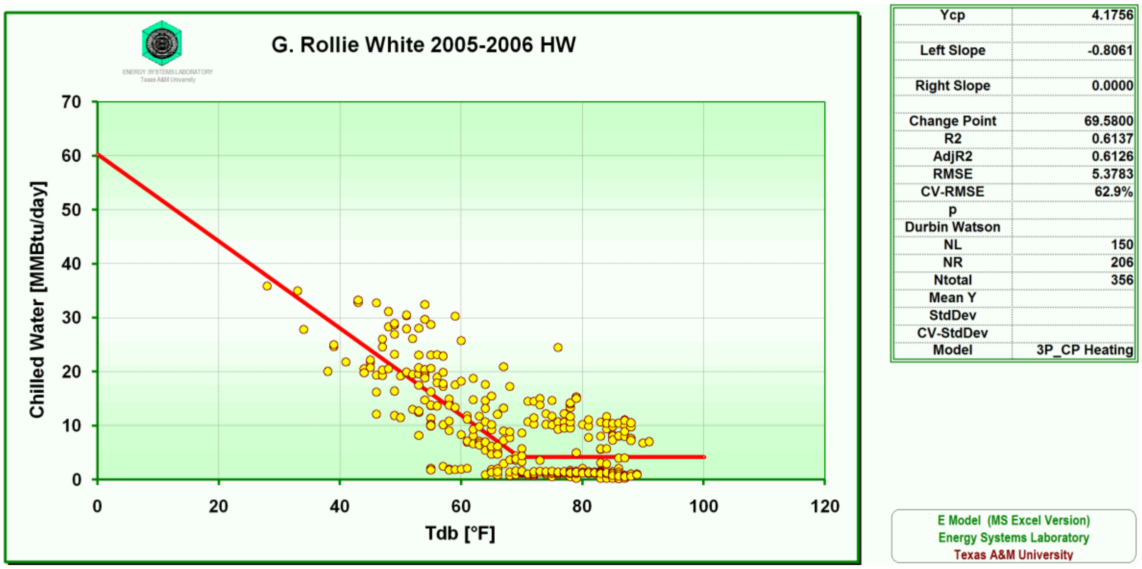
Figure C - 23. Change point model for G. Rollie White 2008-09 chilled water data.



Ycp	4.1756
Left Slope	-0.8061
Right Slope	0.0000
Change Point	69.5800
R2	0.6137
AdjR2	0.6126
RMSE	5.3783
CV-RMSE	62.9%
p	
Durbin Watson	
NL	150
NR	206
Ntotal	356
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

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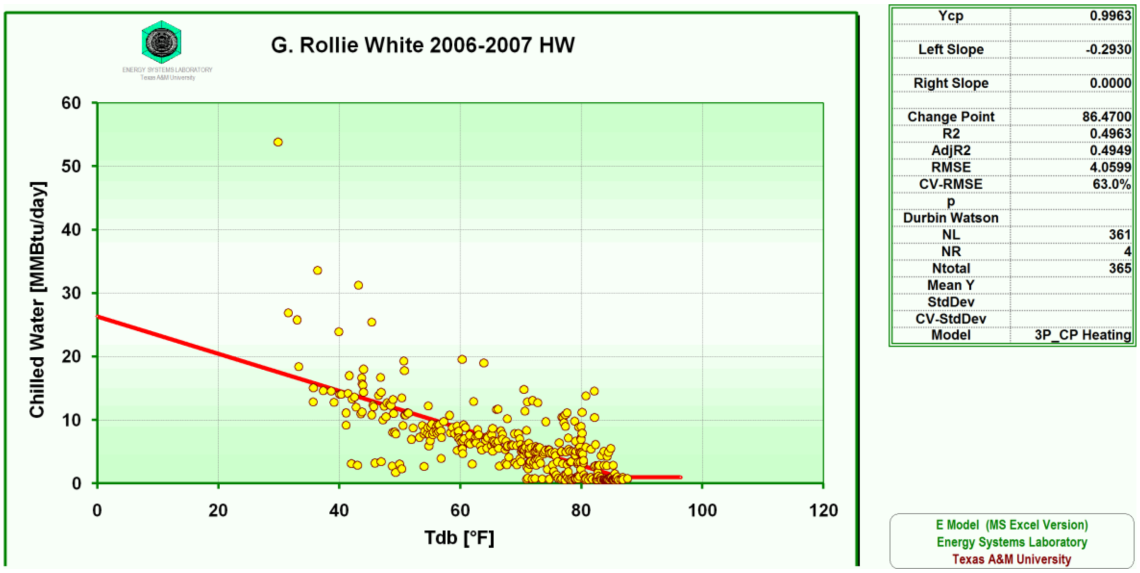
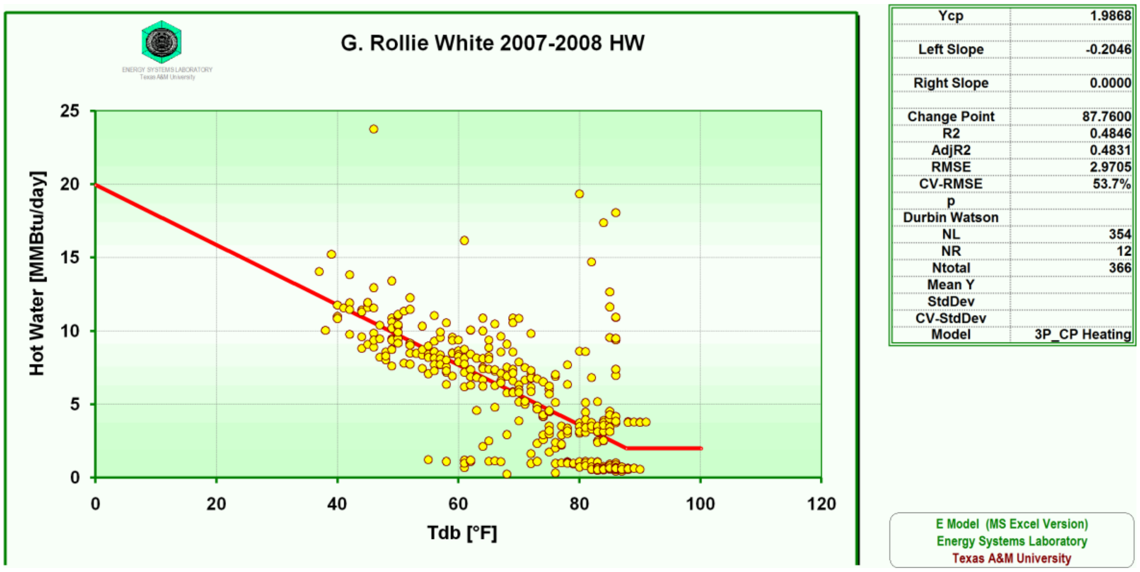
Figure C - 24. Change point model for G. Rollie White 2005-06 hot water data.



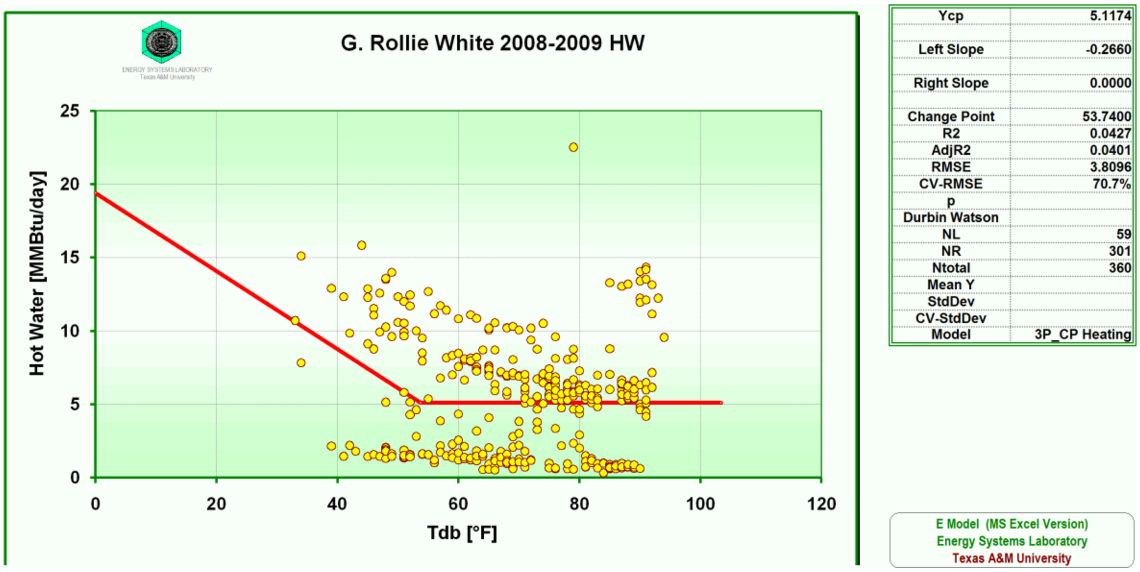
Ycp	0.9963
Left Slope	-0.2930
Right Slope	0.0000
Change Point	86.4700
R2	0.4963
AdjR2	0.4949
RMSE	4.0599
CV-RMSE	63.0%
p	
Durbin Watson	
NL	361
NR	4
Ntotal	365
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 25. Change point model for G. Rollie White 2006-07 hot water data.



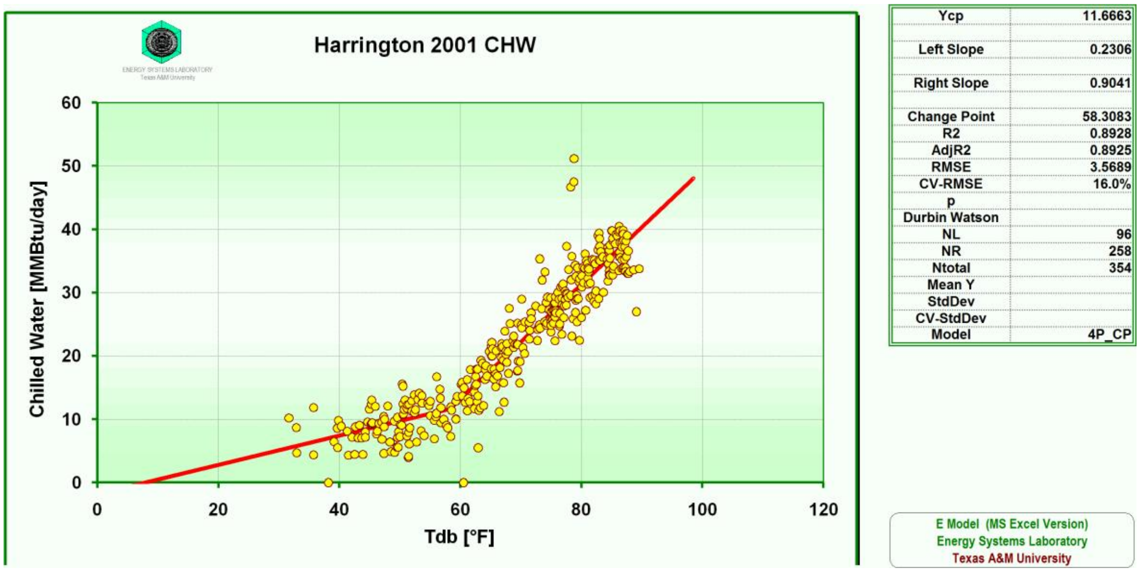
Ycp	1.9868
Left Slope	-0.2046
Right Slope	0.0000
Change Point	87.7600
R2	0.4846
AdjR2	0.4831
RMSE	2.9705
CV-RMSE	53.7%
p	
Durbin Watson	
NL	354
NR	12
Ntotal	366
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 26. Change point model for G. Rollie White 2007-08 hot water data.



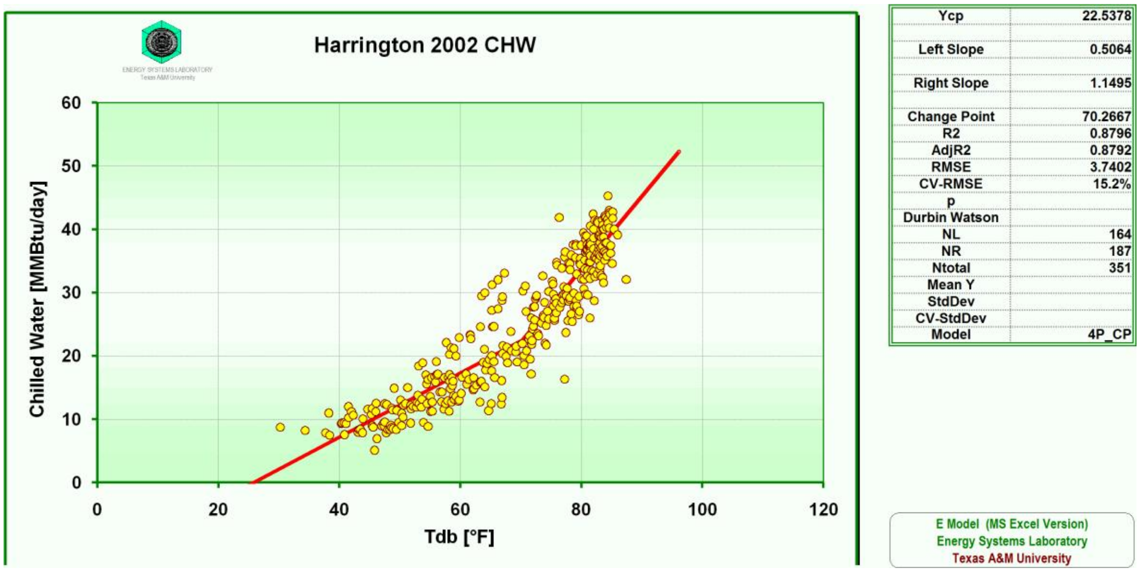
Ycp	5.1174
Left Slope	-0.2660
Right Slope	0.0000
Change Point	53.7400
R2	0.0427
AdjR2	0.0401
RMSE	3.8096
CV-RMSE	70.7%
p	
Durbin Watson	
NL	59
NR	301
Ntotal	360
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 27. Change point model for G. Rollie White 2008-09 hot water data.



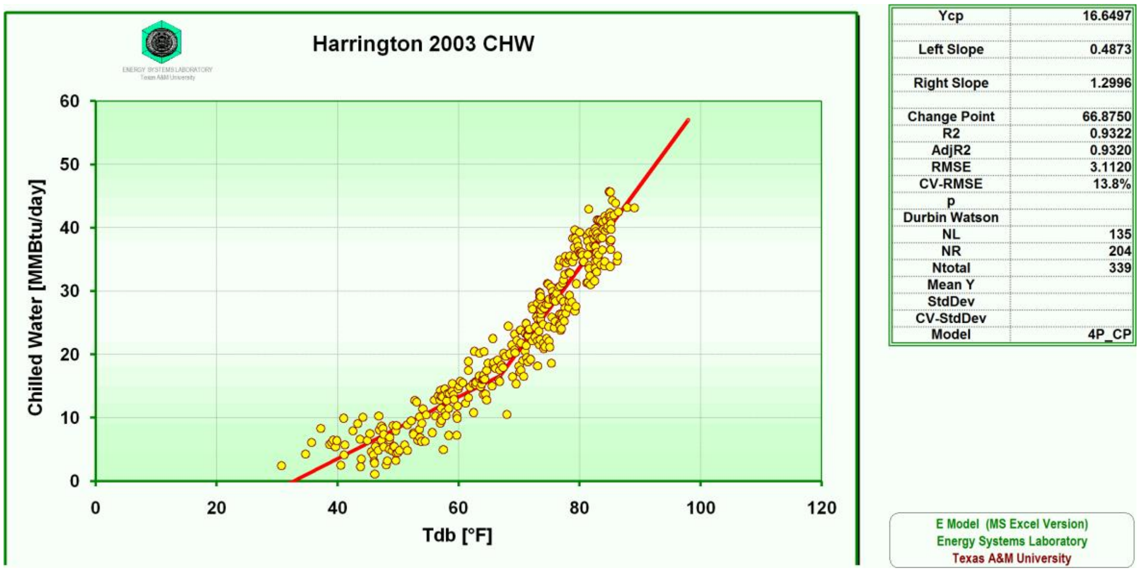
Ycp	11.6663
Left Slope	0.2306
Right Slope	0.9041
Change Point	58.3083
R2	0.8928
AdjR2	0.8925
RMSE	3.5689
CV-RMSE	16.0%
p	
Durbin Watson	
NL	96
NR	258
Ntotal	354
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 28. Change point model for Harrington 2001 chilled water data.



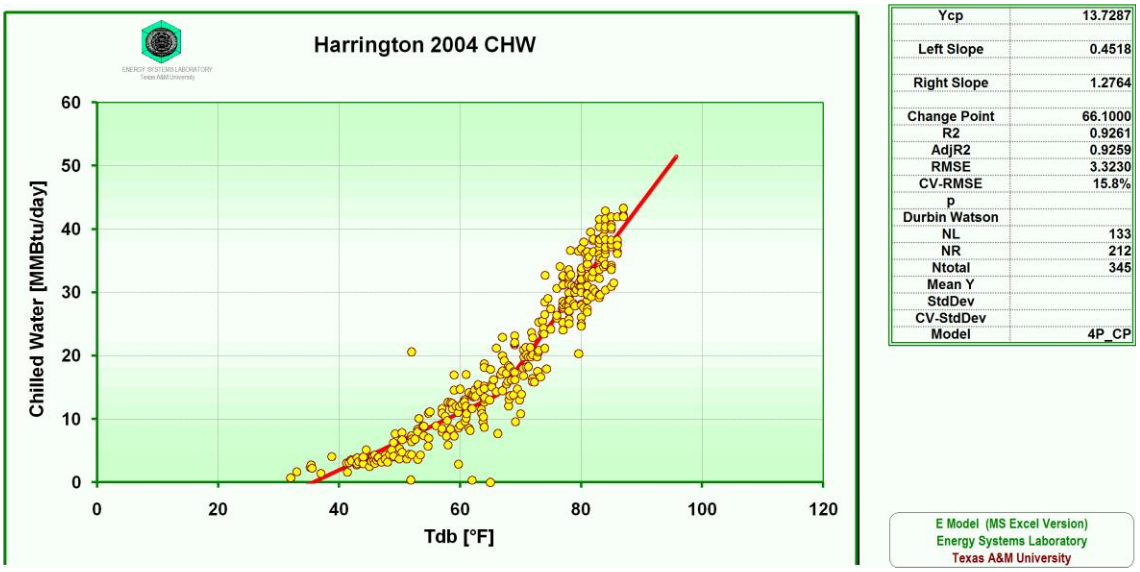
Ycp	22.5378
Left Slope	0.5064
Right Slope	1.1495
Change Point	70.2667
R2	0.8796
AdjR2	0.8792
RMSE	3.7402
CV-RMSE	15.2%
p	
Durbin Watson	
NL	164
NR	187
Ntotal	351
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 29. Change point model for Harrington 2002 chilled water data.



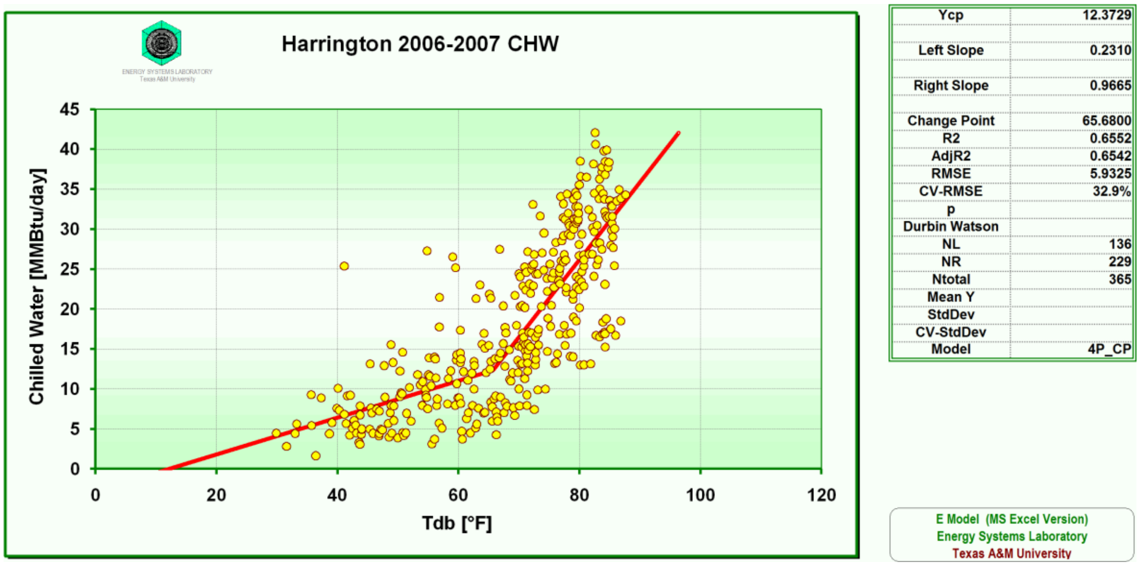
Ycp	16.6497
Left Slope	0.4873
Right Slope	1.2996
Change Point	66.8750
R2	0.9322
AdjR2	0.9320
RMSE	3.1120
CV-RMSE	13.8%
p	
Durbin Watson	
NL	135
NR	204
Ntotal	339
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 30. Change point model for Harrington 2003 chilled water data.



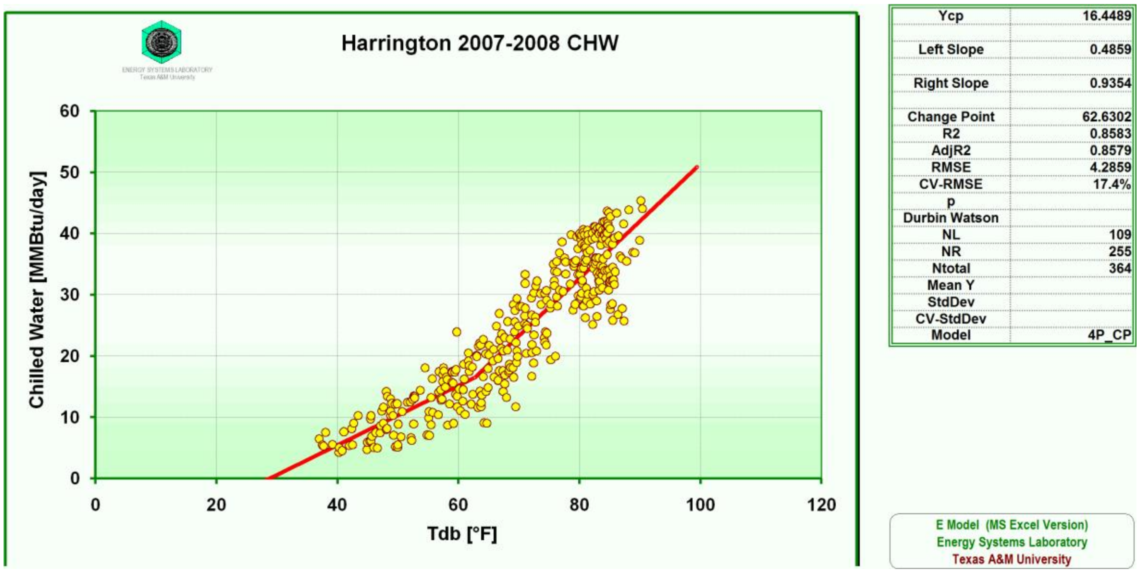
Ycp	13.7287
Left Slope	0.4518
Right Slope	1.2764
Change Point	66.1000
R2	0.9261
AdjR2	0.9259
RMSE	3.3230
CV-RMSE	15.8%
p	
Durbin Watson	
NL	133
NR	212
Ntotal	345
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 31. Change point model for Harrington 2004 chilled water data.



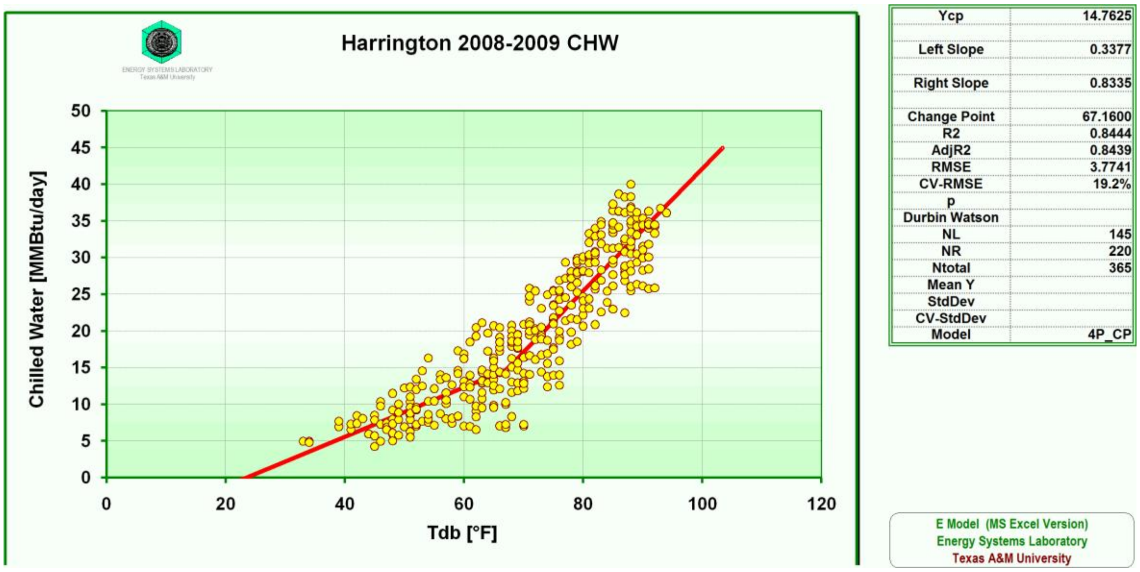
Ycp	12.3729
Left Slope	0.2310
Right Slope	0.9665
Change Point	65.6800
R2	0.6552
AdjR2	0.6542
RMSE	5.9325
CV-RMSE	32.9%
p	
Durbin Watson	
NL	136
NR	229
Ntotal	365
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 32. Change point model for Harrington 2006-07 chilled water data.



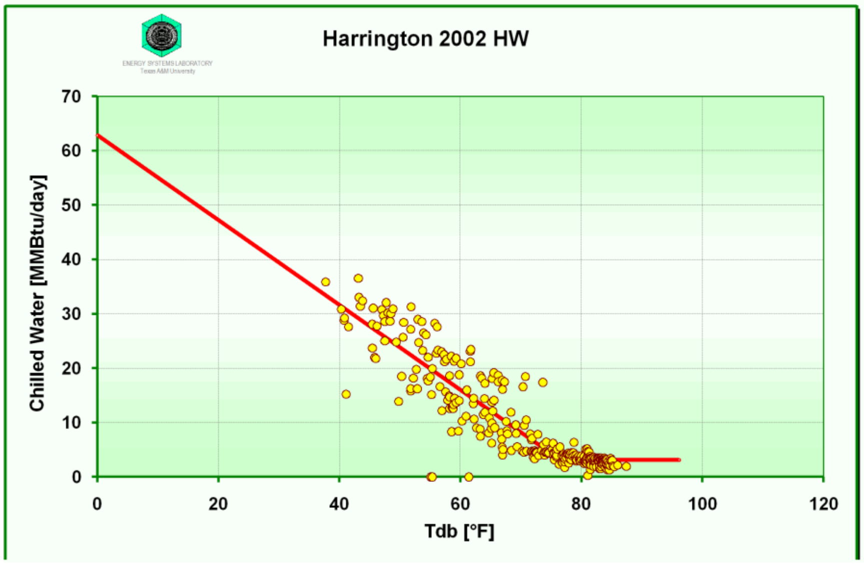
Ycp	16.4489
Left Slope	0.4859
Right Slope	0.9354
Change Point	62.6302
R2	0.8583
AdjR2	0.8579
RMSE	4.2859
CV-RMSE	17.4%
p	
Durbin Watson	
NL	109
NR	255
Ntotal	364
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 33. Change point model for Harrington 2007-08 chilled water data.



Ycp	14.7625
Left Slope	0.3377
Right Slope	0.8335
Change Point	67.1600
R2	0.8444
AdjR2	0.8439
RMSE	3.7741
CV-RMSE	19.2%
p	
Durbin Watson	
NL	145
NR	220
Ntotal	365
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 34. Change point model for Harrington 2008-09 chilled water data.



Ycp	3.1265
Left Slope	-0.7806
Right Slope	0.0000
Change Point	76.4808
R2	0.8264
AdjR2	0.8259
RMSE	3.7788
CV-RMSE	39.0%
p	
Durbin Watson	
NL	175
NR	139
Ntotal	314
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

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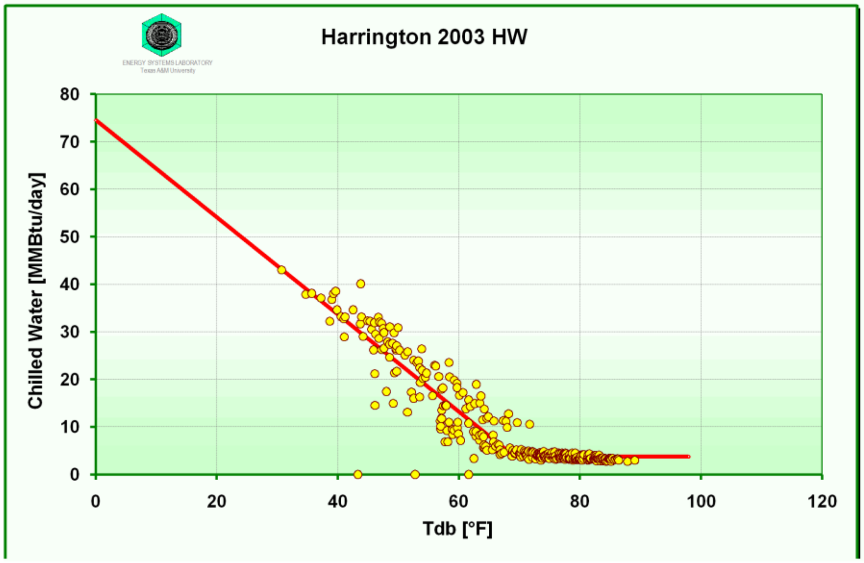
Figure C - 35. Change point model for Harrington 2002 hot water data.



Ycp	3.7828
Left Slope	-1.0222
Right Slope	0.0000
Change Point	69.2083
R2	0.8652
AdjR2	0.8648
RMSE	3.6708
CV-RMSE	36.7%
p	
Durbin Watson	
NL	147
NR	193
Ntotal	340
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

E Model (MS Excel Version)
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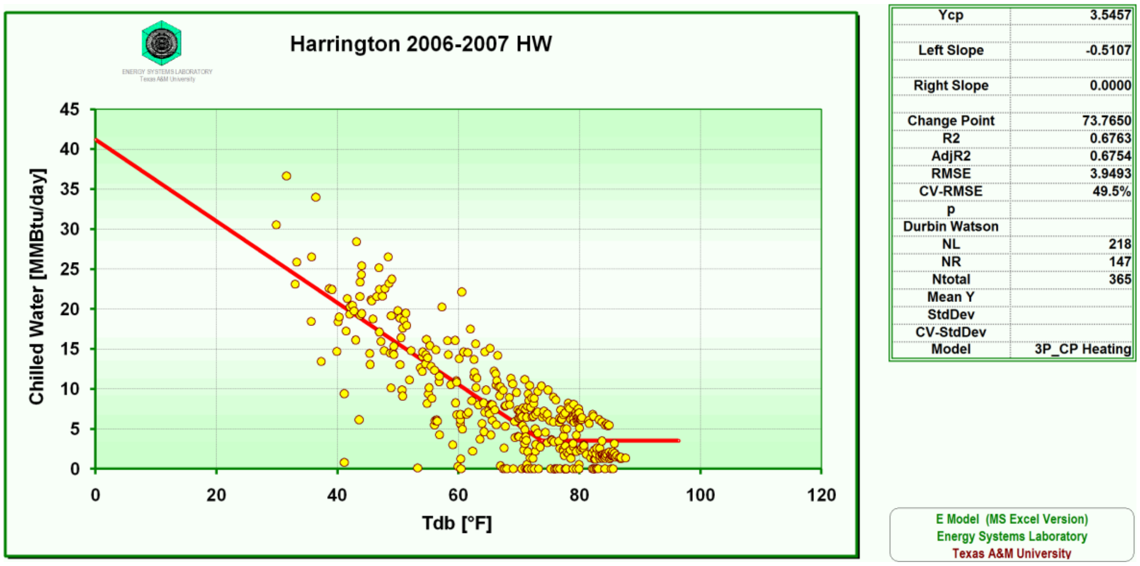
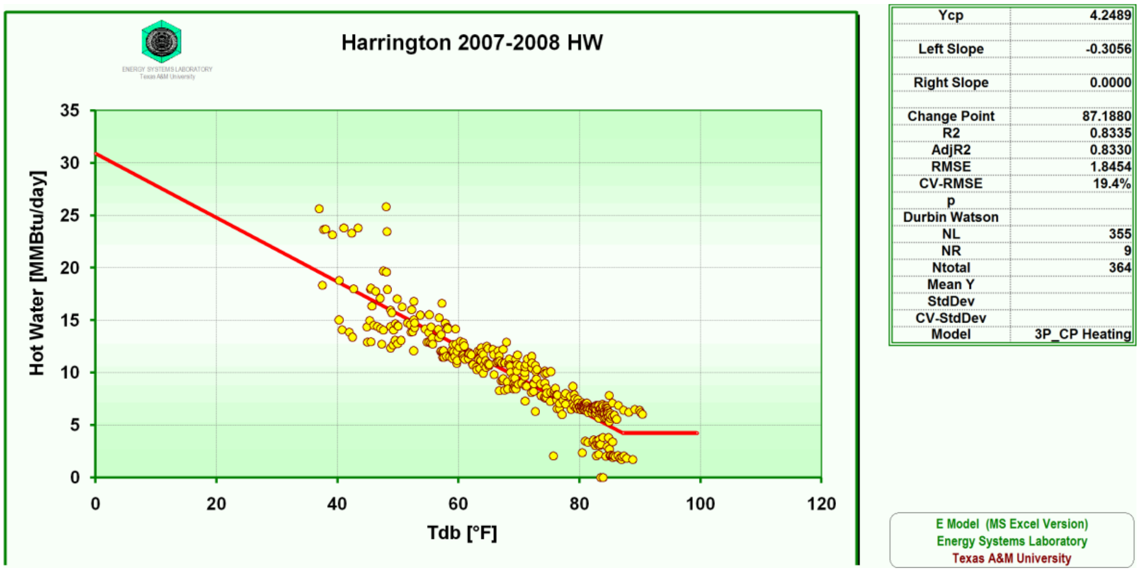
Figure C - 36. Change point model for Harrington 2003 hot water data.



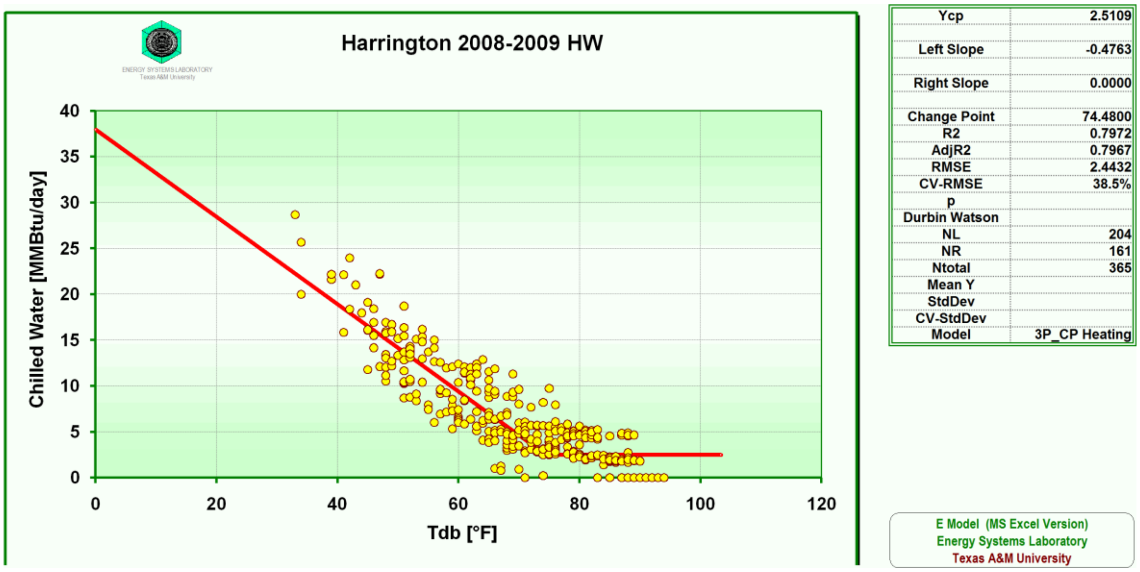
Ycp	3.5457
Left Slope	-0.5107
Right Slope	0.0000
Change Point	73.7650
R2	0.6763
AdjR2	0.6754
RMSE	3.9493
CV-RMSE	49.5%
p	
Durbin Watson	
NL	218
NR	147
Ntotal	365
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 37. Change point model for Harrington 2006-07 hot water data.



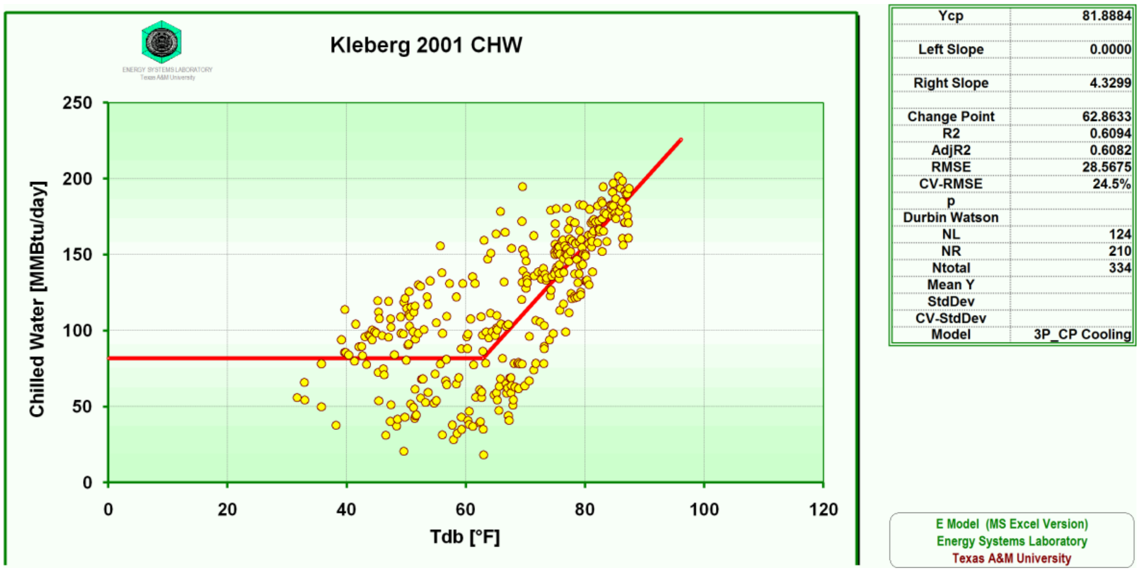
Ycp	4.2489
Left Slope	-0.3056
Right Slope	0.0000
Change Point	87.1880
R2	0.8335
AdjR2	0.8330
RMSE	1.8454
CV-RMSE	19.4%
p	
Durbin Watson	
NL	355
NR	9
Ntotal	364
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 38. Change point model for Harrington 2007-08 hot water data.



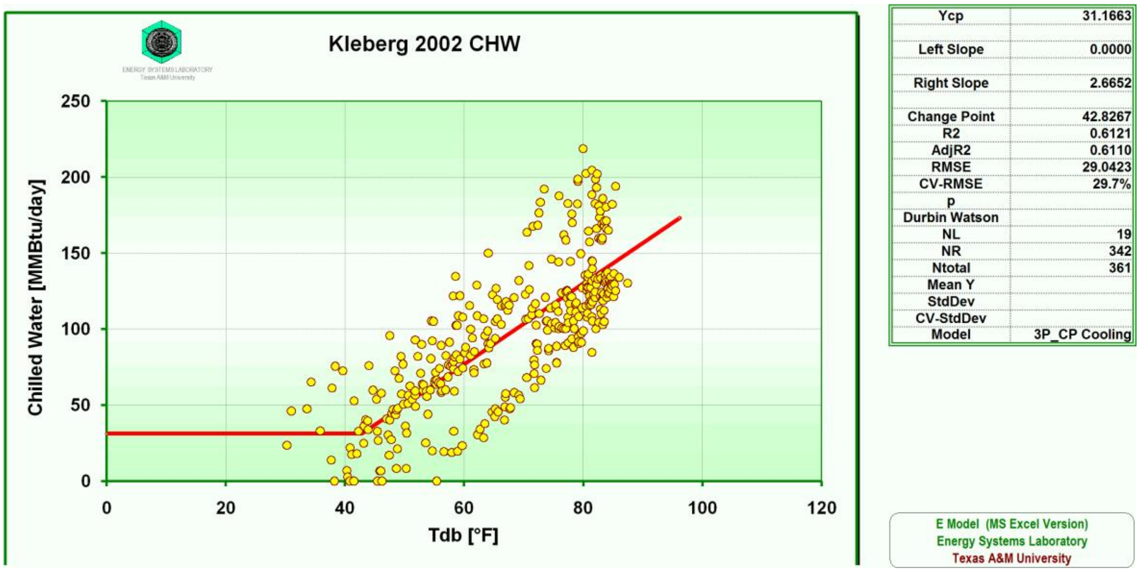
Ycp	2.5109
Left Slope	-0.4763
Right Slope	0.0000
Change Point	74.4800
R2	0.7972
AdjR2	0.7967
RMSE	2.4432
CV-RMSE	38.5%
p	
Durbin Watson	
NL	204
NR	161
Ntotal	365
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 39. Change point model for Harrington 2008-09 hot water data.



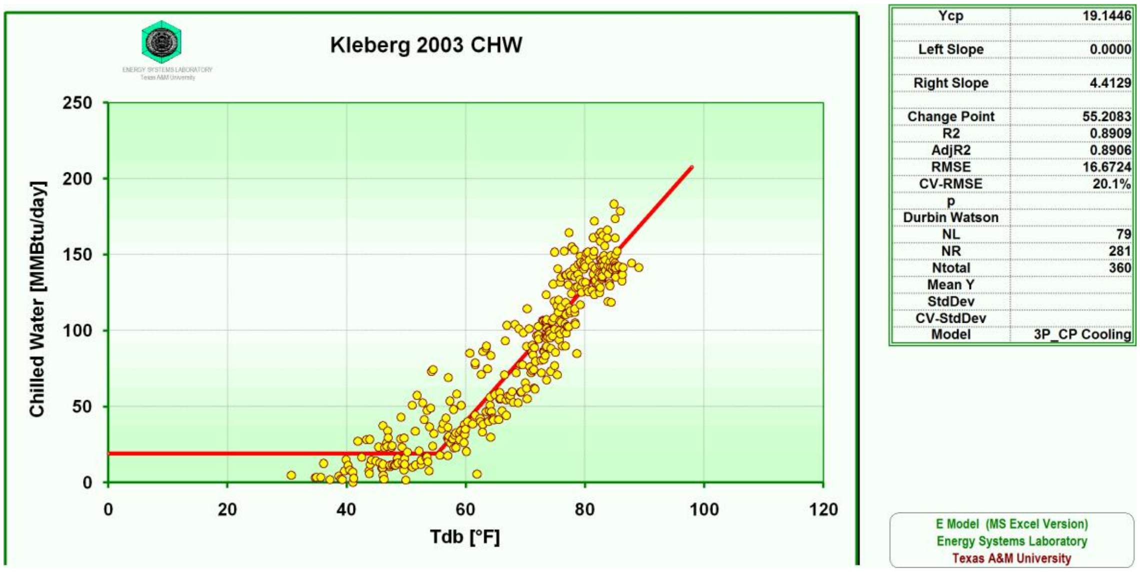
Ycp	81.8884
Left Slope	0.0000
Right Slope	4.3299
Change Point	62.8633
R2	0.6094
AdjR2	0.6082
RMSE	28.5675
CV-RMSE	24.5%
p	
Durbin Watson	
NL	124
NR	210
Ntotal	334
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 40. Change point model for Kleberg 2001 chilled water data.



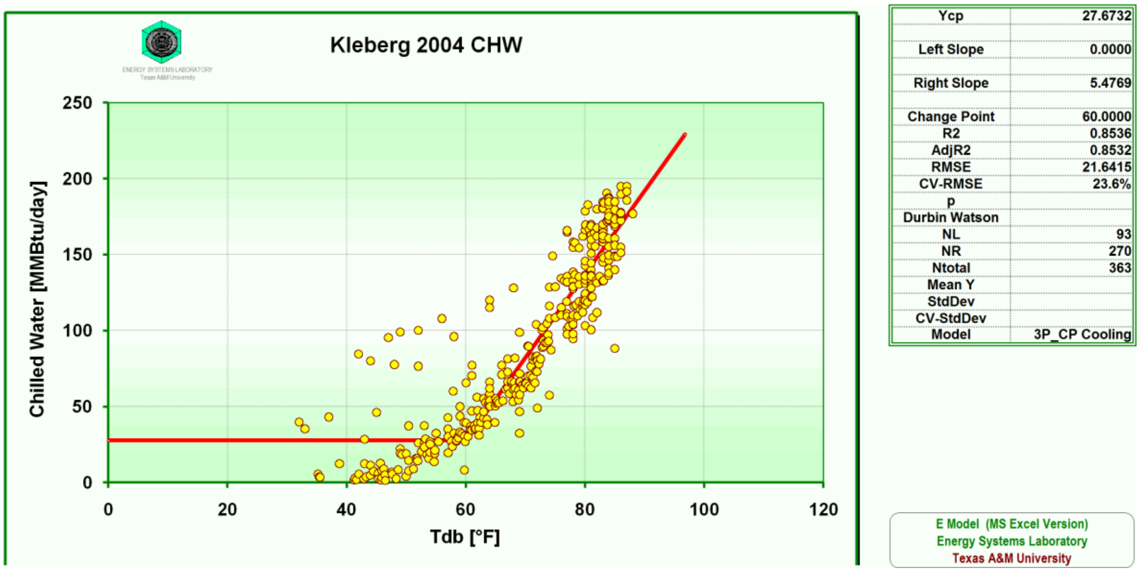
Ycp	31.1663
Left Slope	0.0000
Right Slope	2.6652
Change Point	42.8267
R2	0.6121
AdjR2	0.6110
RMSE	29.0423
CV-RMSE	29.7%
p	
Durbin Watson	
NL	19
NR	342
Ntotal	361
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 41. Change point model for Kleberg 2002 chilled water data.



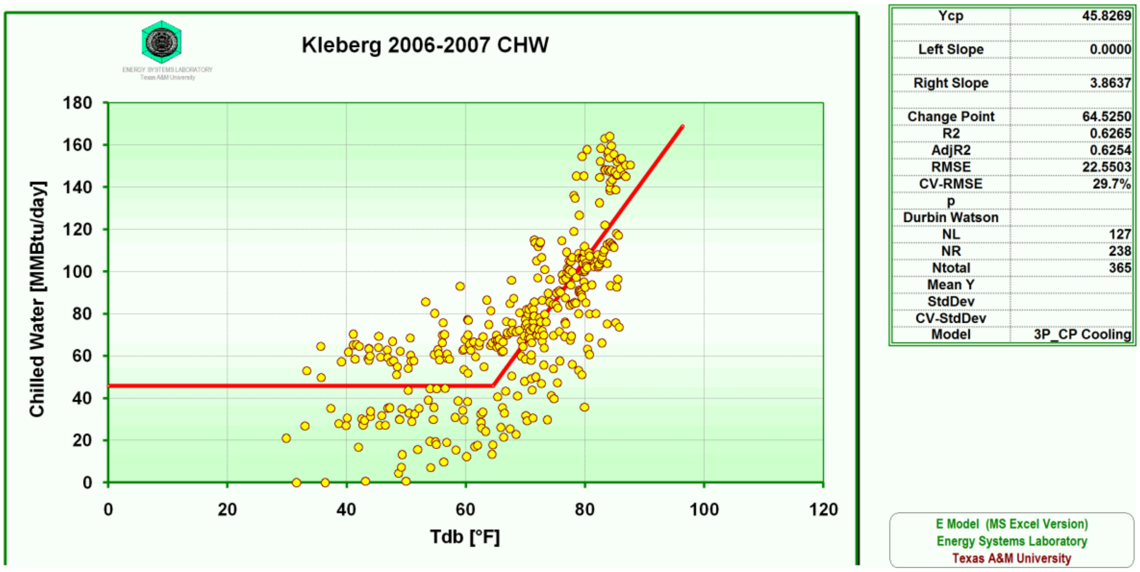
Ycp	19.1446
Left Slope	0.0000
Right Slope	4.4129
Change Point	55.2083
R2	0.8909
AdjR2	0.8906
RMSE	16.6724
CV-RMSE	20.1%
p	
Durbin Watson	
NL	79
NR	281
Ntotal	360
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 42. Change point model for Kleberg 2003 chilled water data.



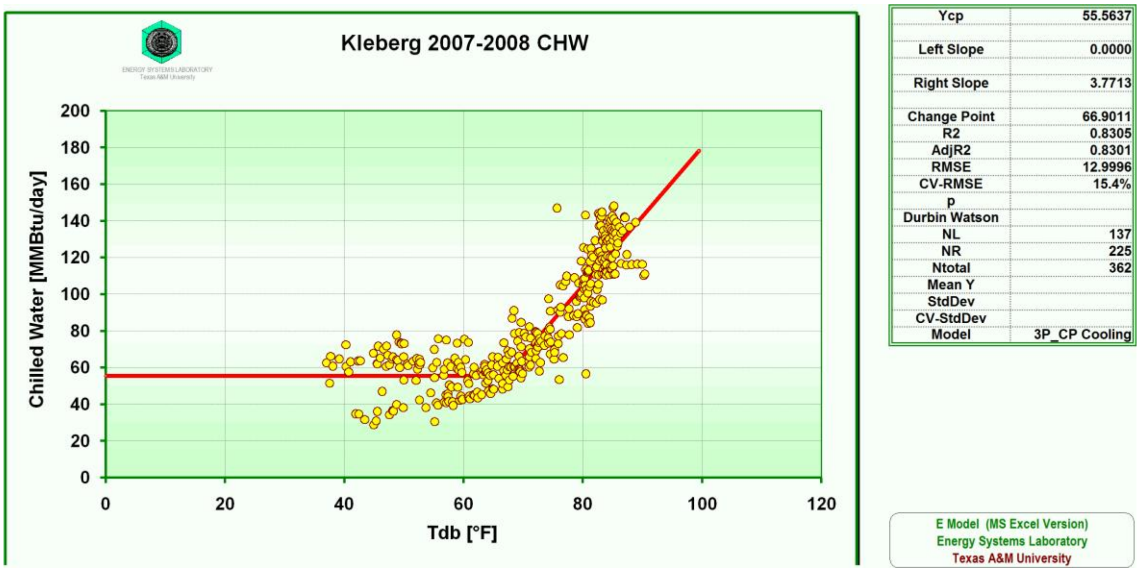
Ycp	27.6732
Left Slope	0.0000
Right Slope	5.4769
Change Point	60.0000
R2	0.8536
AdjR2	0.8532
RMSE	21.6415
CV-RMSE	23.6%
p	
Durbin Watson	
NL	93
NR	270
Ntotal	363
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 43. Change point model for Kleberg 2004 chilled water data.



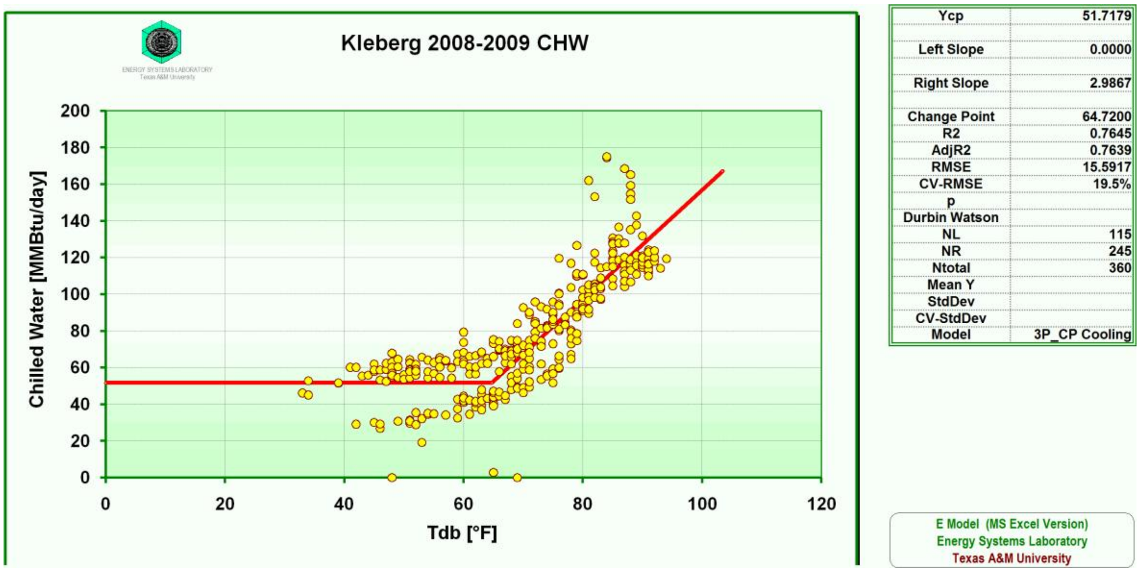
Ycp	45.8269
Left Slope	0.0000
Right Slope	3.8637
Change Point	64.5250
R2	0.6265
AdjR2	0.6254
RMSE	22.5503
CV-RMSE	29.7%
p	
Durbin Watson	
NL	127
NR	238
Ntotal	365
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 44. Change point model for Kleberg 2006-07 chilled water data.



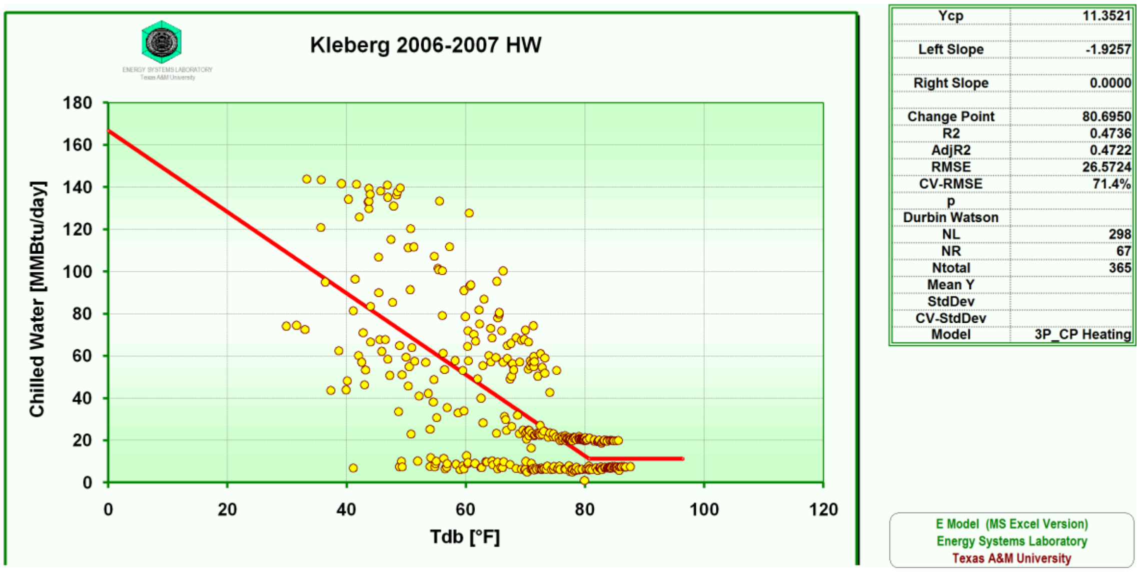
Ycp	55.5637
Left Slope	0.0000
Right Slope	3.7713
Change Point	66.9011
R2	0.8305
AdjR2	0.8301
RMSE	12.9996
CV-RMSE	15.4%
p	
Durbin Watson	
NL	137
NR	225
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 45. Change point model for Kleberg 2007-08 chilled water data.



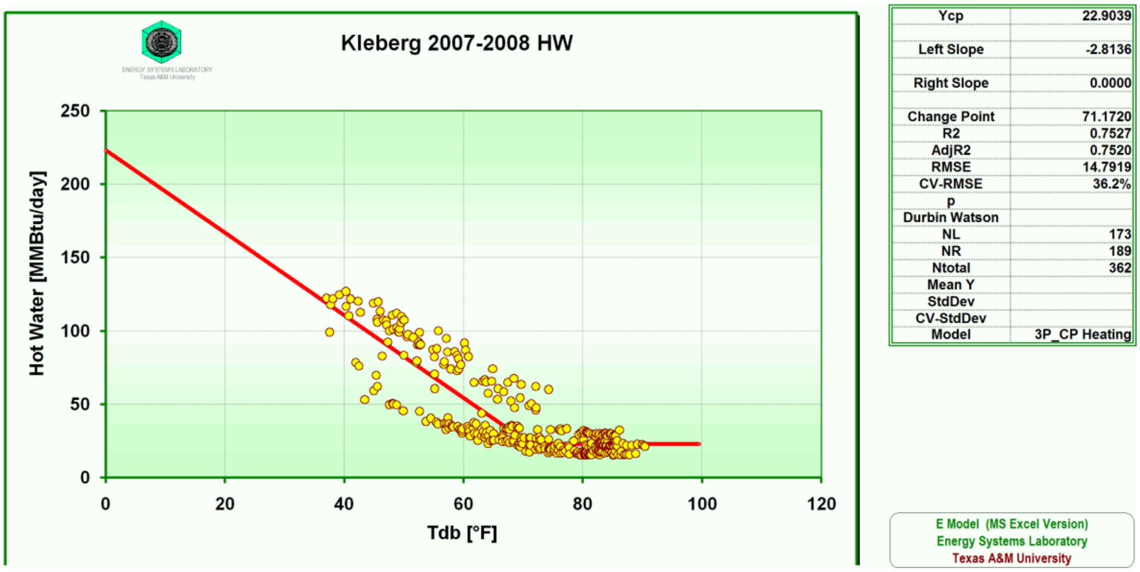
Ycp	51.7179
Left Slope	0.0000
Right Slope	2.9867
Change Point	64.7200
R2	0.7645
AdjR2	0.7639
RMSE	15.5917
CV-RMSE	19.5%
p	
Durbin Watson	
NL	115
NR	245
Ntotal	360
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 46. Change point model for Kleberg 2008-09 chilled water data.



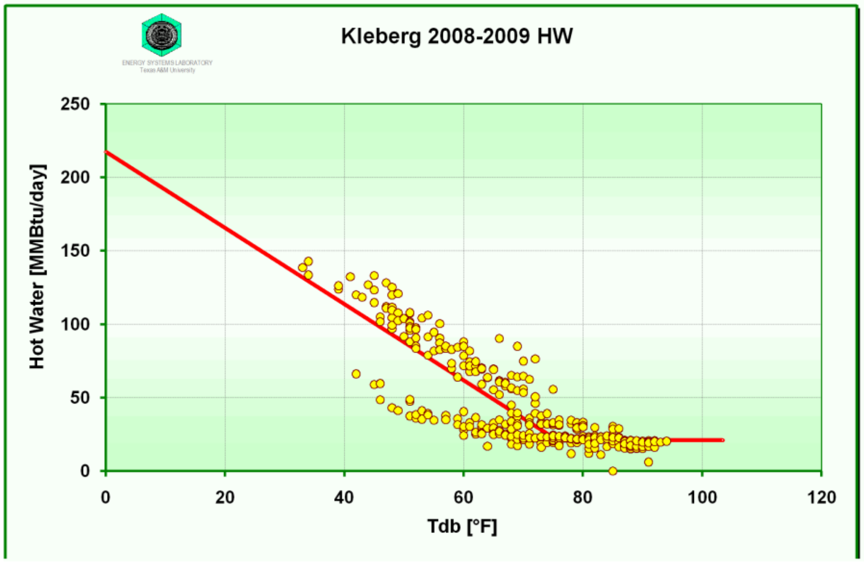
Ycp	11.3521
Left Slope	-1.9257
Right Slope	0.0000
Change Point	80.6950
R2	0.4736
AdjR2	0.4722
RMSE	26.5724
CV-RMSE	71.4%
p	
Durbin Watson	
NL	298
NR	67
Ntotal	365
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 47. Change point model for Kleberg 2006-07 hot water data.



Ycp	22.9039
Left Slope	-2.8136
Right Slope	0.0000
Change Point	71.1720
R2	0.7527
AdjR2	0.7520
RMSE	14.7919
CV-RMSE	36.2%
p	
Durbin Watson	
NL	173
NR	189
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

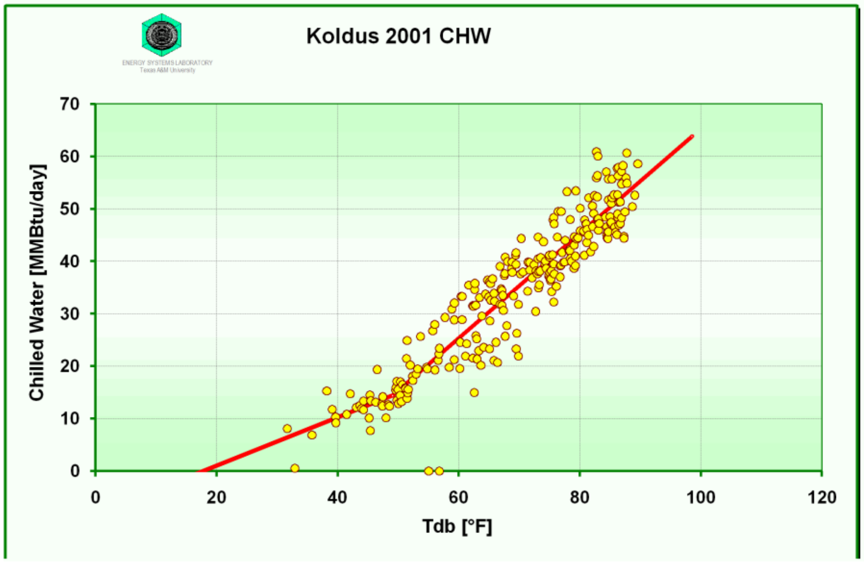
Figure C - 48. Change point model for Kleberg 2007-08 hot water data.



Ycp	21.0255
Left Slope	-2.5936
Right Slope	0.0000
Change Point	75.7000
R2	0.7257
AdjR2	0.7250
RMSE	16.7783
CV-RMSE	38.6%
p	
Durbin Watson	
NL	211
NR	149
Ntotal	360
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

E Model (MS Excel Version)
Energy Systems Laboratory
Texas A&M University

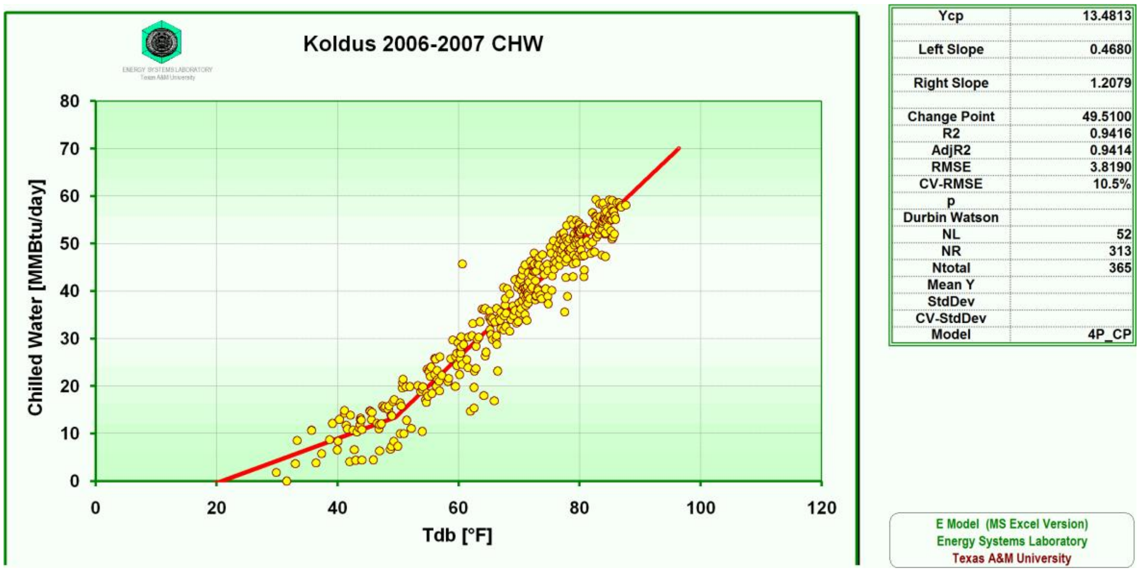
Figure C - 49. Change point model for Kleberg 2008-09 hot water data.



Ycp	14.4283
Left Slope	0.4605
Right Slope	0.9981
Change Point	49.0417
R2	0.8760
AdjR2	0.8755
RMSE	4.9537
CV-RMSE	14.3%
p	
Durbin Watson	
NL	26
NR	236
Ntotal	262
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

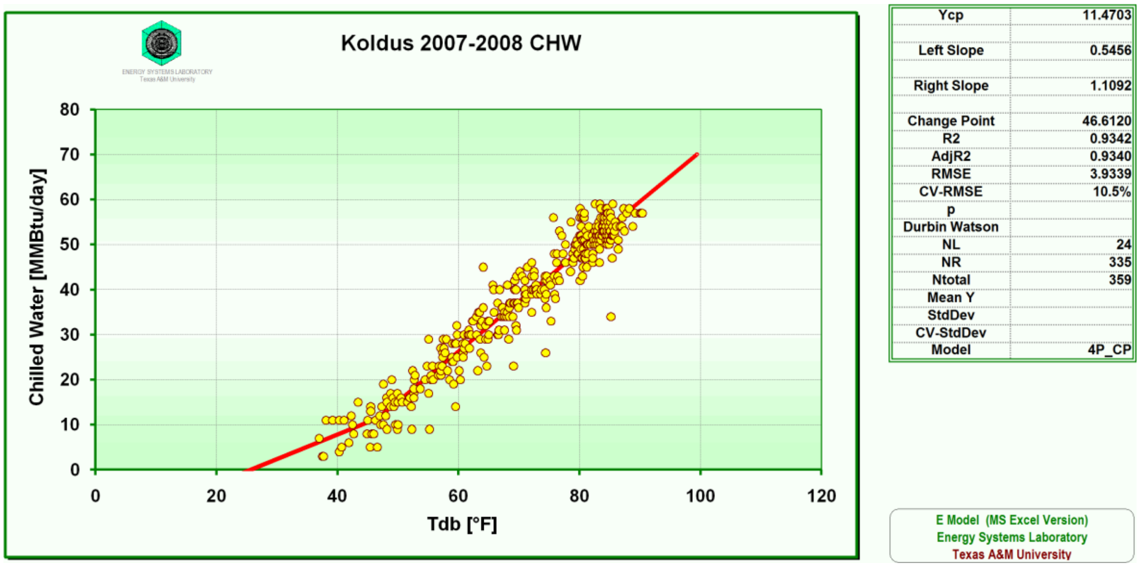
E Model (MS Excel Version)
Energy Systems Laboratory
Texas A&M University

Figure C - 50. Change point model for Koldus 2001 chilled water data.



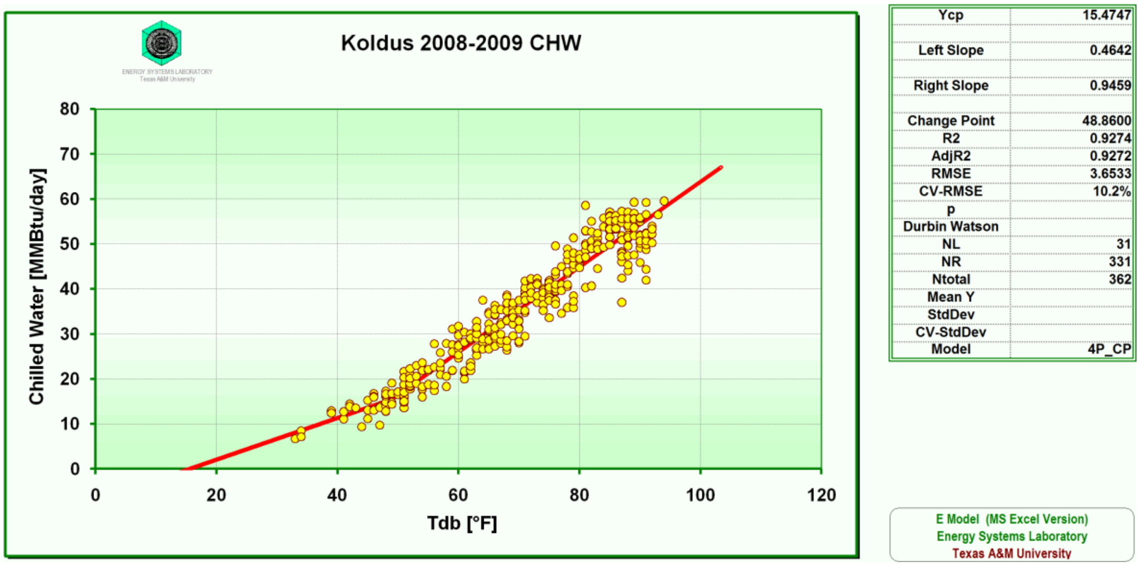
Ycp	13.4813
Left Slope	0.4680
Right Slope	1.2079
Change Point	49.5100
R2	0.9416
AdjR2	0.9414
RMSE	3.8190
CV-RMSE	10.5%
p	
Durbin Watson	
NL	52
NR	313
Ntotal	365
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 51. Change point model for Koldus 2006-07 chilled water data.



Ycp	11.4703
Left Slope	0.5456
Right Slope	1.1092
Change Point	46.6120
R2	0.9342
AdjR2	0.9340
RMSE	3.9339
CV-RMSE	10.5%
p	
Durbin Watson	
NL	24
NR	335
Ntotal	359
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

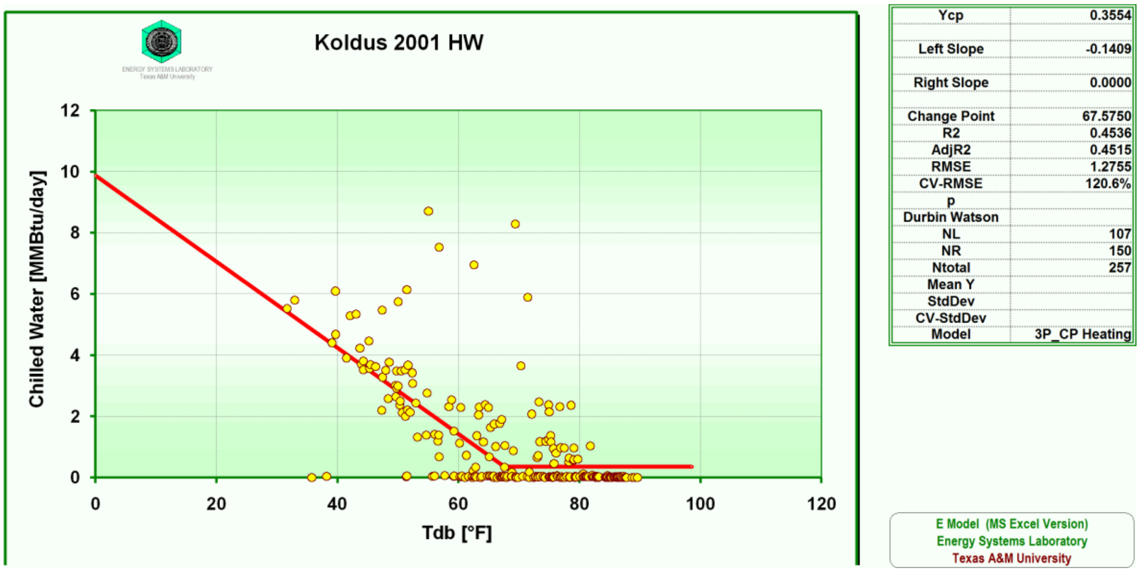
Figure C - 52. Change point model for Koldus 2007-08 chilled water data.



Ycp	15.4747
Left Slope	0.4642
Right Slope	0.9459
Change Point	48.8600
R2	0.9274
AdjR2	0.9272
RMSE	3.6533
CV-RMSE	10.2%
p	
Durbin Watson	
NL	31
NR	331
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

E Model (MS Excel Version)
Energy Systems Laboratory
Texas A&M University

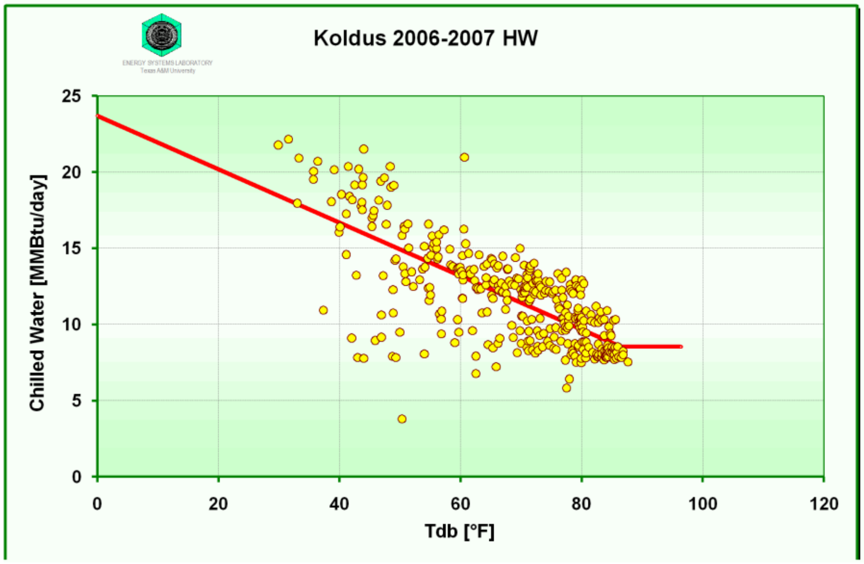
Figure C - 53. Change point model for Koldus 2008-09 chilled water data.



Ycp	0.3554
Left Slope	-0.1409
Right Slope	0.0000
Change Point	67.5750
R2	0.4536
AdjR2	0.4515
RMSE	1.2755
CV-RMSE	120.6%
p	
Durbin Watson	
NL	107
NR	150
Ntotal	257
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

E Model (MS Excel Version)
Energy Systems Laboratory
Texas A&M University

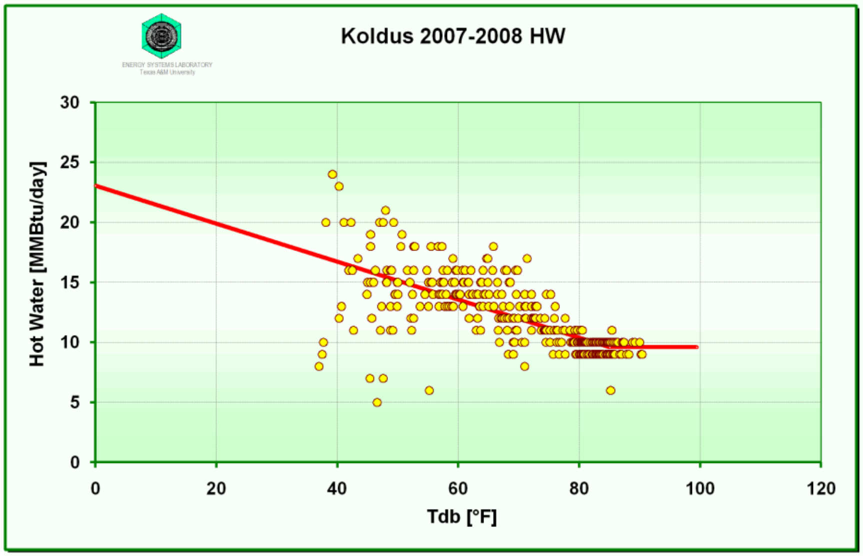
Figure C - 54. Change point model for Koldus 2001 hot water data.



Ycp	8.5394
Left Slope	-0.1753
Right Slope	0.0000
Change Point	86.4700
R2	0.5167
AdjR2	0.5154
RMSE	2.3318
CV-RMSE	19.8%
p	
Durbin Watson	
NL	361
NR	4
Ntotal	365
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

E Model (MS Excel Version)
Energy Systems Laboratory
Texas A&M University

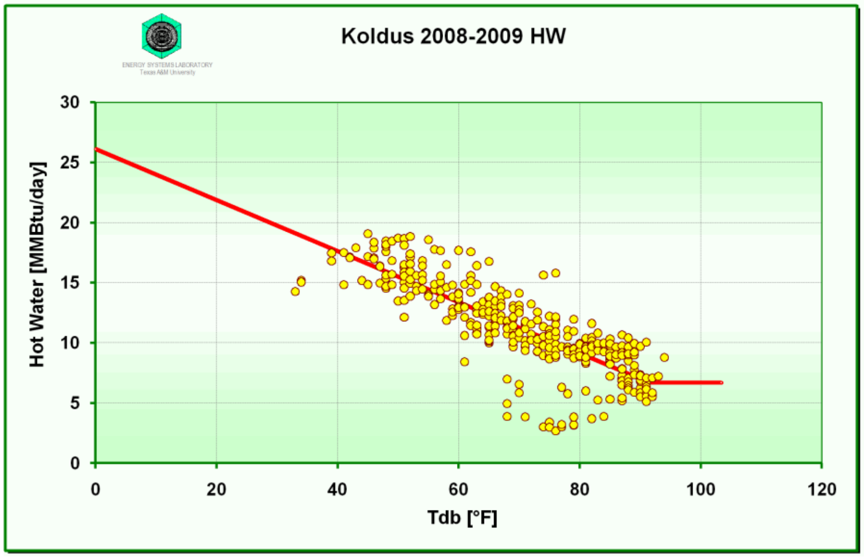
Figure C - 55. Change point model for Koldus 2006-07 hot water data.



Ycp	9.5937
Left Slope	-0.1584
Right Slope	0.0000
Change Point	85.0600
R2	0.5009
AdjR2	0.4995
RMSE	2.1259
CV-RMSE	17.7%
p	
Durbin Watson	
NL	328
NR	32
Ntotal	360
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

E Model (MS Excel Version)
Energy Systems Laboratory
Texas A&M University

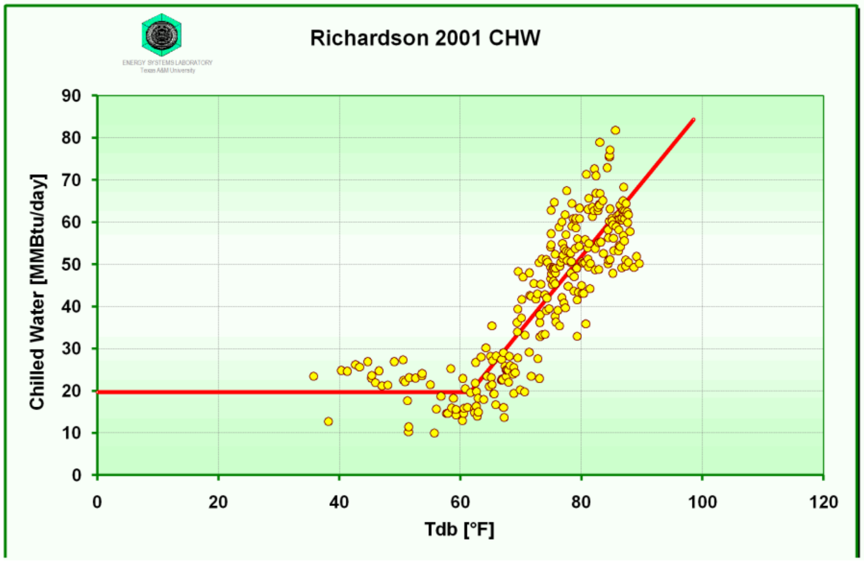
Figure C - 56. Change point model for Koldus 2007-08 hot water data.



Ycp	6.6982
Left Slope	-0.2121
Right Slope	0.0000
Change Point	91.5600
R2	0.6736
AdjR2	0.6727
RMSE	2.0931
CV-RMSE	18.7%
p	
Durbin Watson	
NL	356
NR	6
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

E Model (MS Excel Version)
Energy Systems Laboratory
Texas A&M University

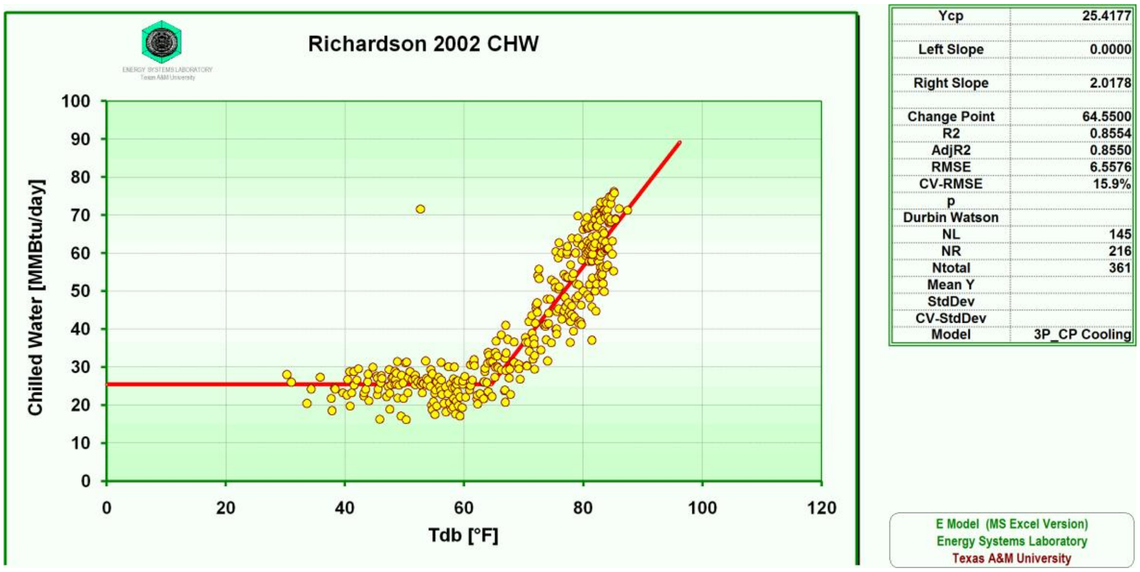
Figure C - 57. Change point model for Koldus 2008-09 hot water data.



Ycp	19.6666
Left Slope	0.0000
Right Slope	1.7512
Change Point	61.5900
R2	0.7866
AdjR2	0.7858
RMSE	8.0505
CV-RMSE	18.8%
p	
Durbin Watson	
NL	41
NR	230
Ntotal	271
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

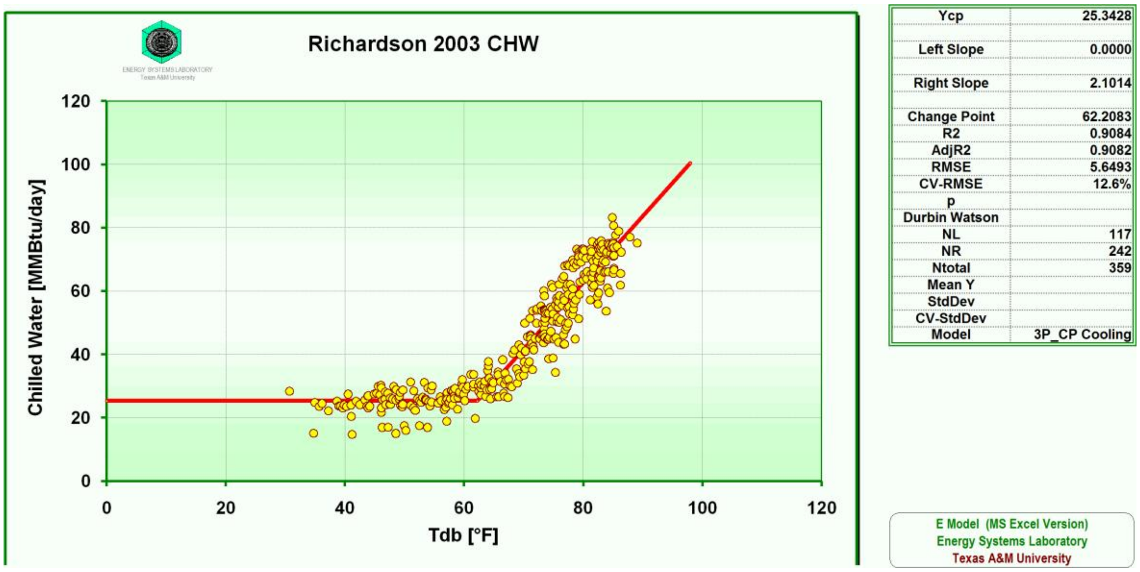
E Model (MS Excel Version)
Energy Systems Laboratory
Texas A&M University

Figure C - 58. Change point model for Richardson 2001 chilled water data.



Ycp	25.4177
Left Slope	0.0000
Right Slope	2.0178
Change Point	64.5500
R2	0.8554
AdjR2	0.8550
RMSE	6.5576
CV-RMSE	15.9%
p	
Durbin Watson	
NL	145
NR	216
Ntotal	361
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 59. Change point model for Richardson 2002 chilled water data.



Ycp	25.3428
Left Slope	0.0000
Right Slope	2.1014
Change Point	62.2083
R2	0.9084
AdjR2	0.9082
RMSE	5.6493
CV-RMSE	12.6%
p	
Durbin Watson	
NL	117
NR	242
Ntotal	359
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 60. Change point model for Richardson 2003 chilled water data.

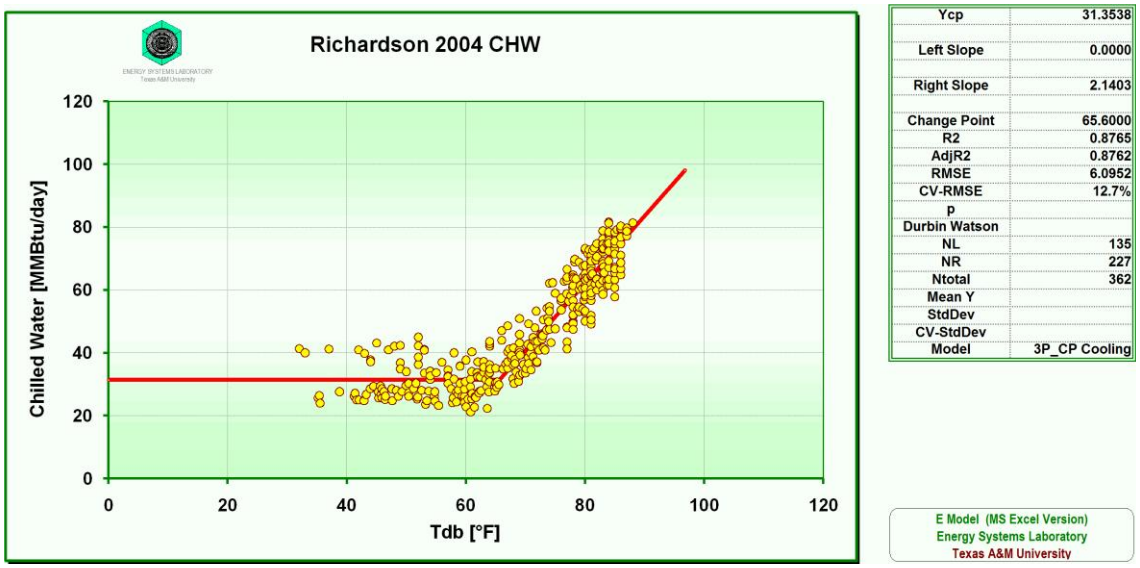


Figure C - 61. Change point model for Richardson 2004 chilled water data.

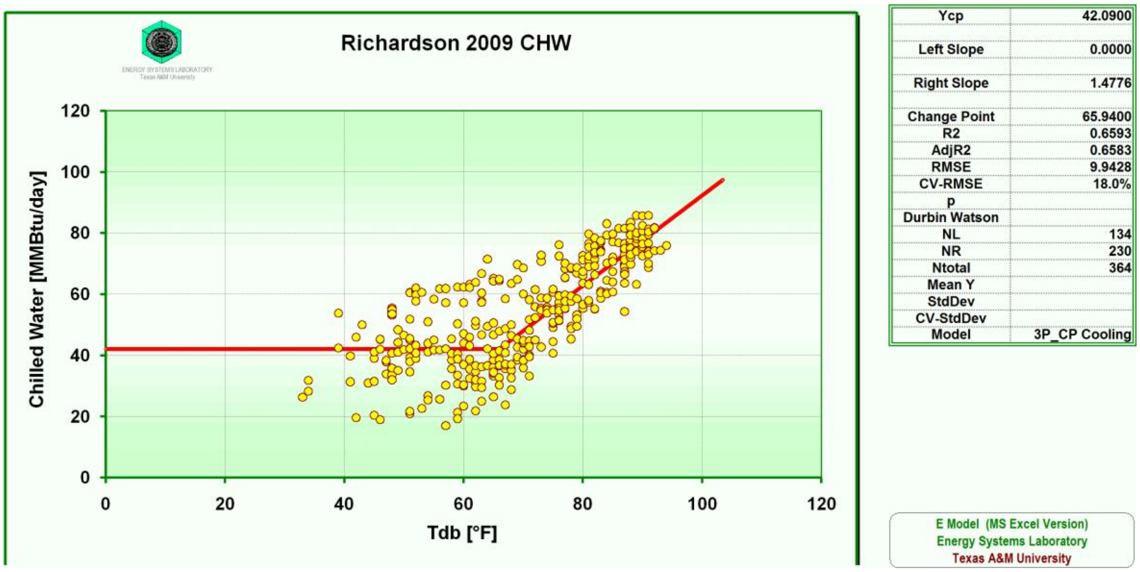
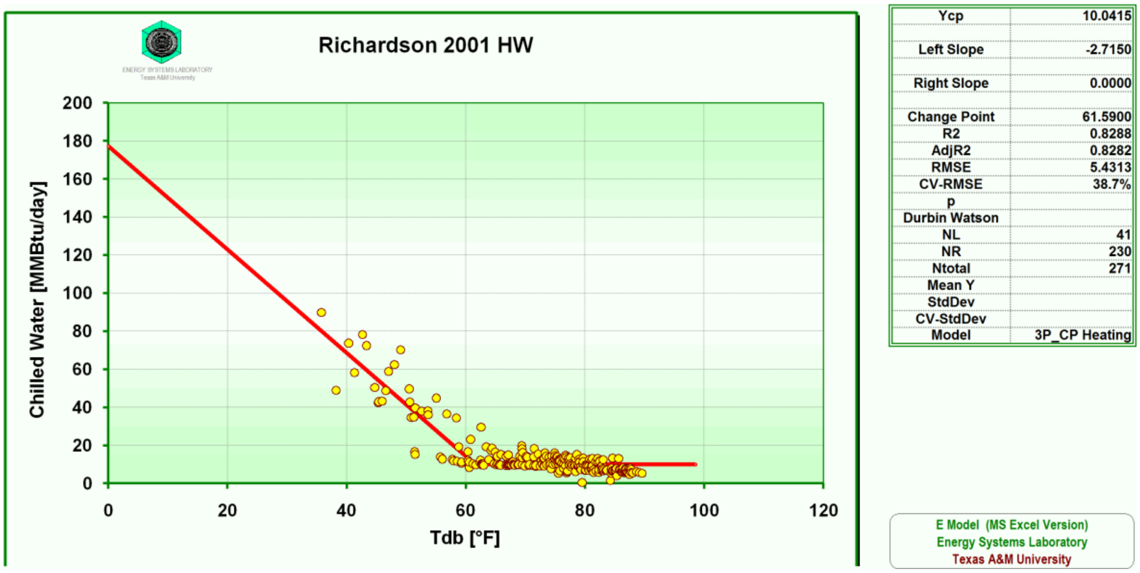
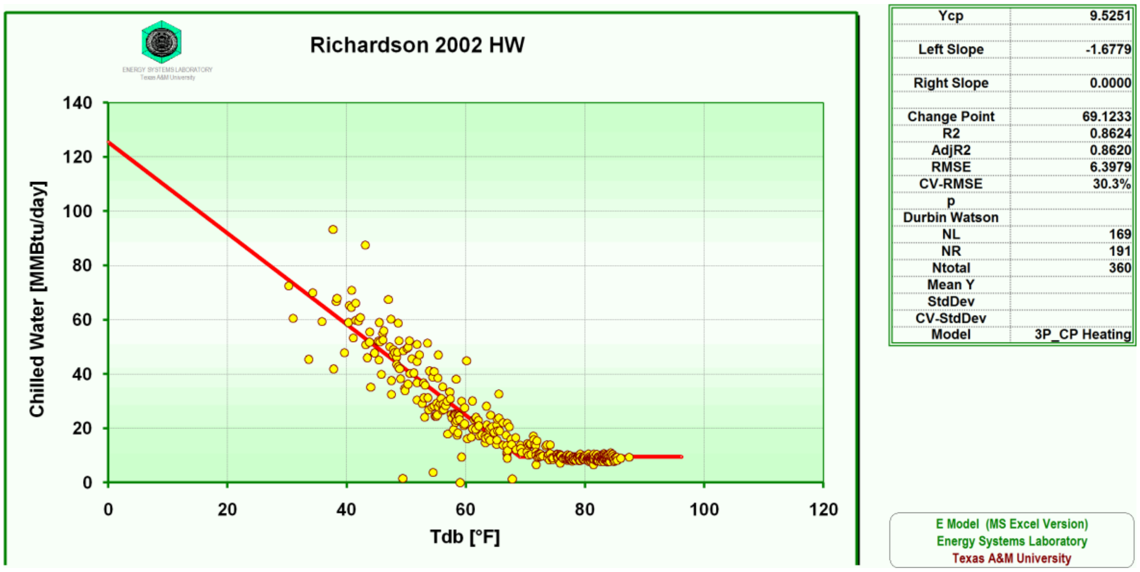


Figure C - 62. Change point model for Richardson 2008-09 chilled water data.



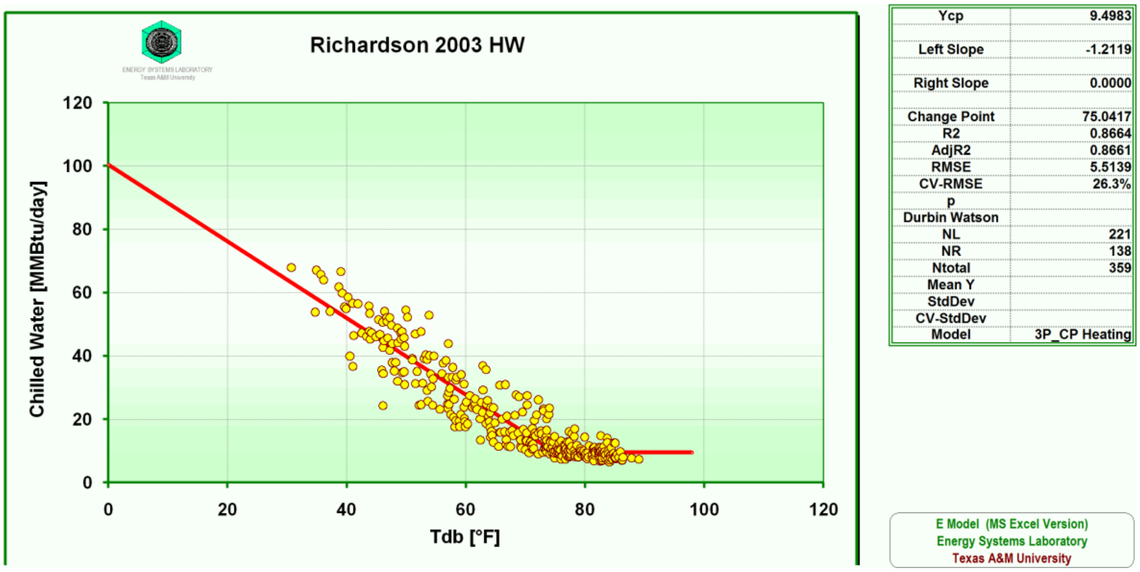
Ycp	10.0415
Left Slope	-2.7150
Right Slope	0.0000
Change Point	61.5900
R2	0.8288
AdjR2	0.8282
RMSE	5.4313
CV-RMSE	38.7%
p	
Durbin Watson	
NL	41
NR	230
Ntotal	271
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 63. Change point model for Richardson 2001 hot water data.



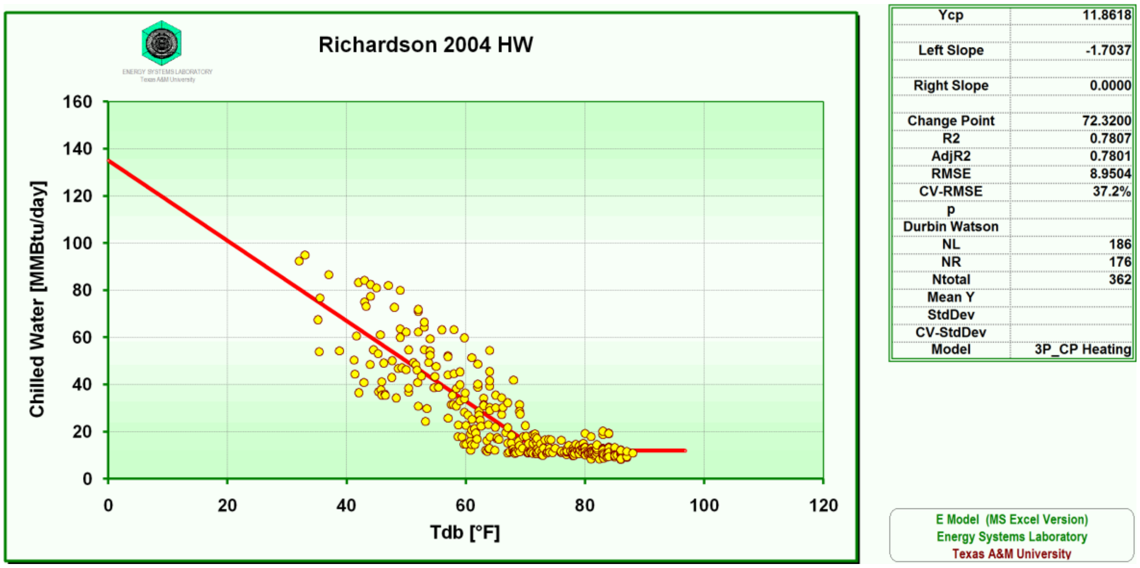
Ycp	9.5251
Left Slope	-1.6779
Right Slope	0.0000
Change Point	69.1233
R2	0.8624
AdjR2	0.8620
RMSE	6.3979
CV-RMSE	30.3%
p	
Durbin Watson	
NL	169
NR	191
Ntotal	360
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 64. Change point model for Richardson 2002 hot water data.



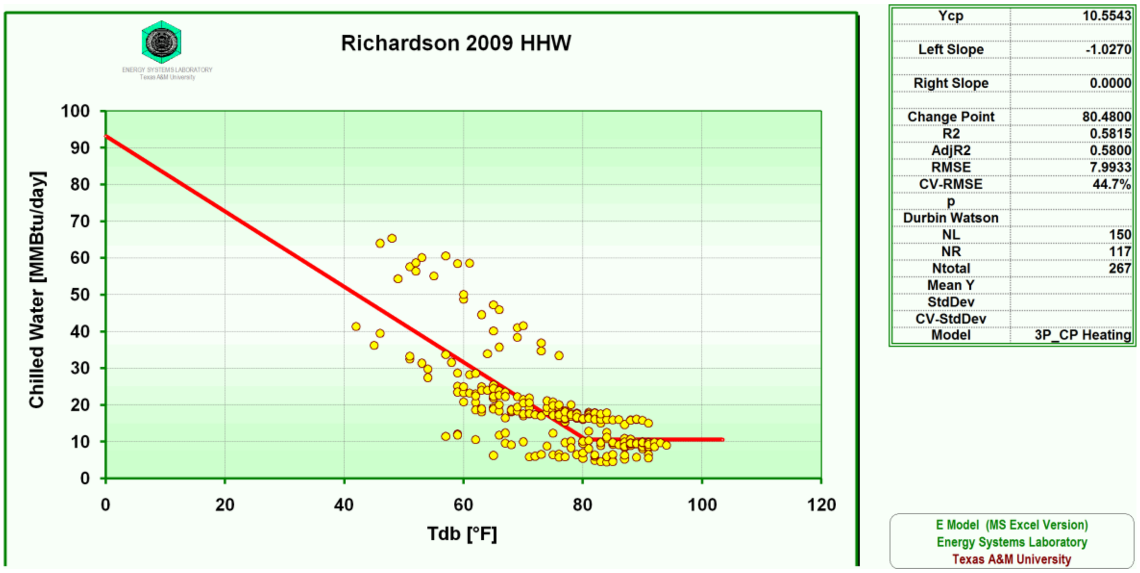
Ycp	9.4983
Left Slope	-1.2119
Right Slope	0.0000
Change Point	75.0417
R2	0.8664
AdjR2	0.8661
RMSE	5.5139
CV-RMSE	26.3%
p	
Durbin Watson	
NL	221
NR	138
Ntotal	359
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 65. Change point model for Richardson 2003 hot water data.



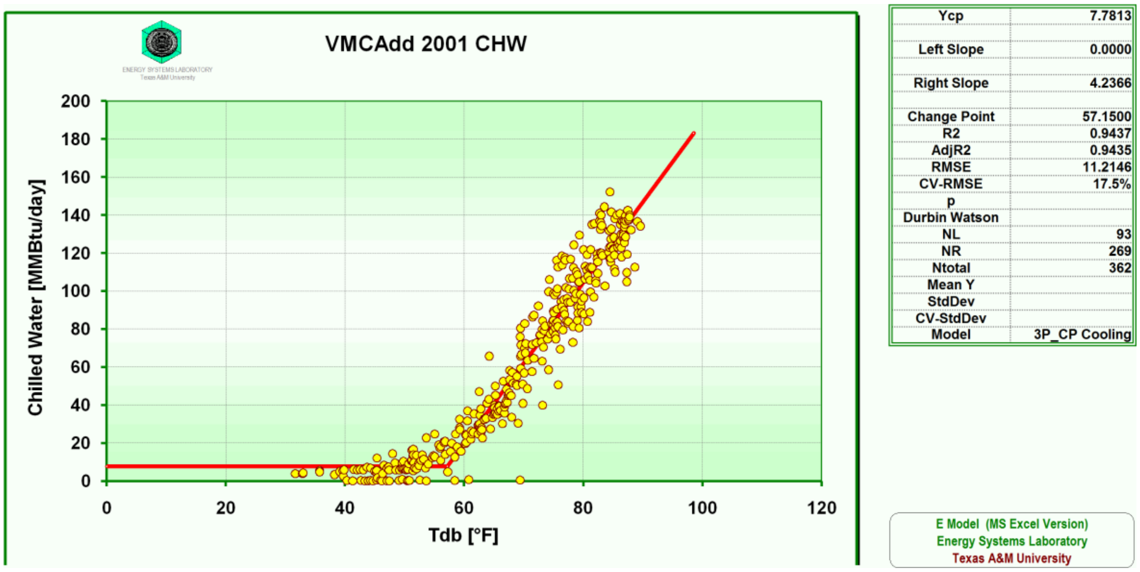
Ycp	11.8618
Left Slope	-1.7037
Right Slope	0.0000
Change Point	72.3200
R2	0.7807
AdjR2	0.7801
RMSE	8.9504
CV-RMSE	37.2%
p	
Durbin Watson	
NL	186
NR	176
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 66. Change point model for Richardson 2004 hot water data.



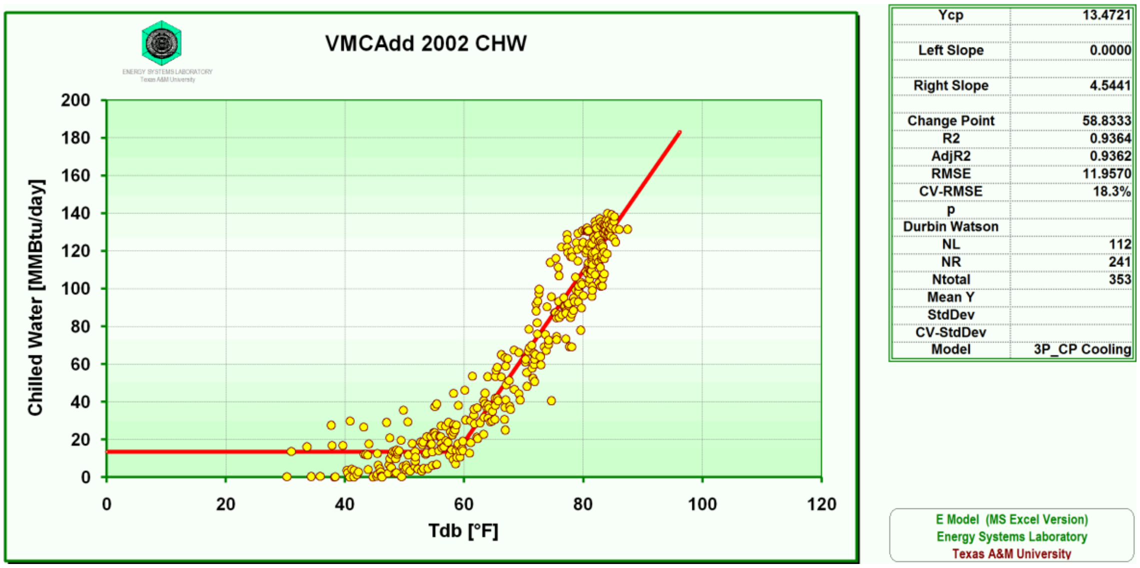
Ycp	10.5543
Left Slope	-1.0270
Right Slope	0.0000
Change Point	80.4800
R2	0.5815
AdjR2	0.5800
RMSE	7.9933
CV-RMSE	44.7%
p	
Durbin Watson	
NL	150
NR	117
Ntotal	267
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 67. Change point model for Richardson 2008-09 hot water data.



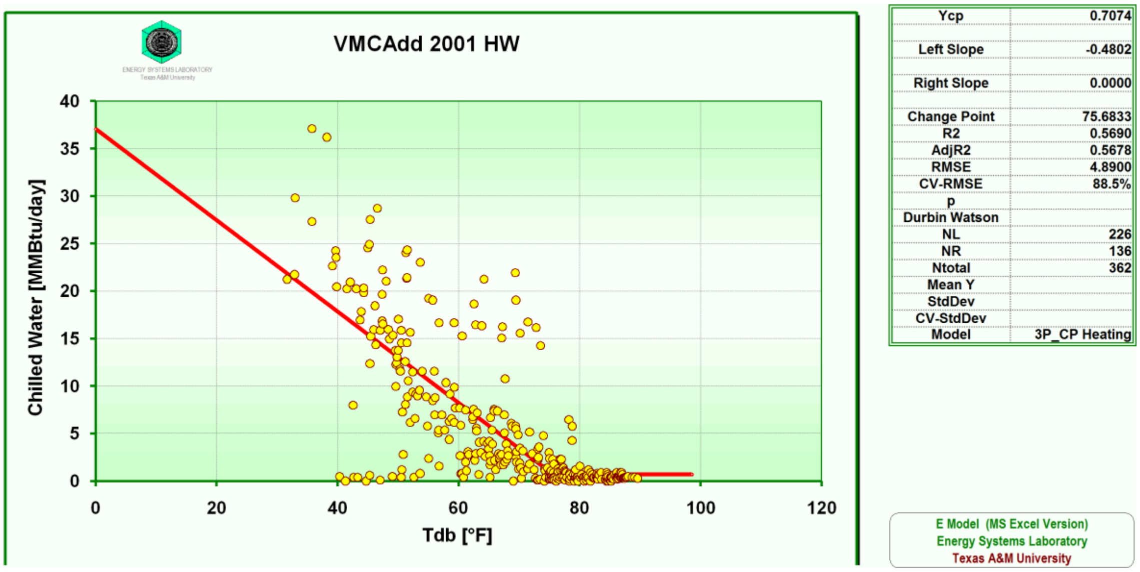
Ycp	7.7813
Left Slope	0.0000
Right Slope	4.2366
Change Point	57.1500
R2	0.9437
AdjR2	0.9435
RMSE	11.2146
CV-RMSE	17.5%
p	
Durbin Watson	
NL	93
NR	269
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 68. Change point model for VMCA 2001 chilled water data.



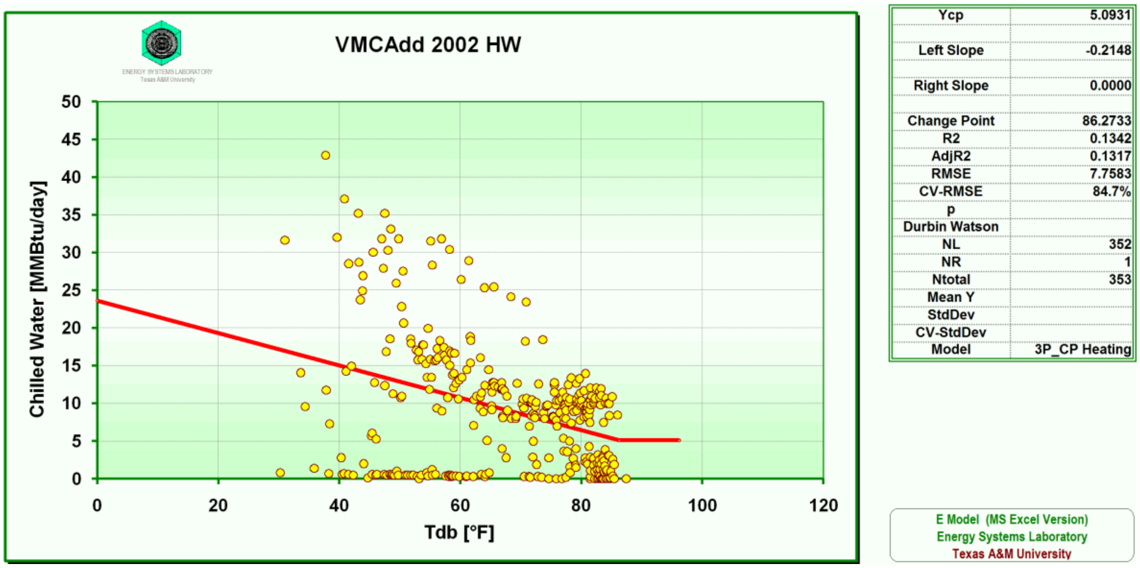
Ycp	13.4721
Left Slope	0.0000
Right Slope	4.5441
Change Point	58.8333
R2	0.9364
AdjR2	0.9362
RMSE	11.9570
CV-RMSE	18.3%
p	
Durbin Watson	
NL	112
NR	241
Ntotal	353
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 69. Change point model for VMCA 2002 chilled water data.



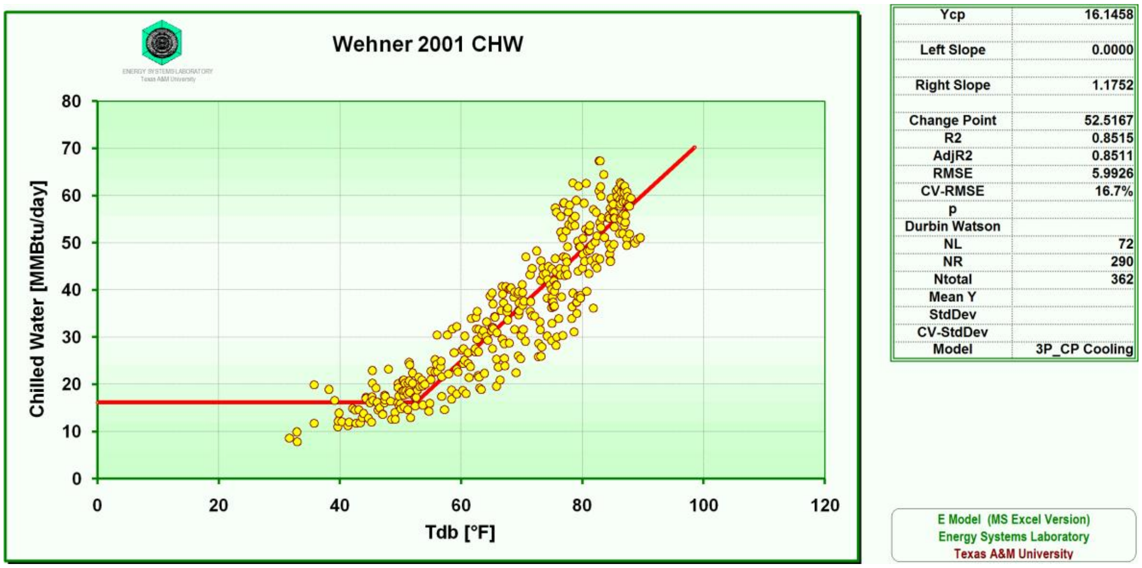
Ycp	0.7074
Left Slope	-0.4802
Right Slope	0.0000
Change Point	75.6833
R2	0.5690
AdjR2	0.5678
RMSE	4.8900
CV-RMSE	88.5%
p	
Durbin Watson	
NL	226
NR	136
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 70. Change point model for VMCA 2001 hot water data.



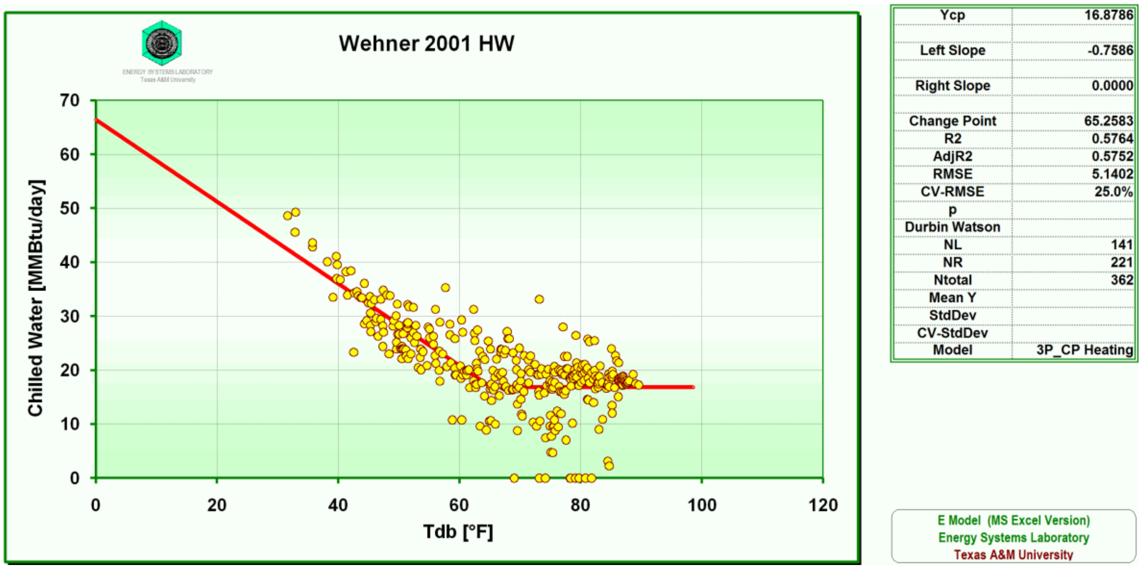
Ycp	5.0931
Left Slope	-0.2148
Right Slope	0.0000
Change Point	86.2733
R2	0.1342
AdjR2	0.1317
RMSE	7.7583
CV-RMSE	84.7%
p	
Durbin Watson	
NL	352
NR	1
Ntotal	353
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 71. Change point model for VMCA 2002 hot water data.



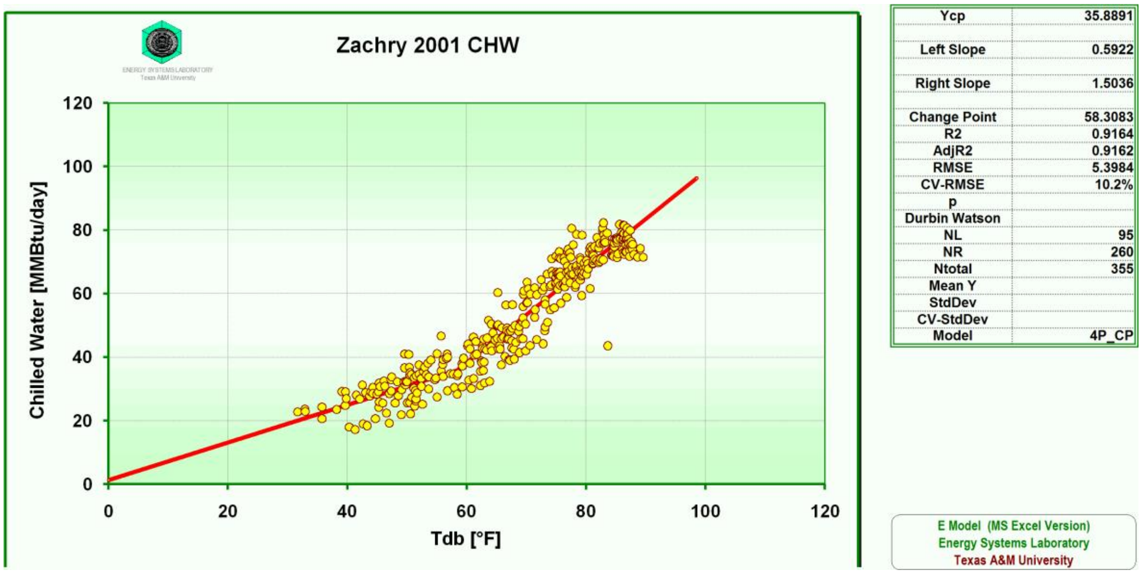
Ycp	16.1458
Left Slope	0.0000
Right Slope	1.1752
Change Point	52.5167
R2	0.8515
AdjR2	0.8511
RMSE	5.9926
CV-RMSE	16.7%
p	
Durbin Watson	
NL	72
NR	290
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Cooling

Figure C - 72. Change point model for Wehner 2001 chilled water data.



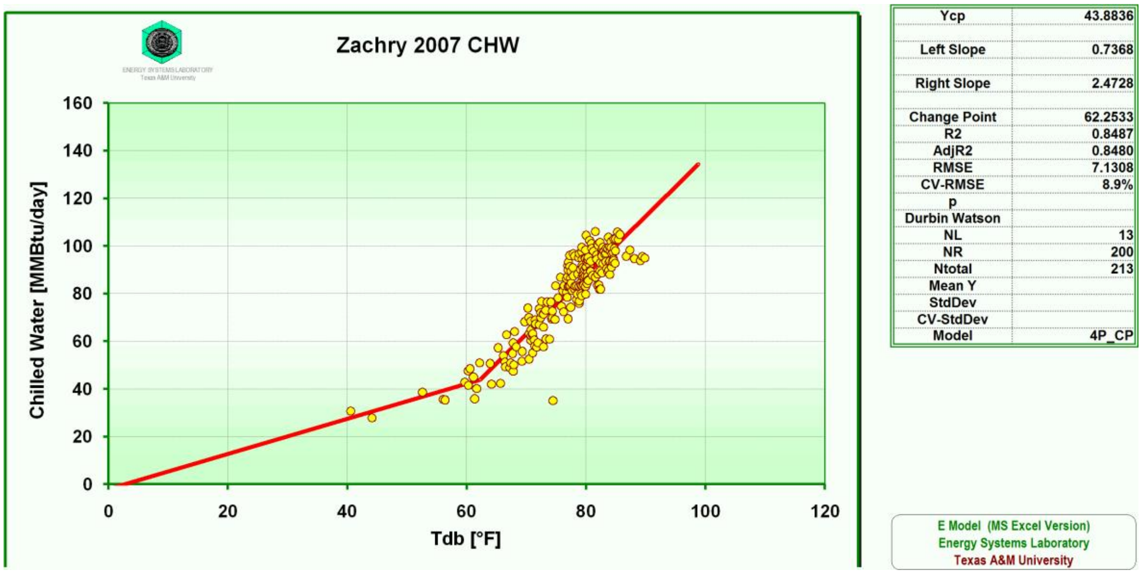
Ycp	16.8786
Left Slope	-0.7586
Right Slope	0.0000
Change Point	65.2583
R2	0.5764
AdjR2	0.5752
RMSE	5.1402
CV-RMSE	25.0%
p	
Durbin Watson	
NL	141
NR	221
Ntotal	362
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 73. Change point model for Wehner 2001 hot water data.



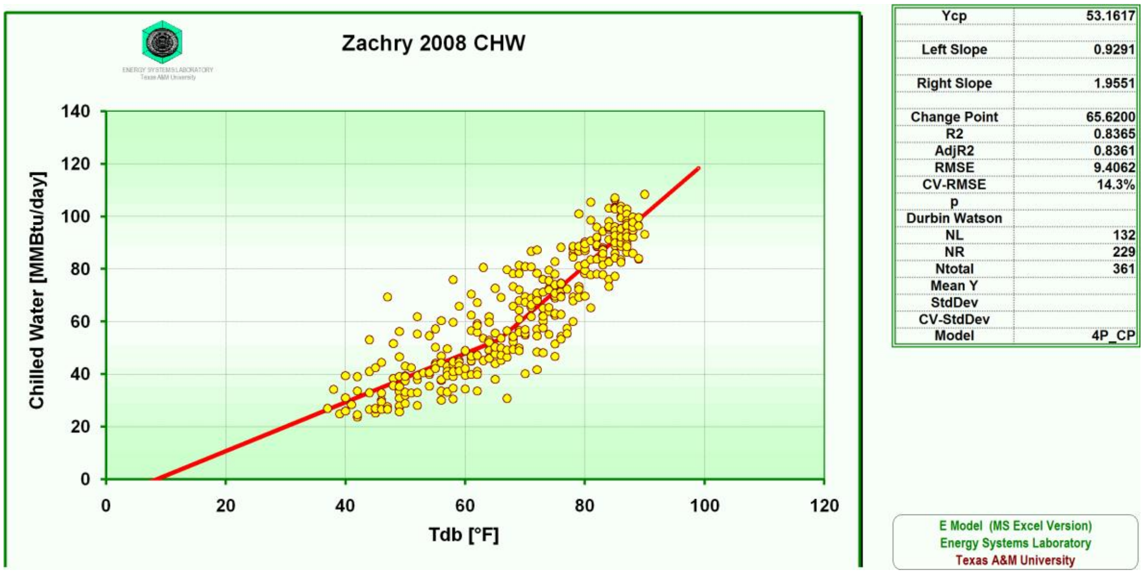
Ycp	35.8891
Left Slope	0.5922
Right Slope	1.5036
Change Point	58.3083
R2	0.9164
AdjR2	0.9162
RMSE	5.3984
CV-RMSE	10.2%
p	
Durbin Watson	
NL	95
NR	260
Ntotal	355
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 74. Change point model for Zachry 2001 chilled water data.



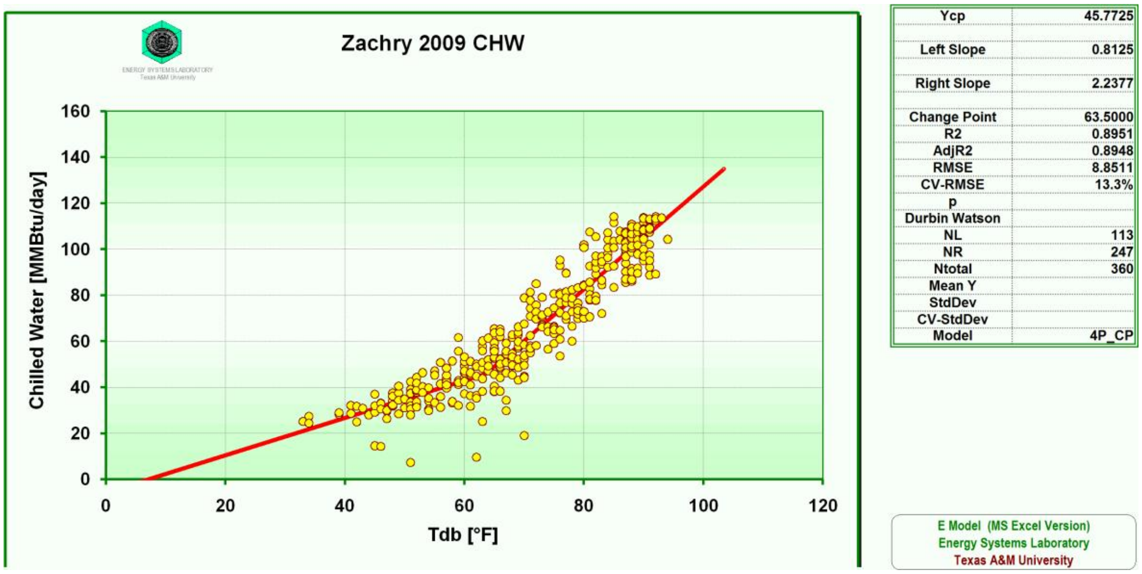
Ycp	43.8836
Left Slope	0.7368
Right Slope	2.4728
Change Point	62.2533
R2	0.8487
AdjR2	0.8480
RMSE	7.1308
CV-RMSE	8.9%
p	
Durbin Watson	
NL	13
NR	200
Ntotal	213
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 75. Change point model for Zachry 2006-07 chilled water data.



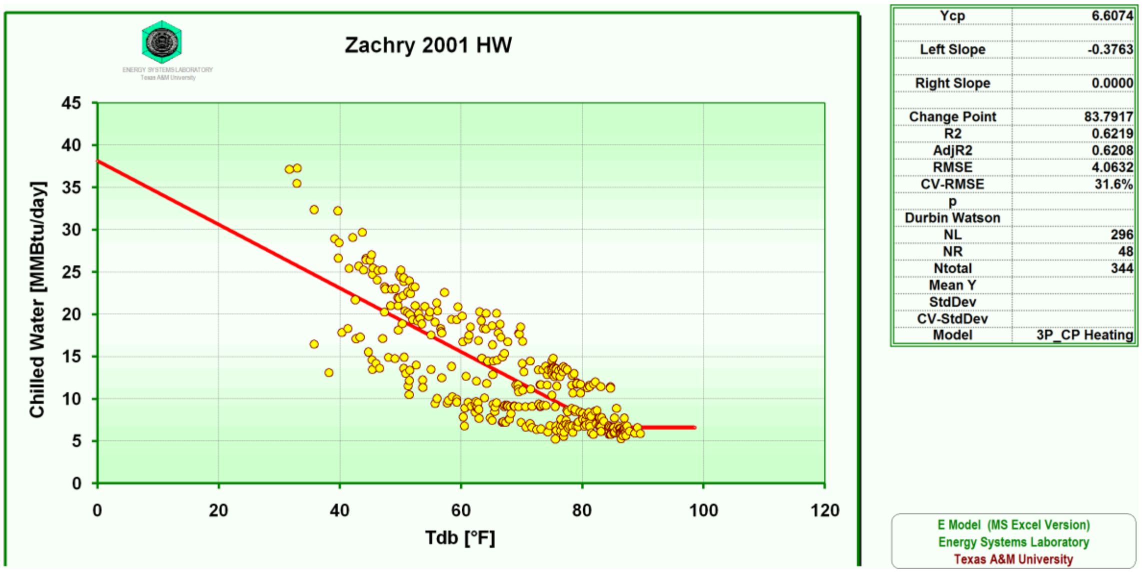
Ycp	53.1617
Left Slope	0.9291
Right Slope	1.9551
Change Point	65.6200
R2	0.8365
AdjR2	0.8361
RMSE	9.4062
CV-RMSE	14.3%
p	
Durbin Watson	
NL	132
NR	229
Ntotal	361
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 76. Change point model for Zachry 2007-08 chilled water data.



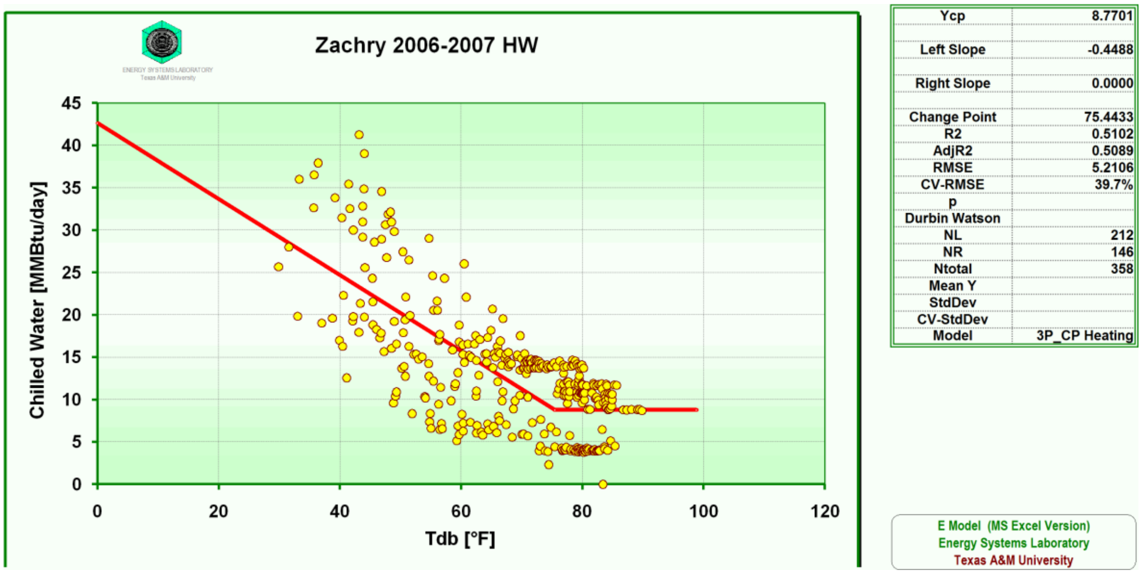
Ycp	45.7725
Left Slope	0.8125
Right Slope	2.2377
Change Point	63.5000
R2	0.8951
AdjR2	0.8948
RMSE	8.8511
CV-RMSE	13.3%
p	
Durbin Watson	
NL	113
NR	247
Ntotal	360
Mean Y	
StdDev	
CV-StdDev	
Model	4P_CP

Figure C - 77. Change point model for Zachry 2008-09 chilled water data.



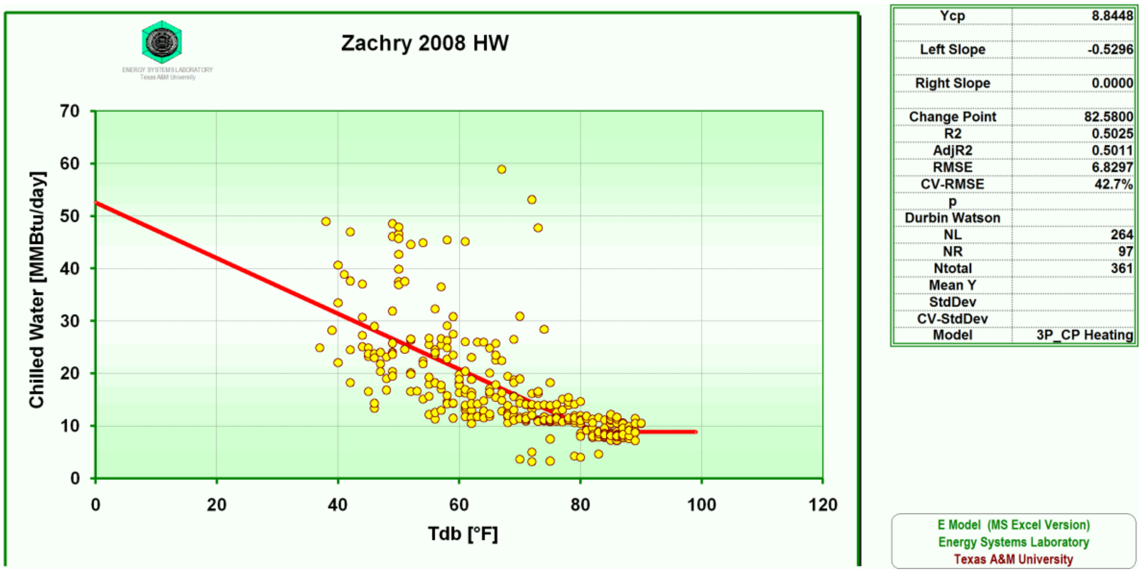
Ycp	6.6074
Left Slope	-0.3763
Right Slope	0.0000
Change Point	83.7917
R2	0.6219
AdjR2	0.6208
RMSE	4.0632
CV-RMSE	31.6%
p	
Durbin Watson	
NL	296
NR	48
Ntotal	344
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 78. Change point model for Zachry 2001 hot water data.



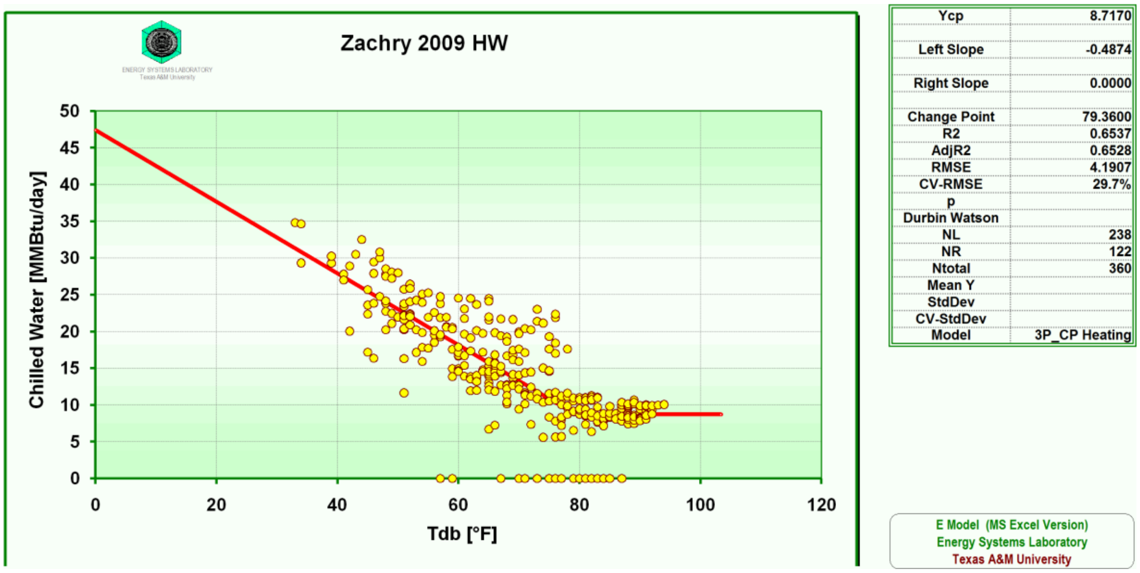
Ycp	8.7701
Left Slope	-0.4488
Right Slope	0.0000
Change Point	75.4433
R2	0.5102
AdjR2	0.5089
RMSE	5.2106
CV-RMSE	39.7%
p	
Durbin Watson	
NL	212
NR	146
Ntotal	358
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 79. Change point model for Zachry 2006-07 hot water data.



Ycp	8.8448
Left Slope	-0.5296
Right Slope	0.0000
Change Point	82.5800
R2	0.5025
AdjR2	0.5011
RMSE	6.8297
CV-RMSE	42.7%
p	
Durbin Watson	
NL	264
NR	97
Ntotal	361
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 80. Change point model for Zachry 2007-08 hot water data.



Ycp	8.7170
Left Slope	-0.4874
Right Slope	0.0000
Change Point	79.3600
R2	0.6537
AdjR2	0.6528
RMSE	4.1907
CV-RMSE	29.7%
p	
Durbin Watson	
NL	238
NR	122
Ntotal	360
Mean Y	
StdDev	
CV-StdDev	
Model	3P_CP Heating

Figure C - 81. Change point model for Zachry 2008-09 hot water data.

APPENDIX D

ENERGY BALANCE PLOTS

The Energy Balance plots for each year and each building are presented in the figures that follow. These plots were used to help determine the reasonableness and validity of the measured consumption data.

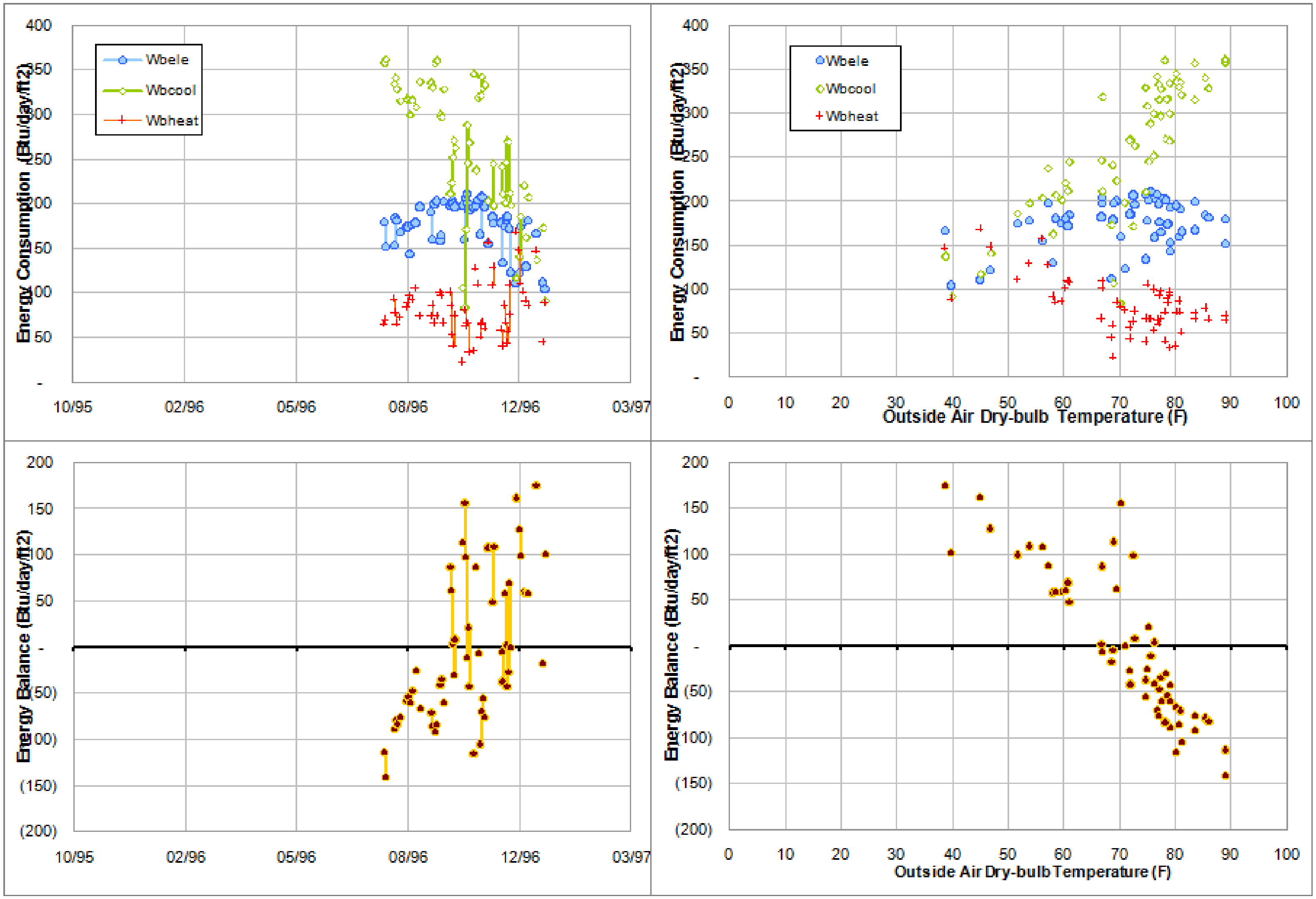


Figure D - 1. Energy balance plots for Blocker 1996 data.

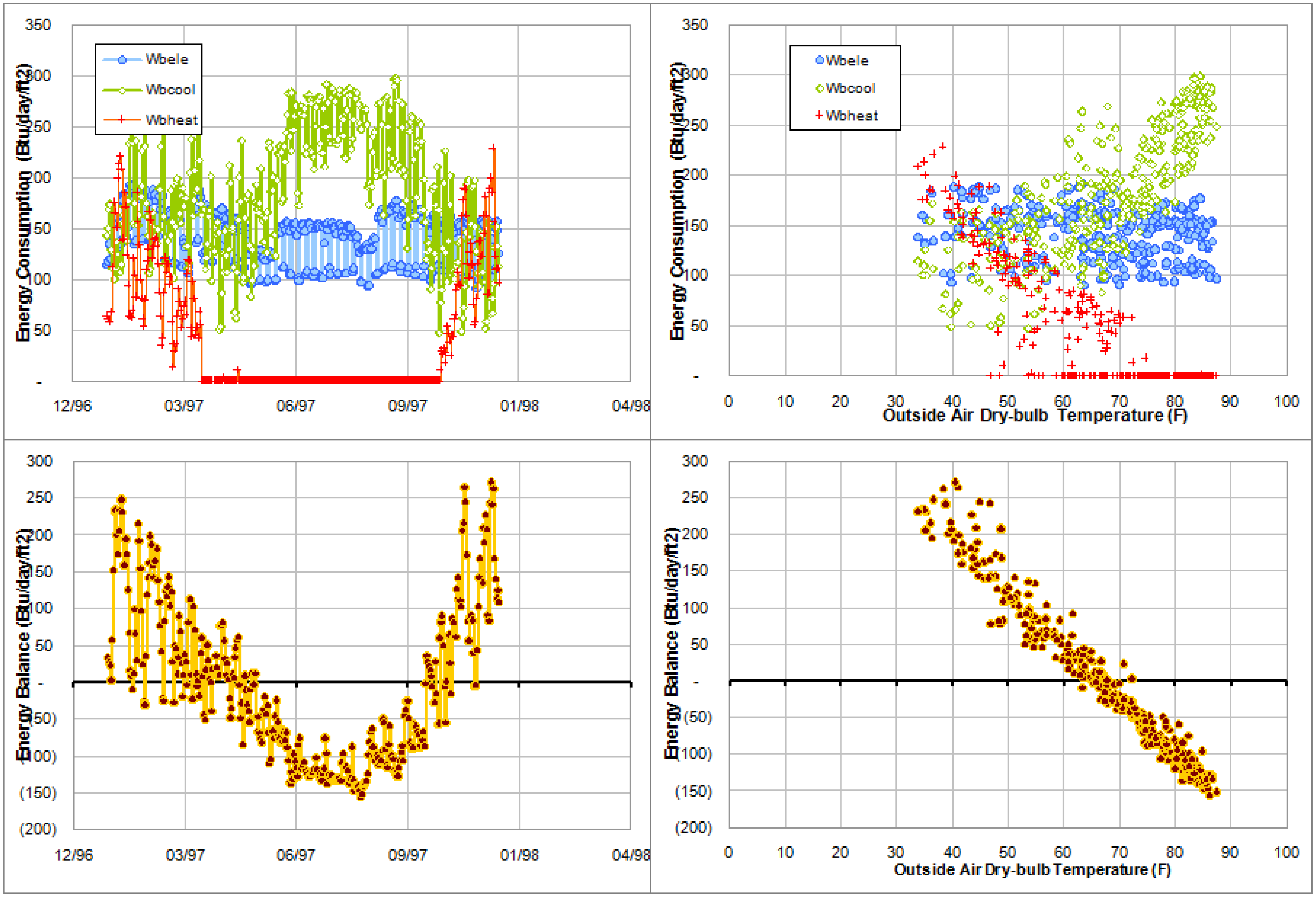


Figure D - 2. Energy balance plots for Blocker 1997 data.

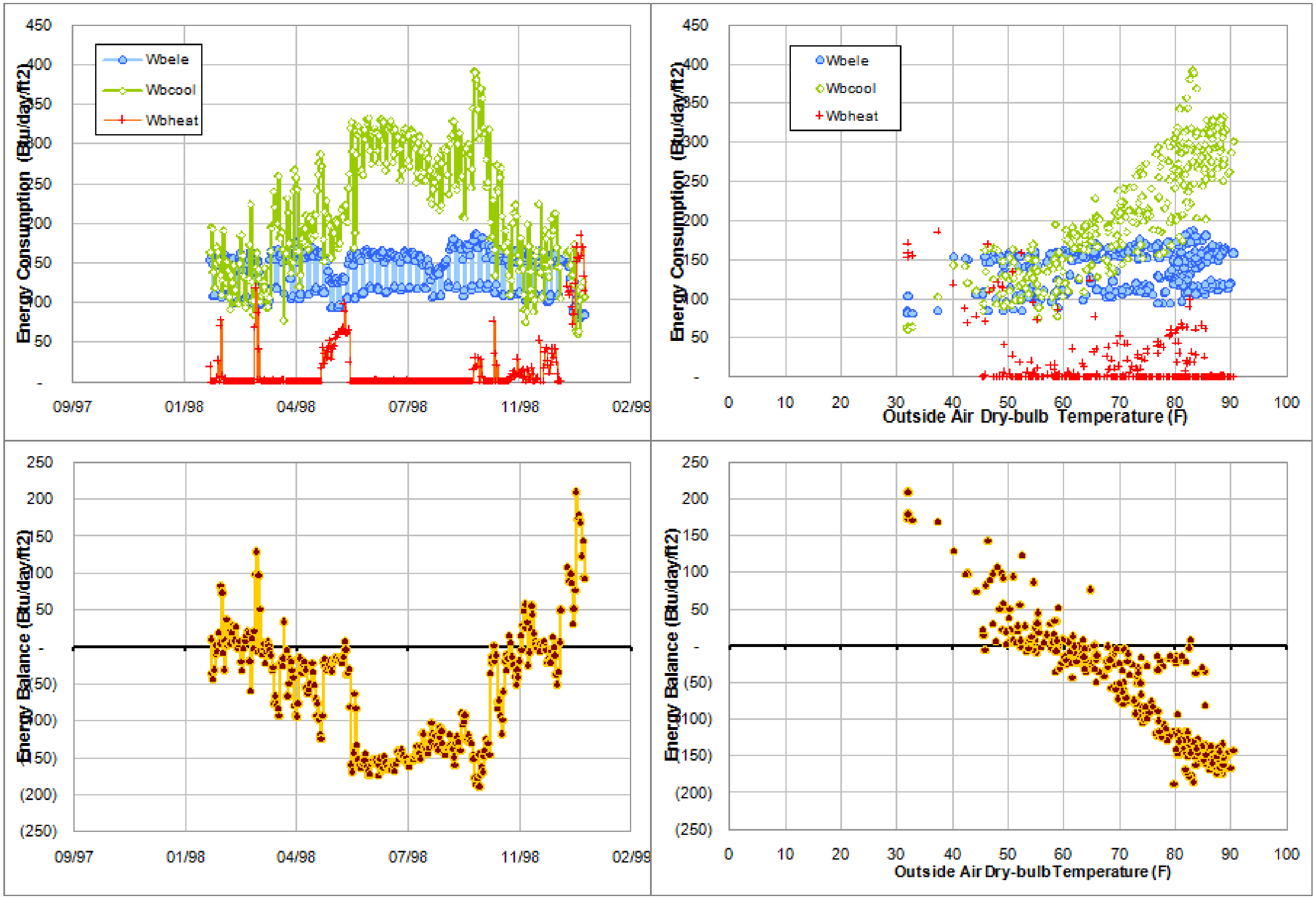


Figure D - 3. Energy balance plots for Blocker 1998 data.

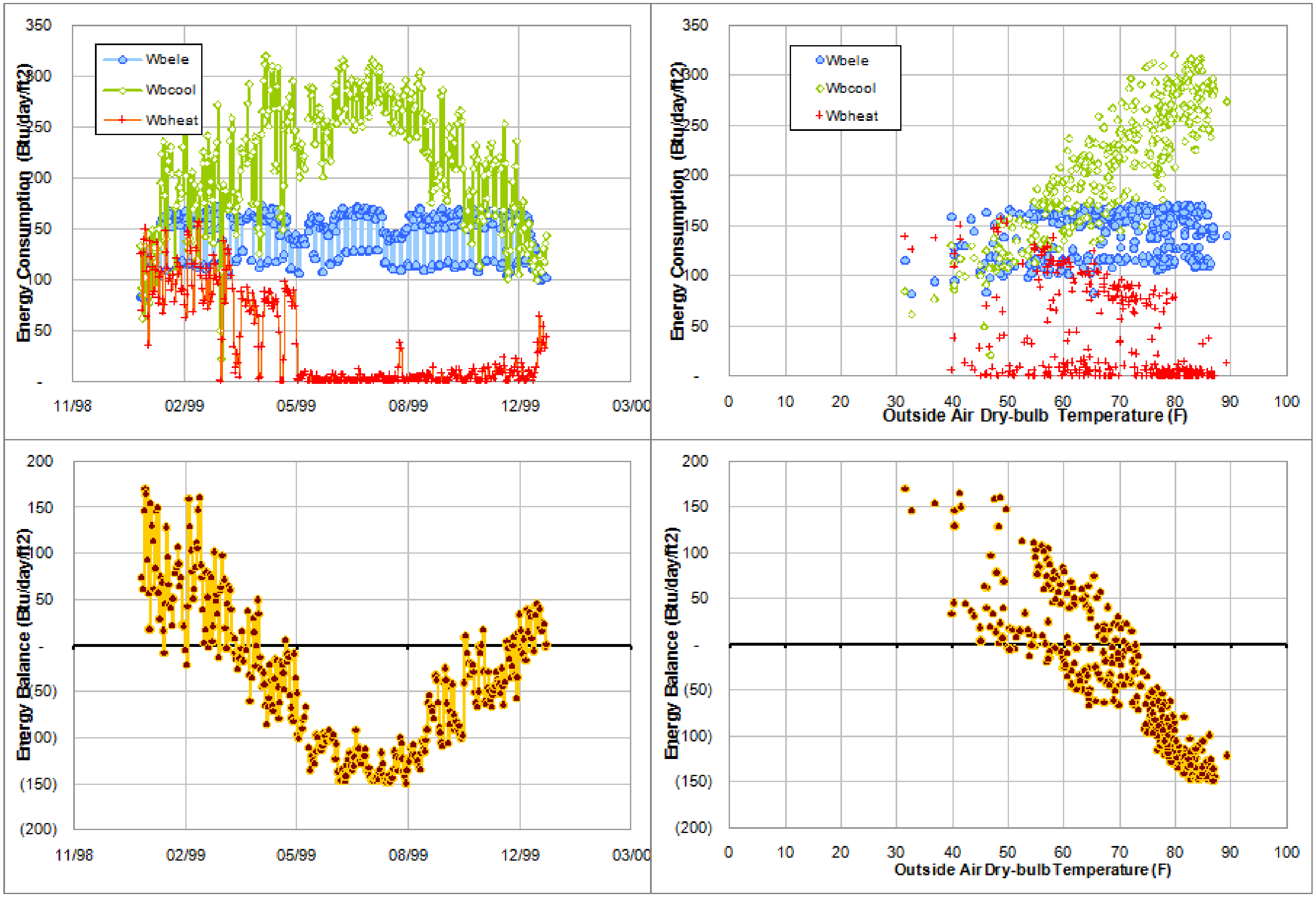


Figure D - 4. Energy balance plots for Blocker 1999 data.

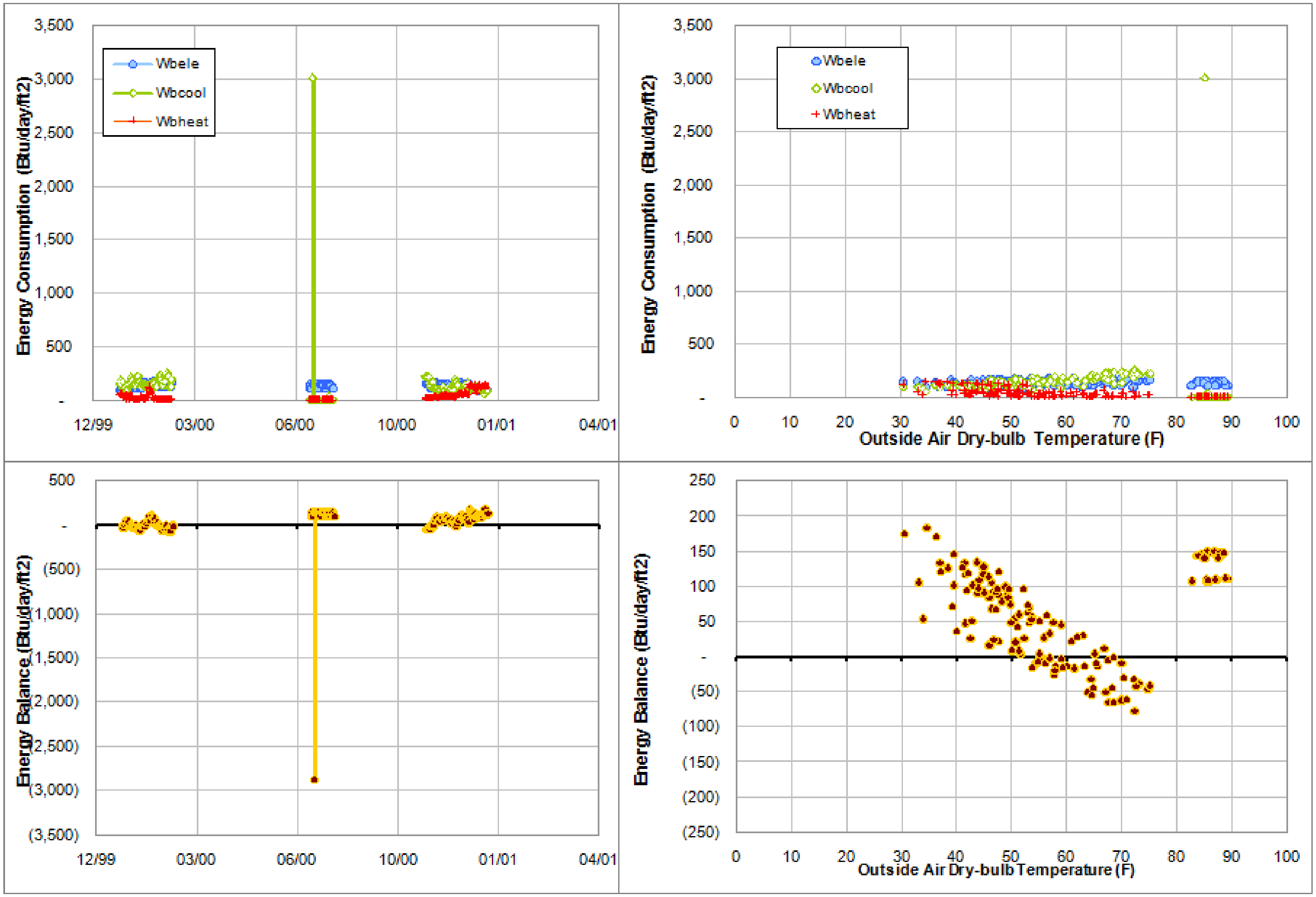


Figure D - 5. Energy balance plots for Blocker 2000 data.

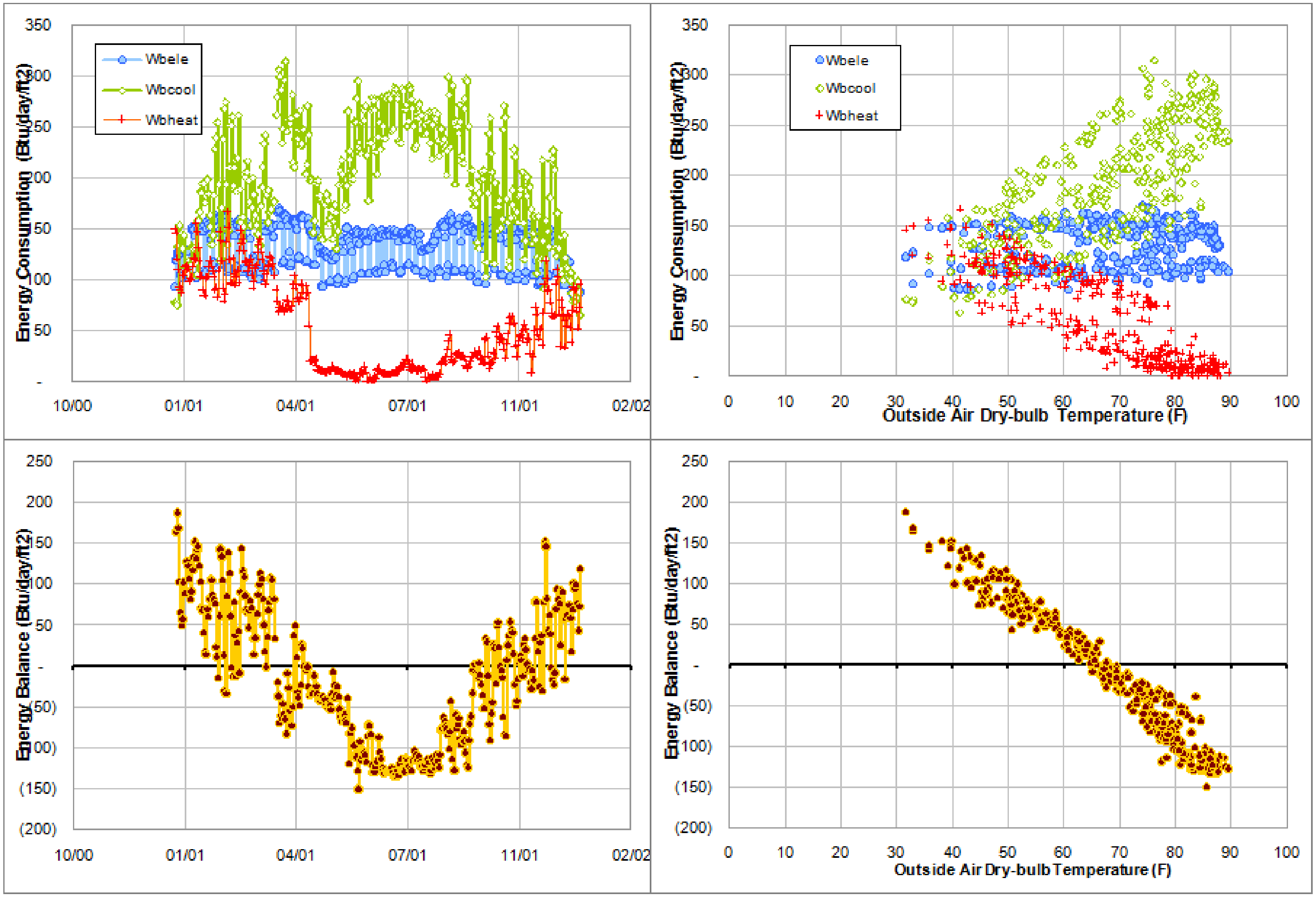


Figure D - 6. Energy balance plots for Blocker 2001 data.

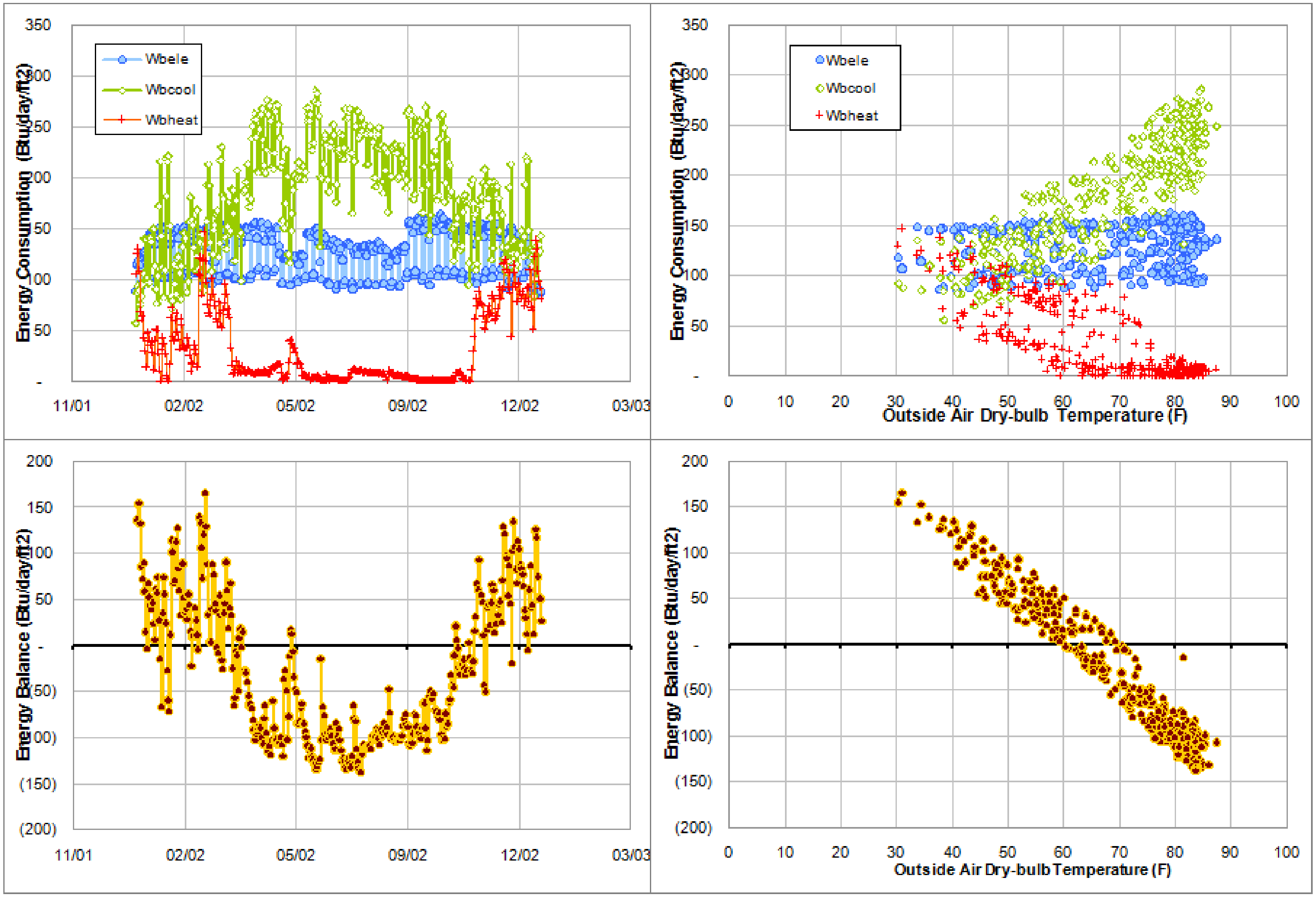


Figure D - 7. Energy balance plots for Blocker 2002 data.

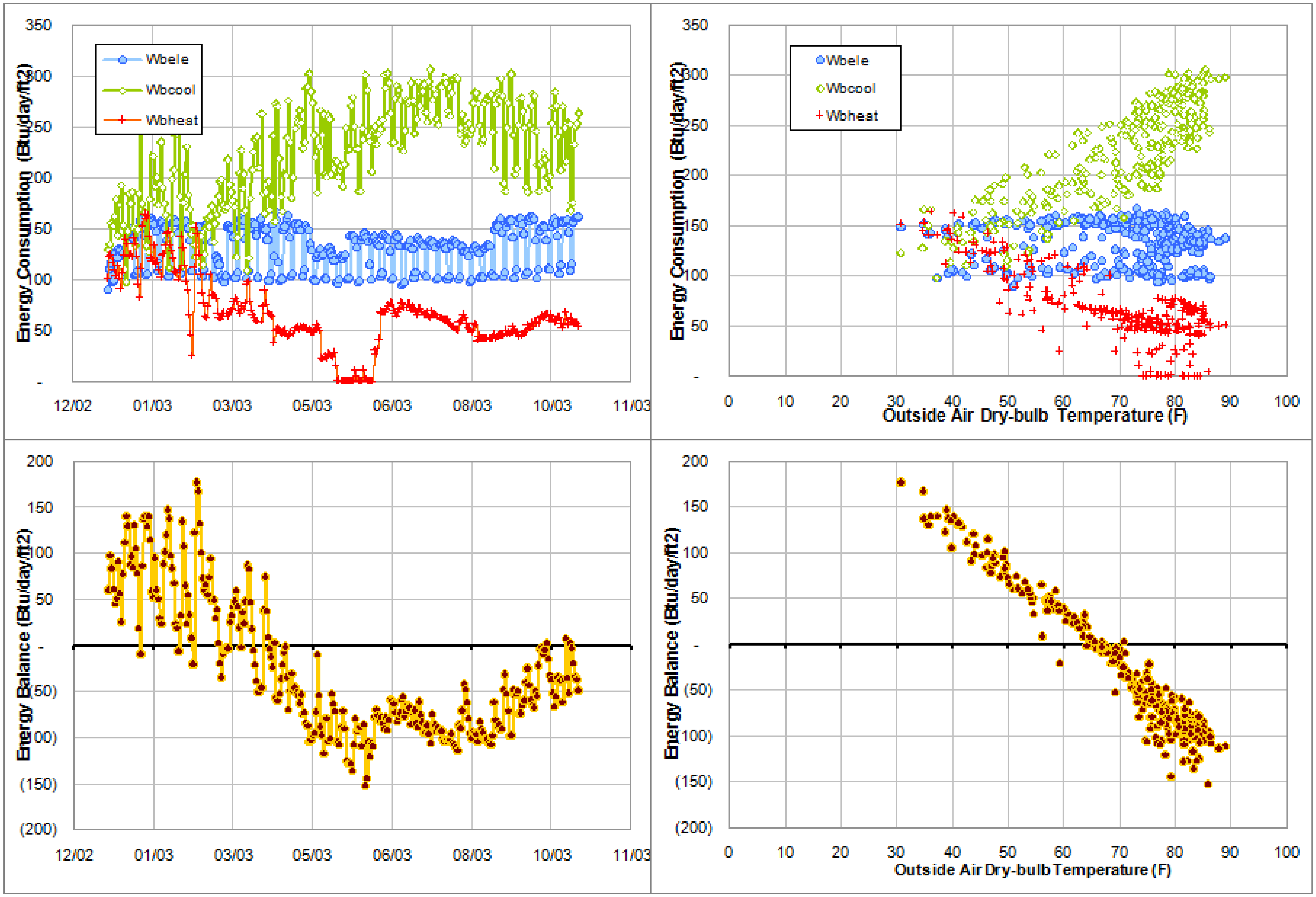


Figure D - 8. Energy balance plots for Blocker 2003 data.

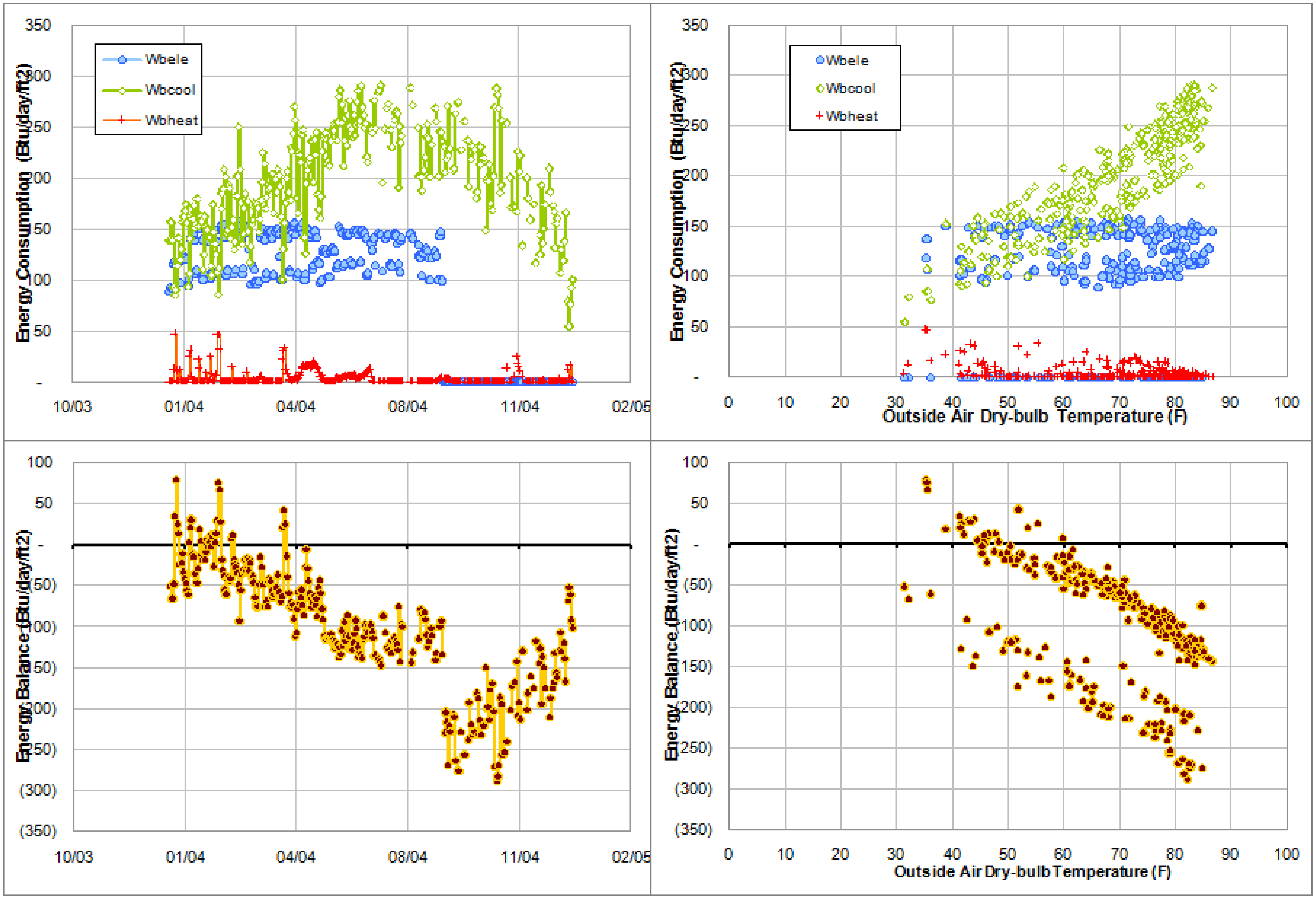


Figure D - 9. Energy balance plots for Blocker 2004 data.

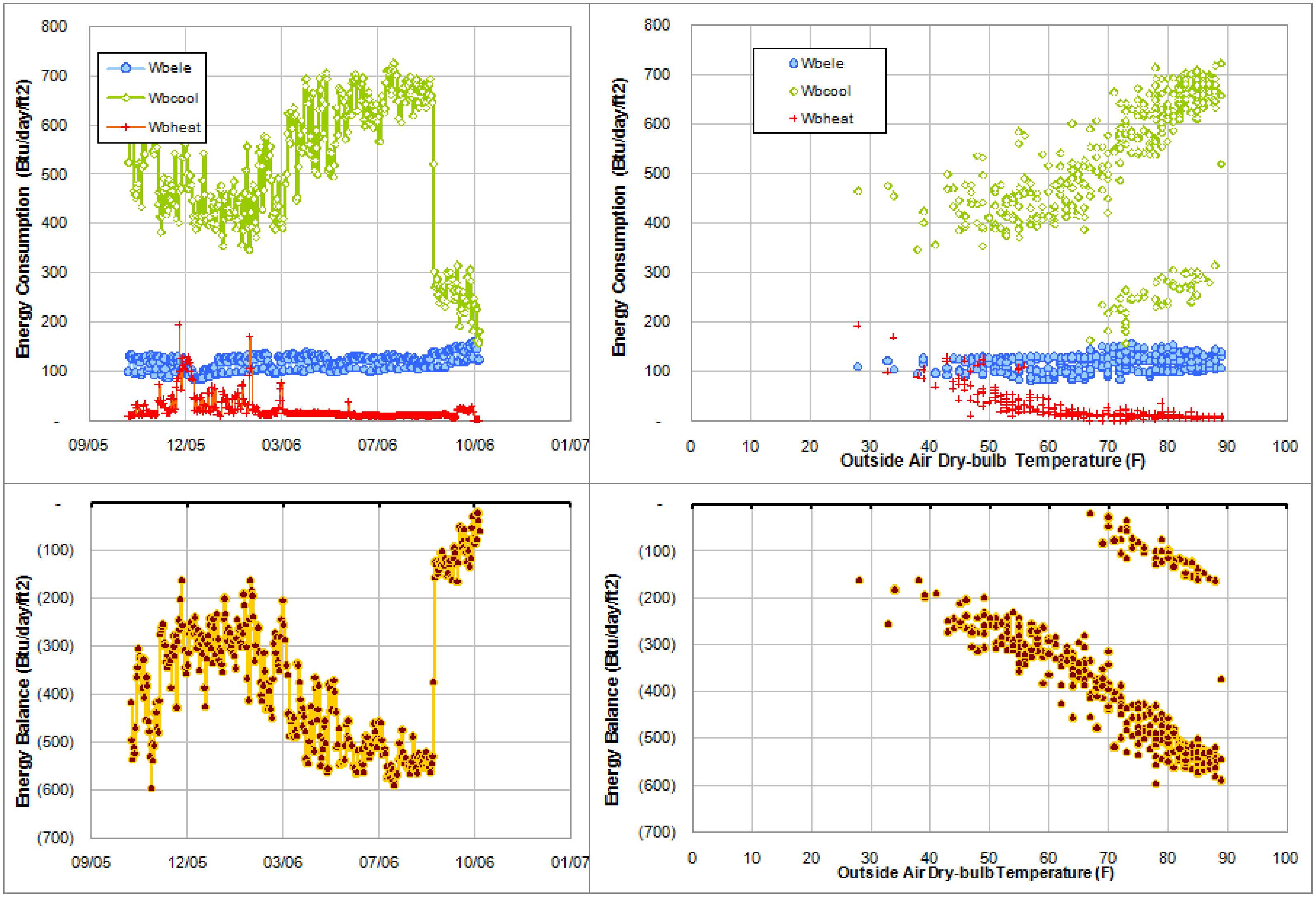


Figure D - 10. Energy balance plots for Blocker 2005-06 data.

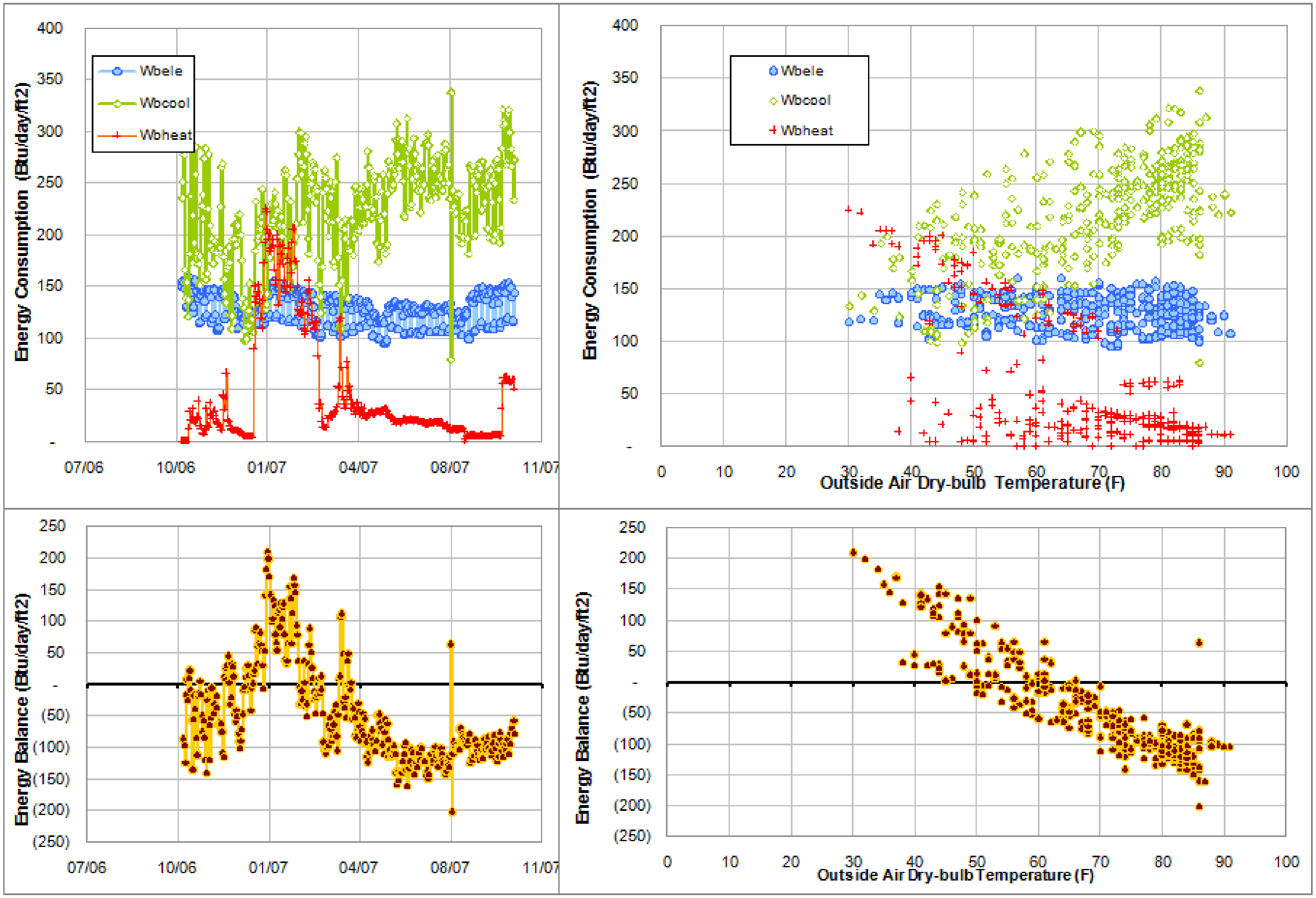


Figure D - 11. Energy balance plots for Blocker 2006-07 data.

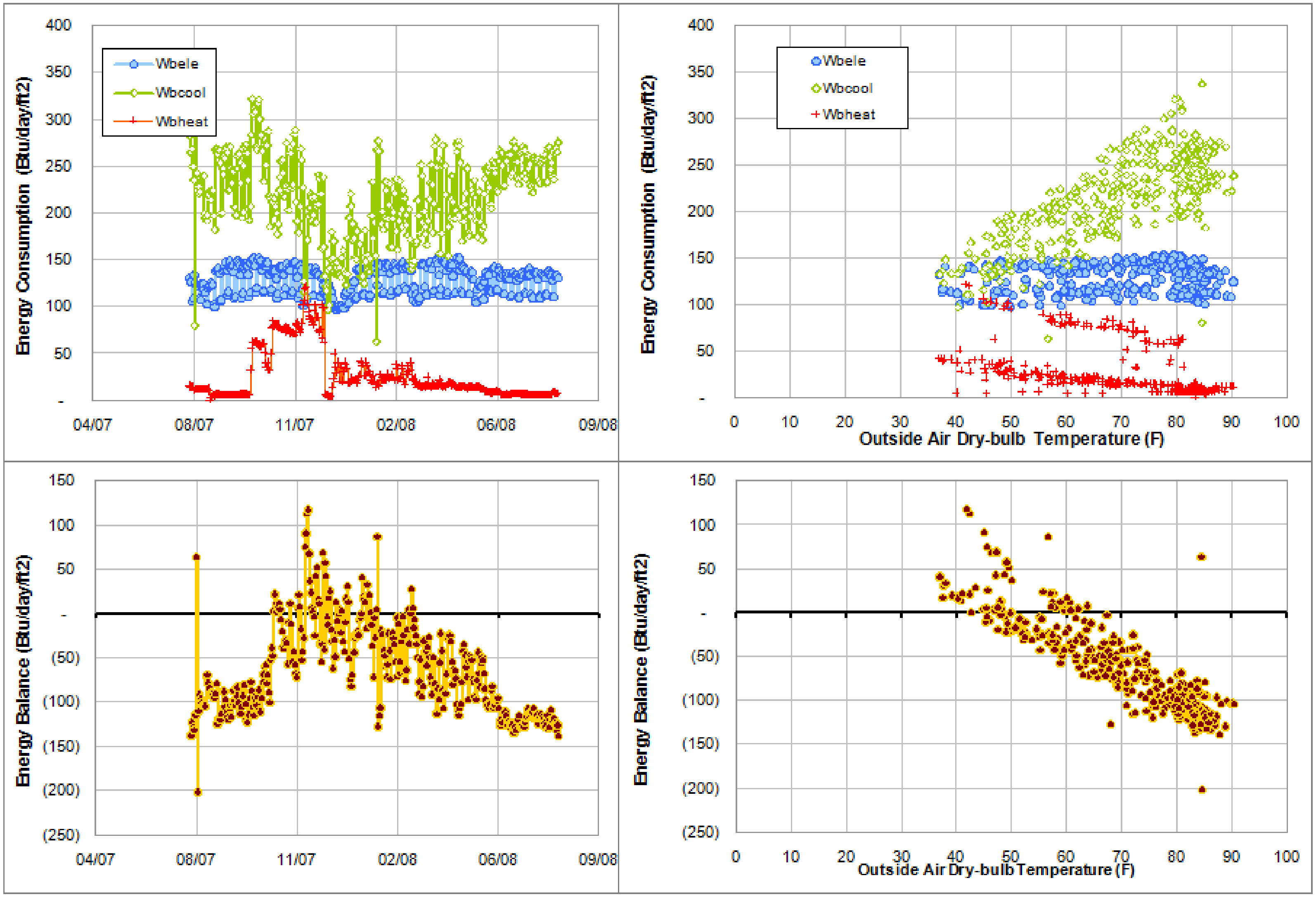


Figure D - 12. Energy balance plots for Blocker 2007-08 data.

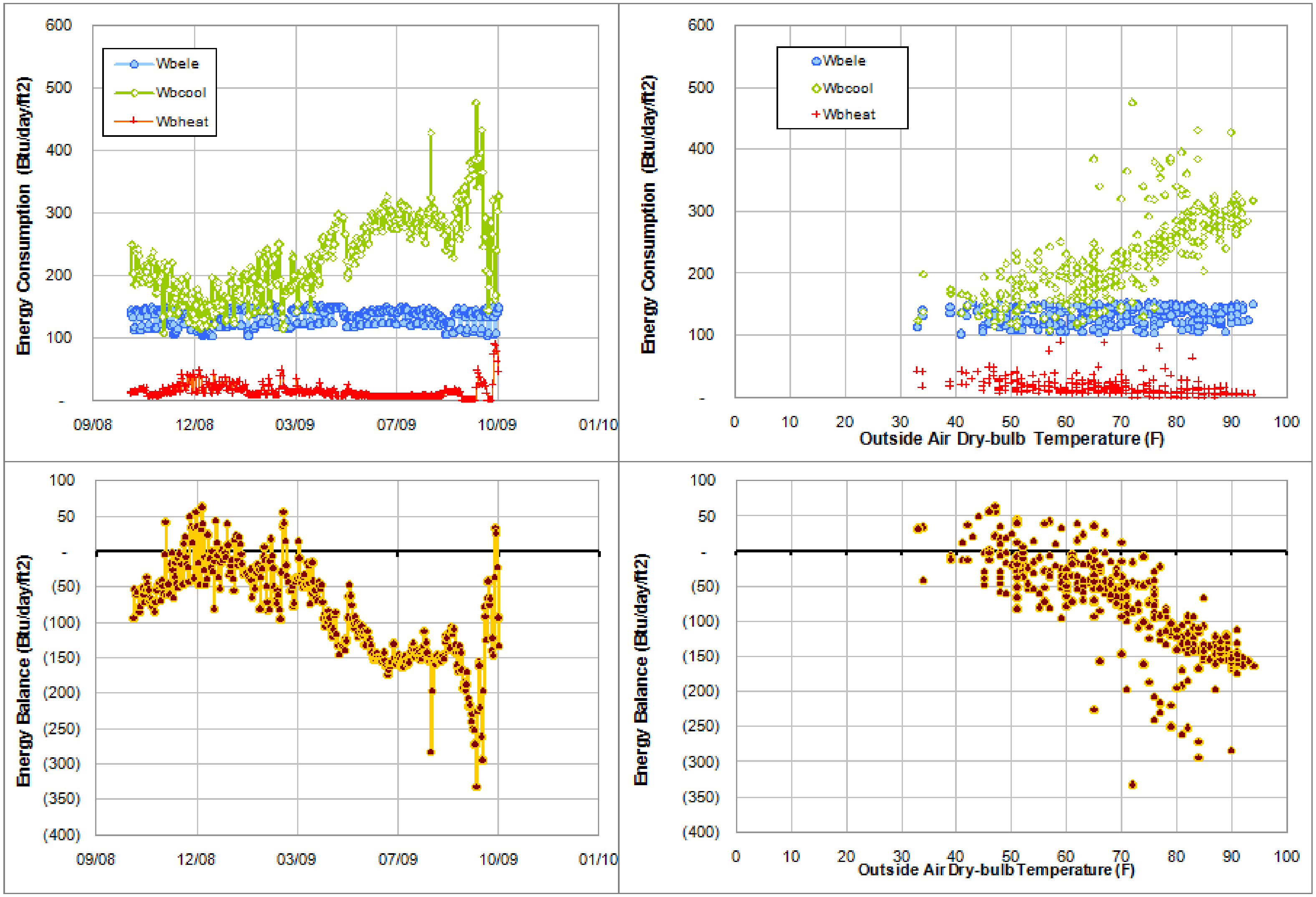


Figure D - 13. Energy balance plots for Blocker 2008-09 data.

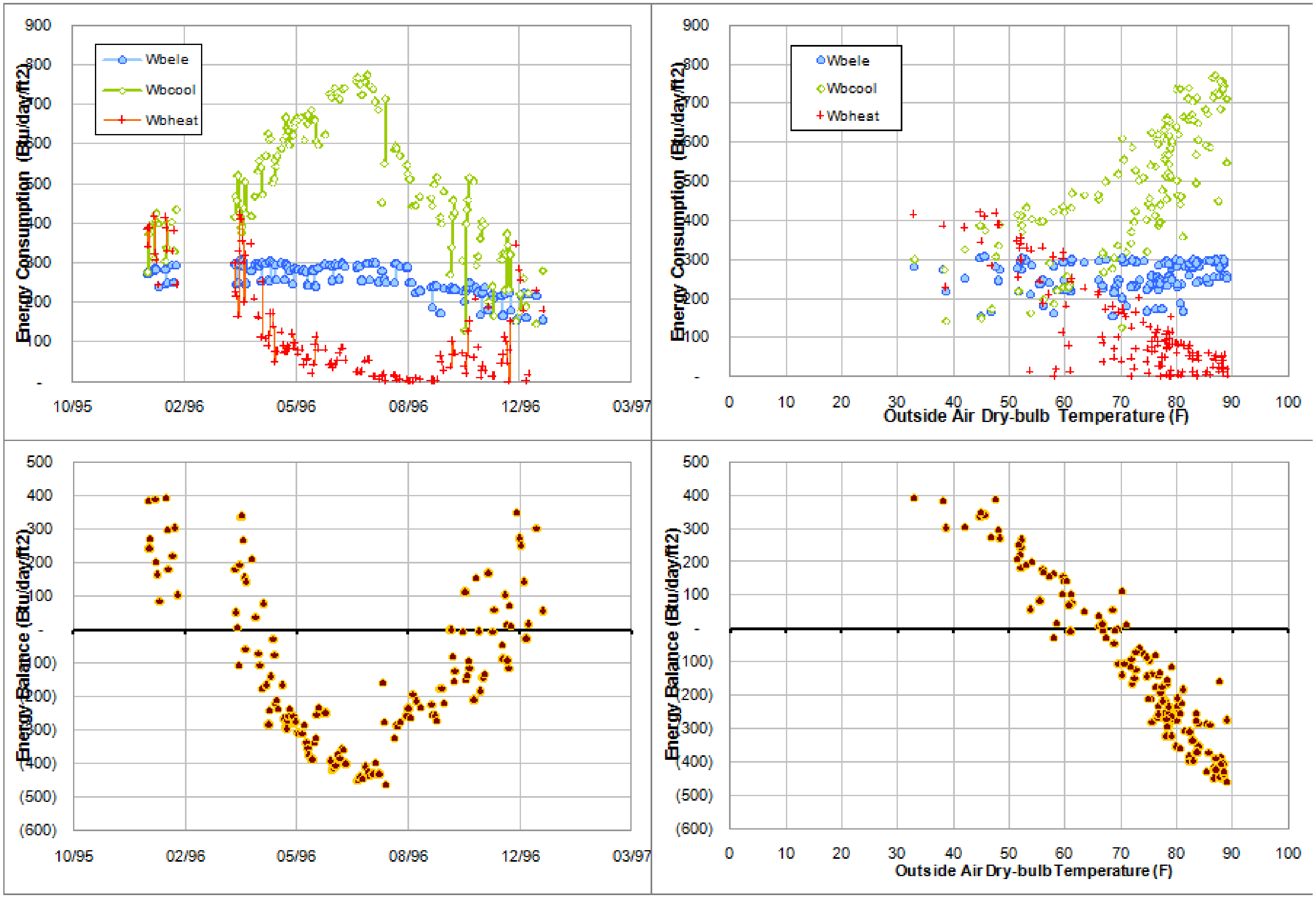


Figure D - 14. Energy balance plots for Eller 1996 data.

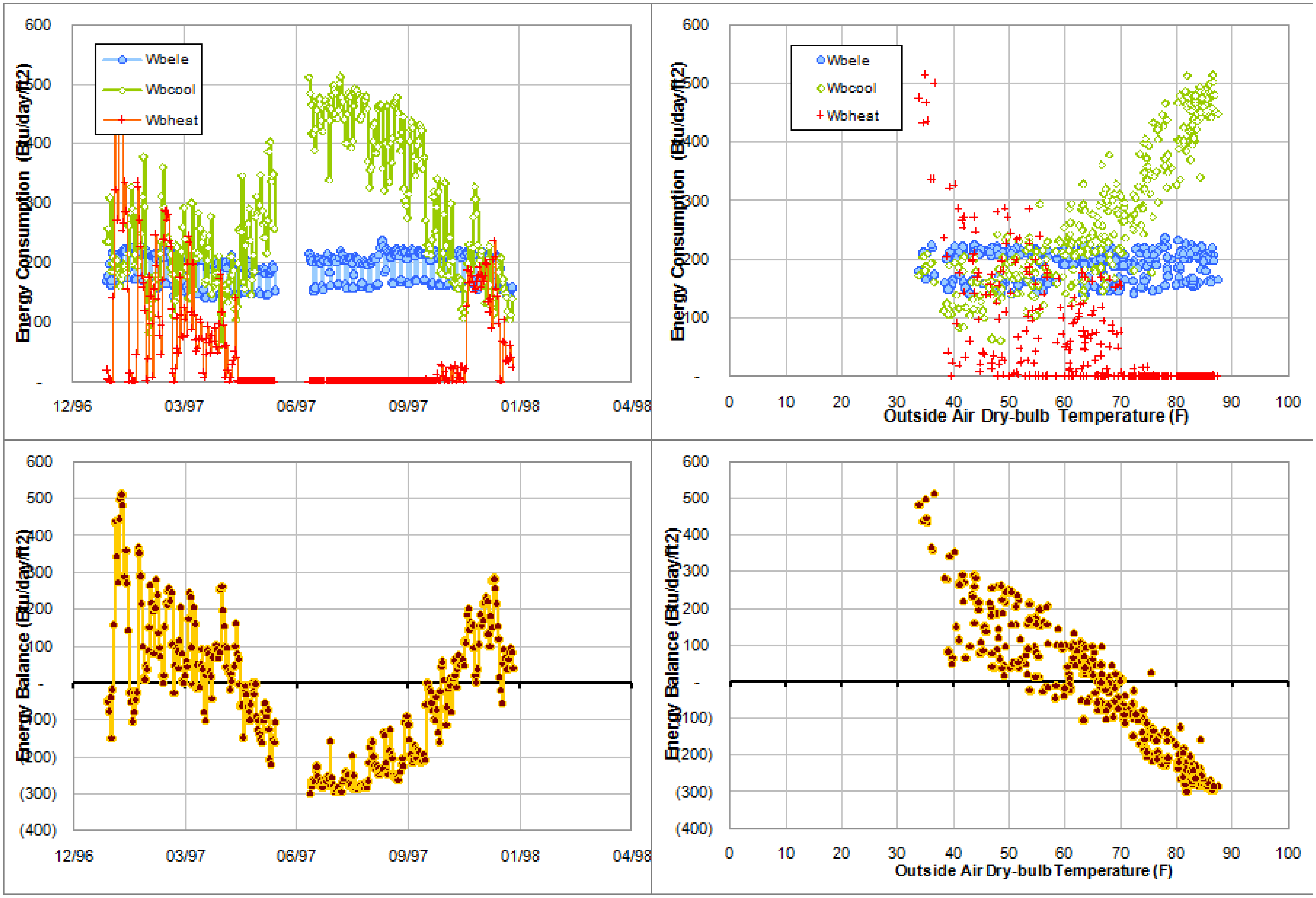


Figure D - 15. Energy balance plots for Eller 1997 data.

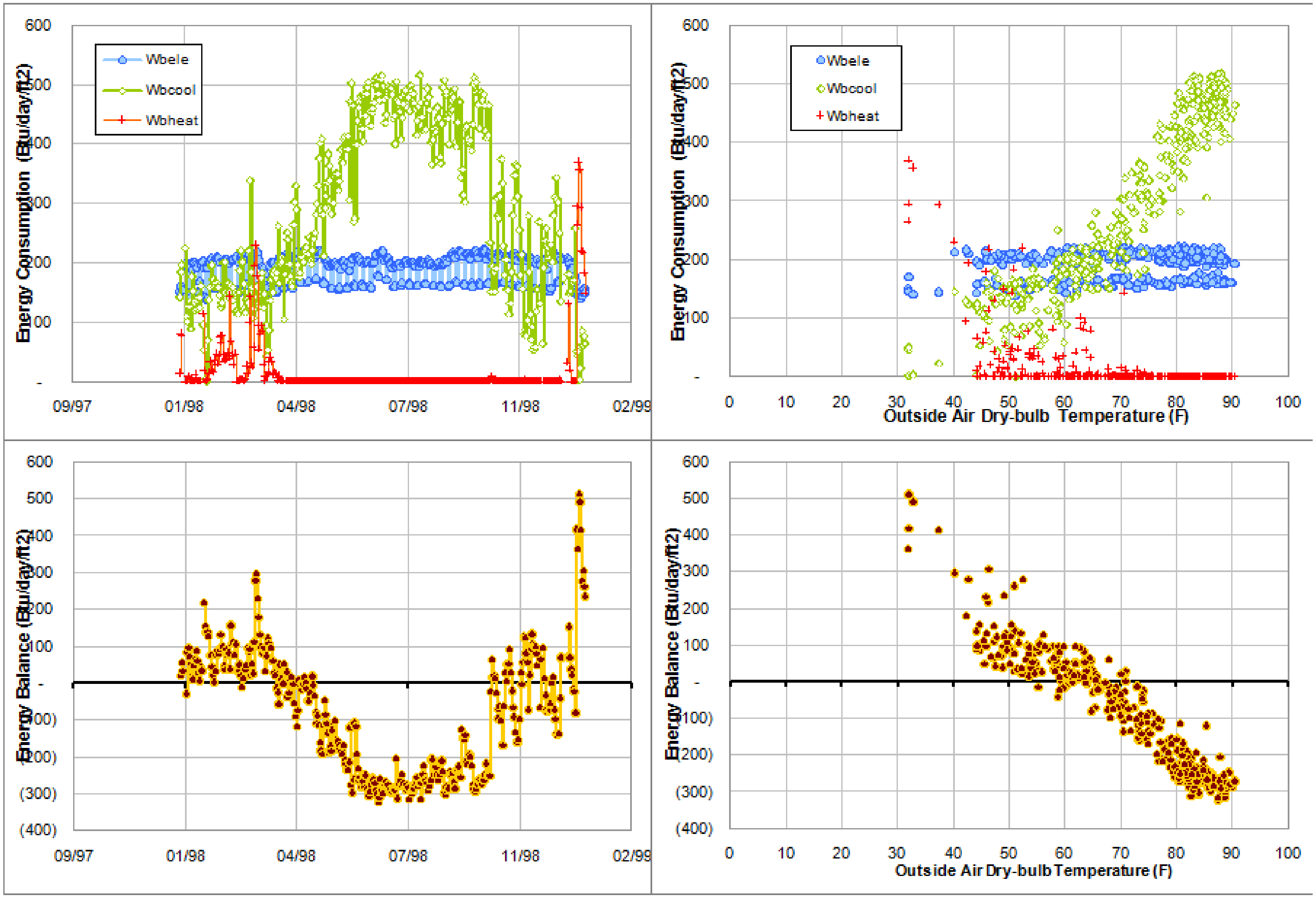


Figure D - 16. Energy balance plots for Eller 1998 data.

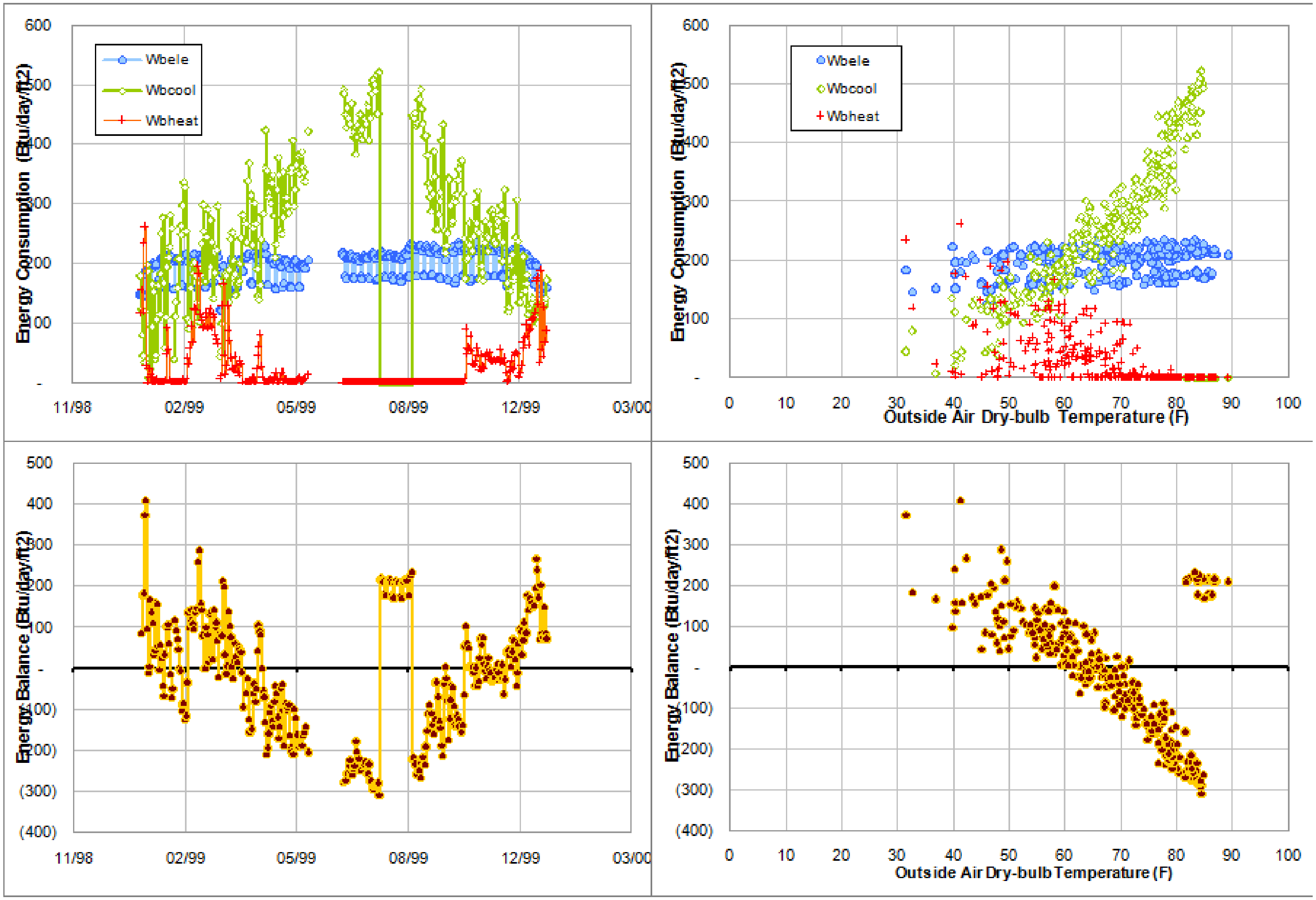


Figure D - 17. Energy balance plots for Eller 1999 data.

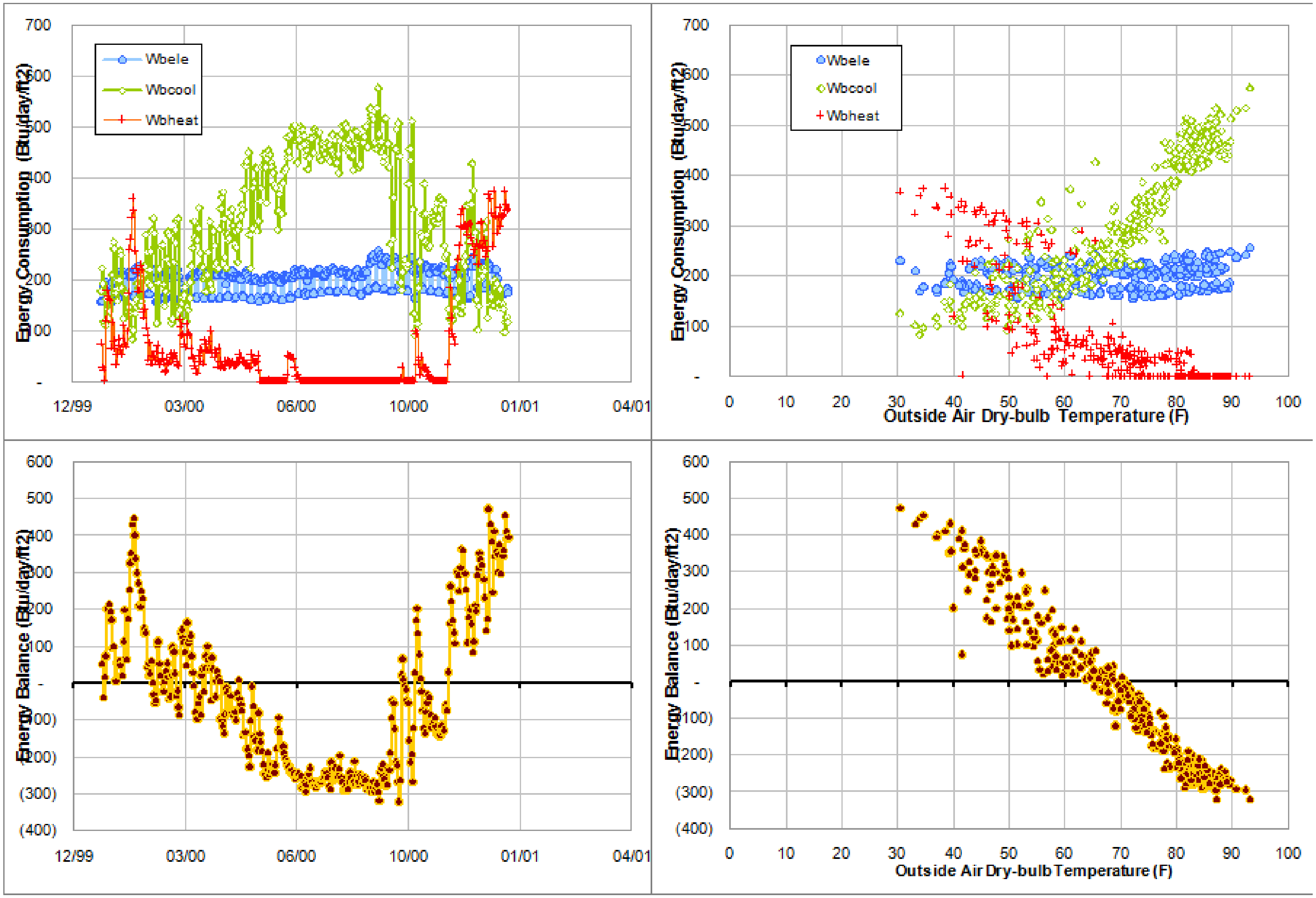


Figure D - 18. Energy balance plots for Eller 2000 data.

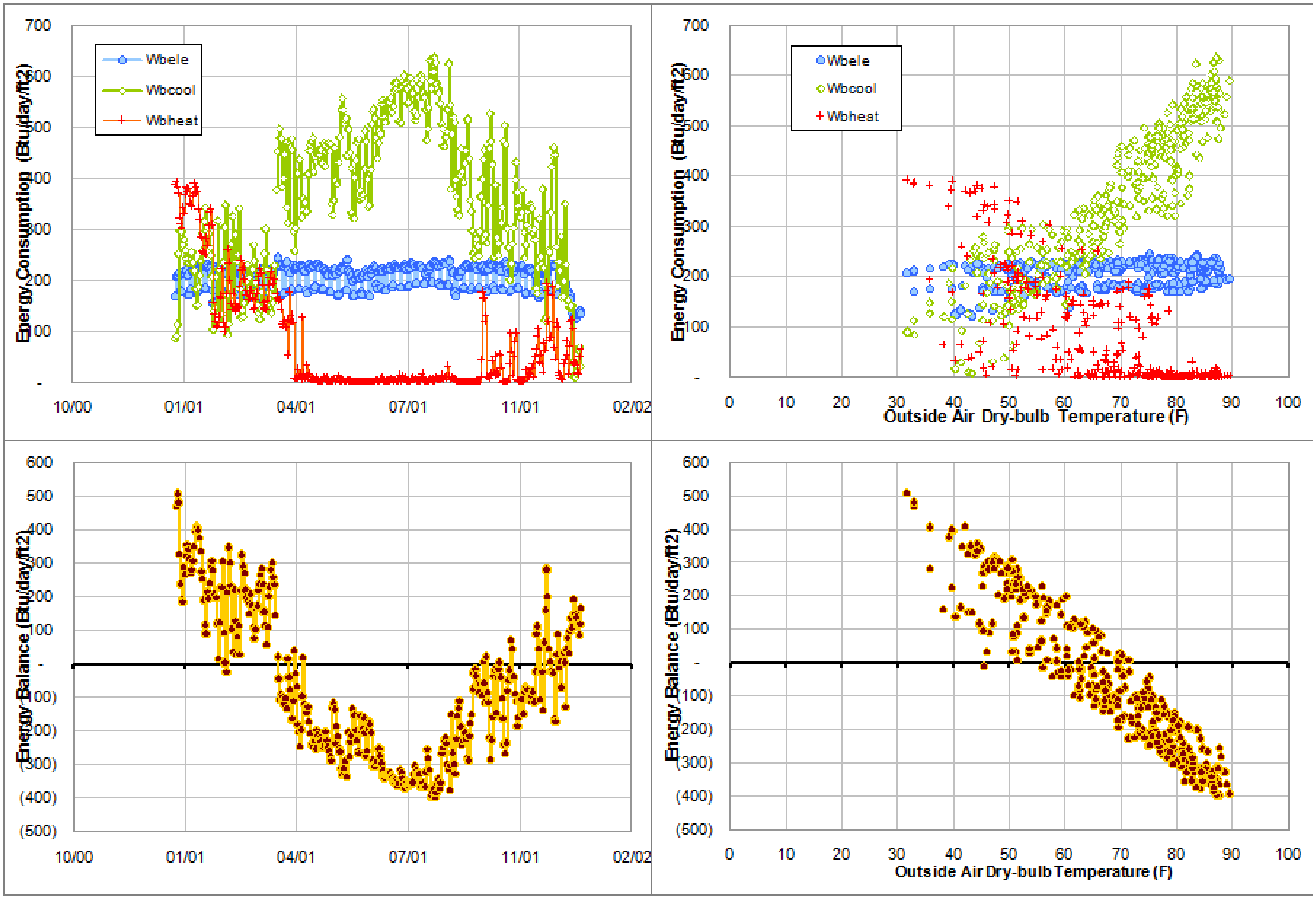


Figure D - 19. Energy balance plots for Eller 2001 data.

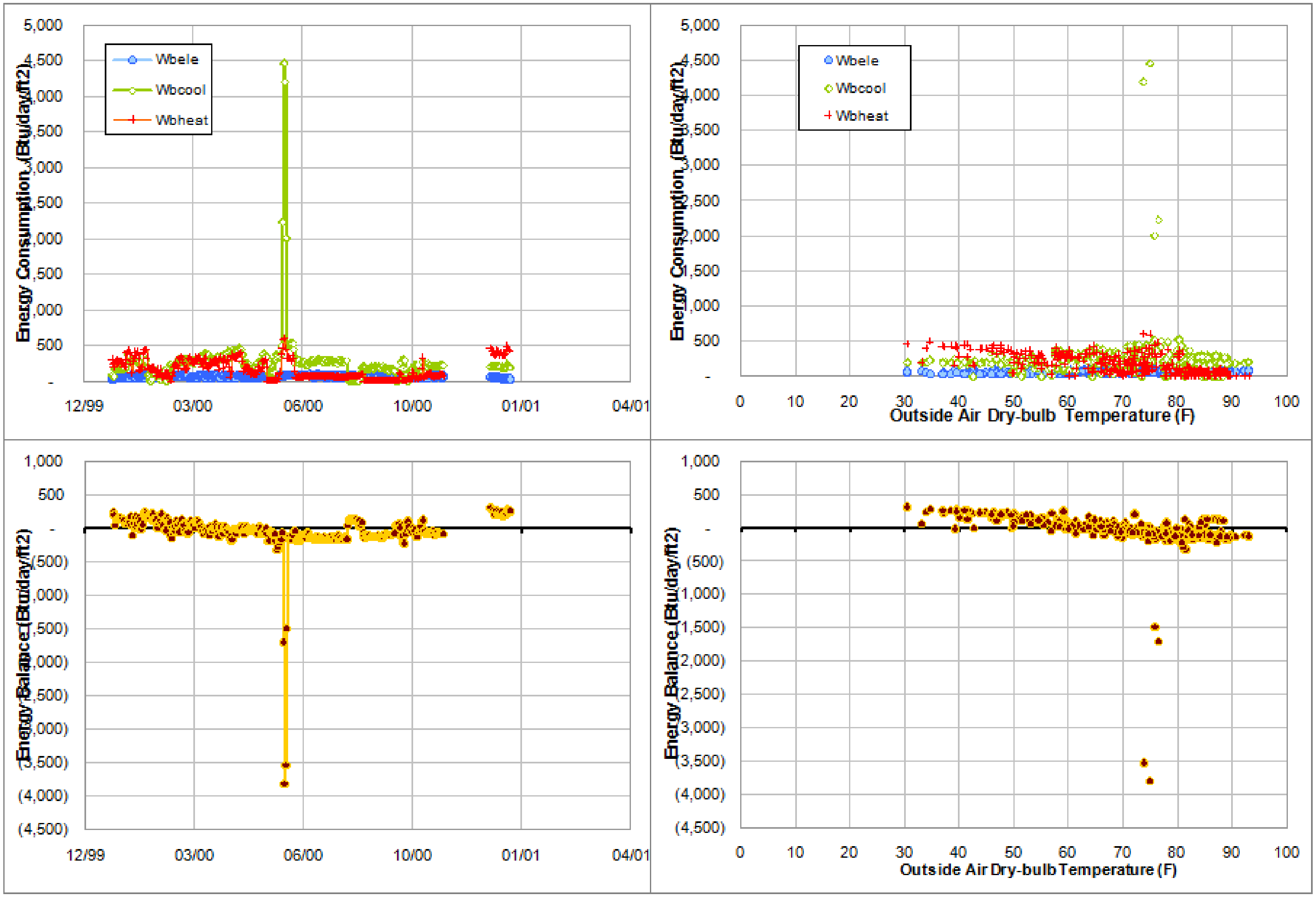


Figure D - 20. Energy balance plots for G. Rollie White 2000 data.

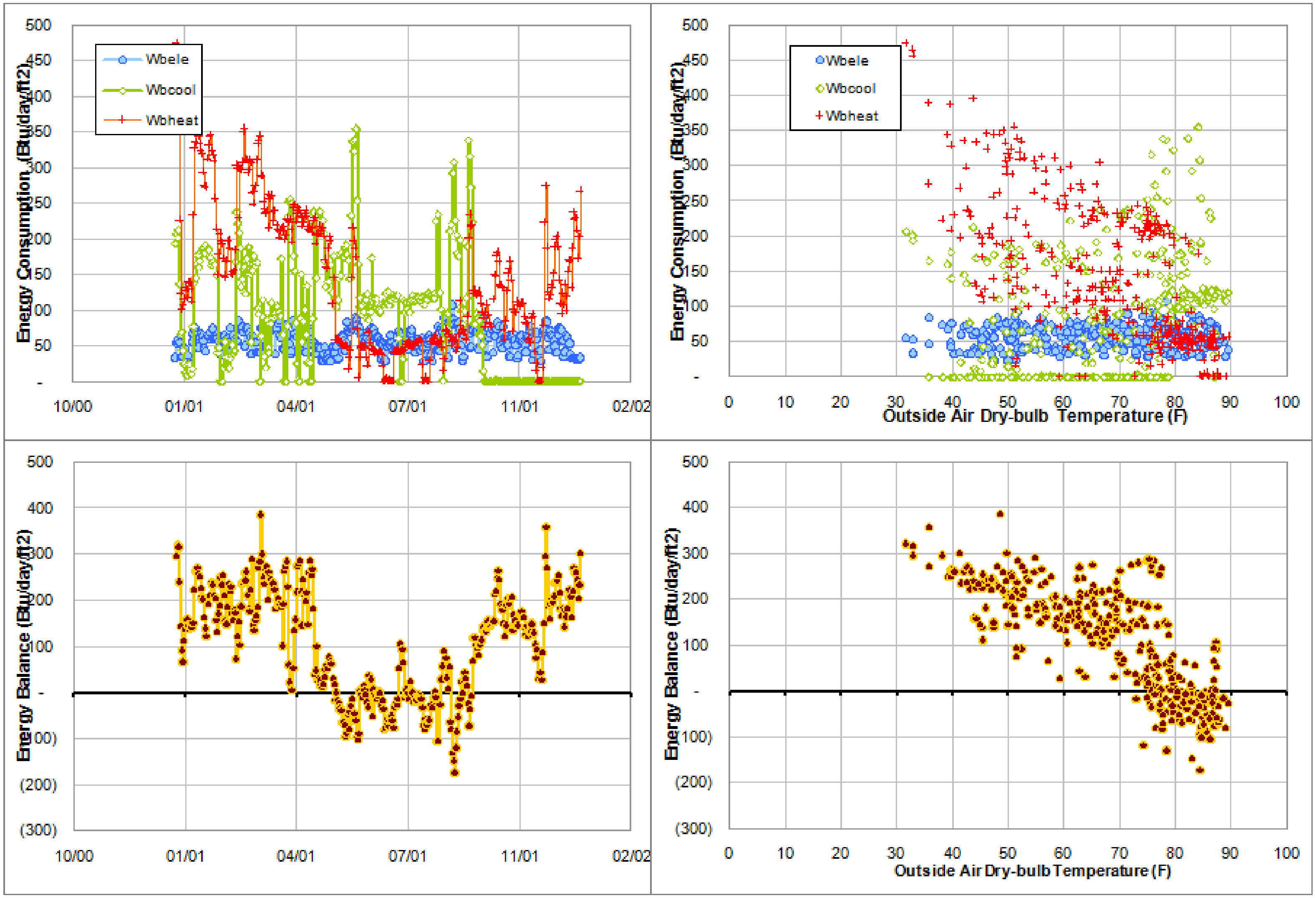


Figure D - 21. Energy balance plots for G. Rollie White 2001 data.

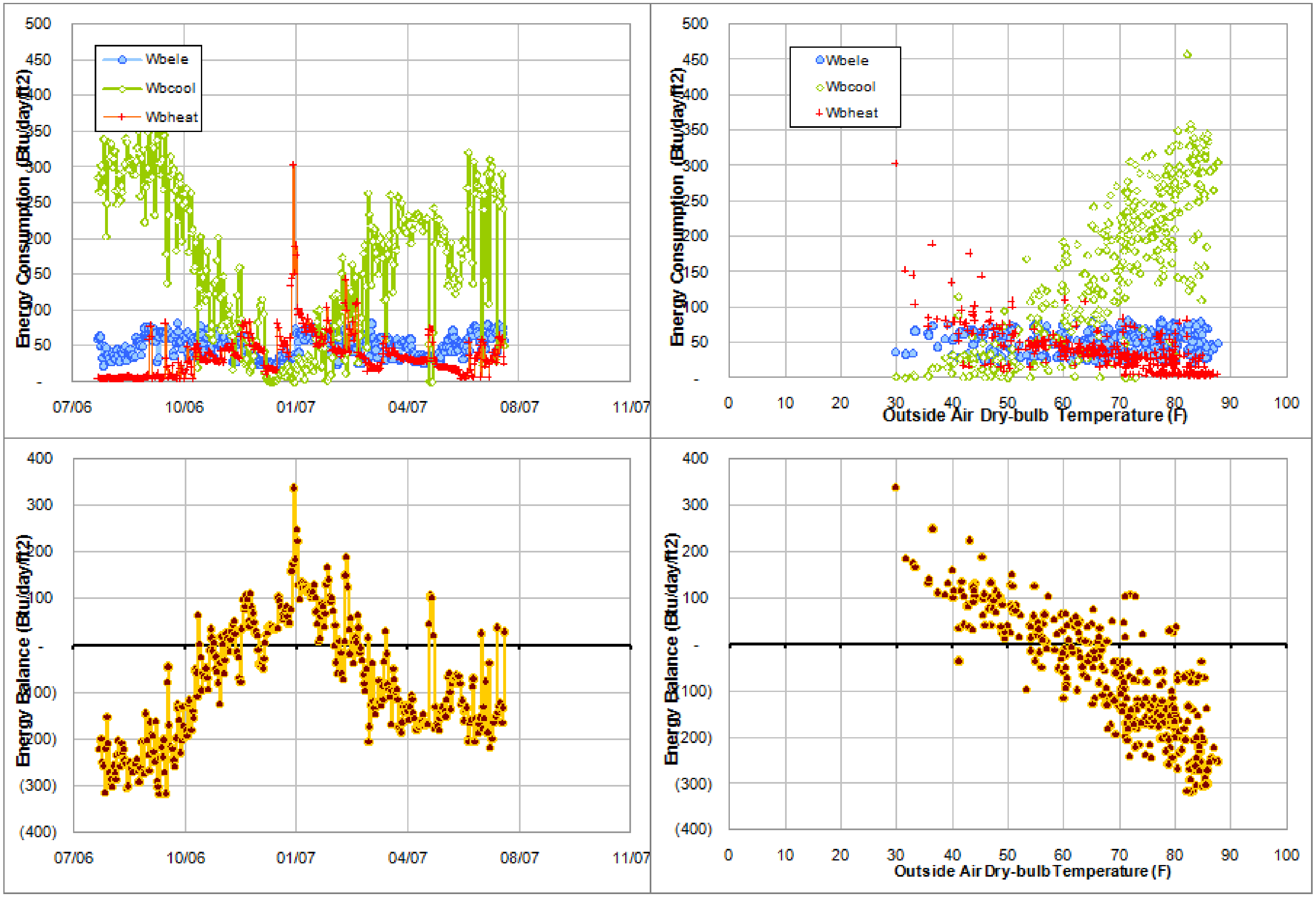


Figure D - 22. Energy balance plots for G. Rollie White 2006-07 data.

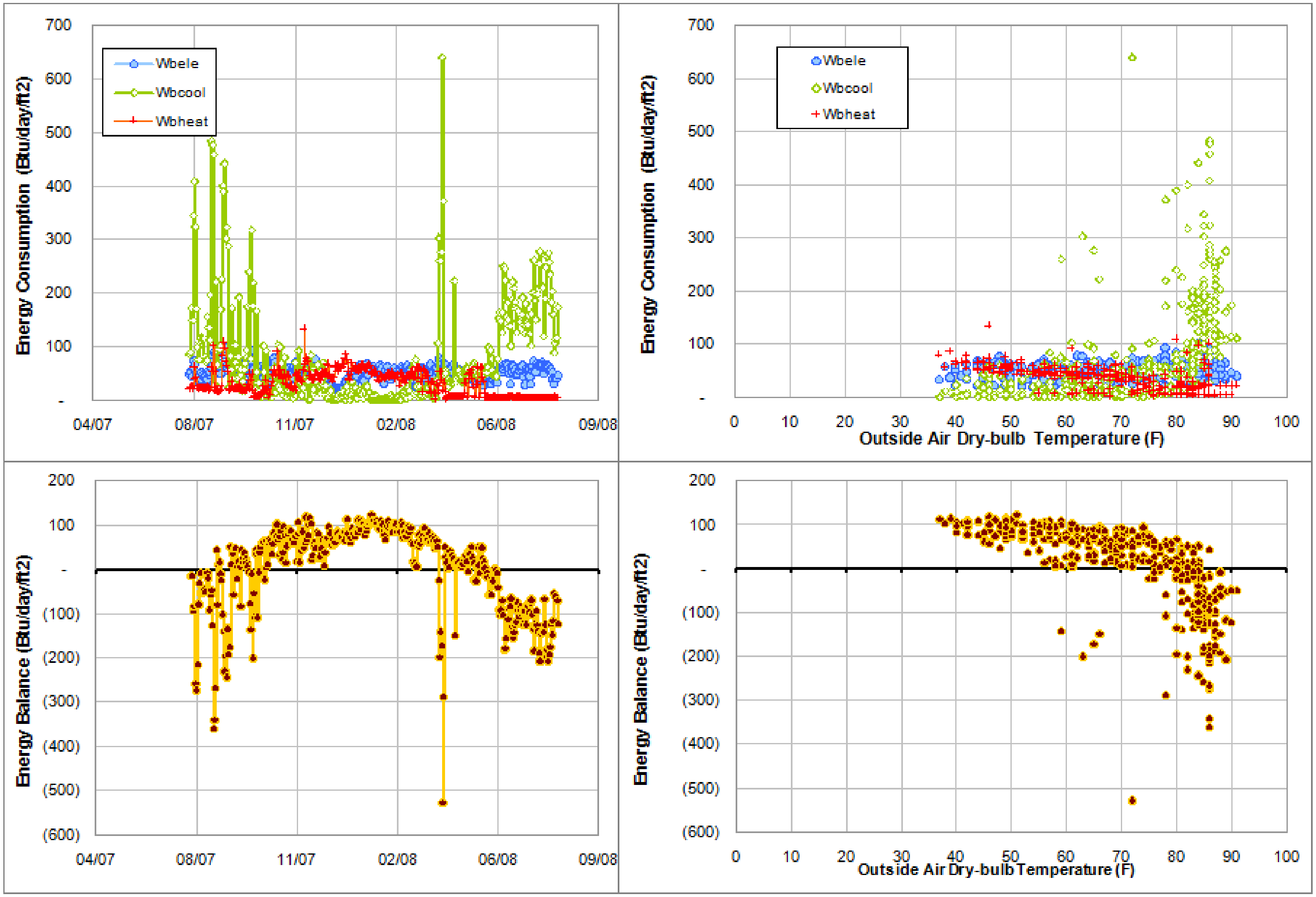


Figure D - 23. Energy balance plots for G. Rollie White 2007-08 data.

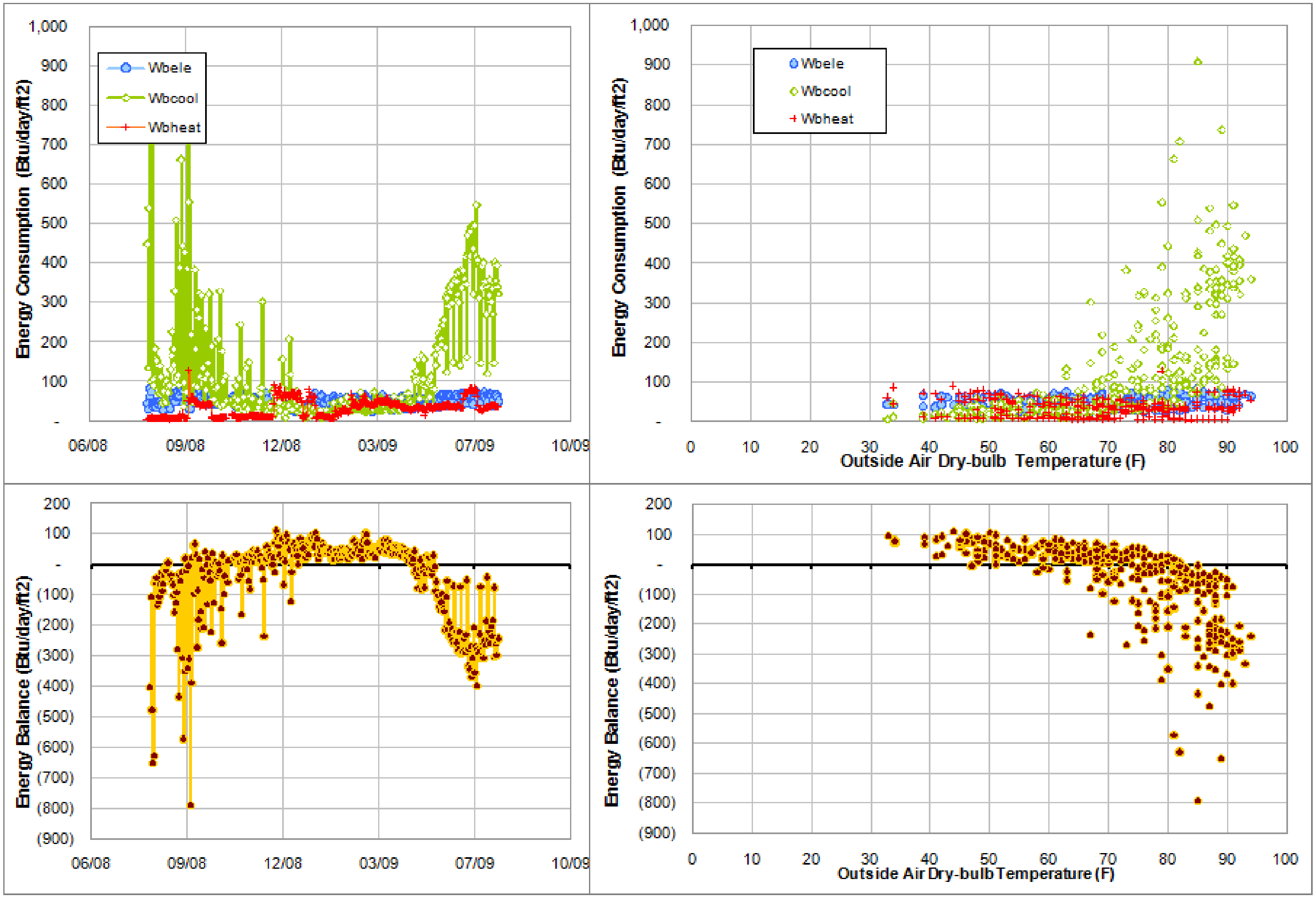


Figure D - 24. Energy balance plots for G. Rollie White 2008-09 data.

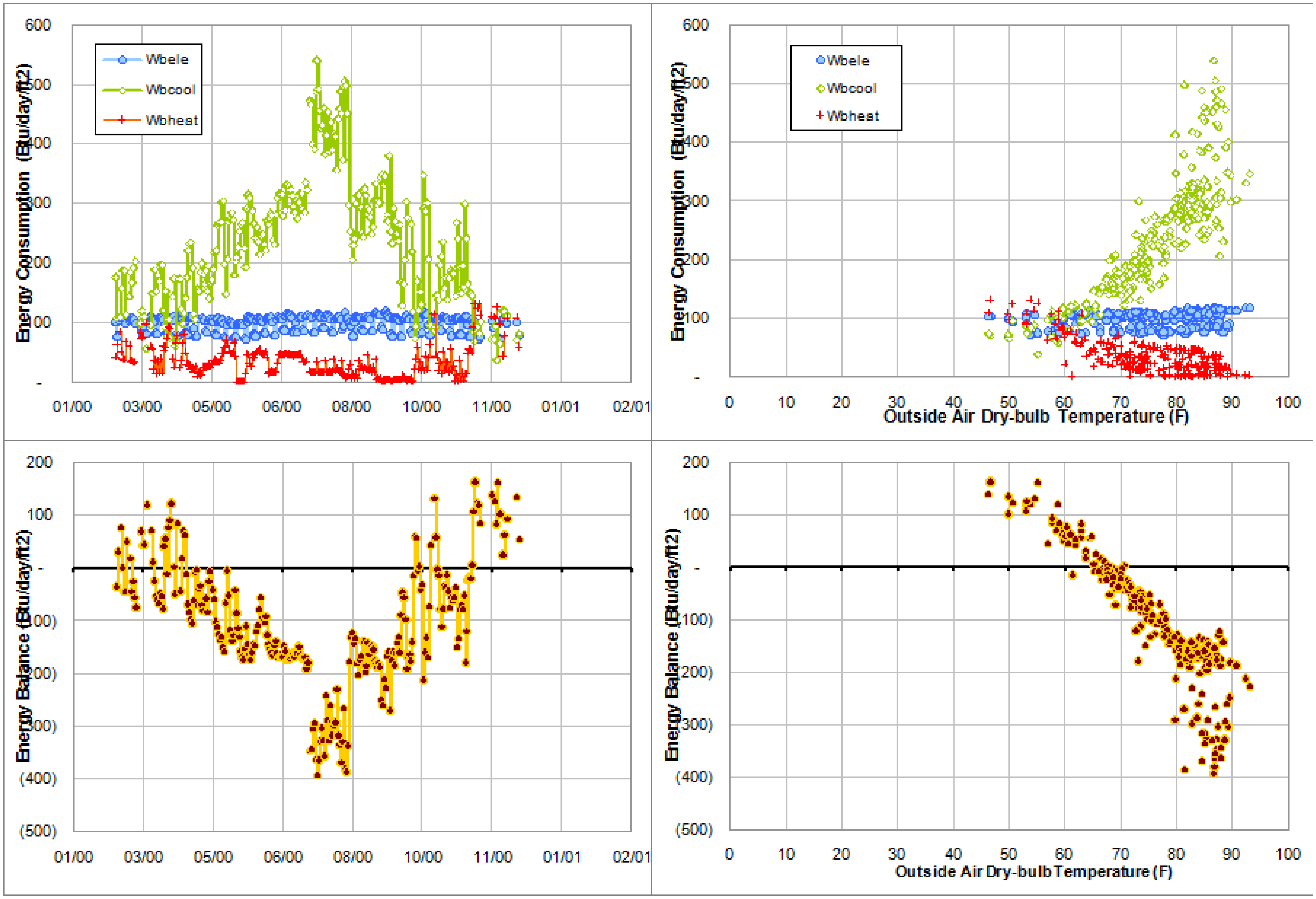


Figure D - 25. Energy balance plots for Harrington 2000 data.

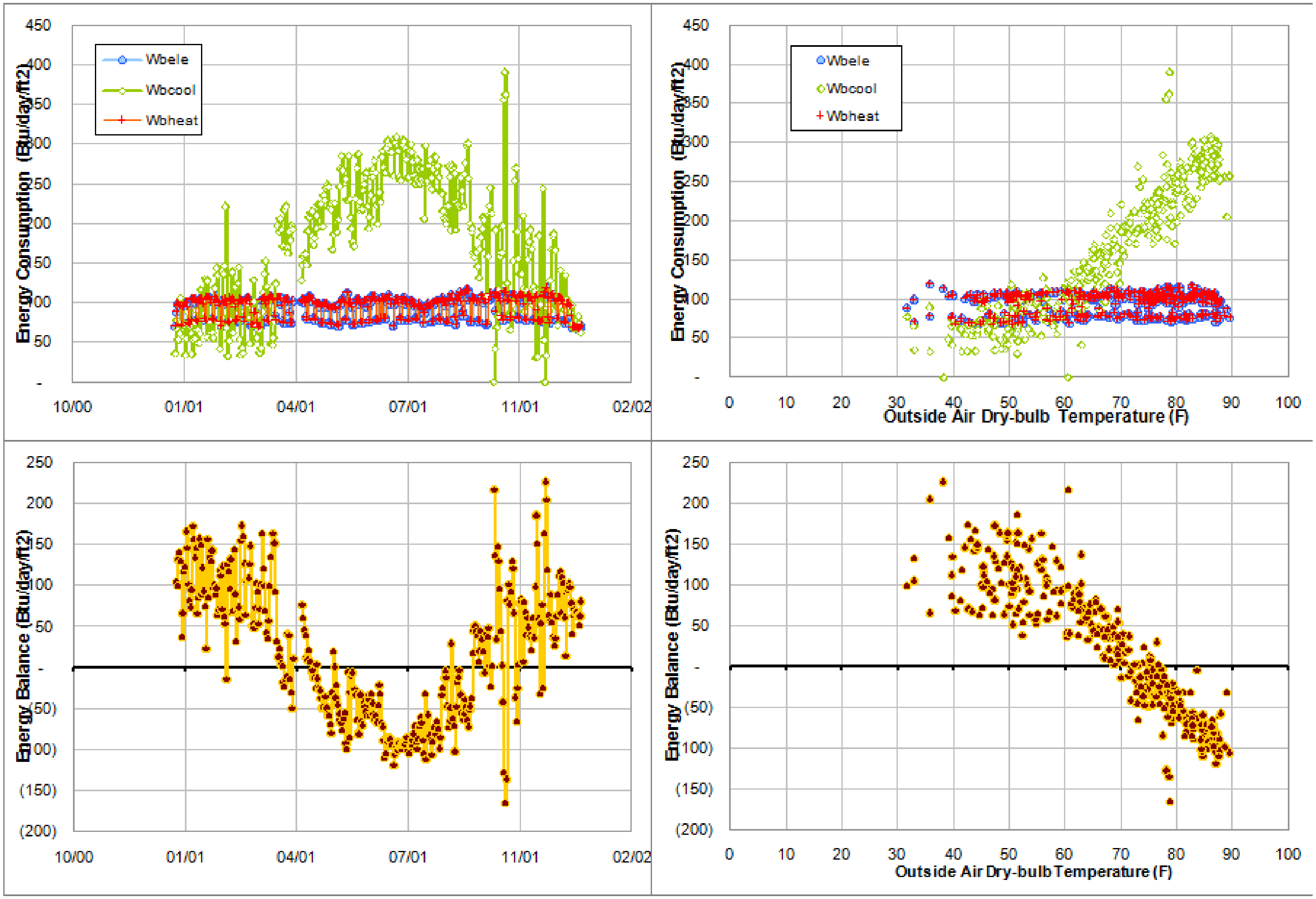


Figure D - 26. Energy balance plots for Harrington 2001 data.

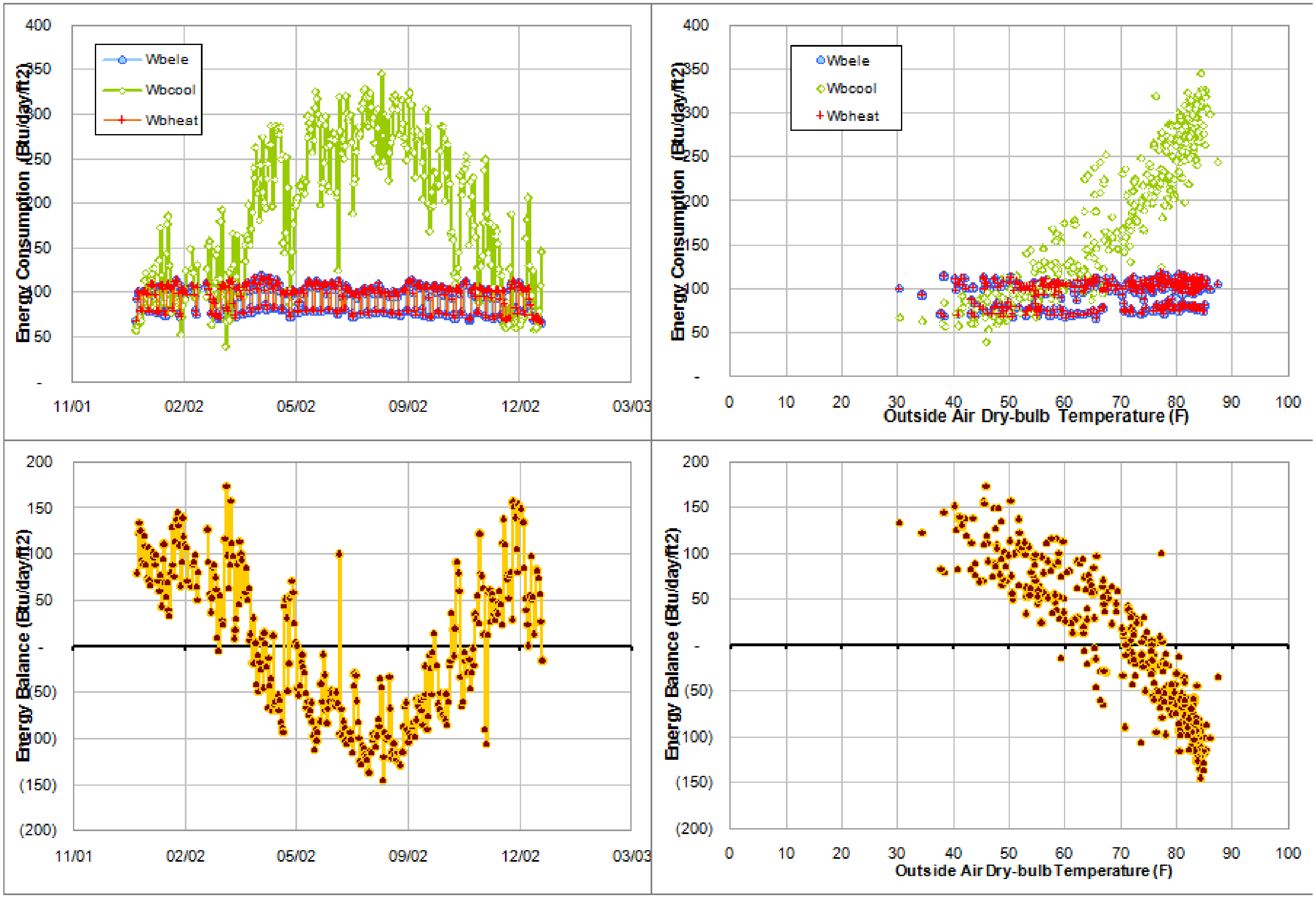


Figure D - 27. Energy balance plots for Harrington 2002 data.

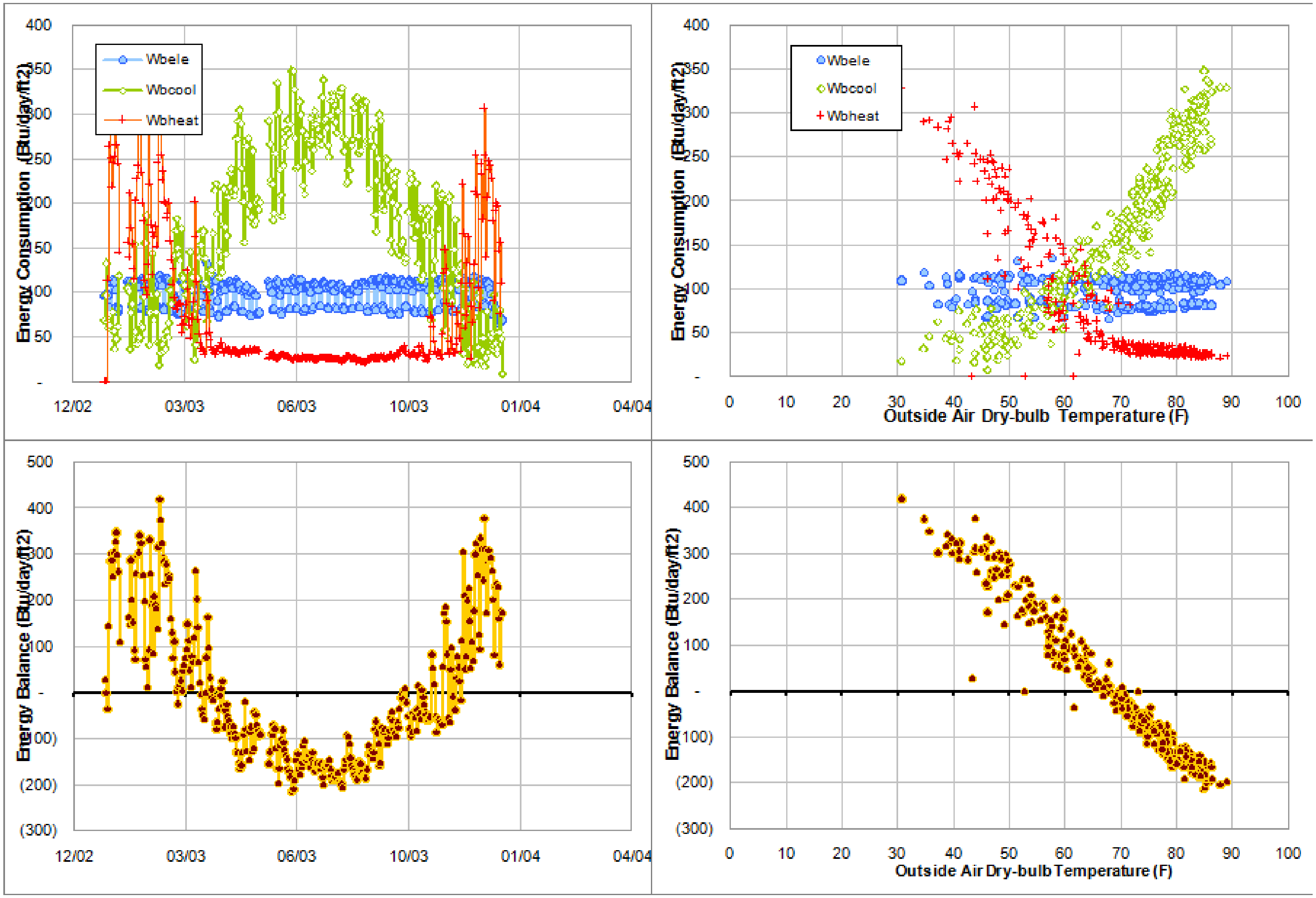


Figure D - 28. Energy balance plots for Harrington 2003 data.

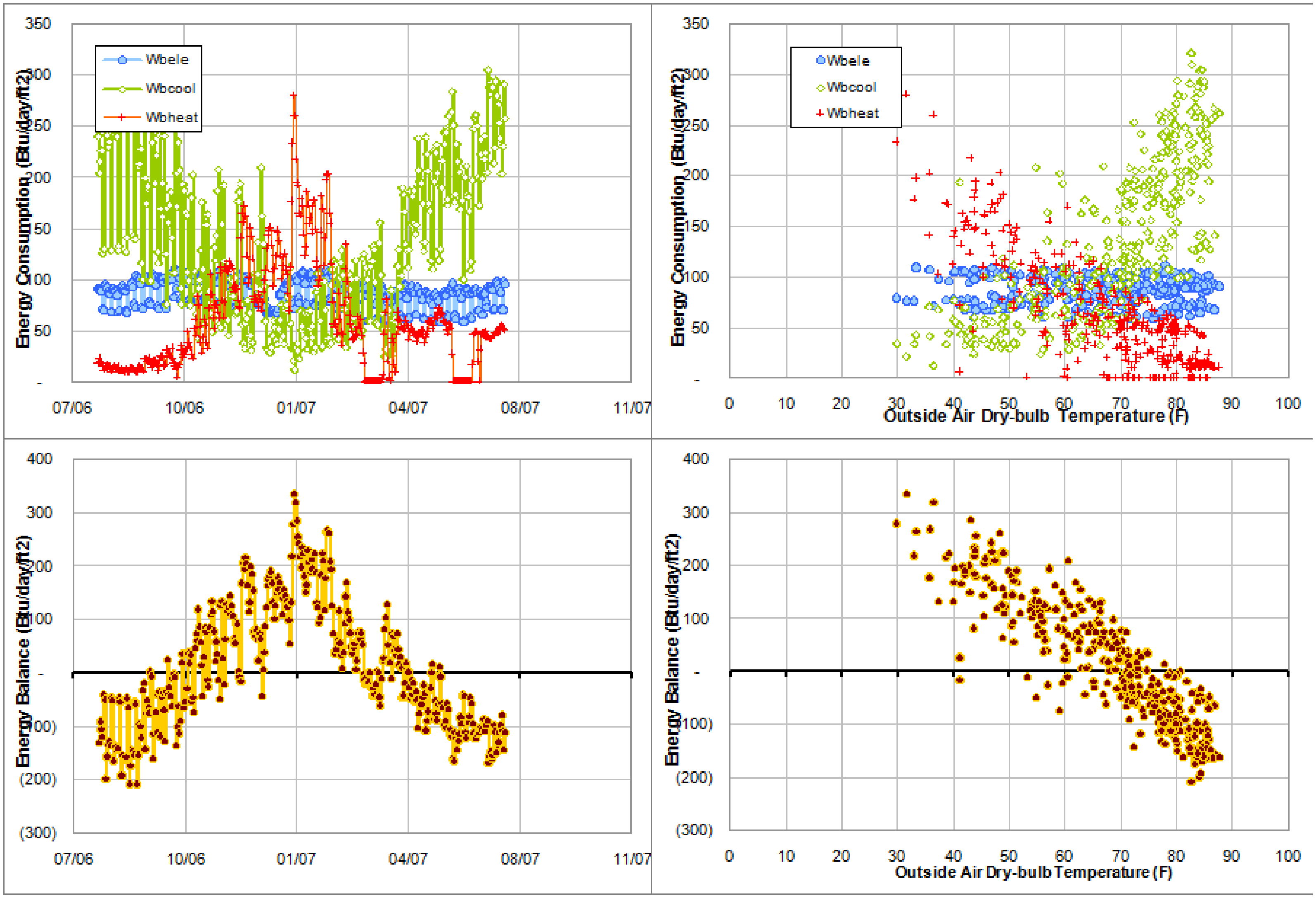


Figure D - 29. Energy balance plots for Harrington 2006-07 data.

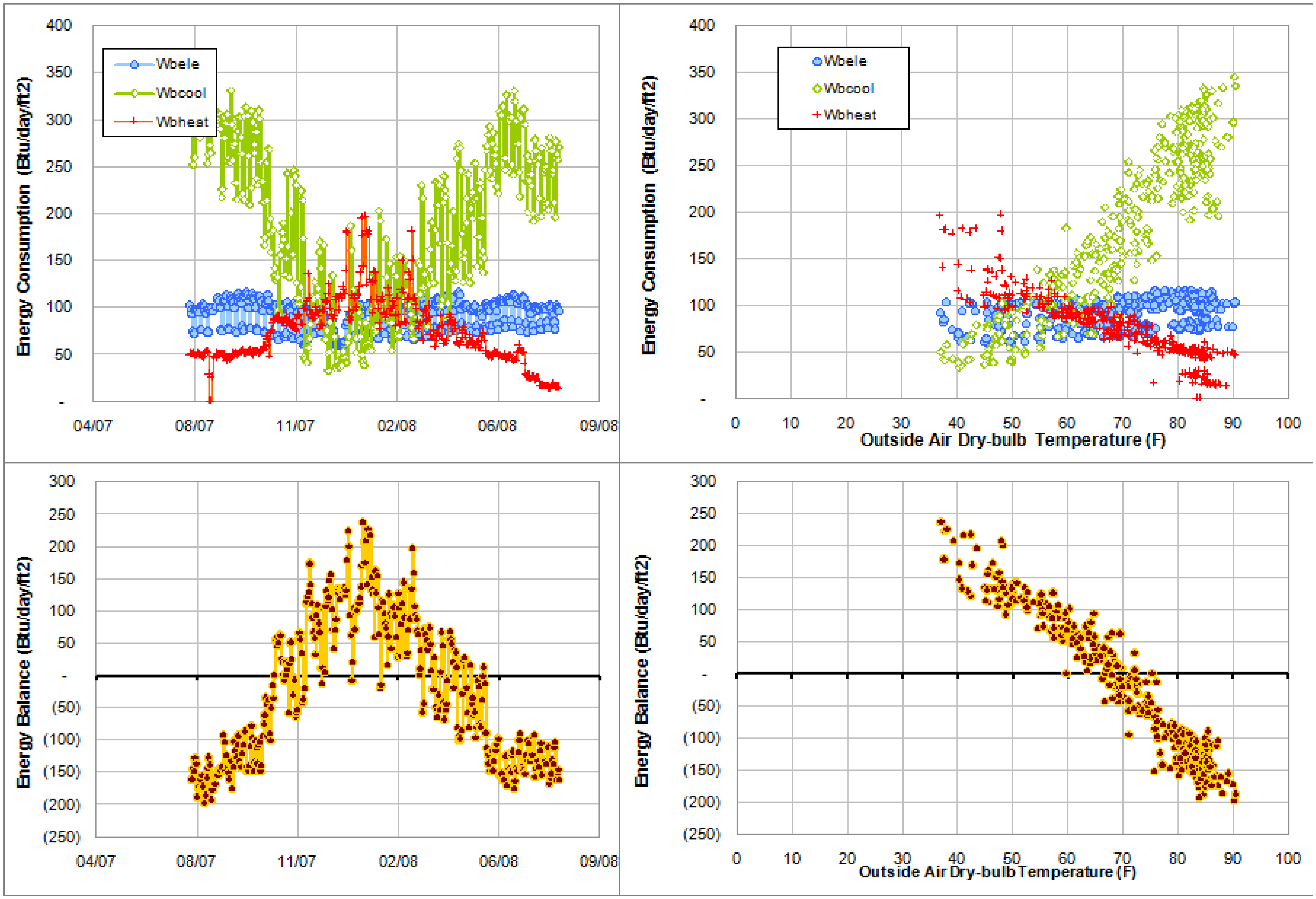


Figure D - 30. Energy balance plots for Harrington 2007-08 data.

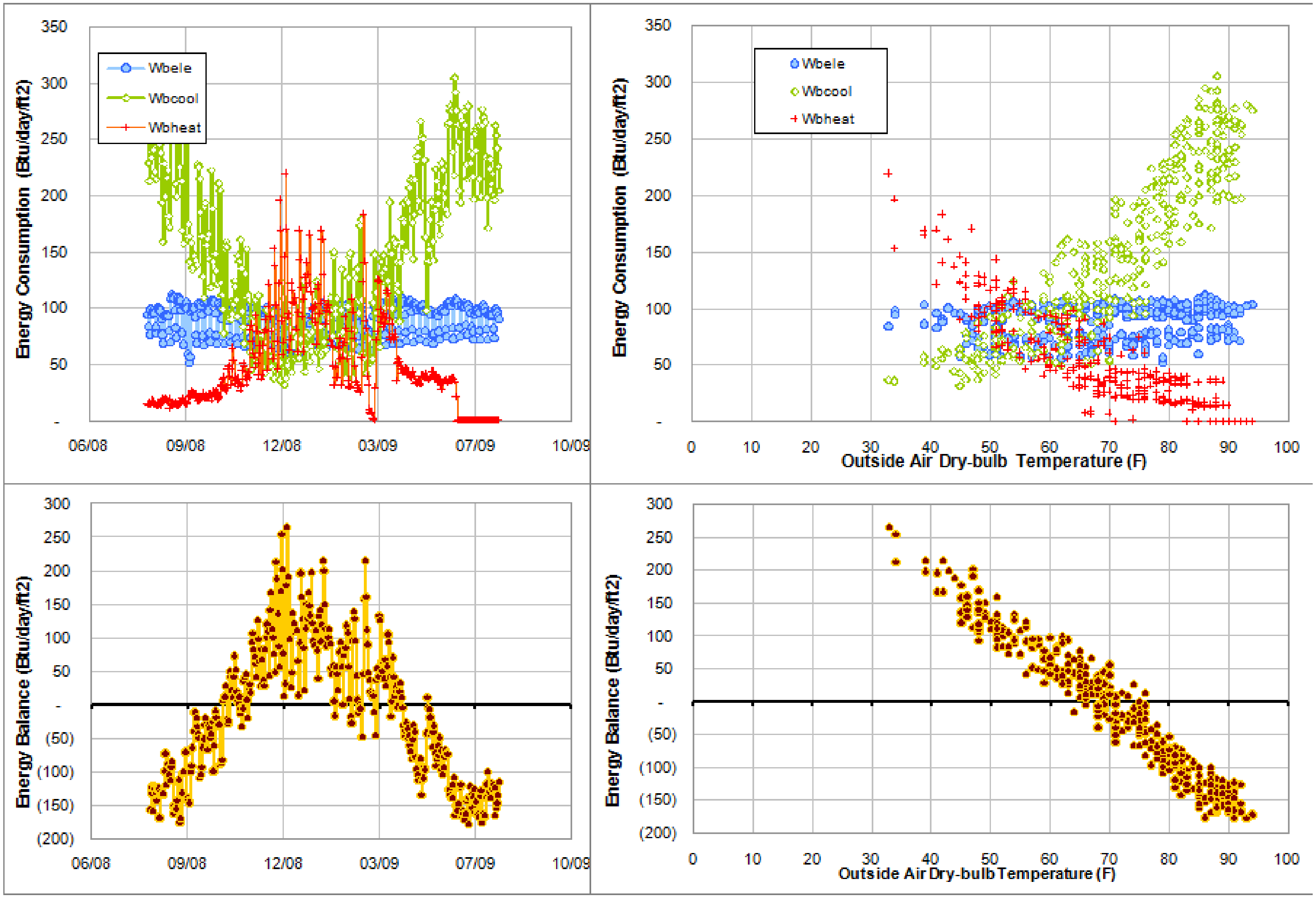


Figure D - 31. Energy balance plots for Harrington 2008-09 data.

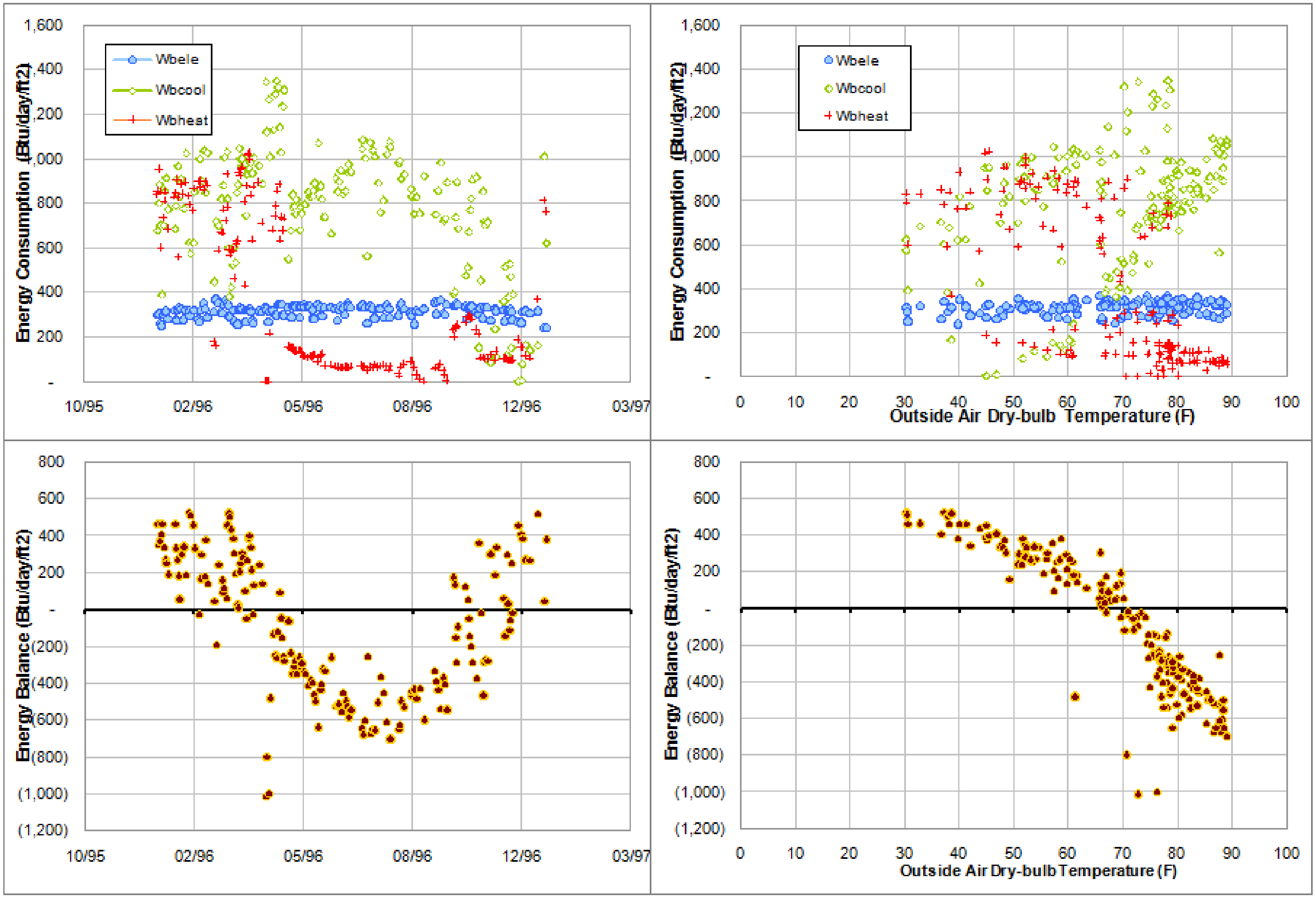


Figure D - 32. Energy balance plots for Kleberg 1996 data.

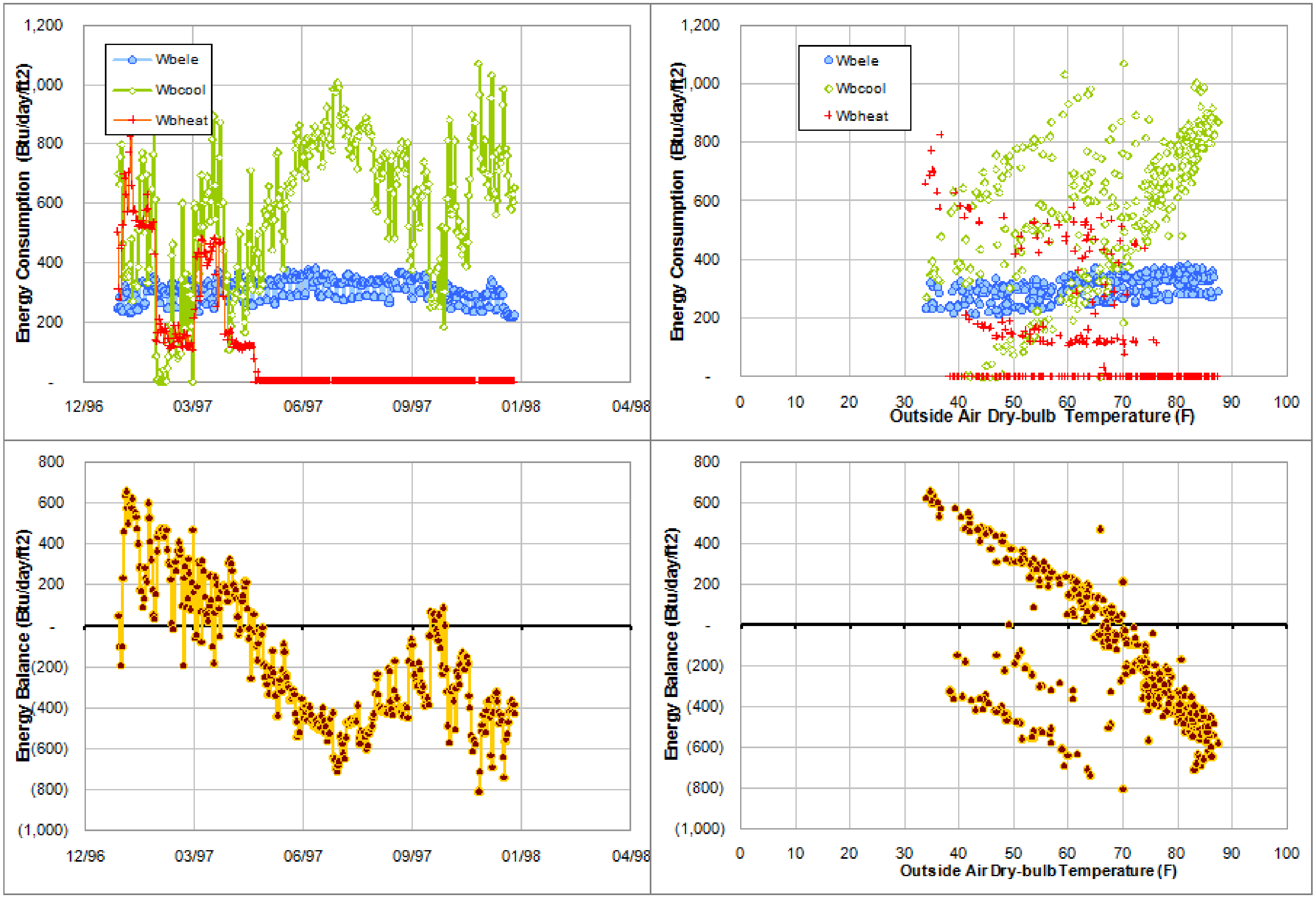


Figure D - 33. Energy balance plots for Kleberg 1997 data.

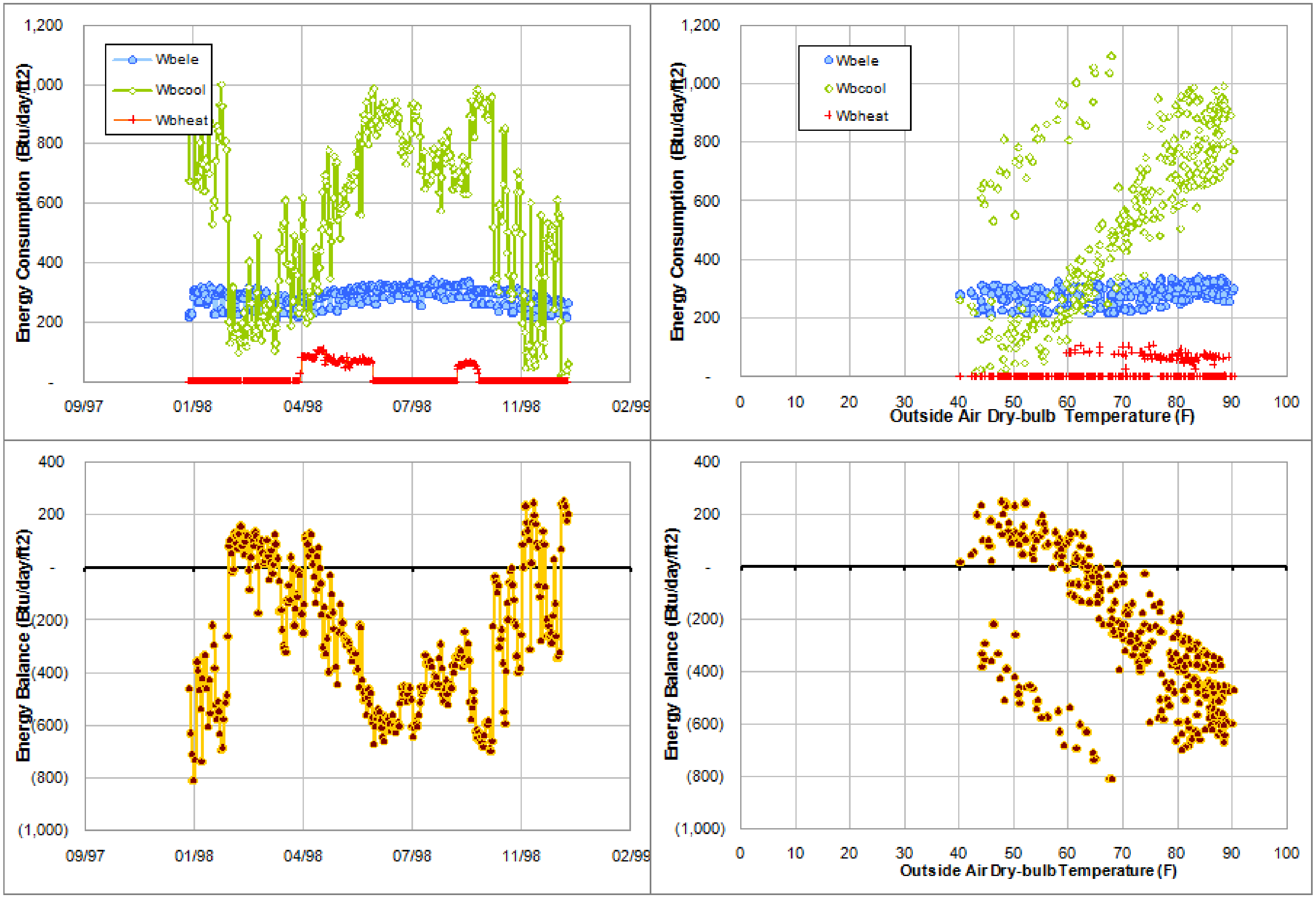


Figure D - 34. Energy balance plots for Kleberg 1998 data.

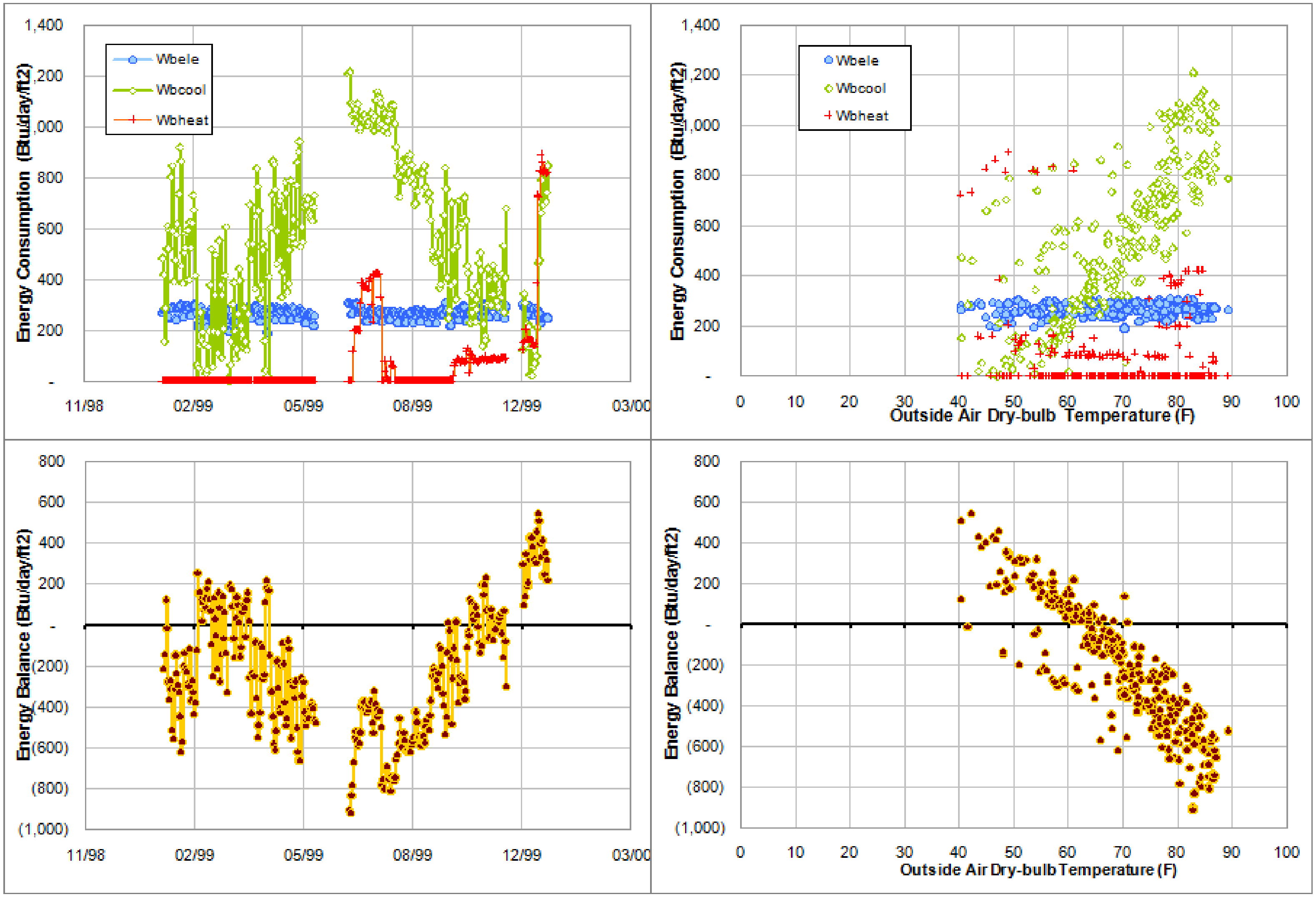


Figure D - 35. Energy balance plots for Kleberg 1999 data.

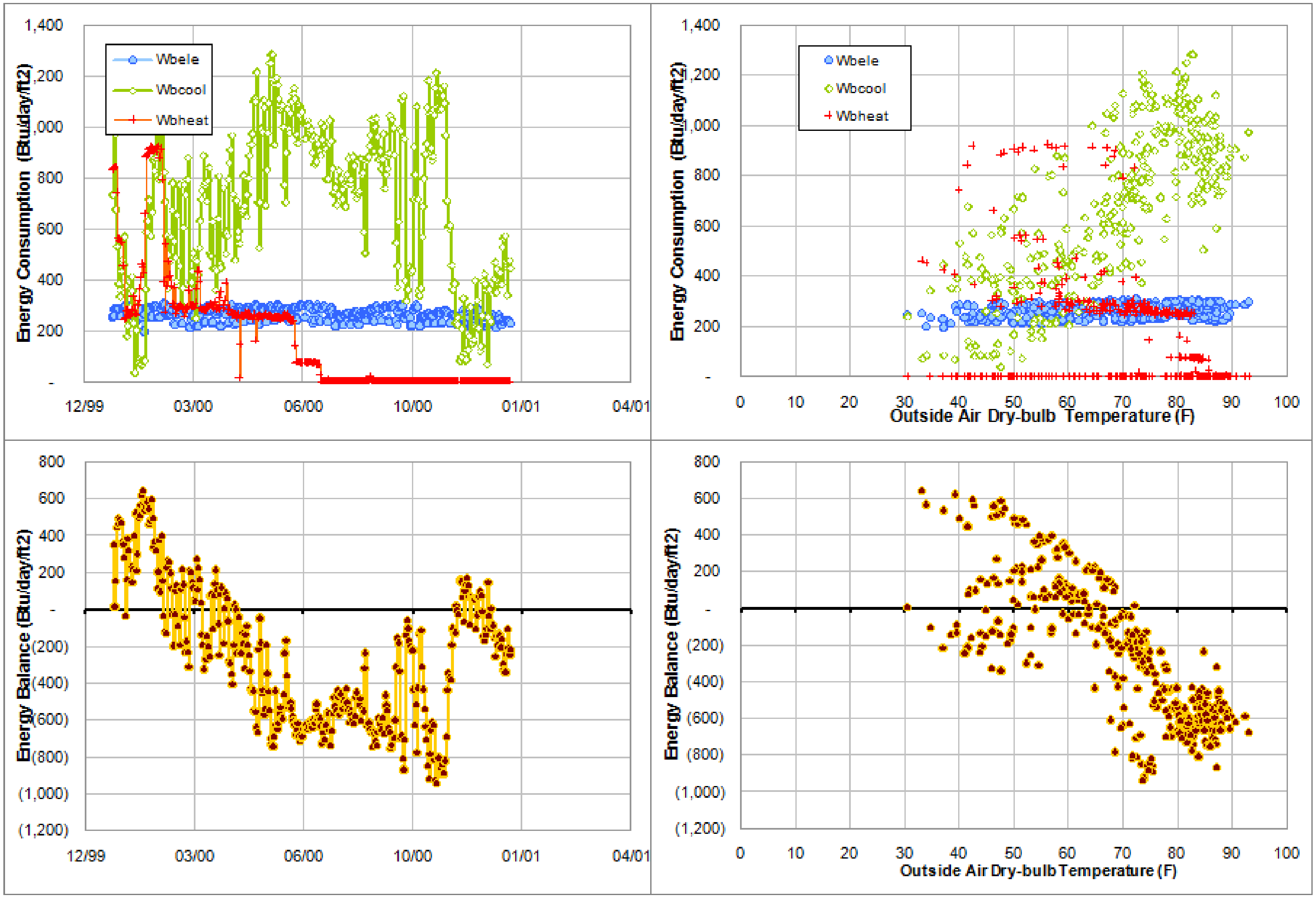


Figure D - 36. Energy balance plots for Kleberg 2000 data.

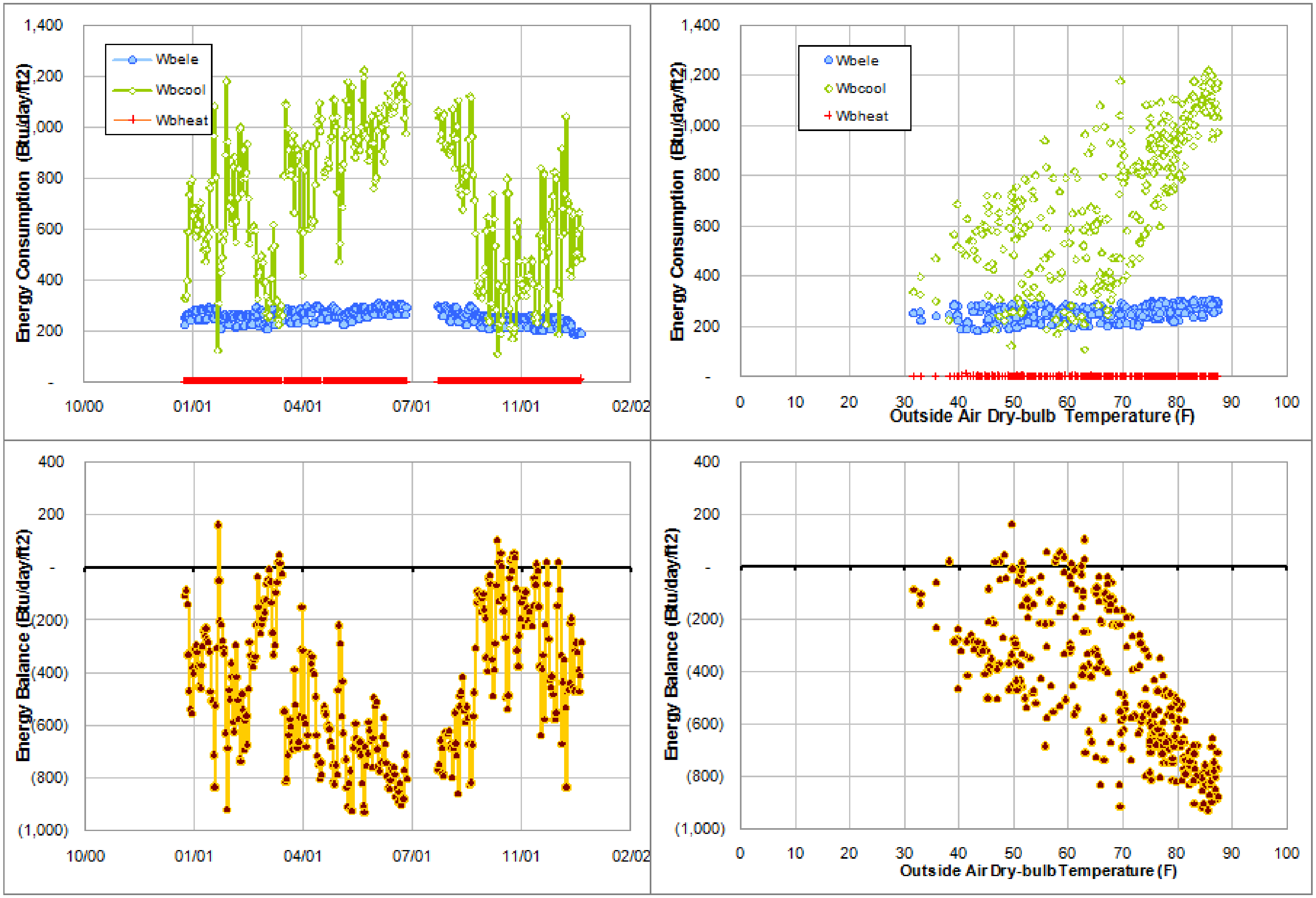


Figure D - 37. Energy balance plots for Kleberg 2001 data.

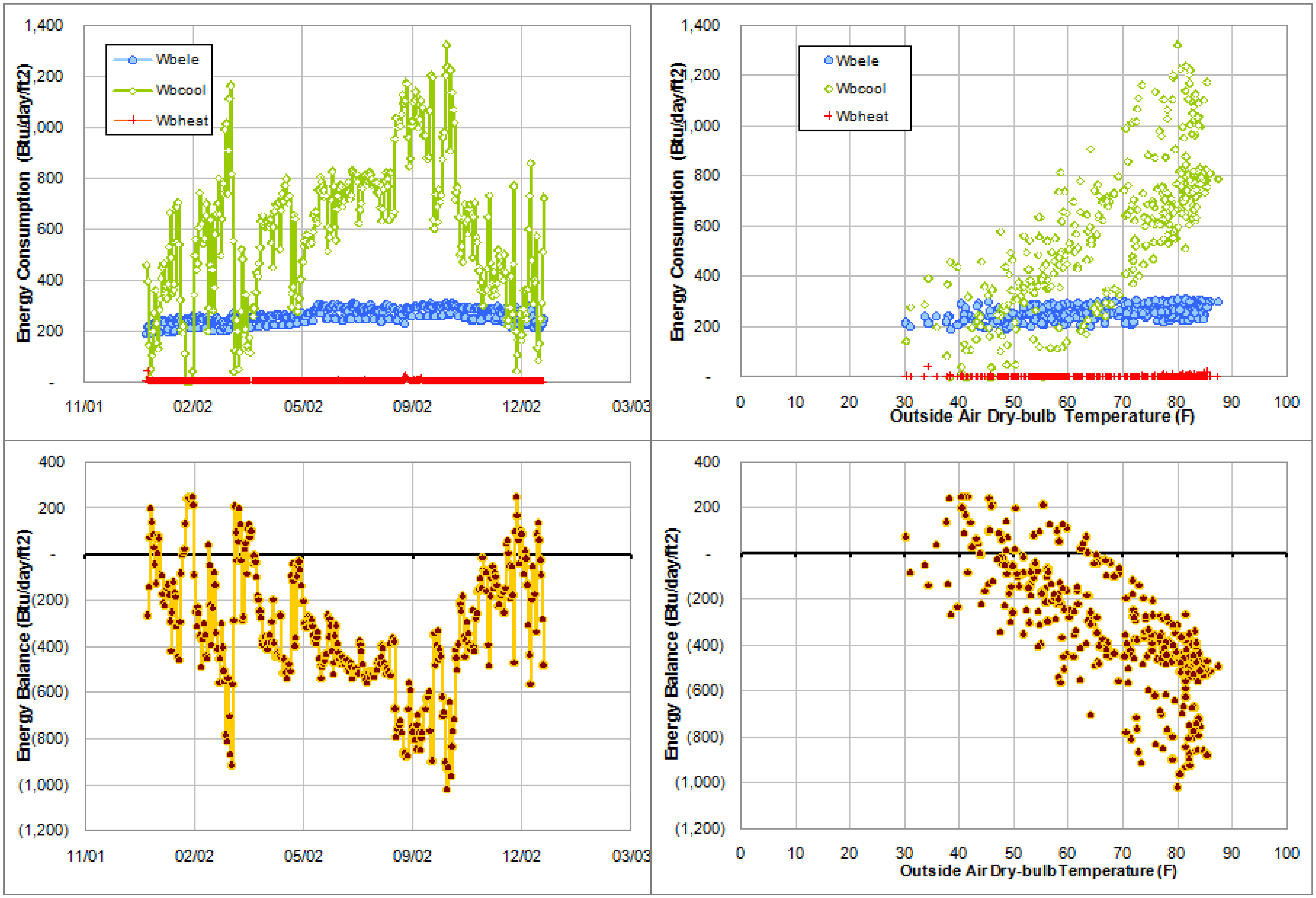


Figure D - 38. Energy balance plots for Kleberg 2002 data.

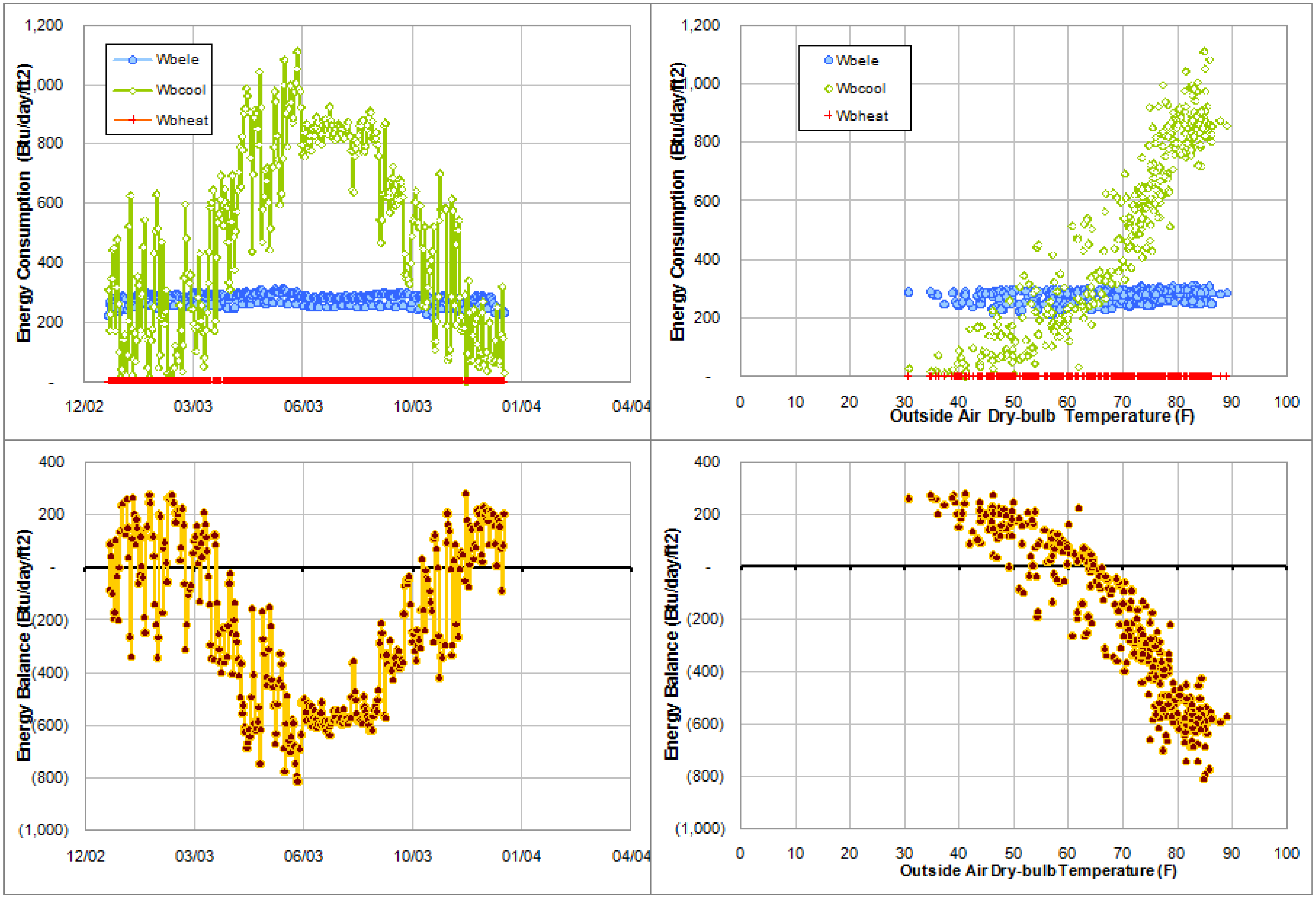


Figure D - 39. Energy balance plots for Kleberg 2003 data.

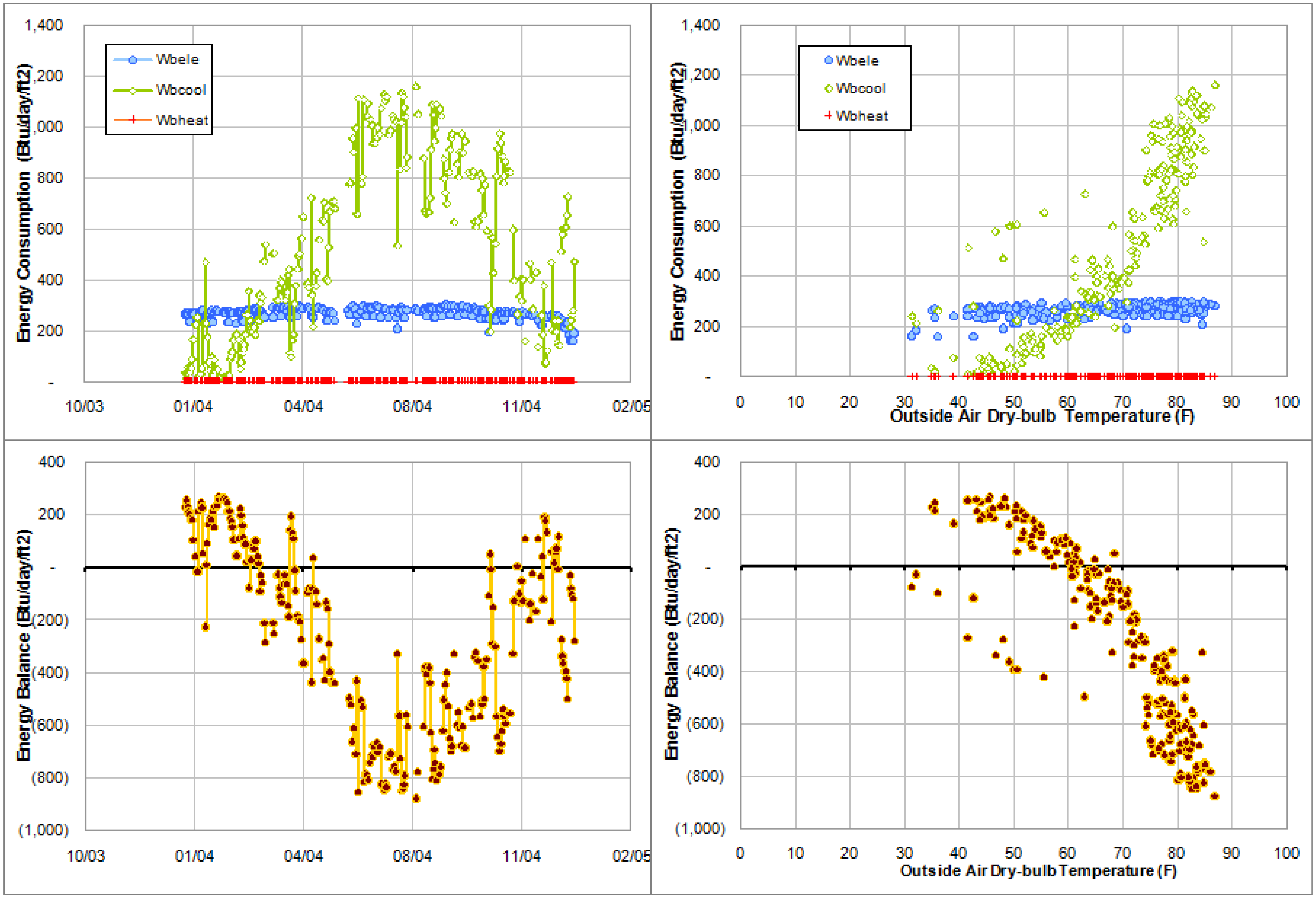


Figure D - 40. Energy balance plots for Kleberg 2004 data.

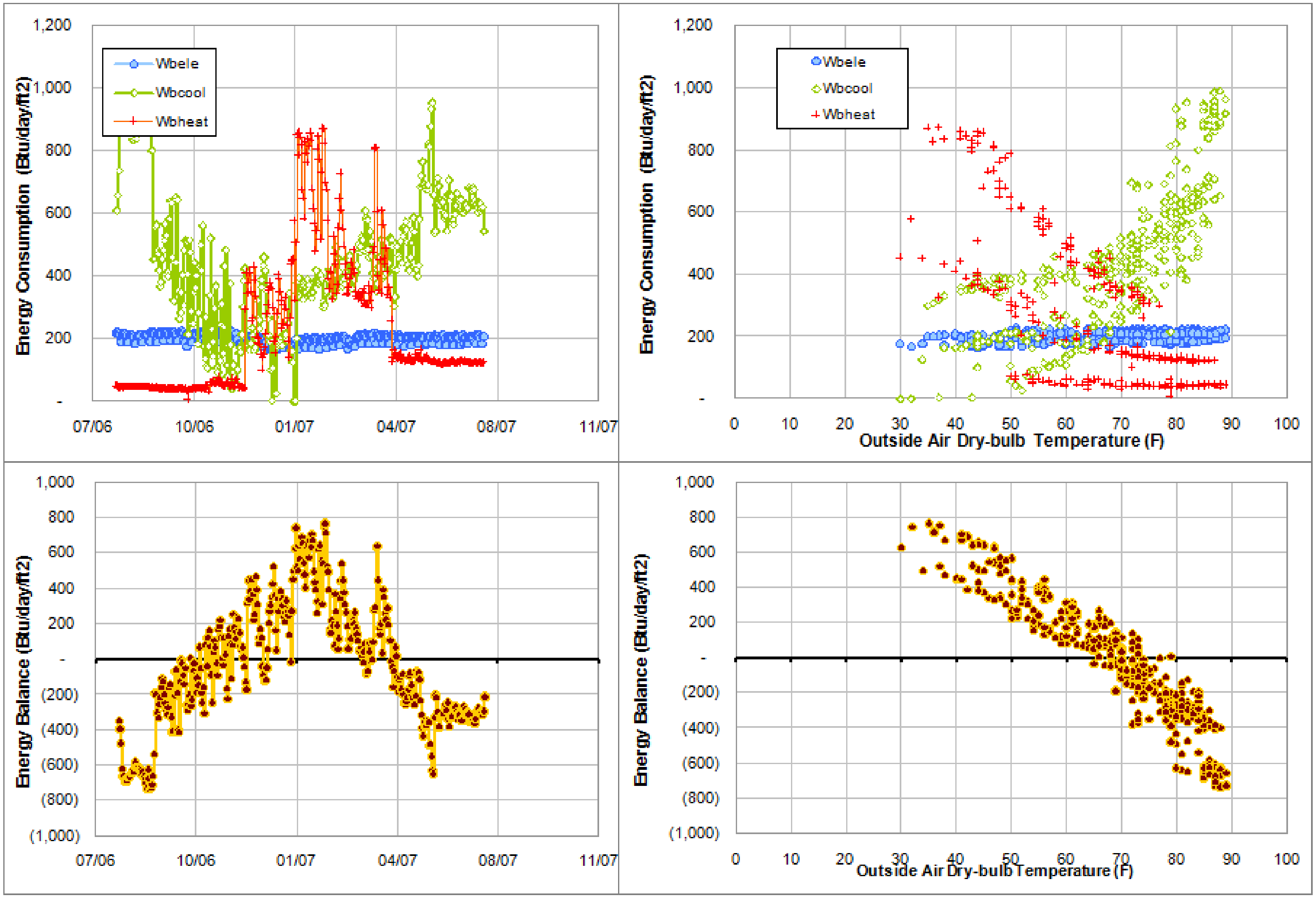


Figure D - 41. Energy balance plots for Kleberg 2006-07 data.

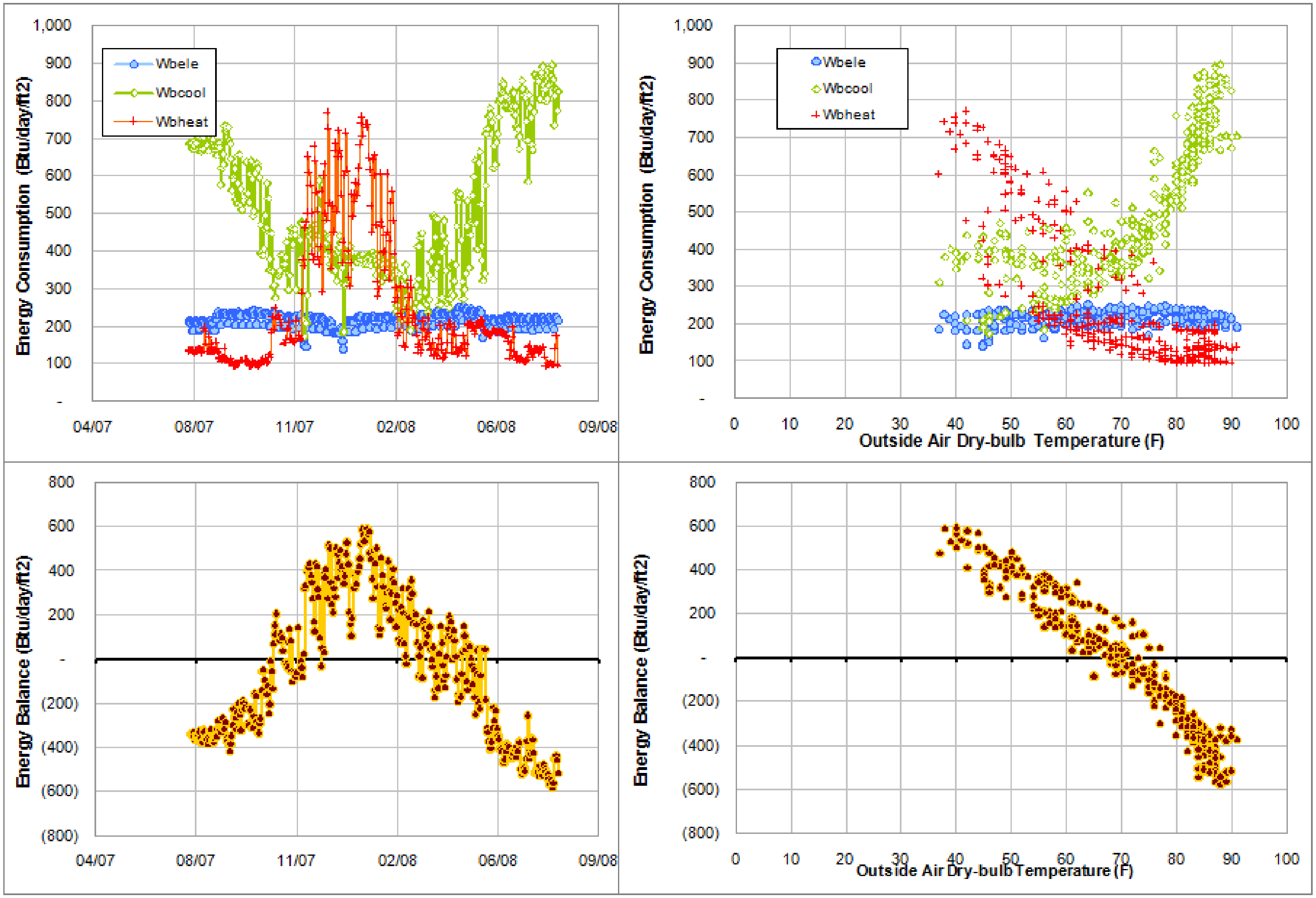


Figure D - 42. Energy balance plots for Kleberg 2007-08 data.

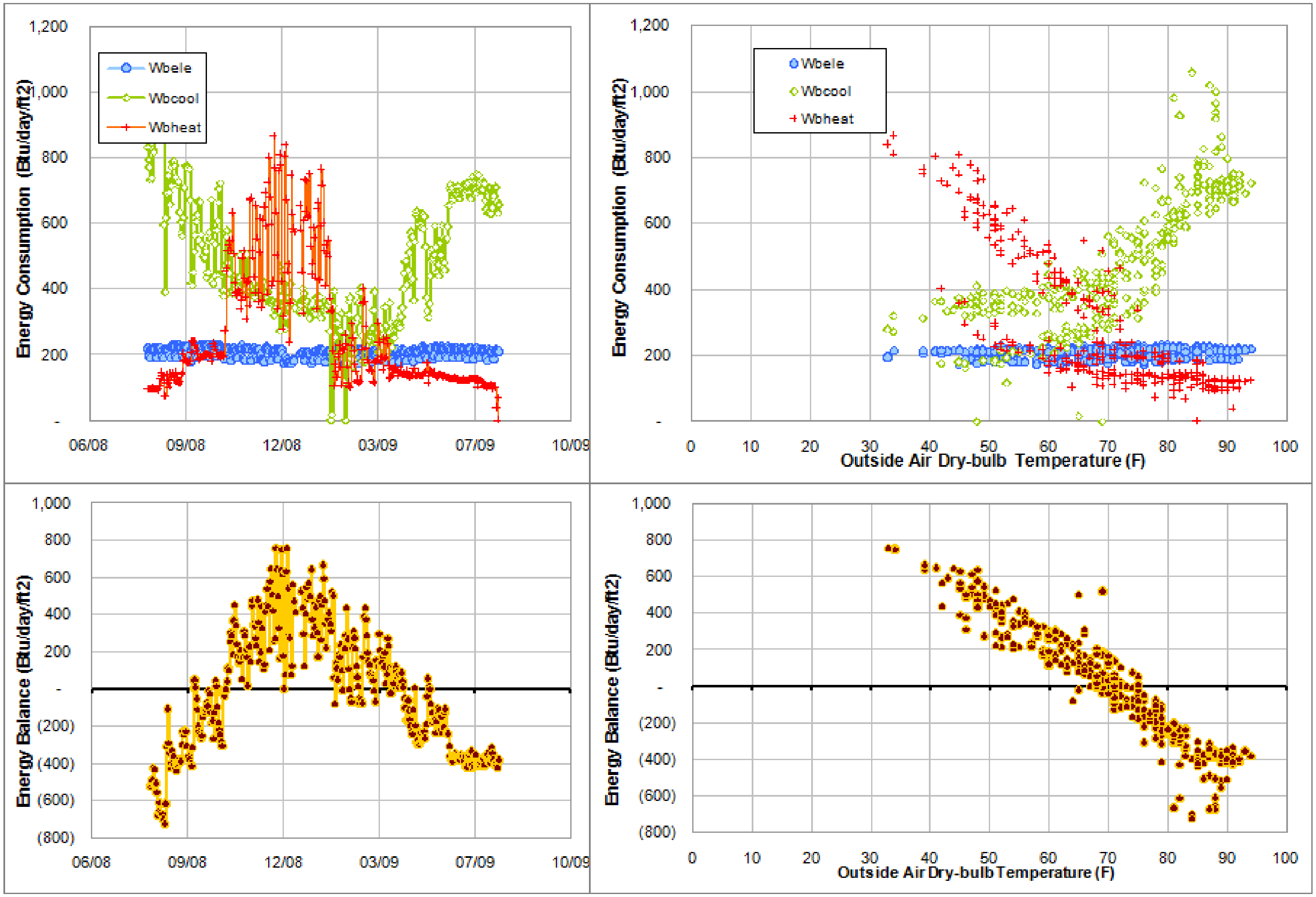


Figure D - 43. Energy balance plots for Kleberg 2008-09 data.

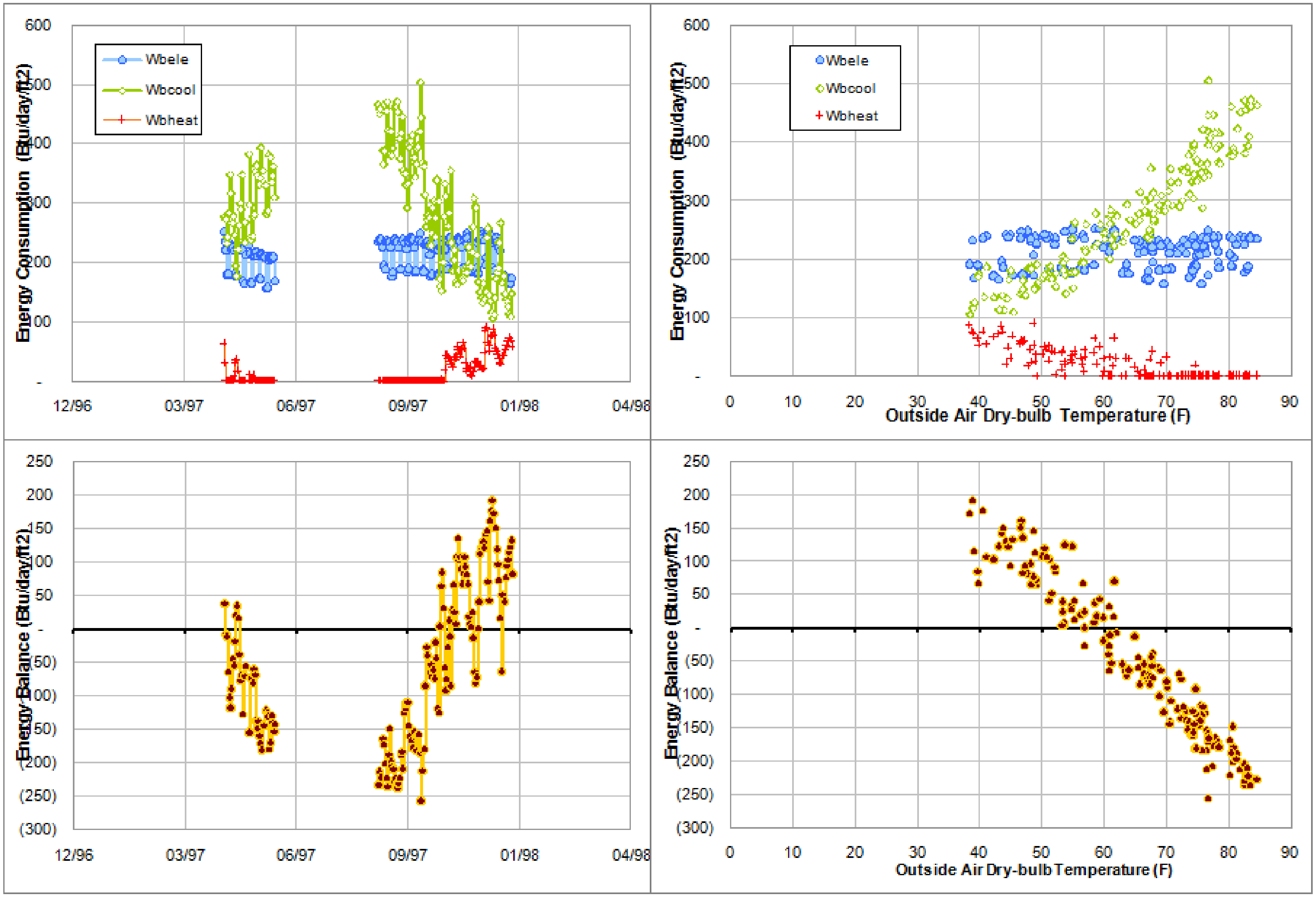


Figure D - 44. Energy balance plots for Koldus 1997 data.

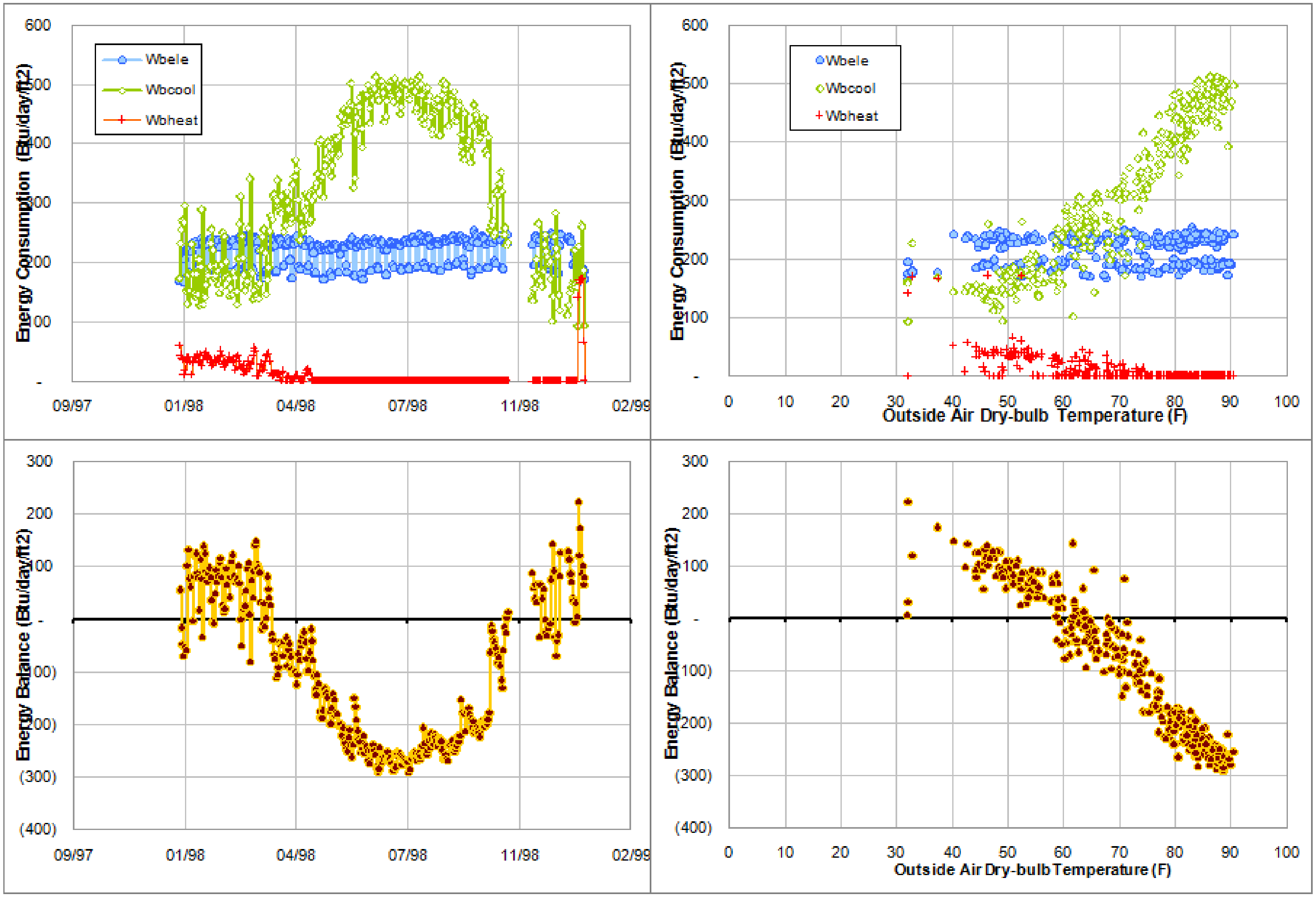


Figure D - 45. Energy balance plots for Koldus 1998 data.

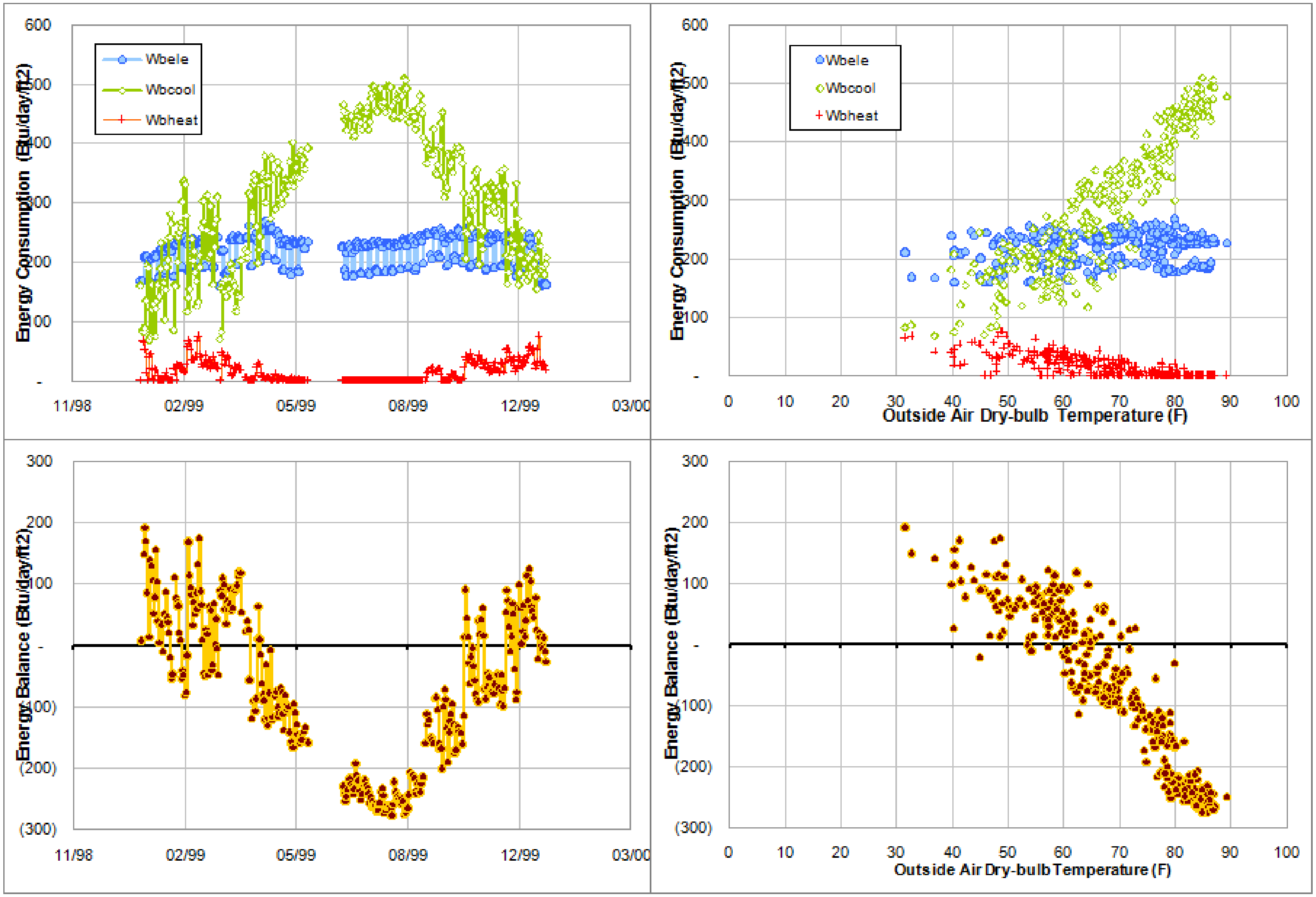


Figure D - 46. Energy balance plots for Koldus 1999 data.

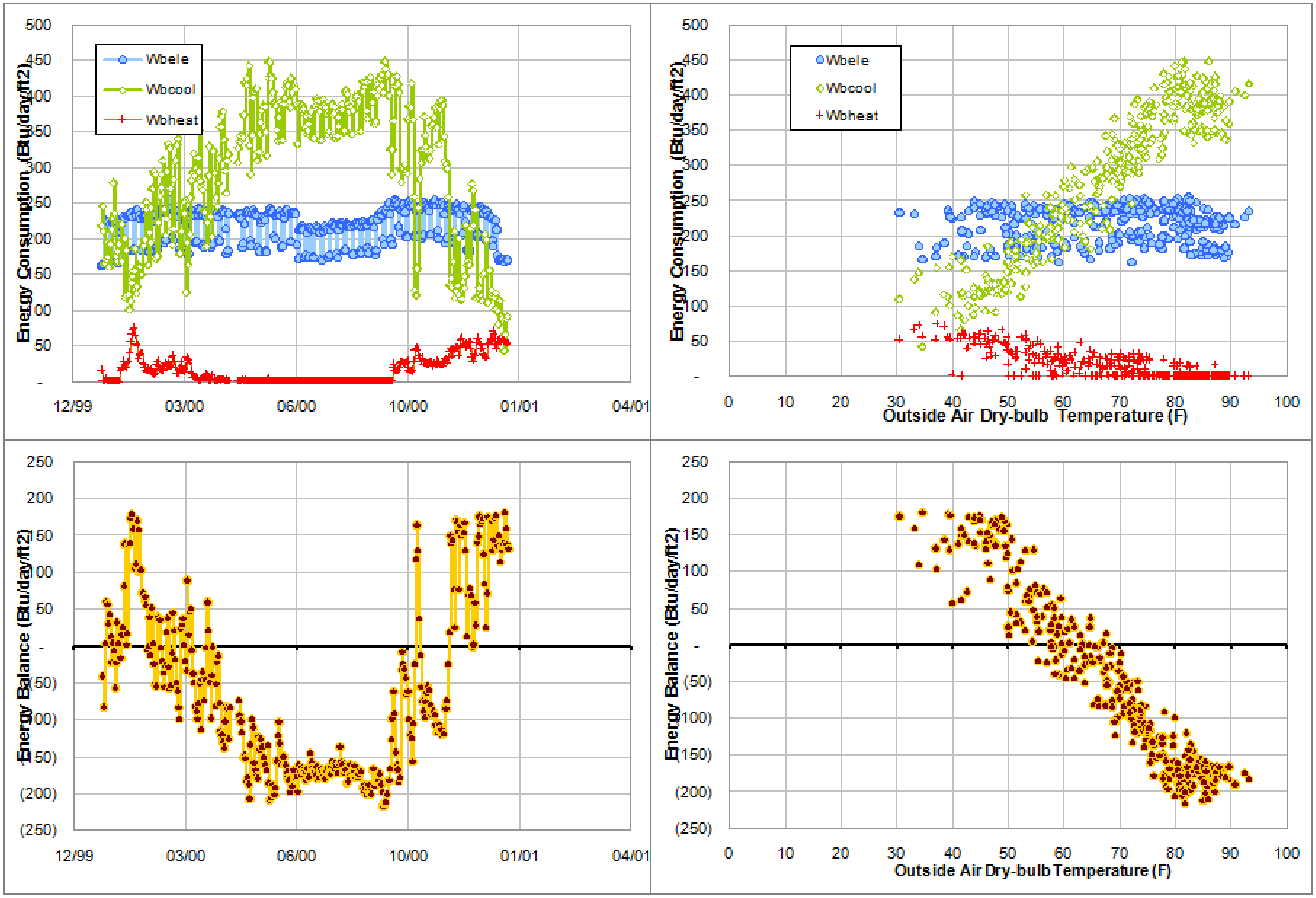


Figure D - 47. Energy balance plots for Koldus 2000 data.

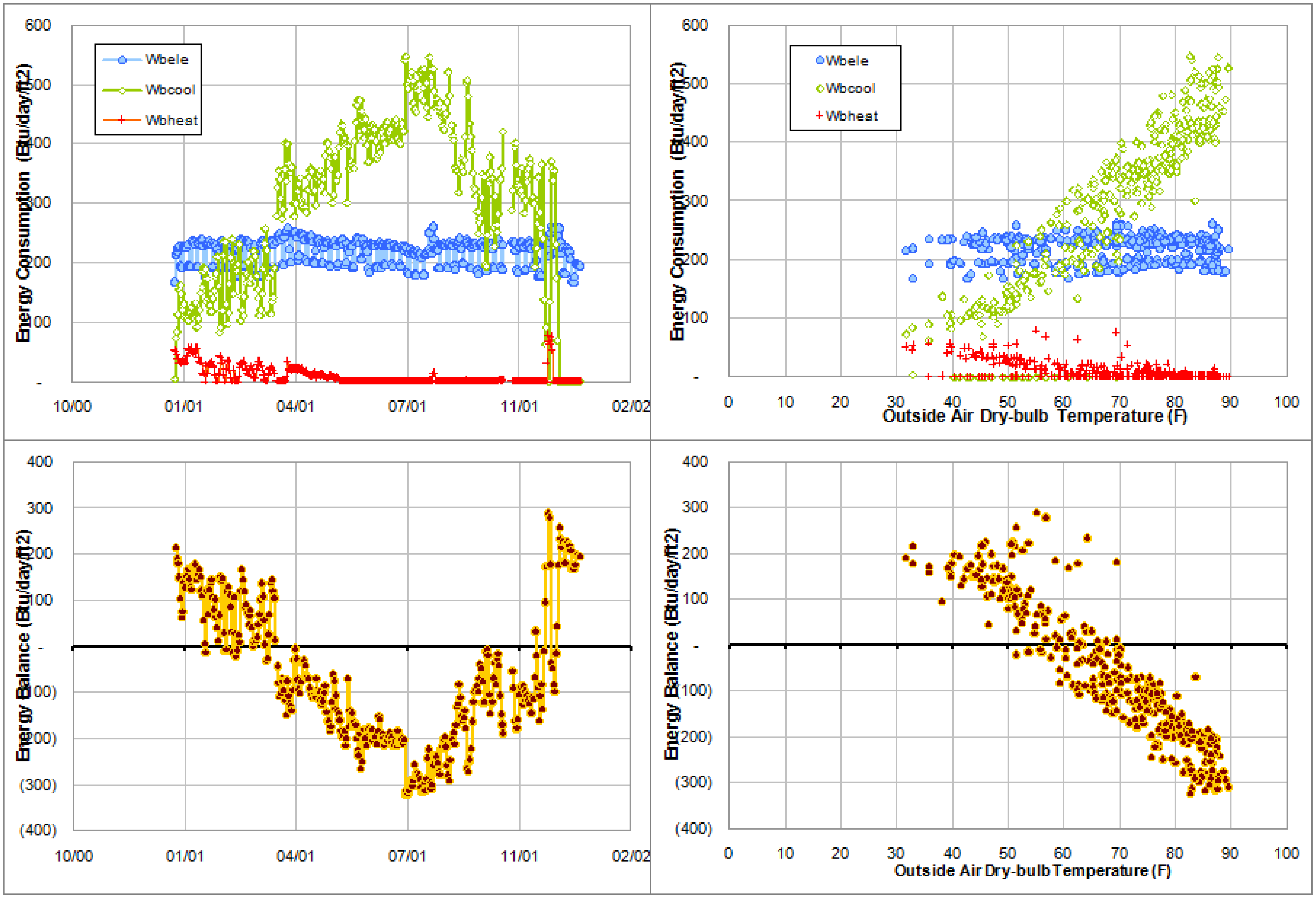


Figure D - 48. Energy balance plots for Koldus 2001 data.

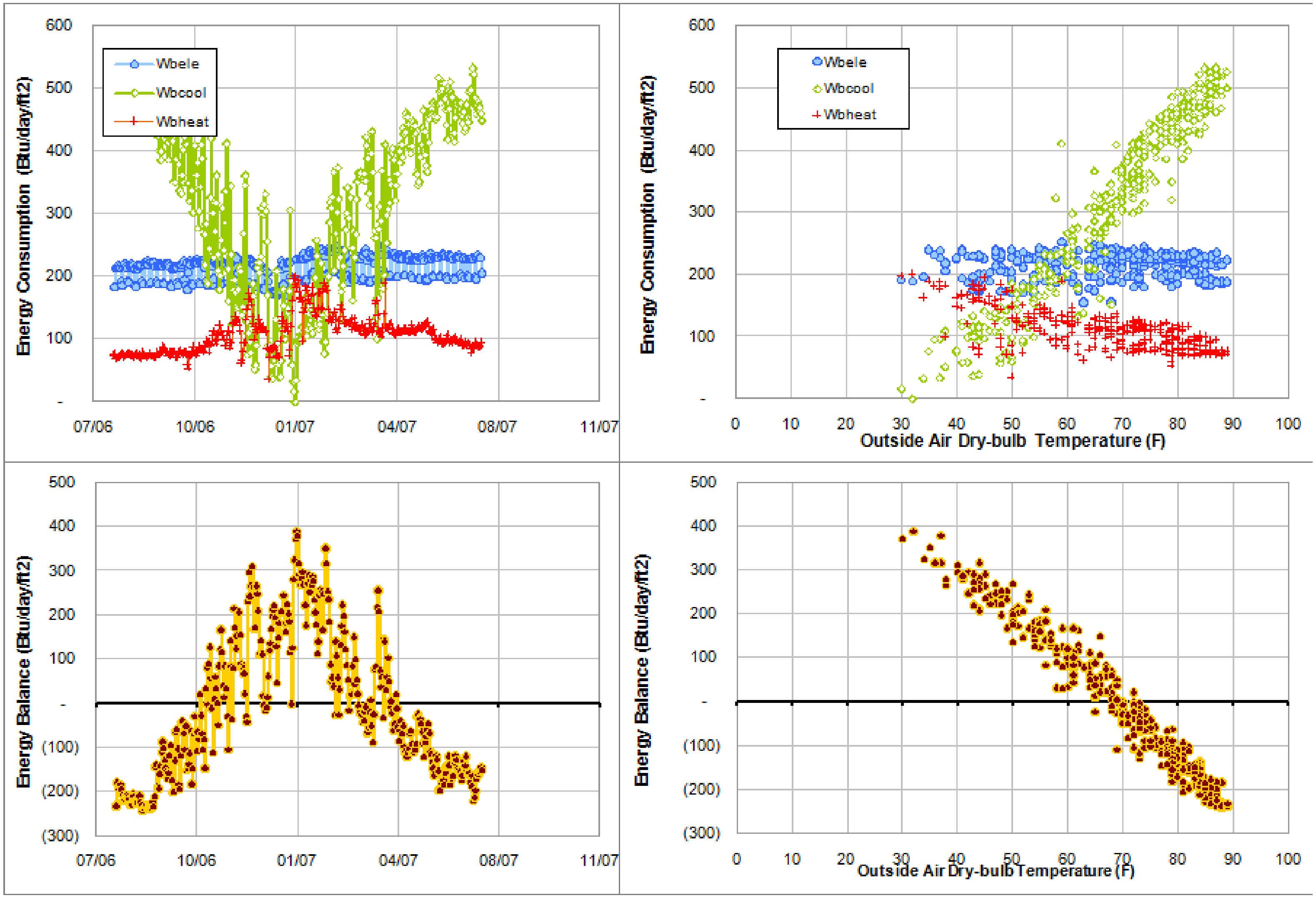


Figure D - 49. Energy balance plots for Koldus 2006-07 data.

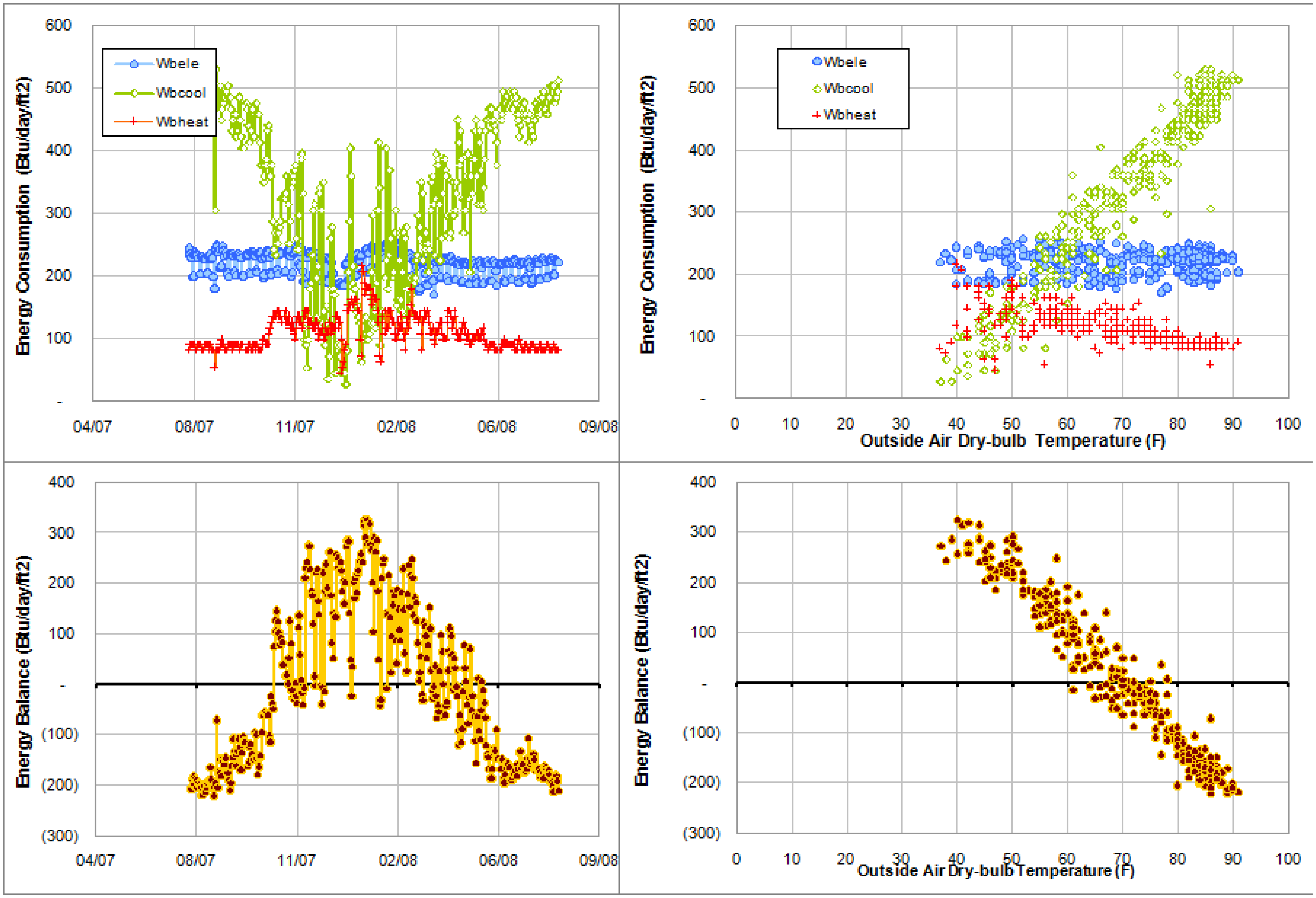


Figure D - 50. Energy balance plots for Koldus 2007-08 data.

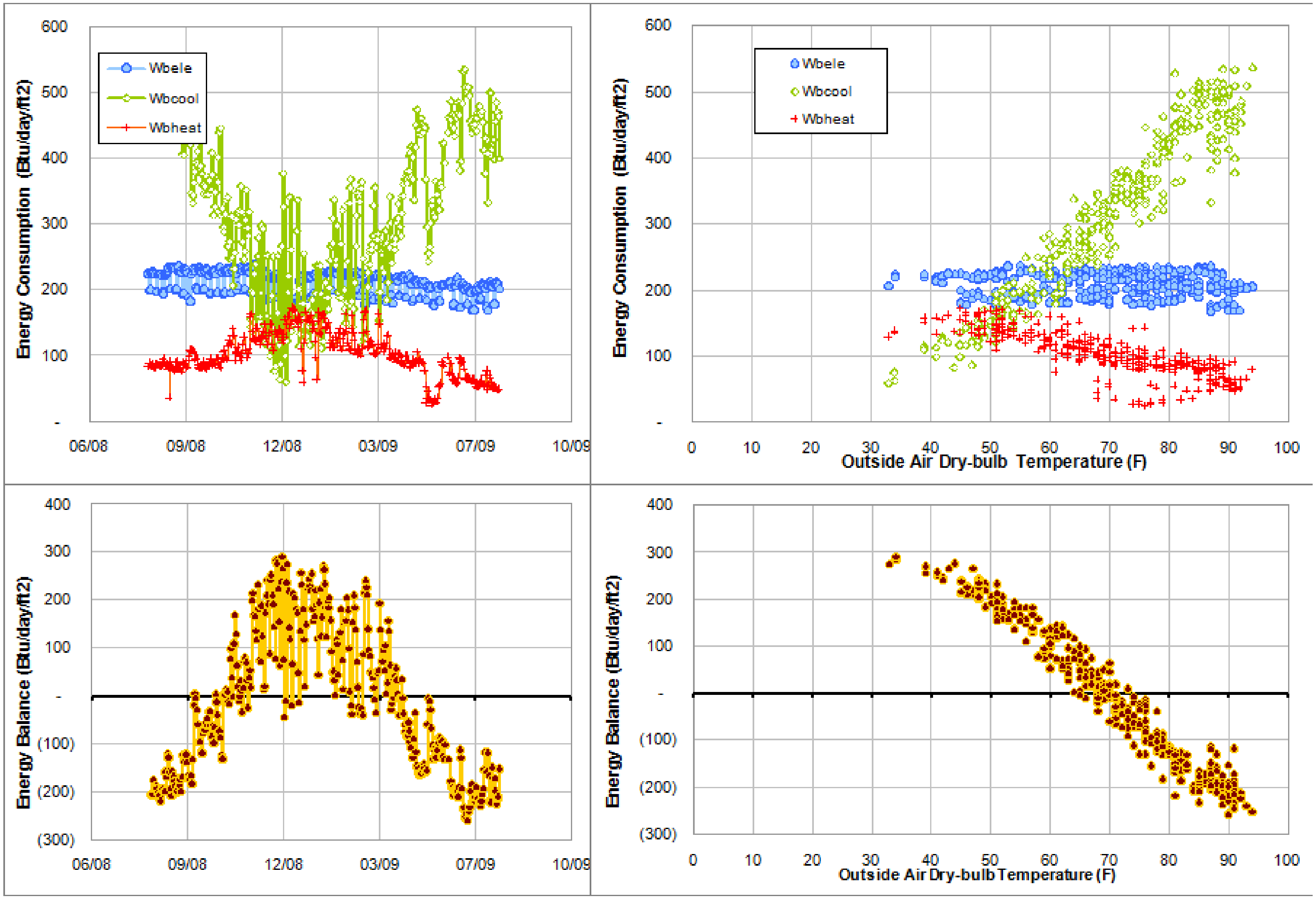


Figure D - 51. Energy balance plots for Koldus 2008-09 data.

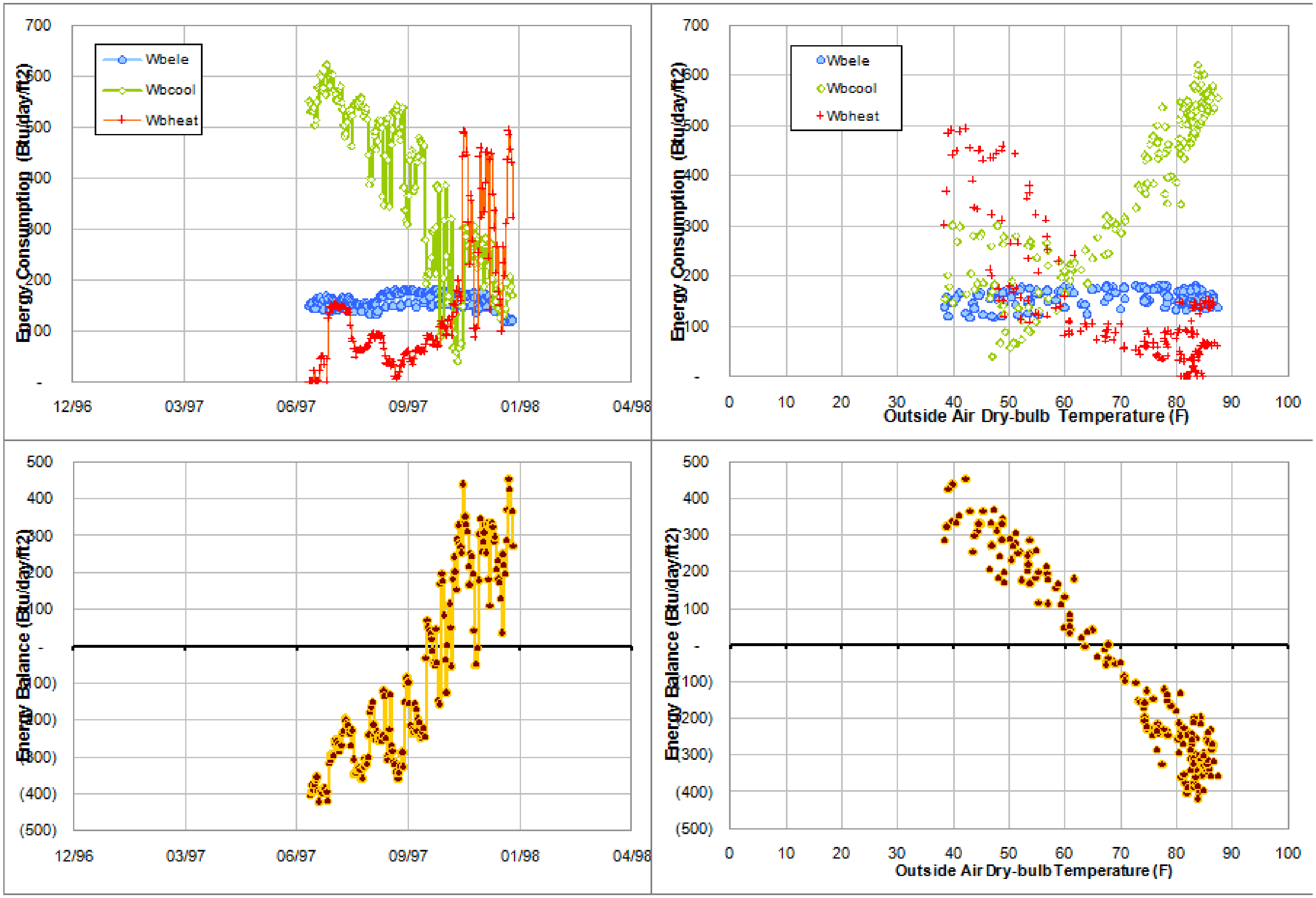


Figure D - 52. Energy balance plots for Richardson 1997 data.

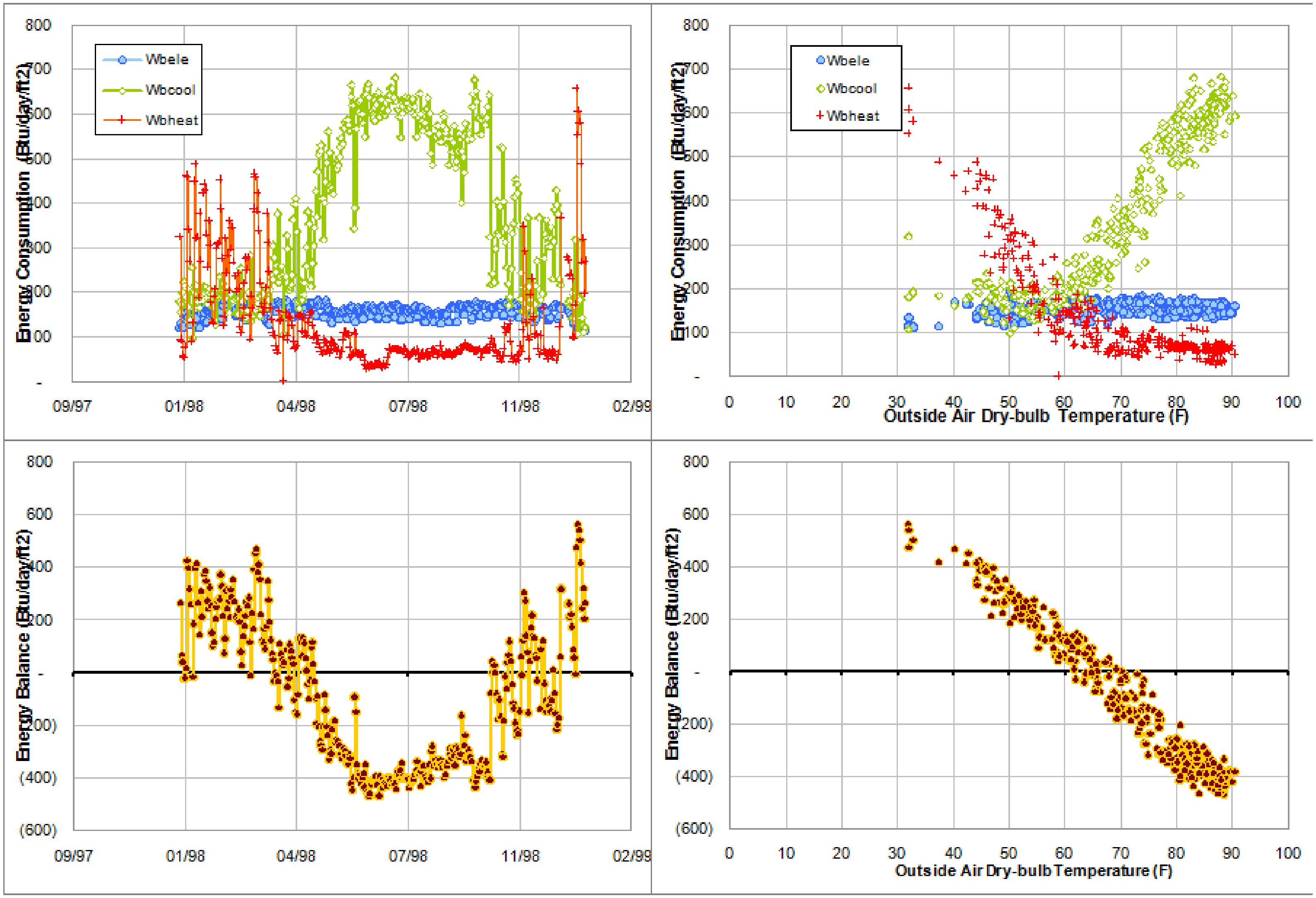


Figure D - 53. Energy balance plots for Richardson 1998 data.

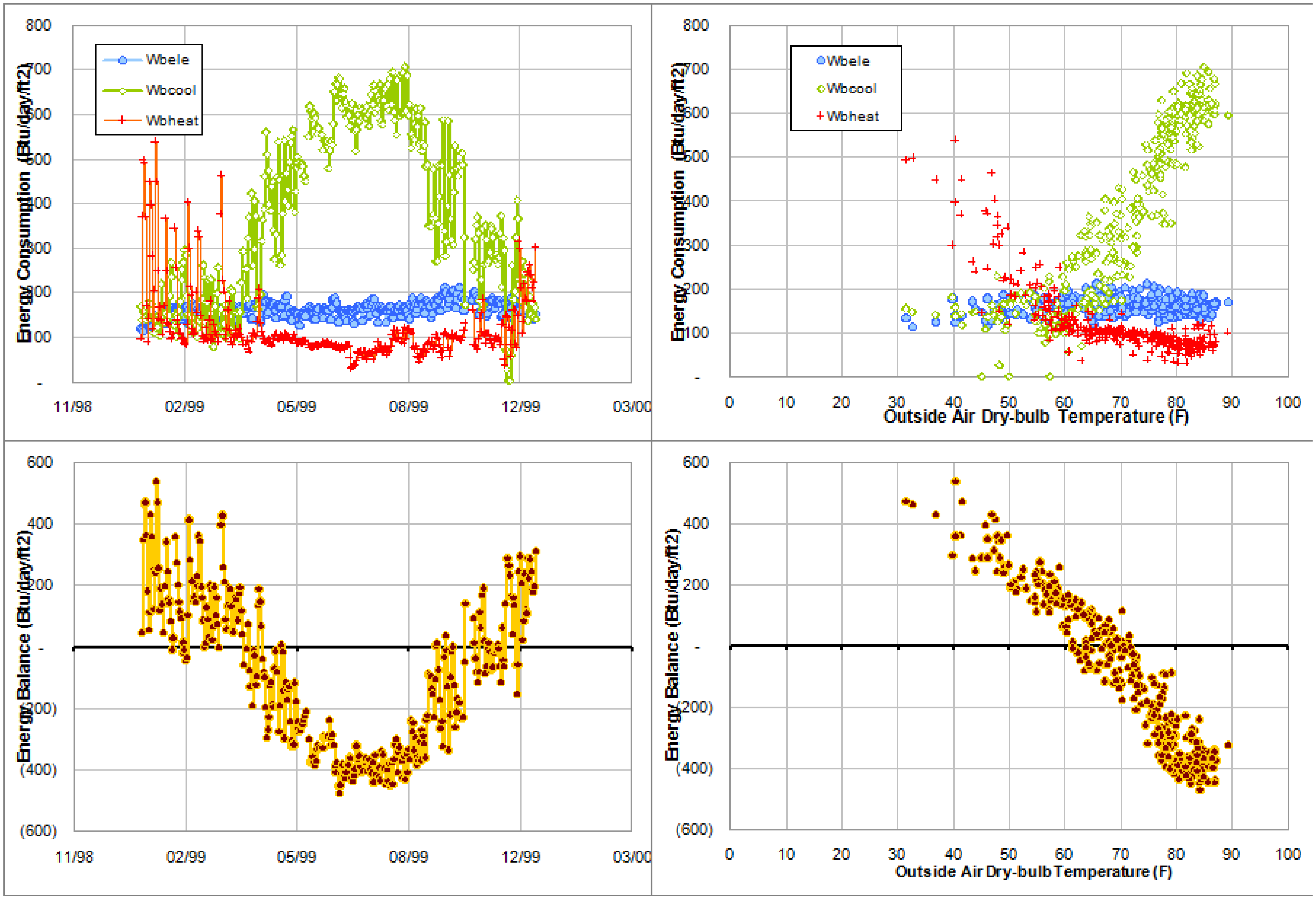


Figure D - 54. Energy balance plots for Richardson 1999 data.

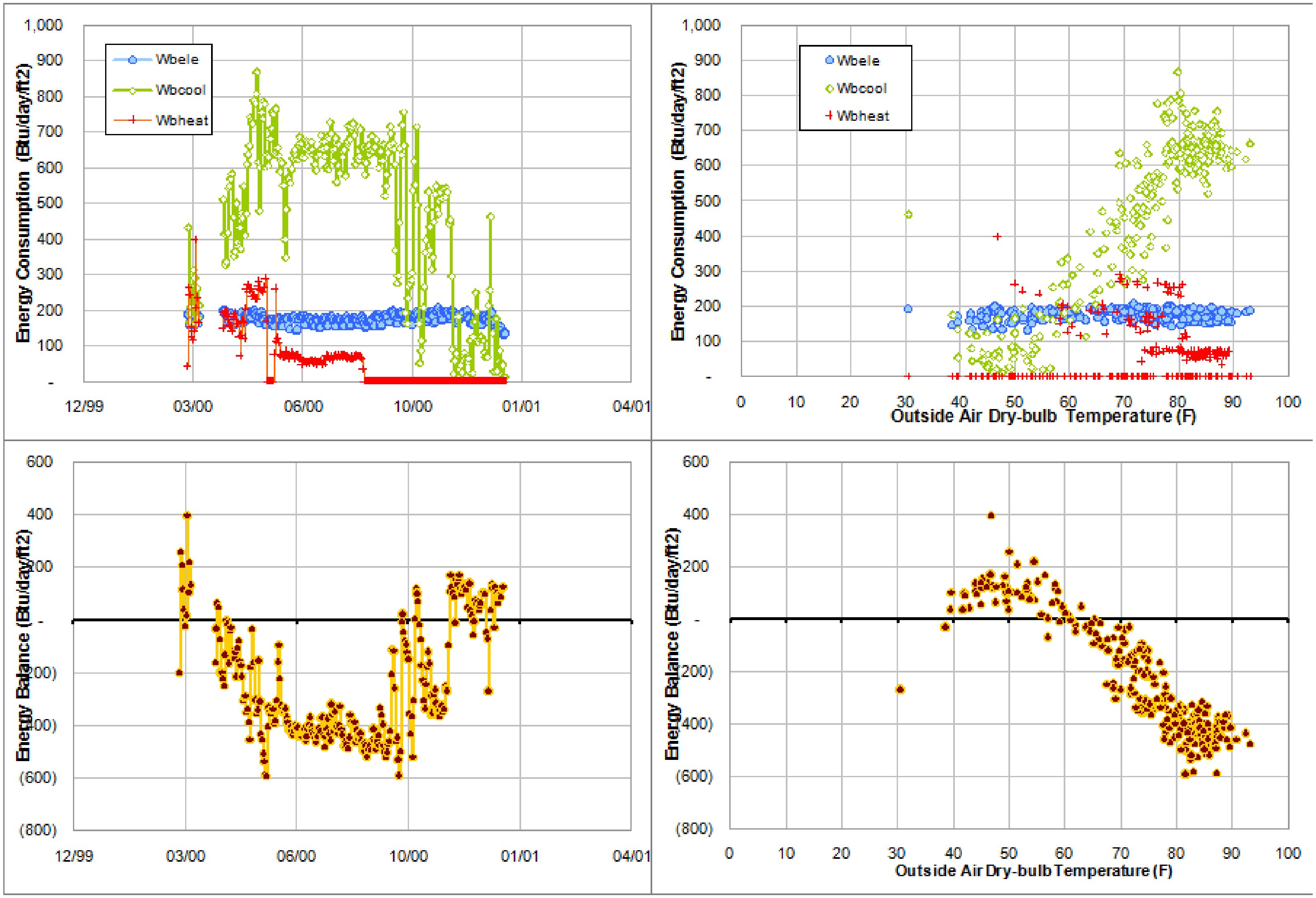


Figure D - 55. Energy balance plots for Richardson 2000 data.

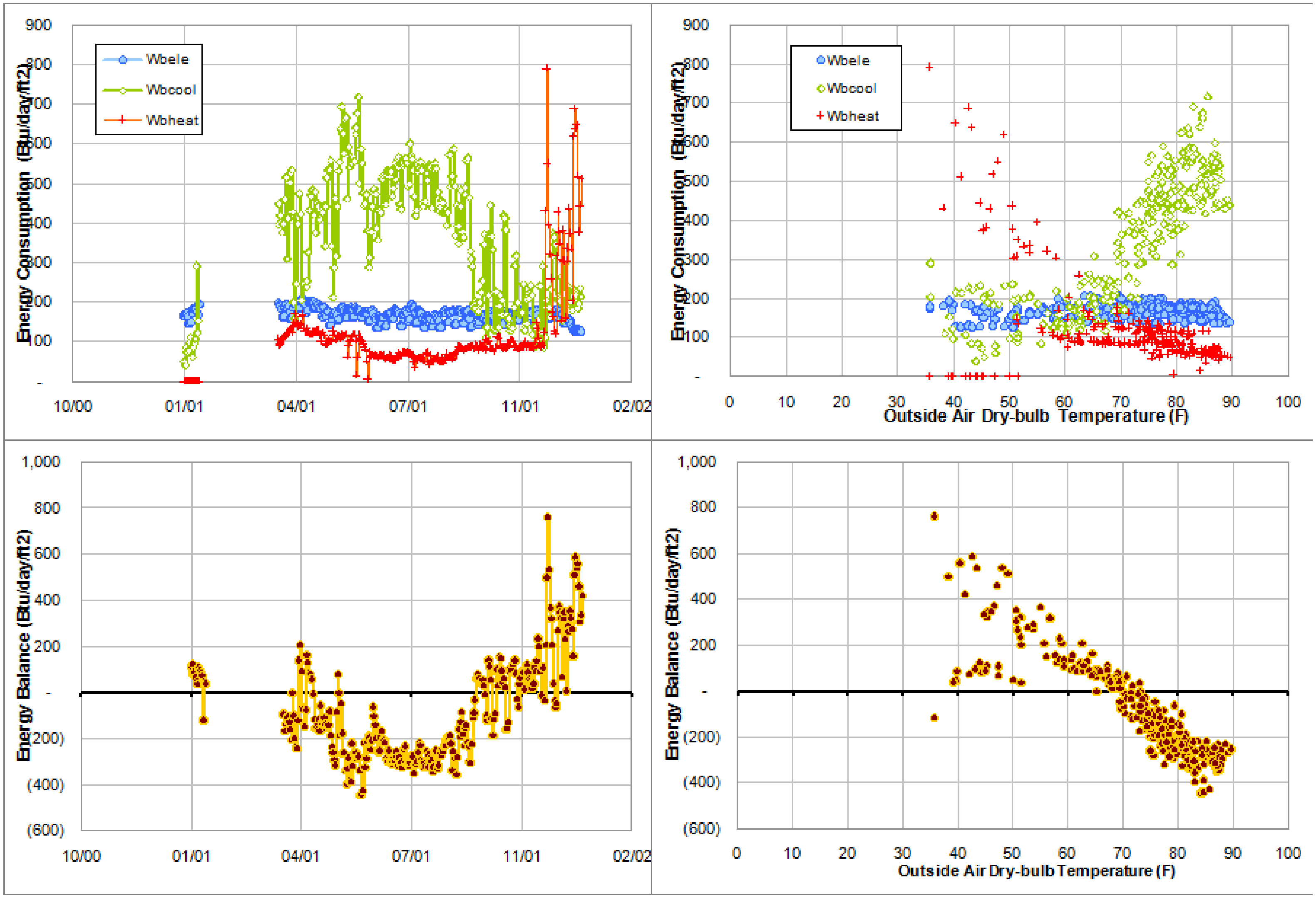


Figure D - 56. Energy balance plots for Richardson 2001 data.

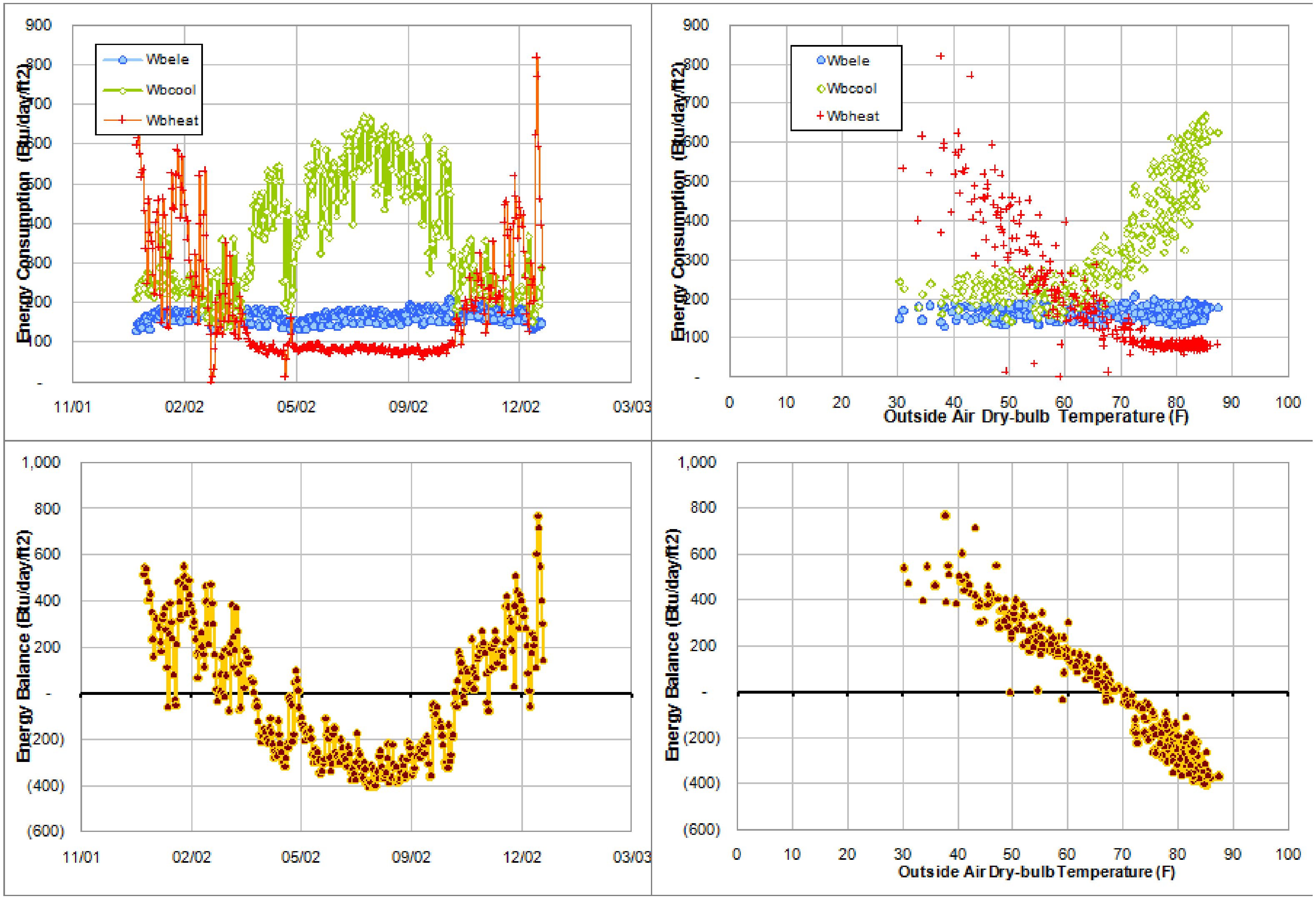


Figure D - 57. Energy balance plots for Richardson 2002 data.

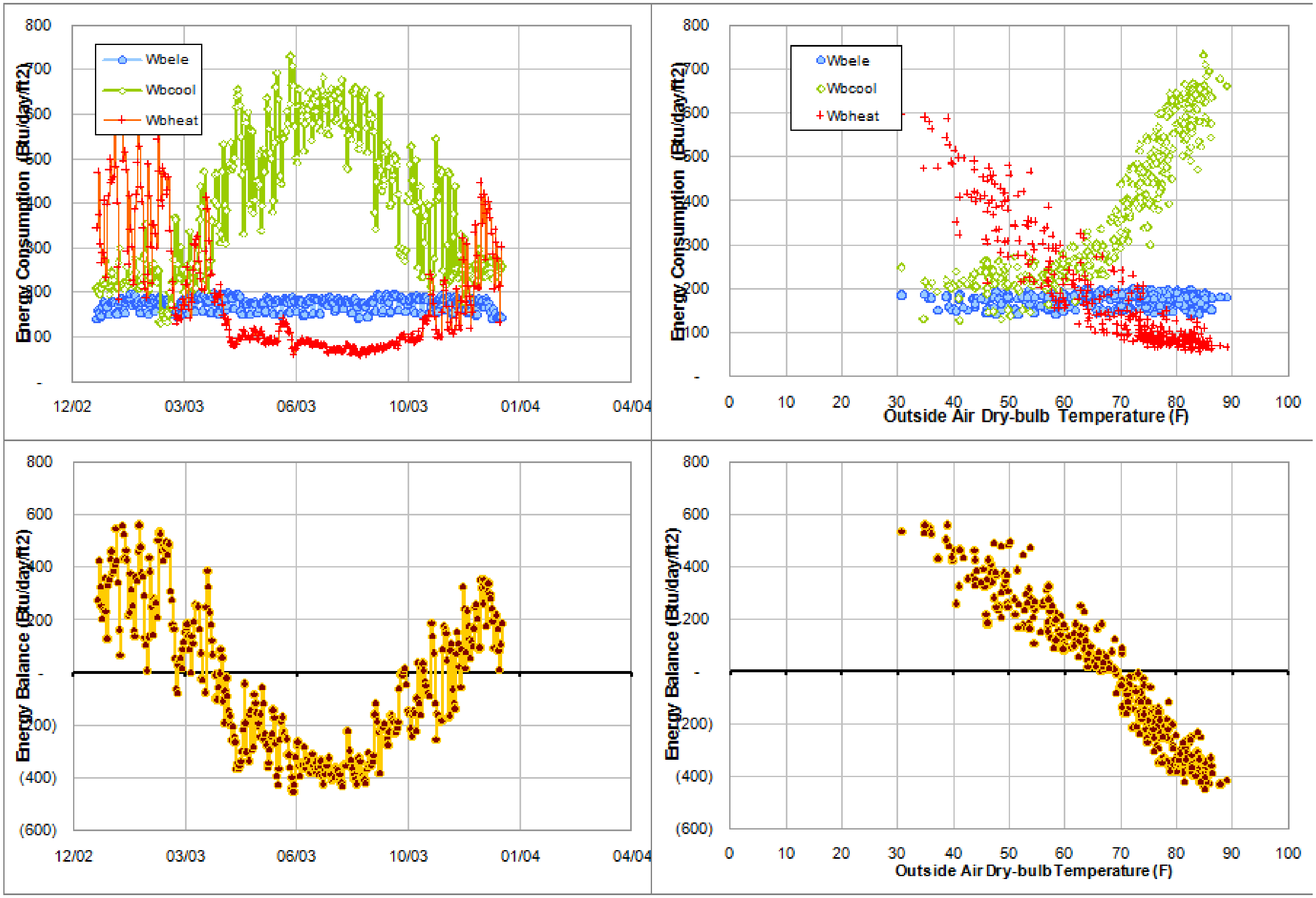


Figure D - 58. Energy balance plots for Richardson 2003 data.

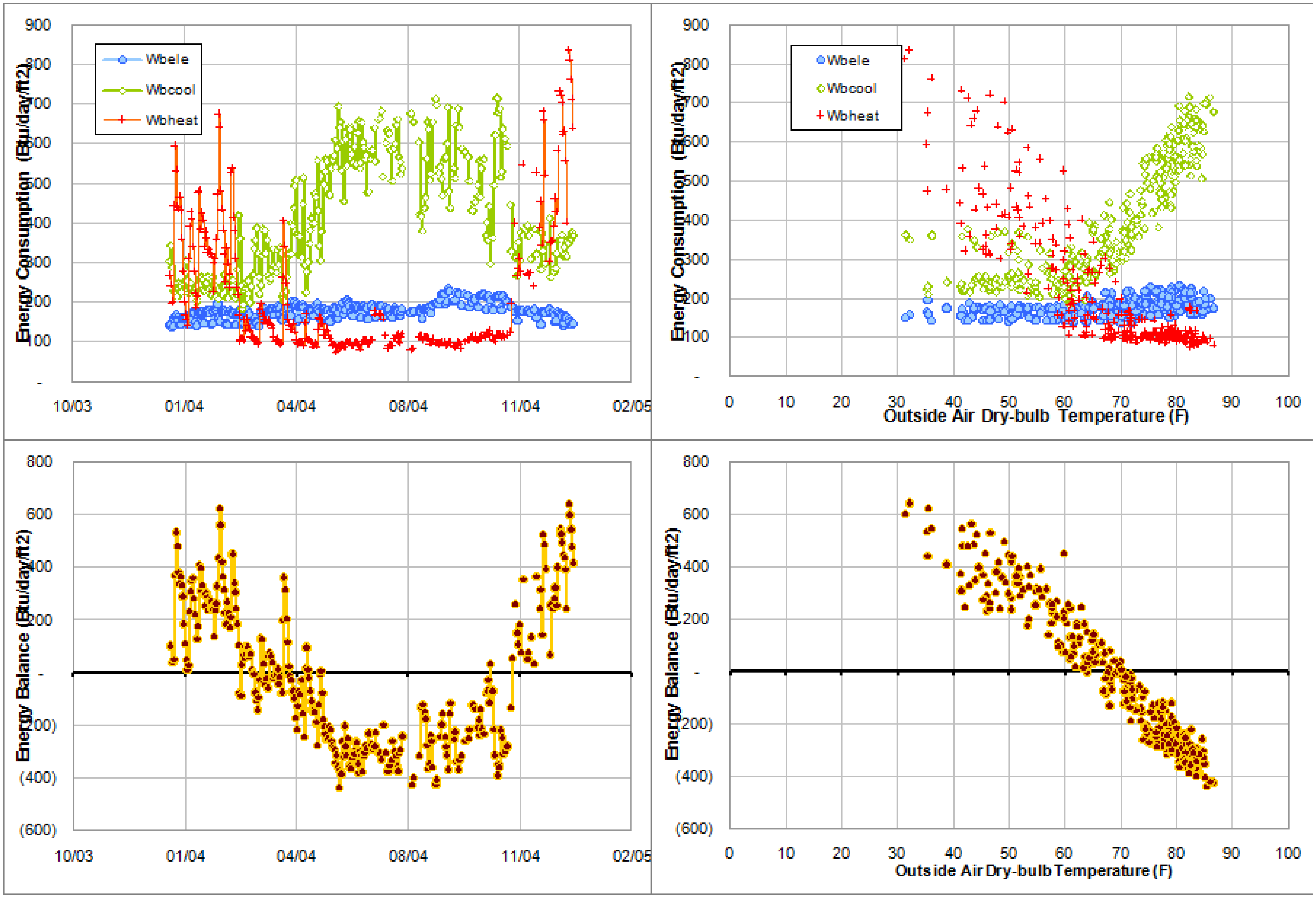


Figure D - 59. Energy balance plots for Richardson 2004 data.

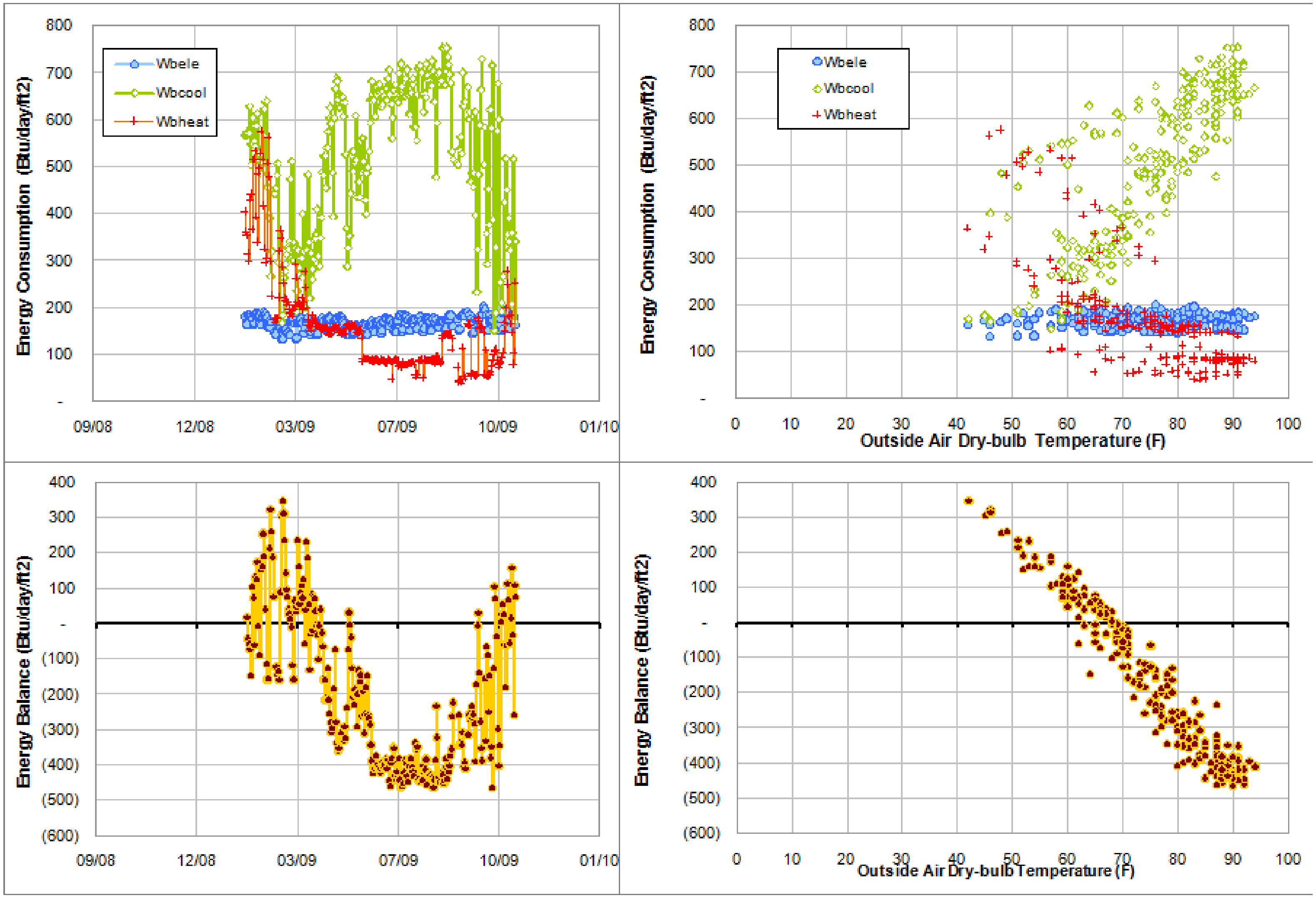


Figure D - 60. Energy balance plots for Richardson 2009 data.

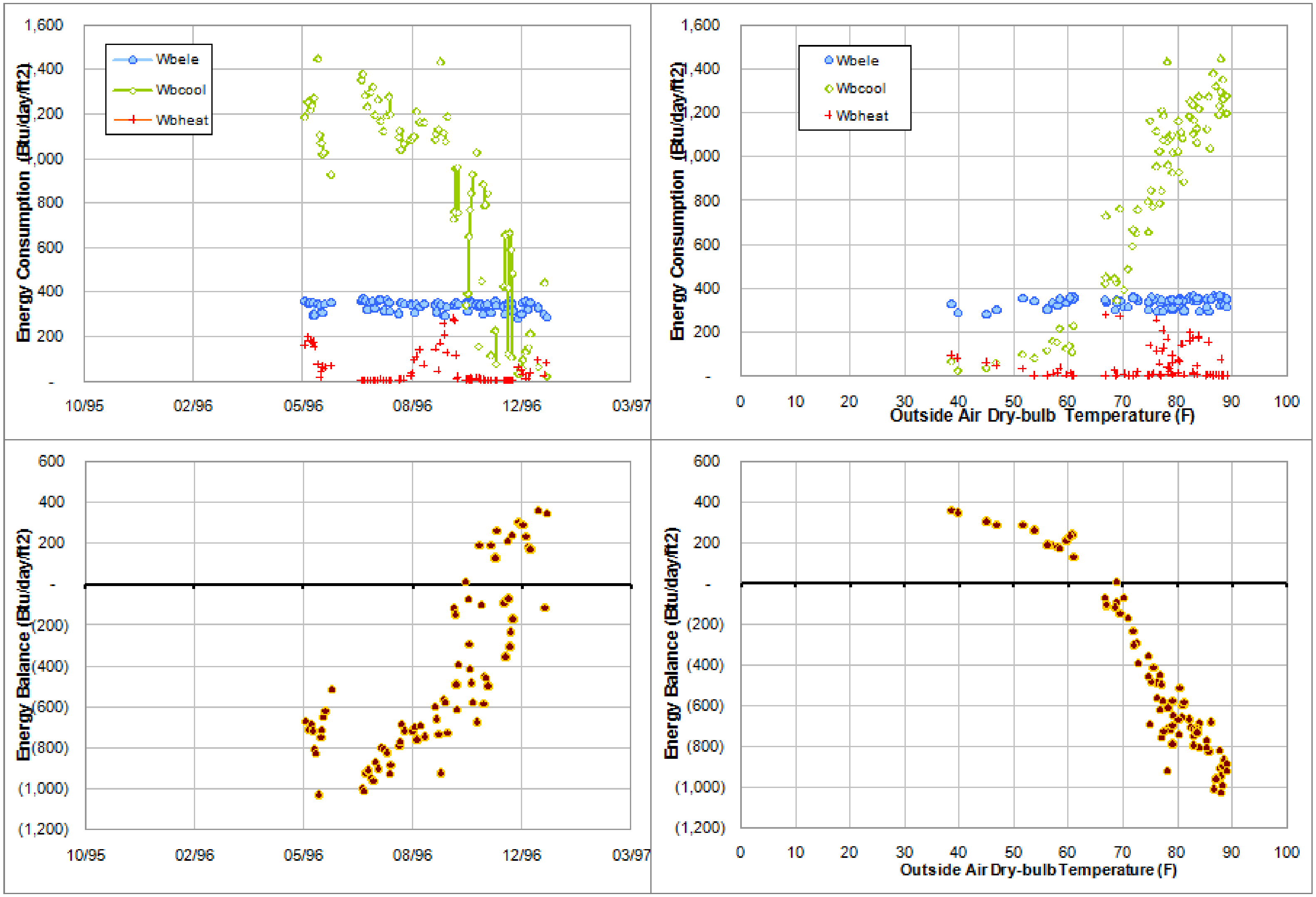


Figure D - 61. Energy balance plots for VMCA 1996 data.

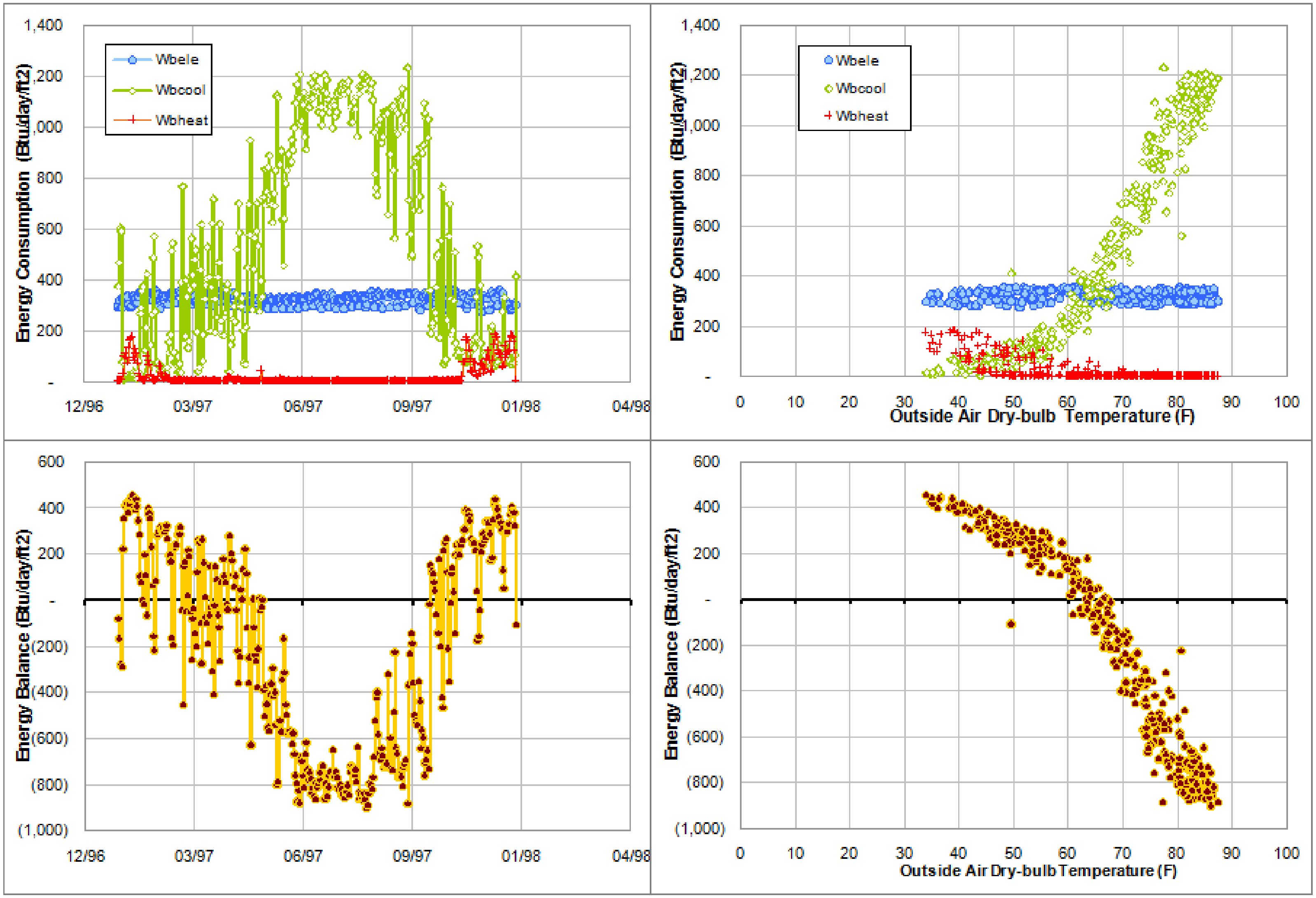


Figure D - 62. Energy balance plots for VMCA 1997 data.

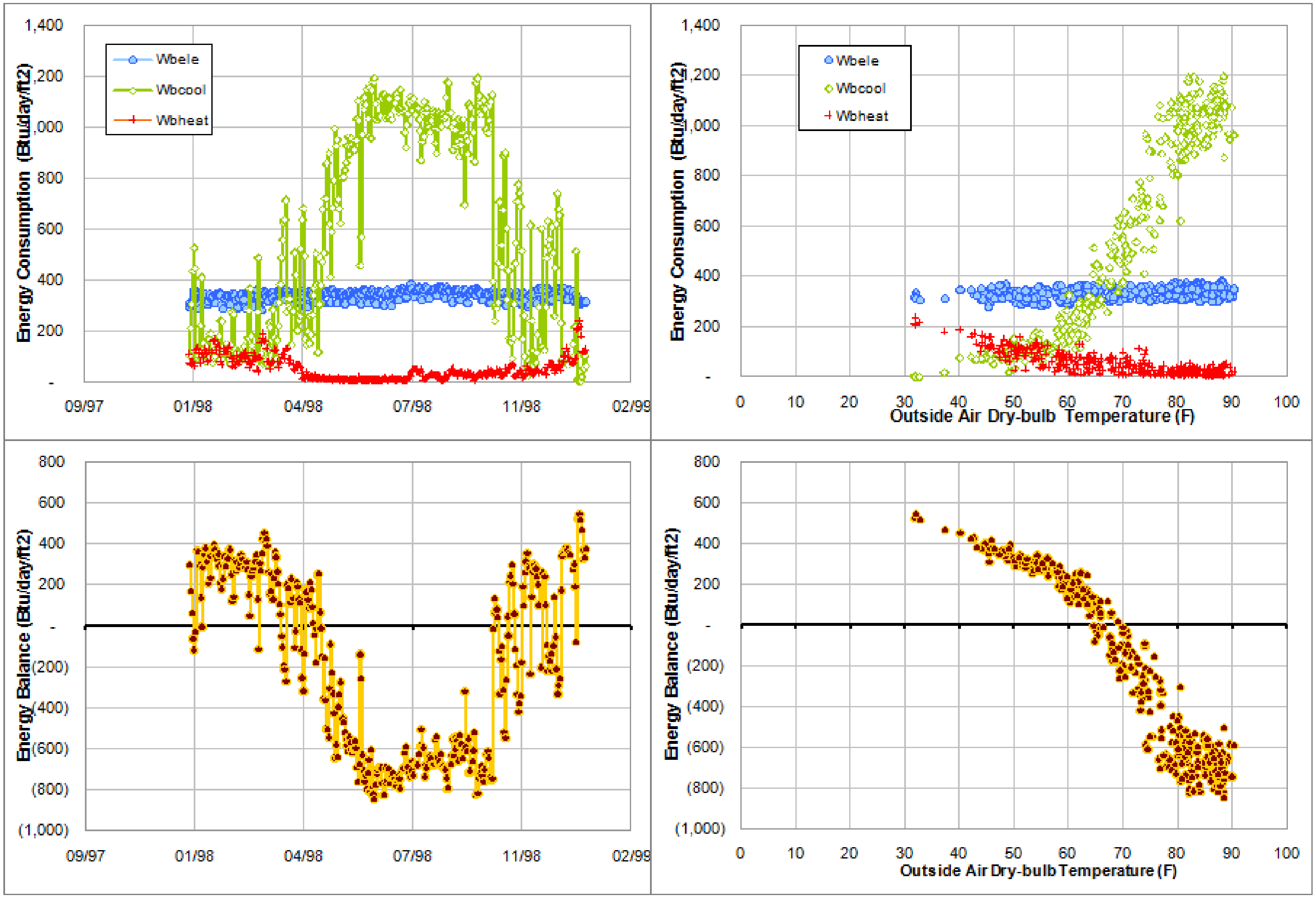


Figure D - 63. Energy balance plots for VMCA 1998 data.

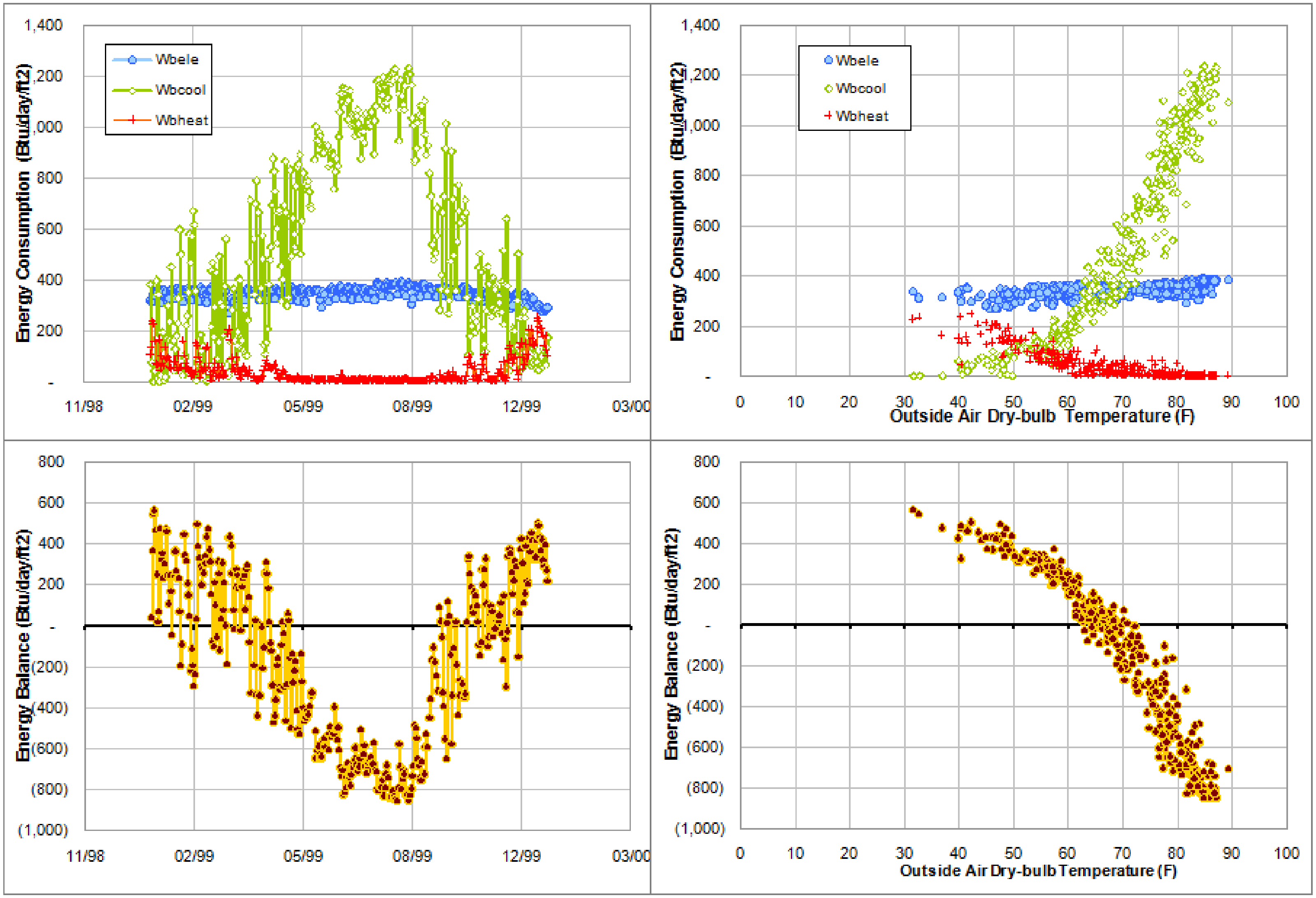


Figure D - 64. Energy balance plots for VMCA 1999 data.

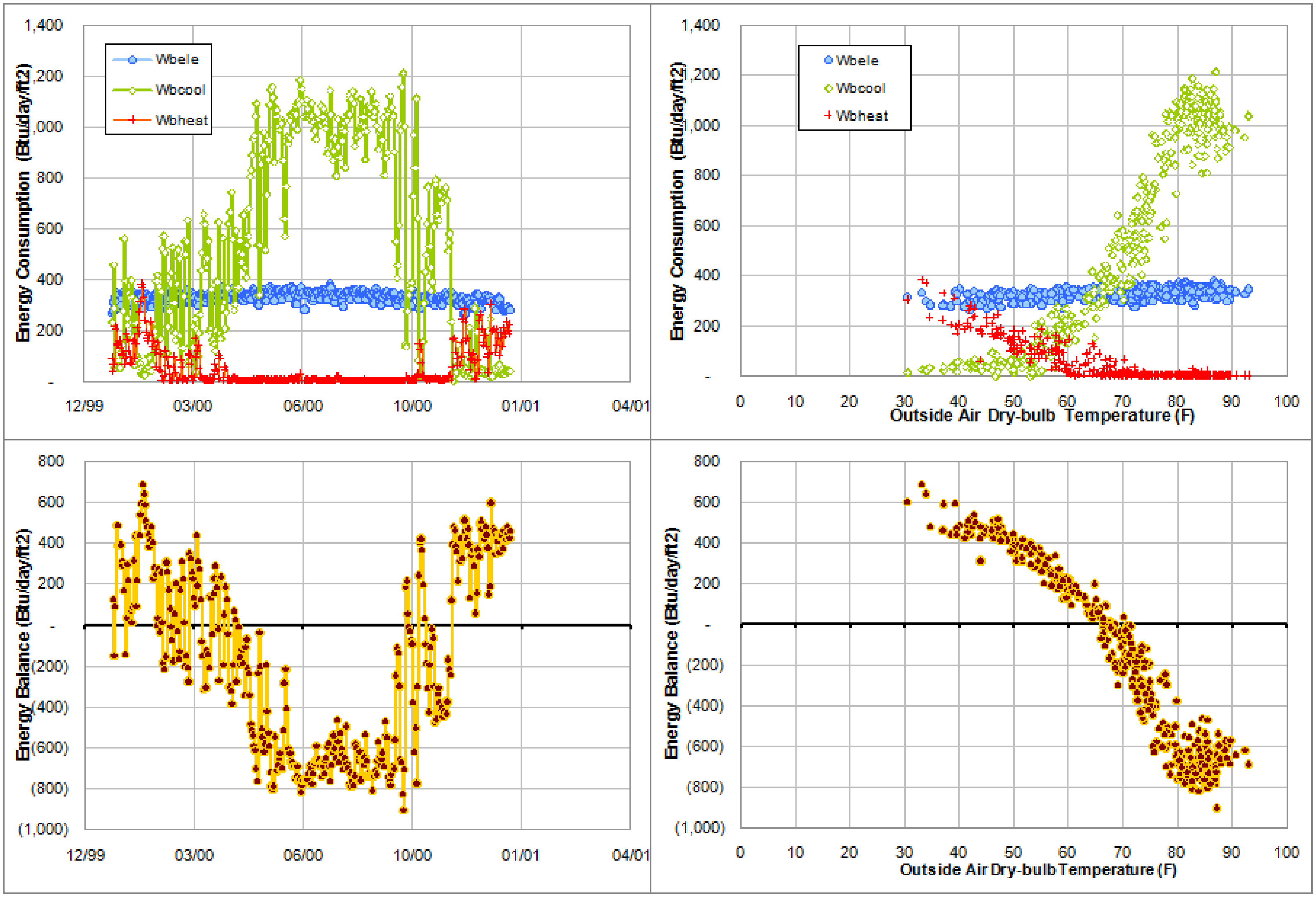


Figure D - 65. Energy balance plots for VMCA 2000 data.

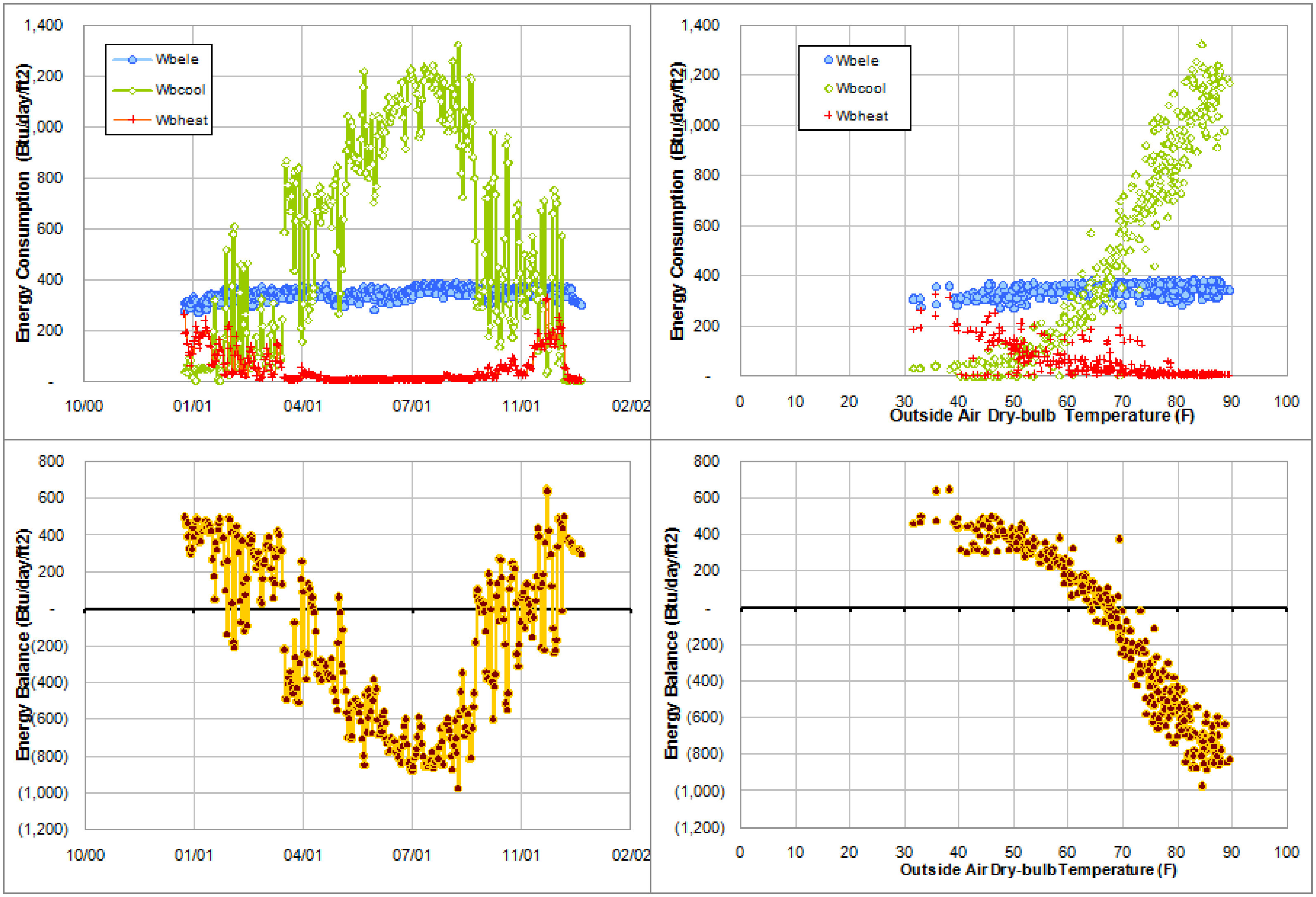


Figure D - 66. Energy balance plots for VMCA 2001 data.

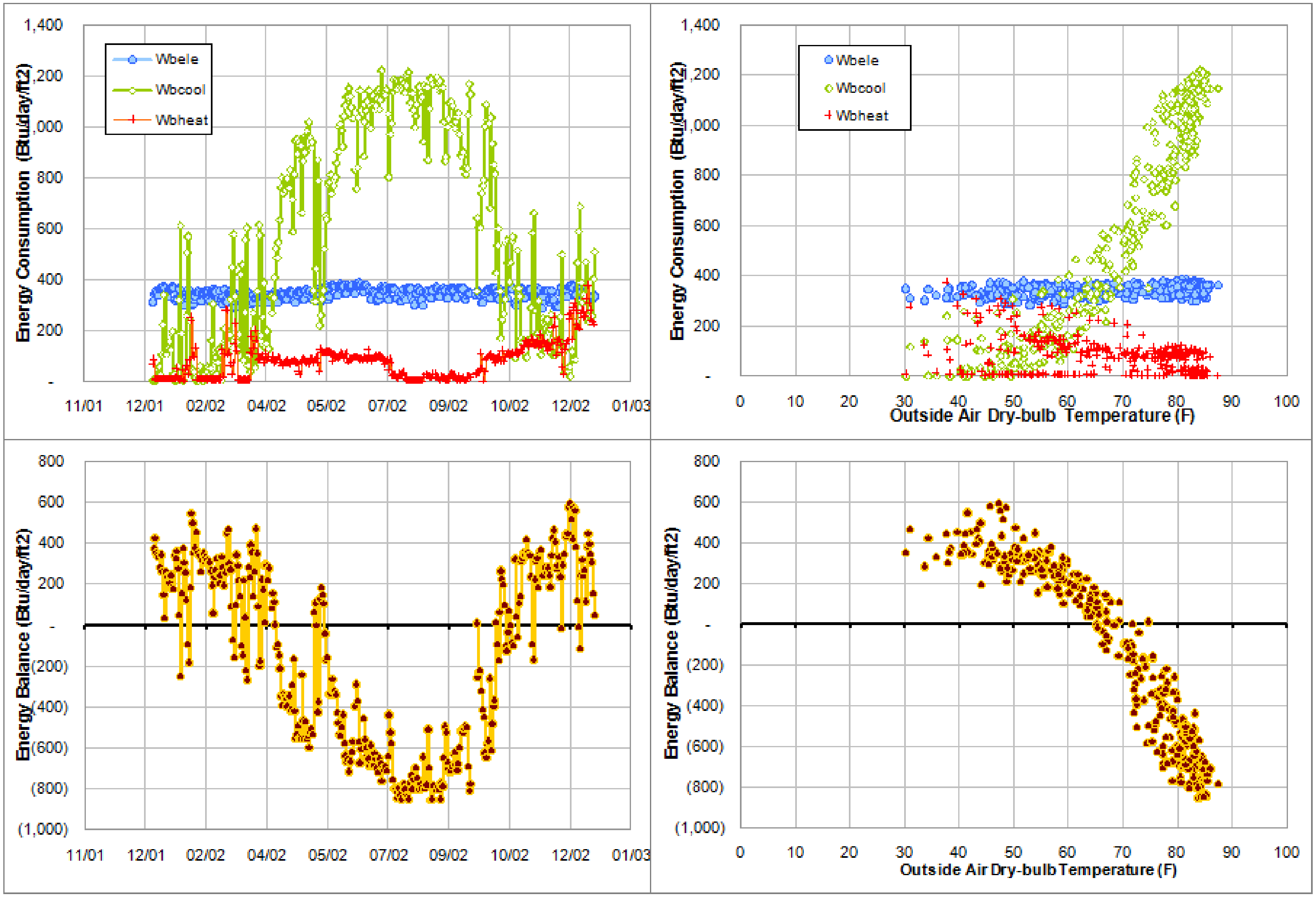


Figure D - 67. Energy balance plots for VMCA 2002 data.

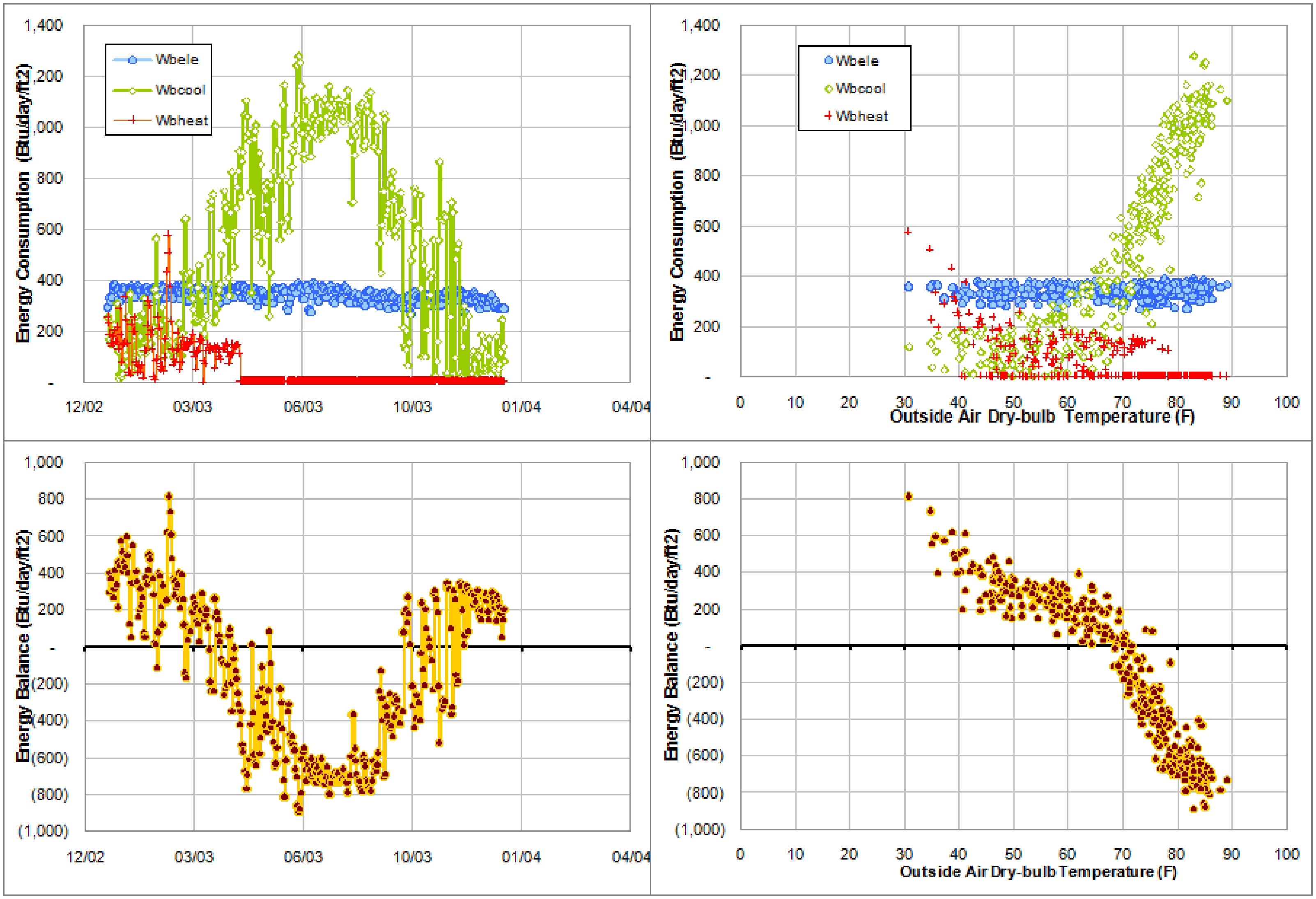


Figure D - 68. Energy balance plots for VMCA 2003 data.

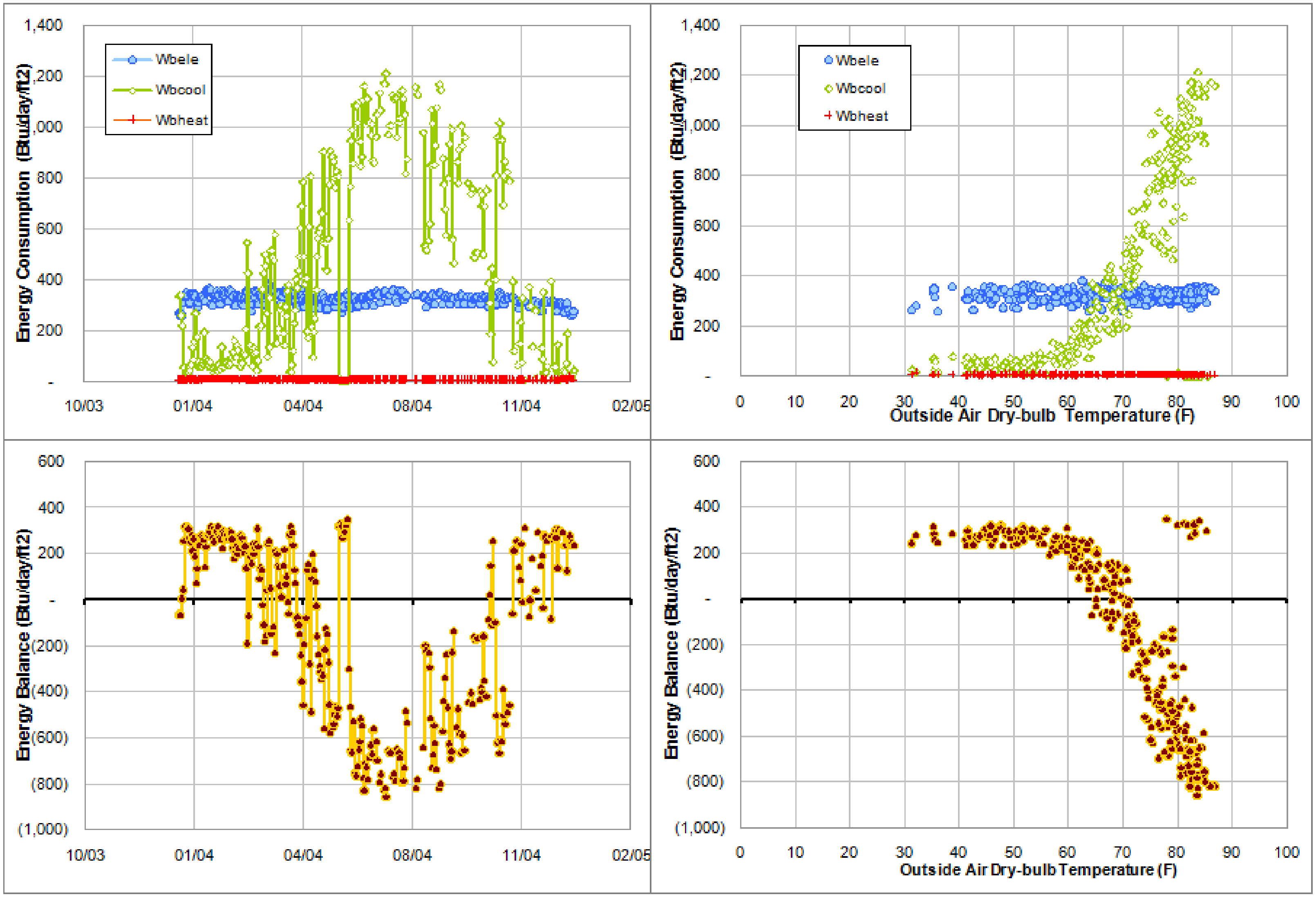


Figure D - 69. Energy balance plots for VMCA 2004 data.

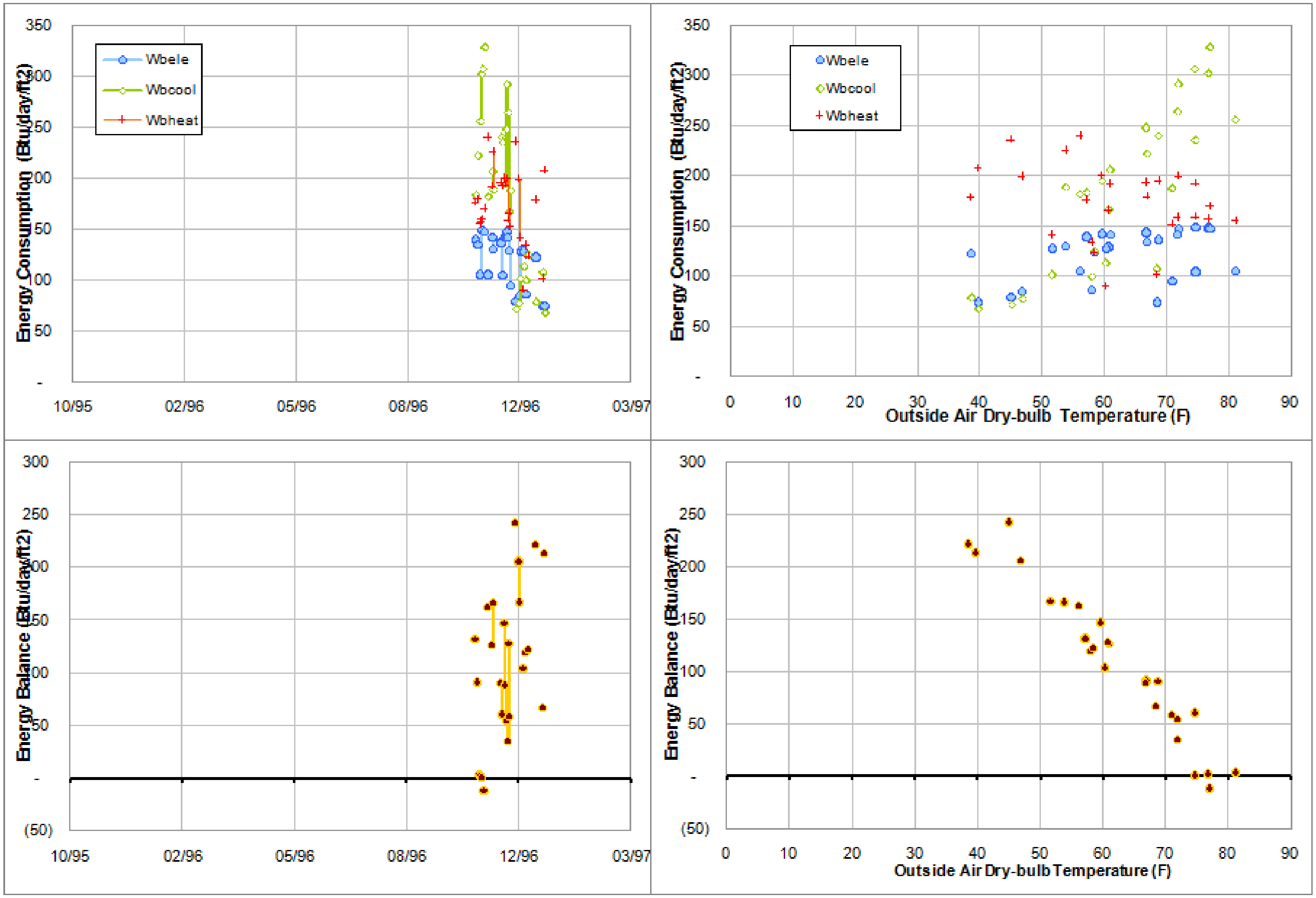


Figure D - 70. Energy balance plots for Wehner 1996 data.

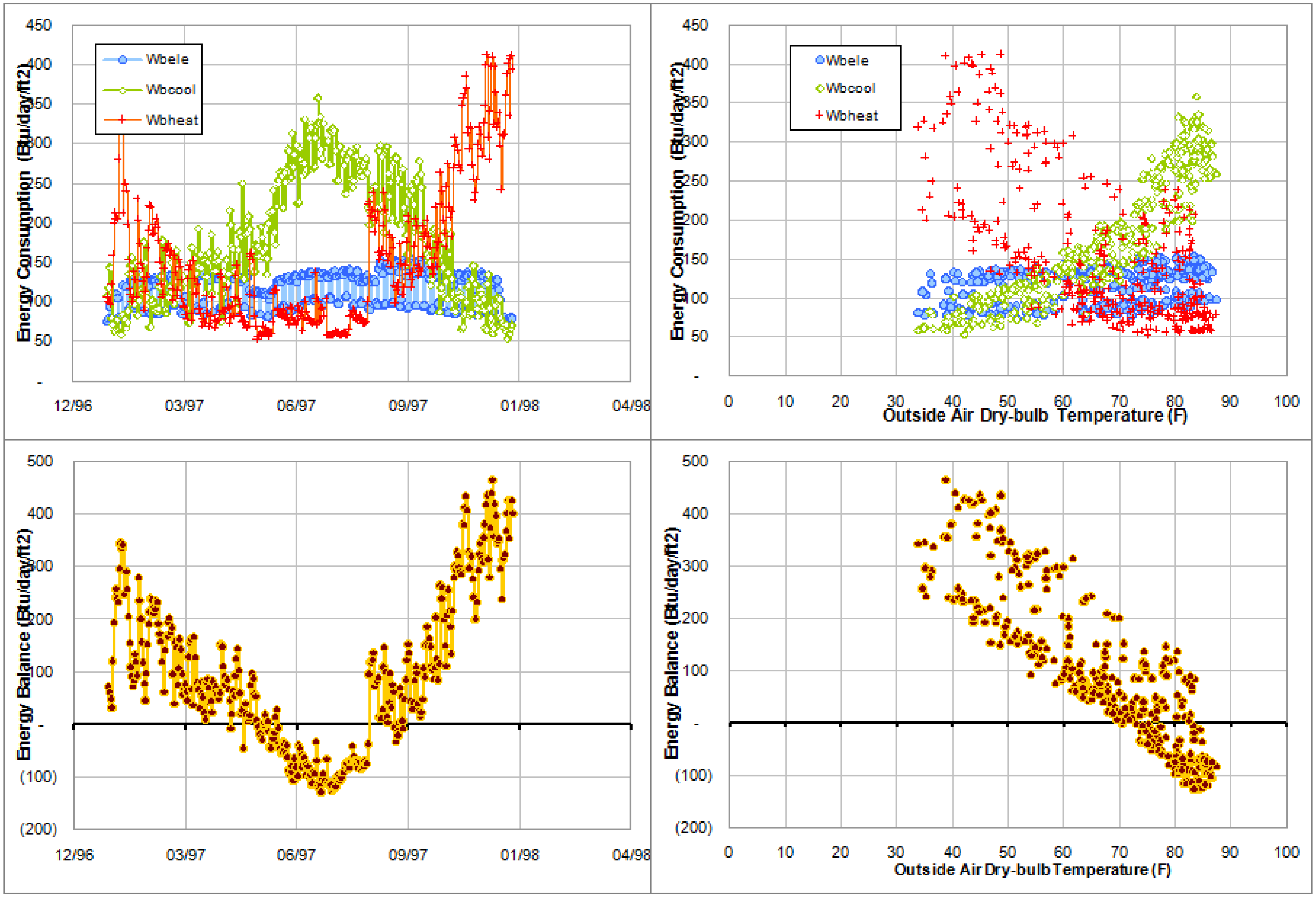


Figure D - 71. Energy balance plots for Wehner 1997 data.

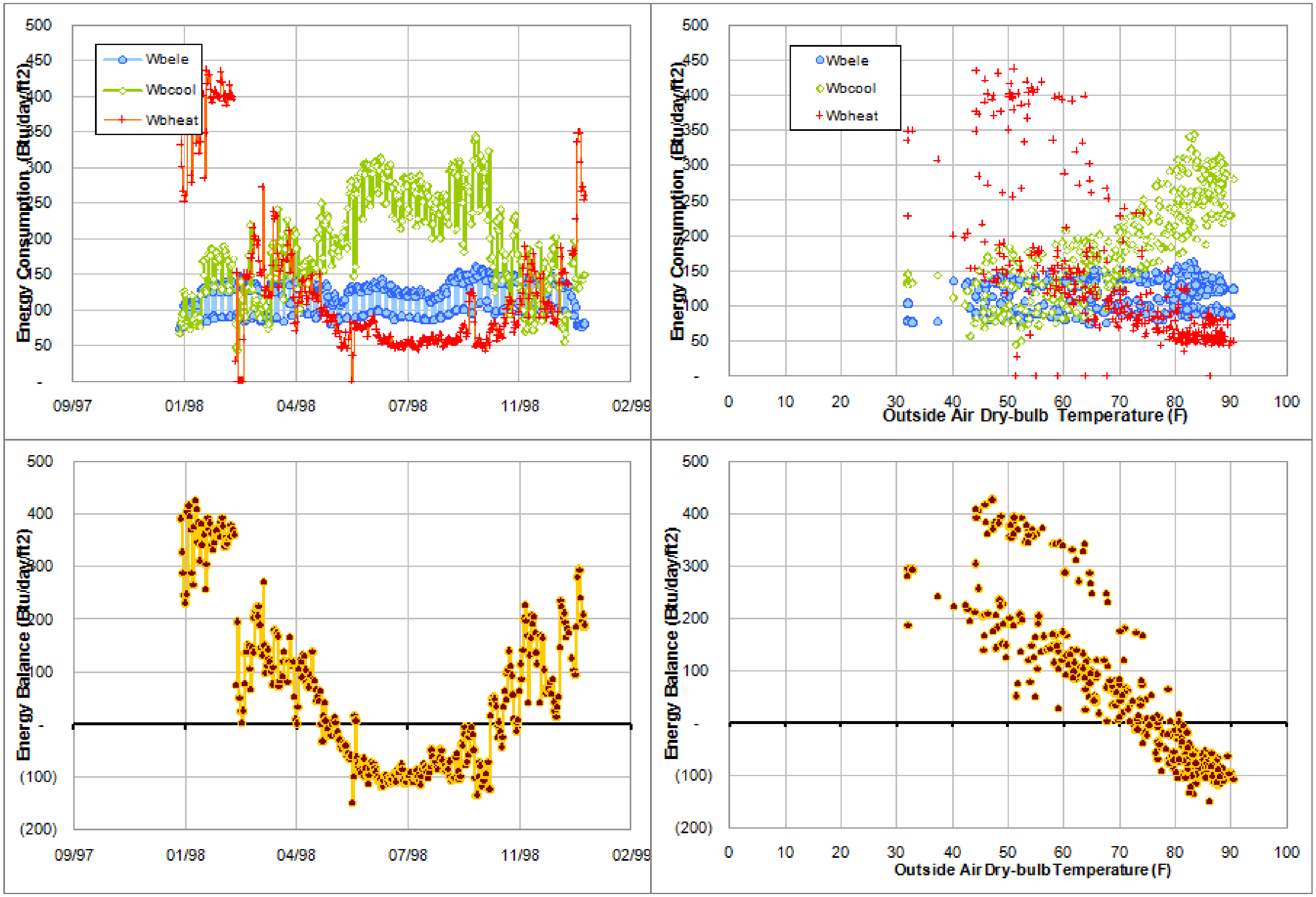


Figure D - 72. Energy balance plots for Wehner 1998 data.

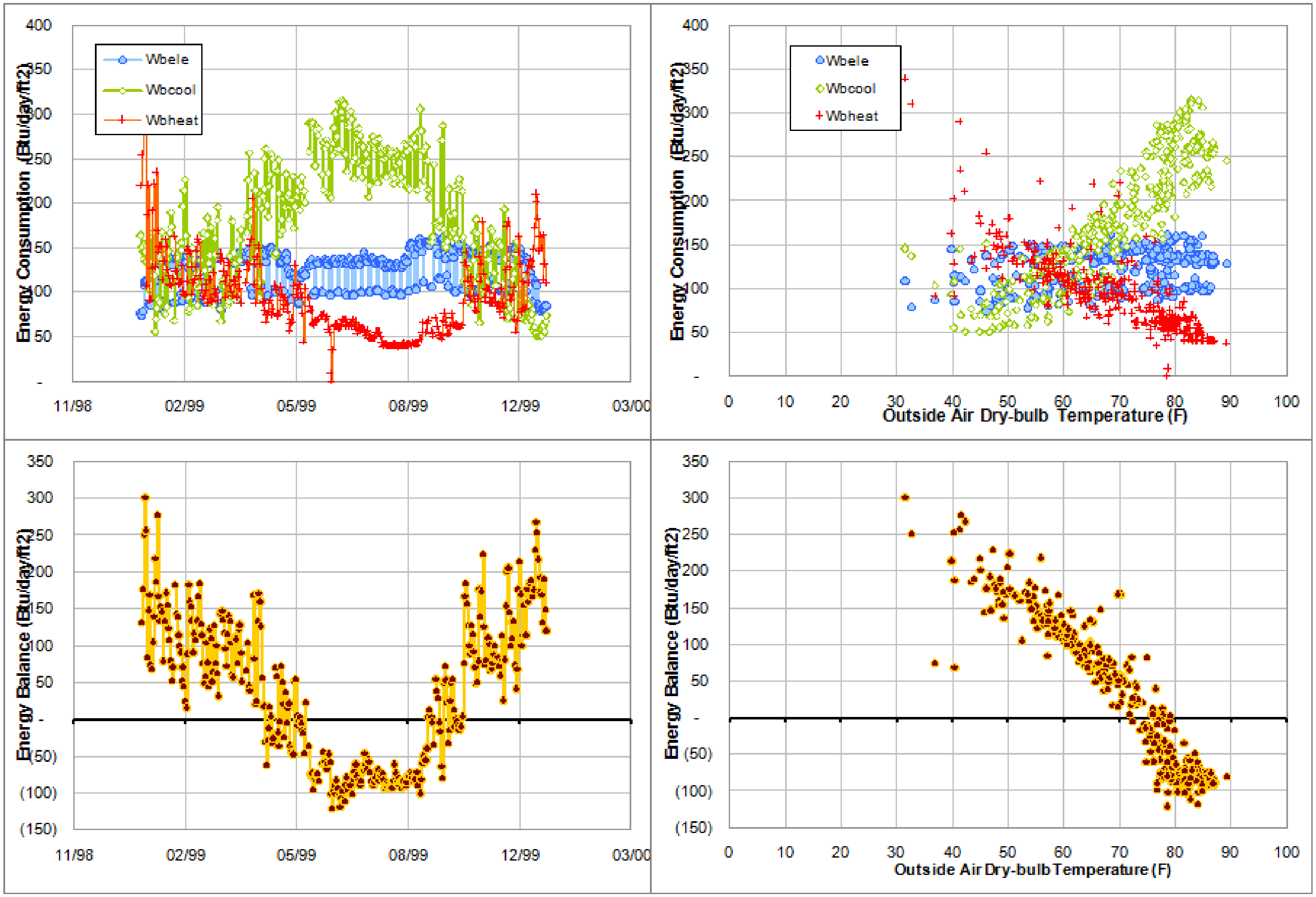


Figure D - 73. Energy balance plots for Wehner 1999 data.

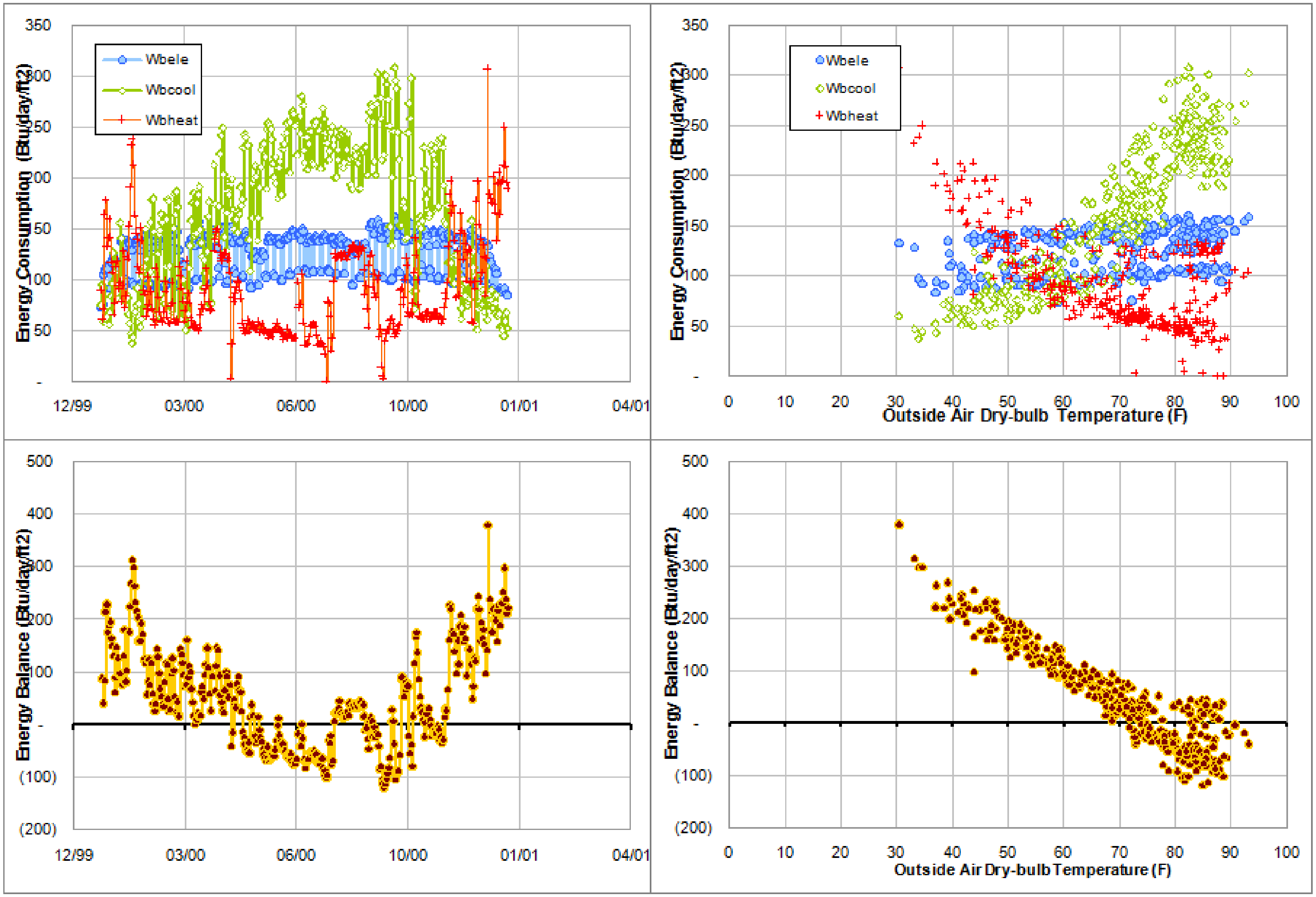


Figure D - 74. Energy balance plots for Wehner 2000 data.

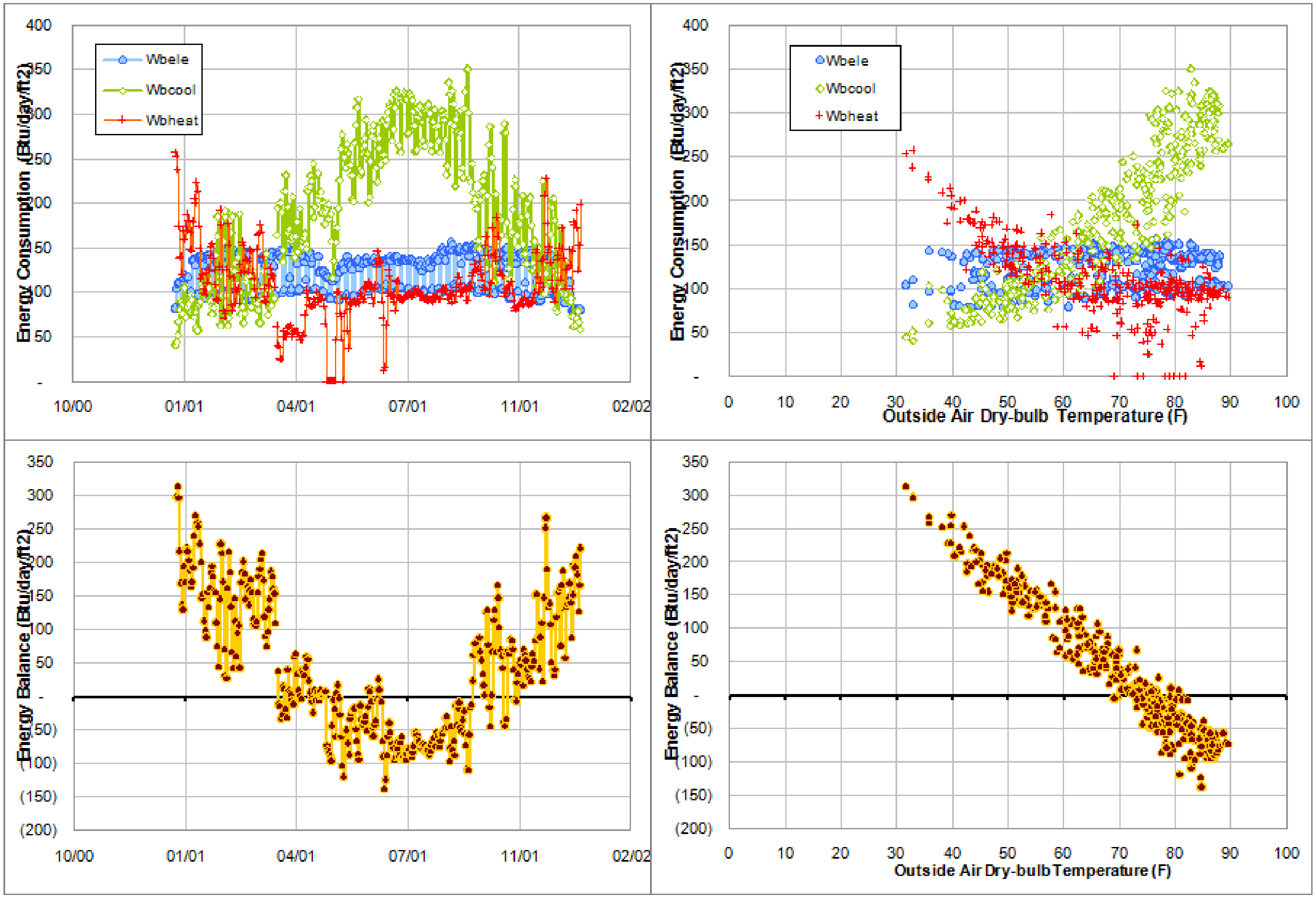


Figure D - 75. Energy balance plots for Wehner 2001 data.

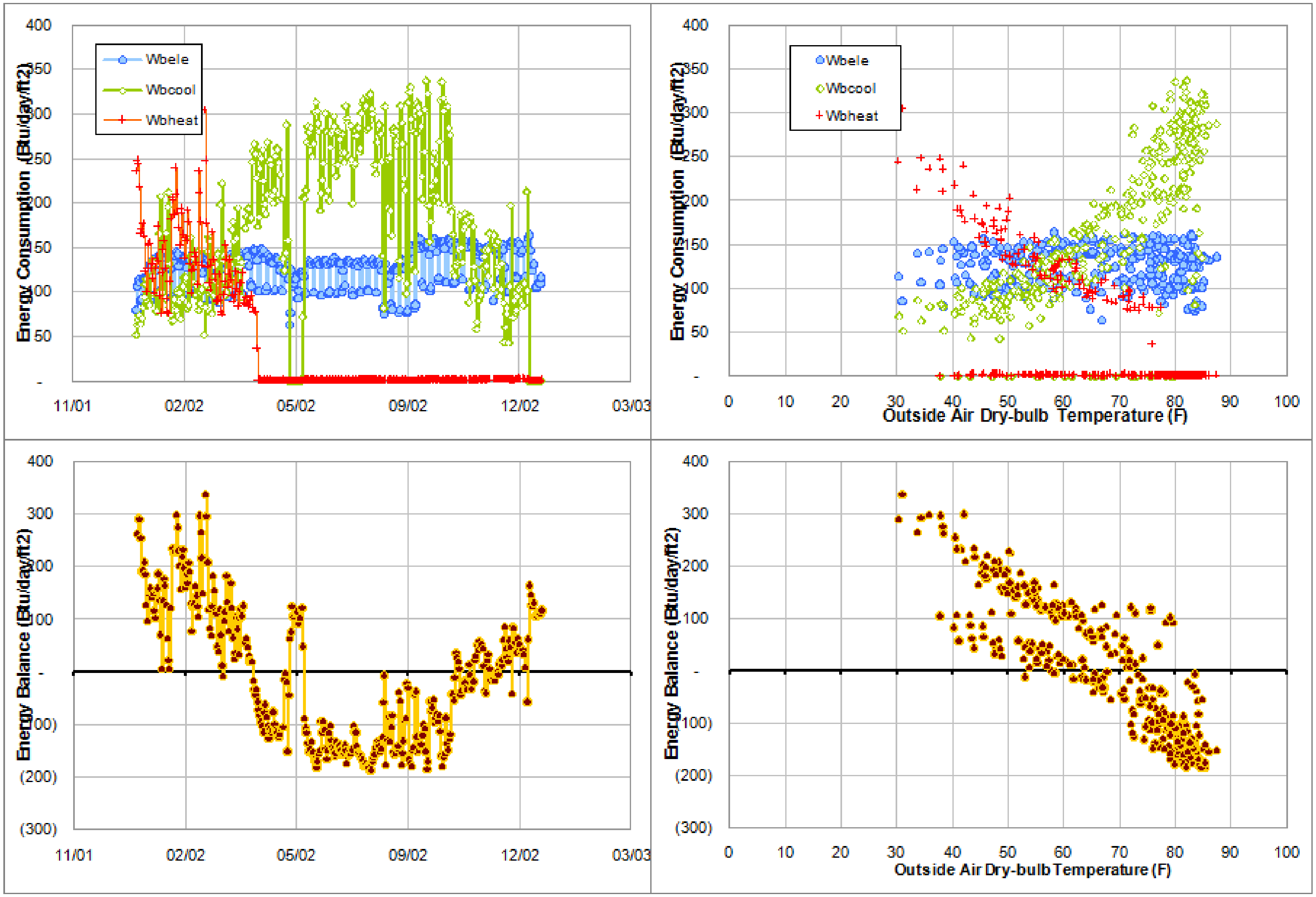


Figure D - 76. Energy balance plots for Wehner 2002 data.

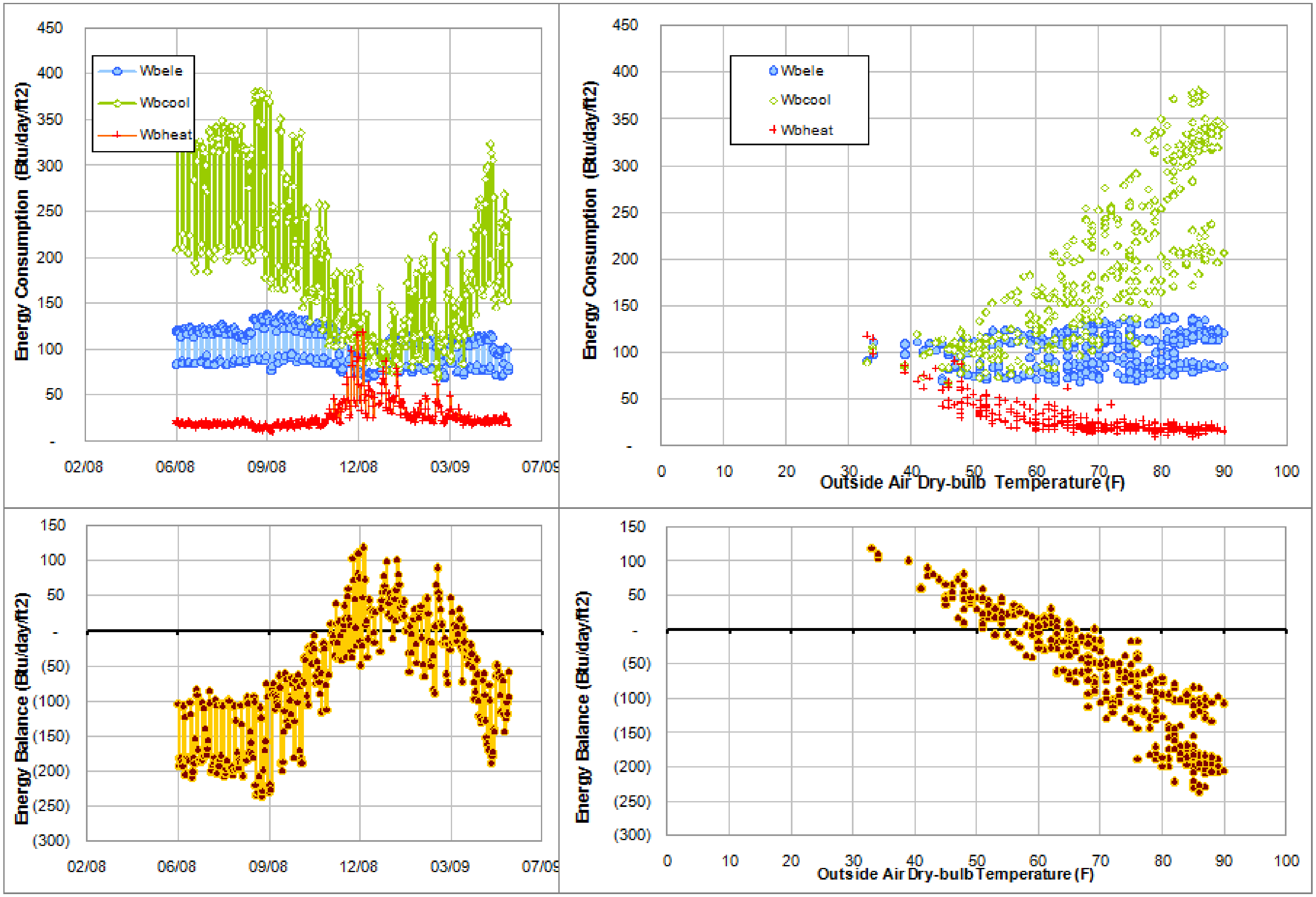


Figure D - 77. Energy balance plots for Wehner 2008-09 data.

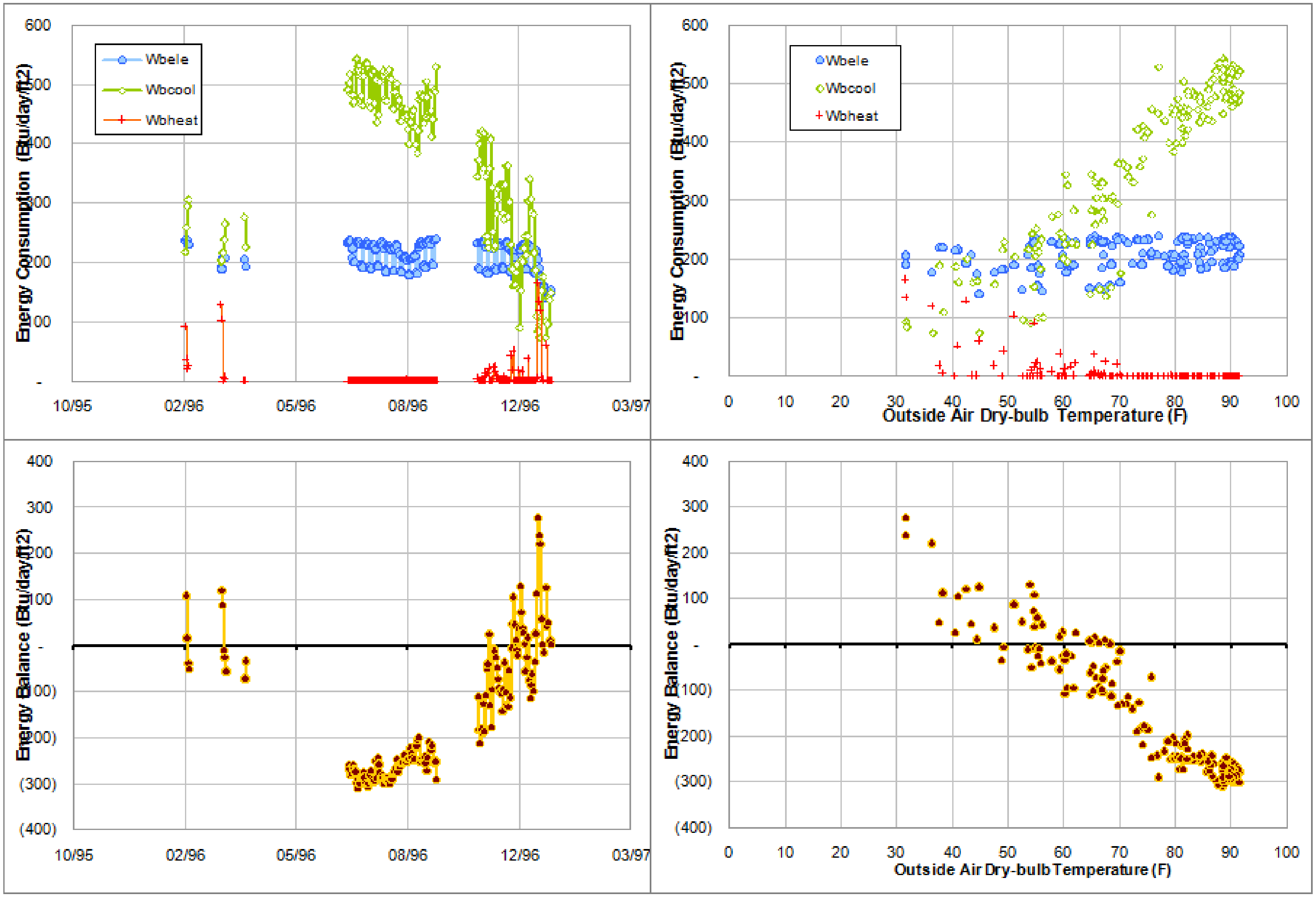


Figure D - 78. Energy balance plots for Zachry 1996 data.

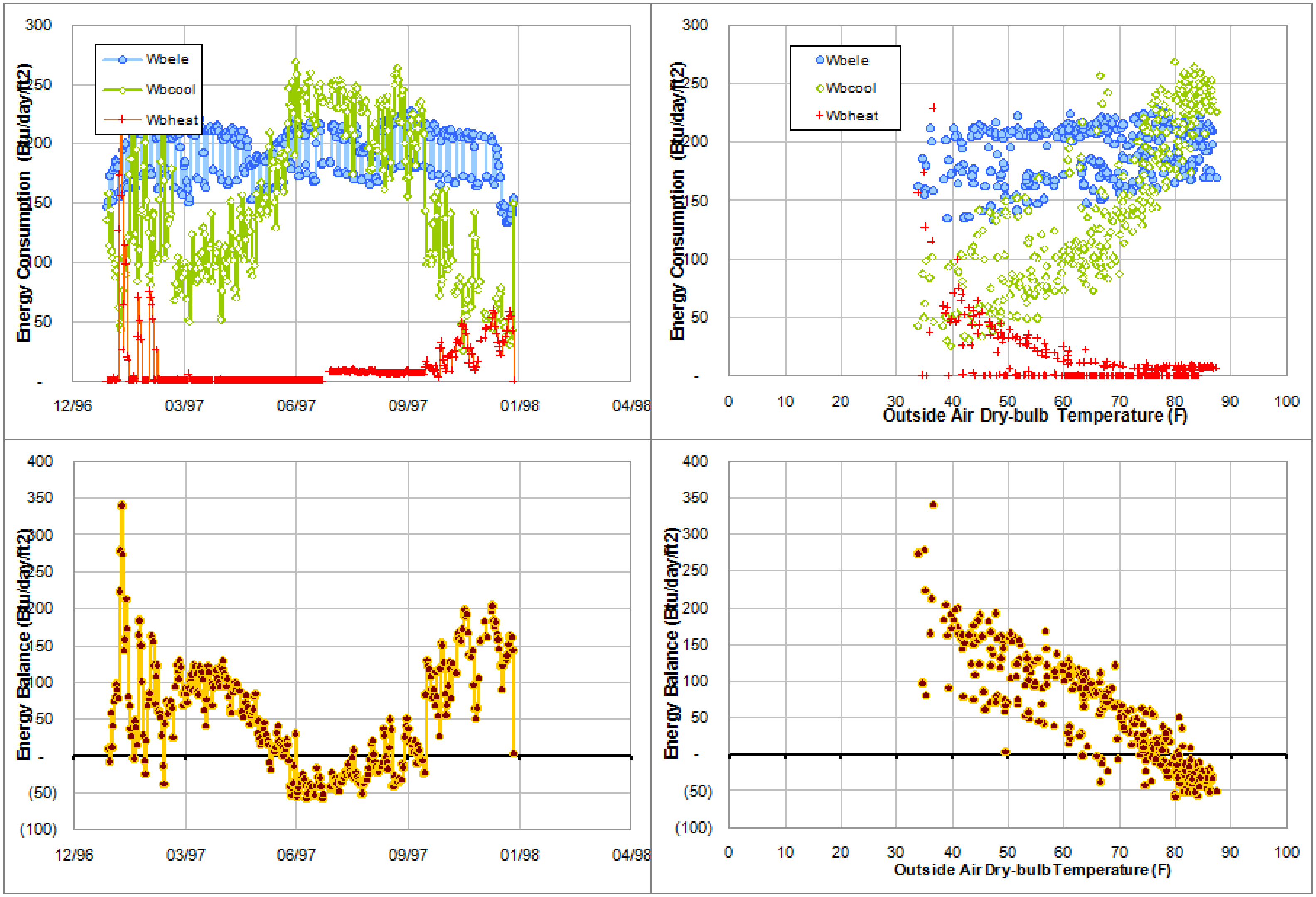


Figure D - 79. Energy balance plots for Zachry 1997 data.

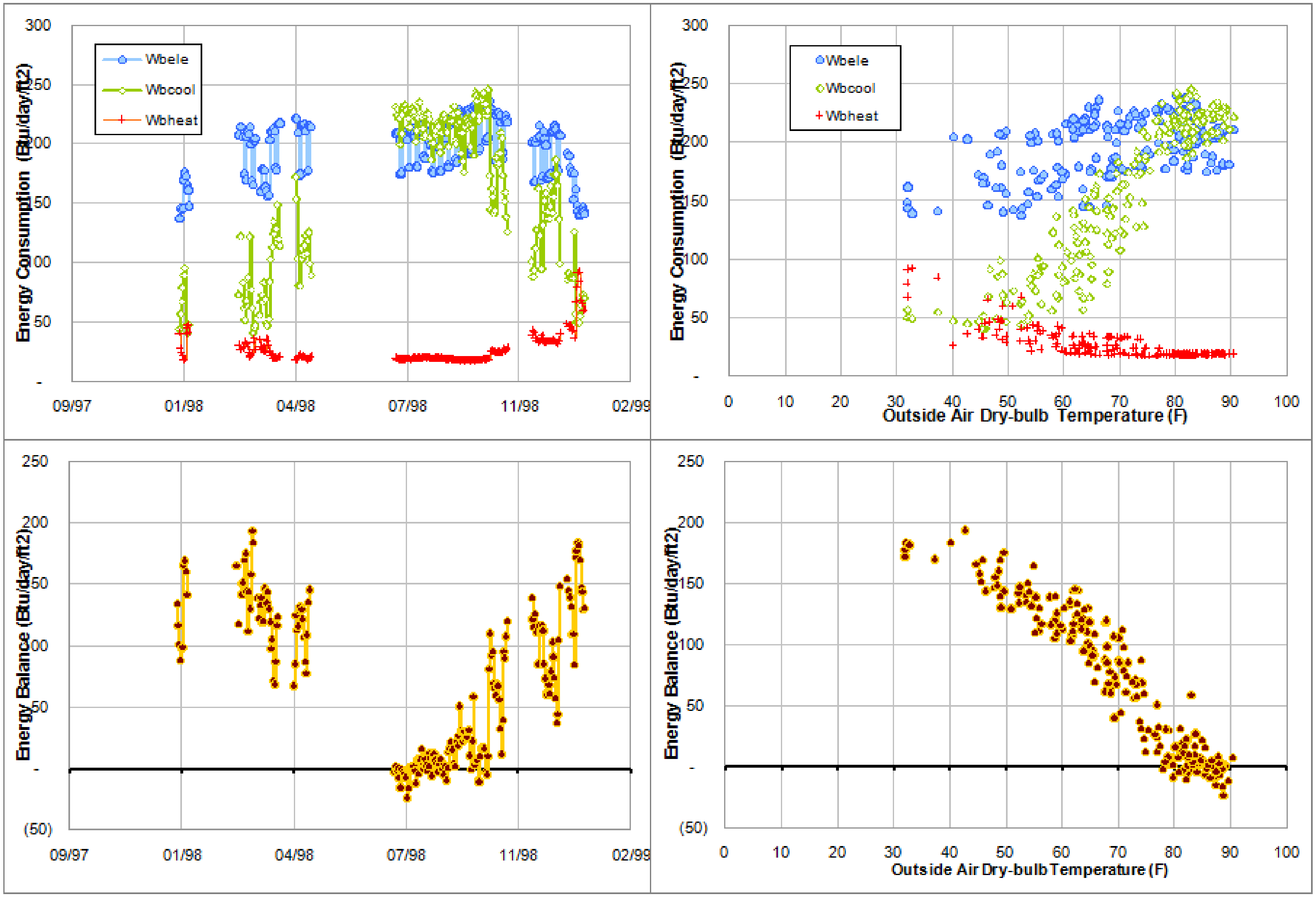


Figure D - 80. Energy balance plots for Zachry 1998 data.

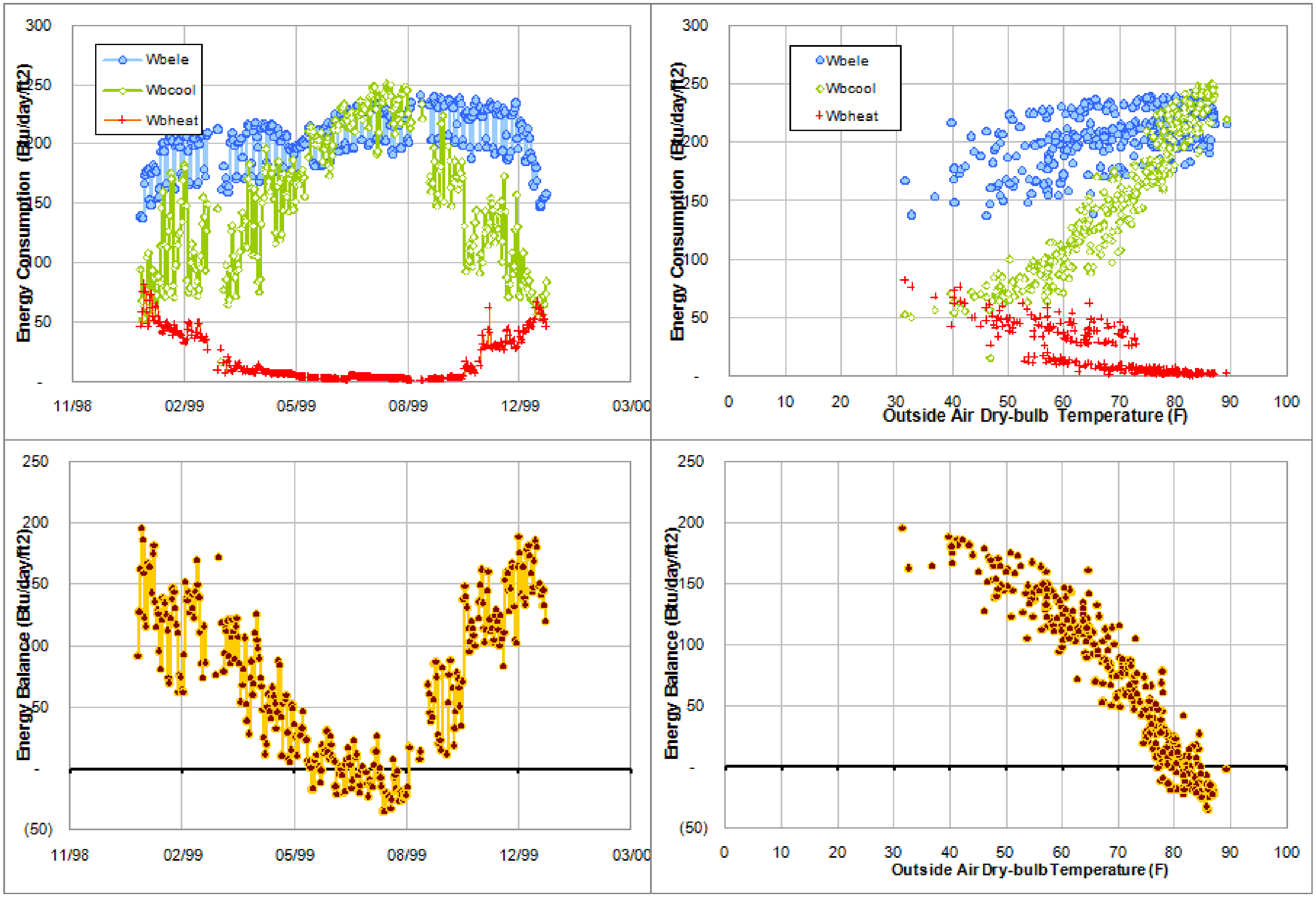


Figure D - 81. Energy balance plots for Zachry 1999 data.

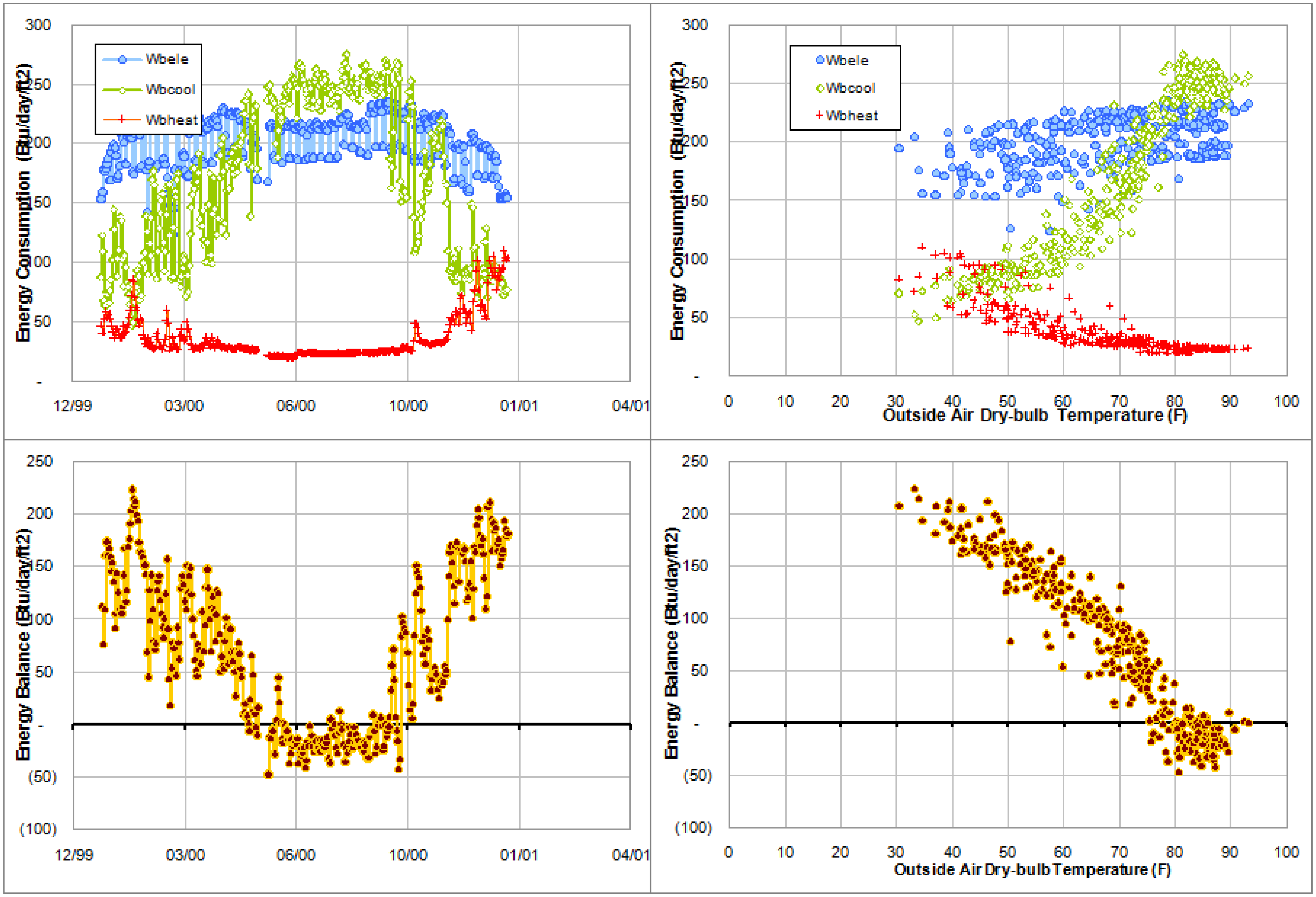


Figure D - 82. Energy balance plots for Zachry 2000 data.

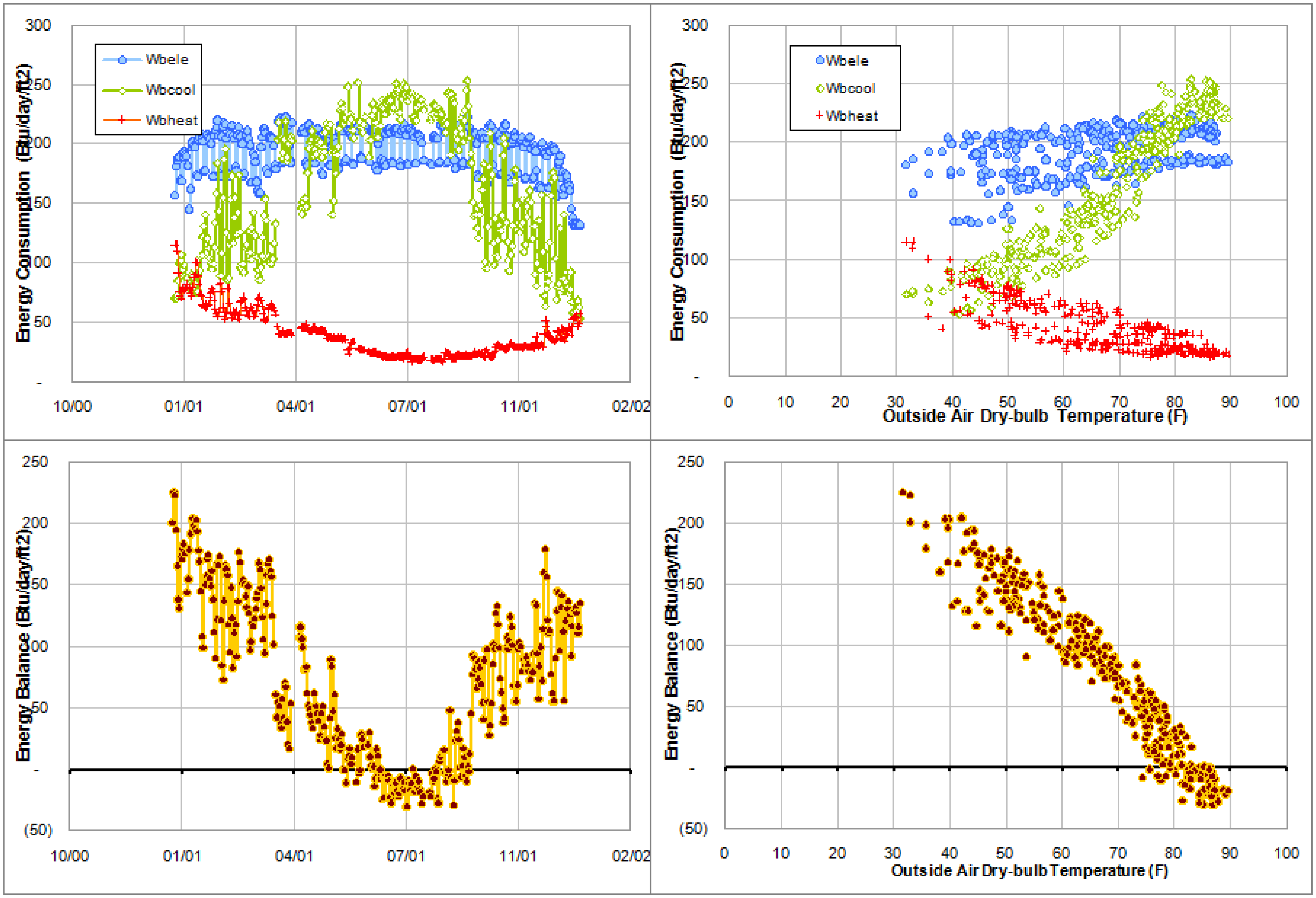


Figure D - 83. Energy balance plots for Zachry 2001 data.

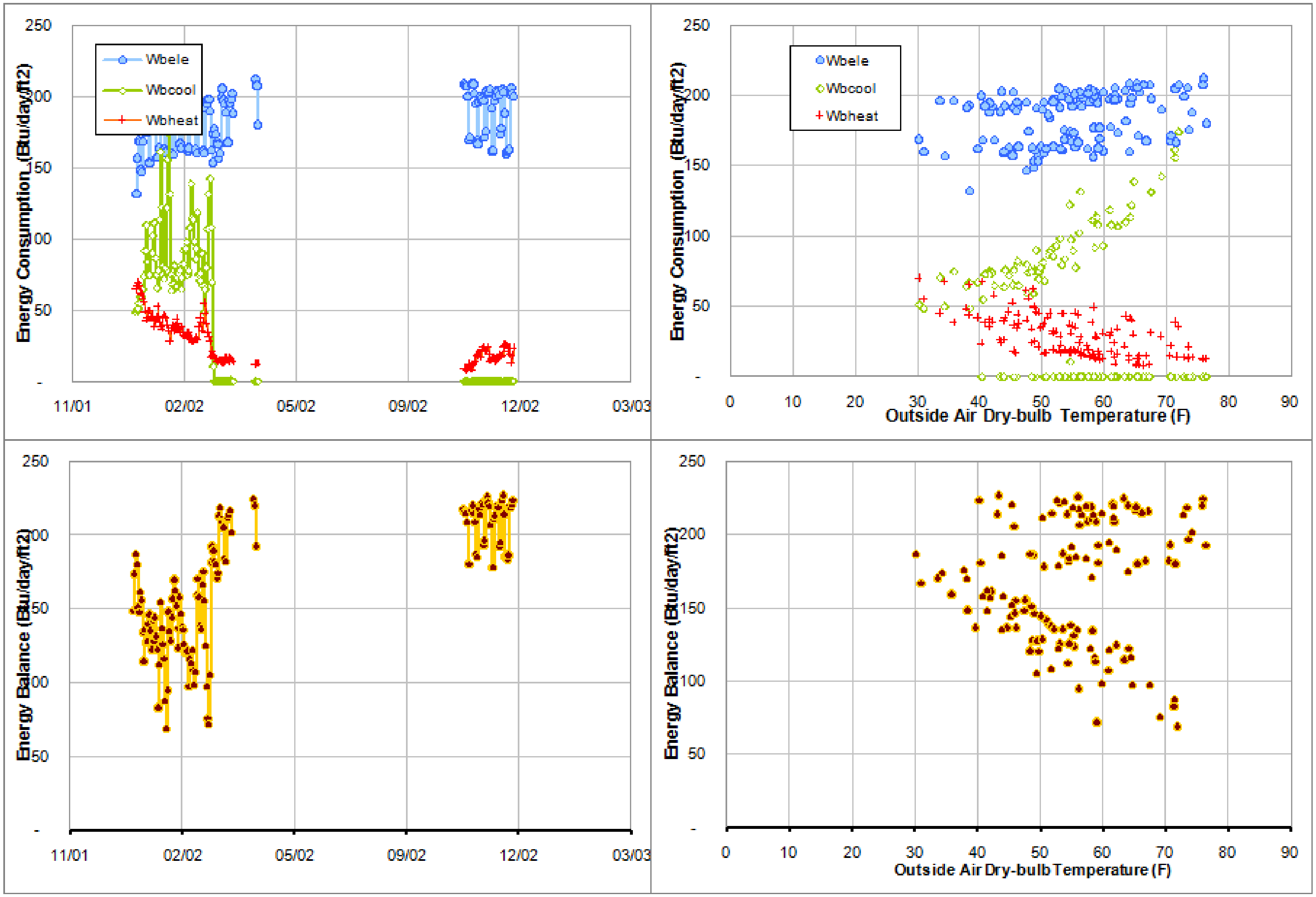


Figure D - 84. Energy balance plots for Zachry 2002 data.

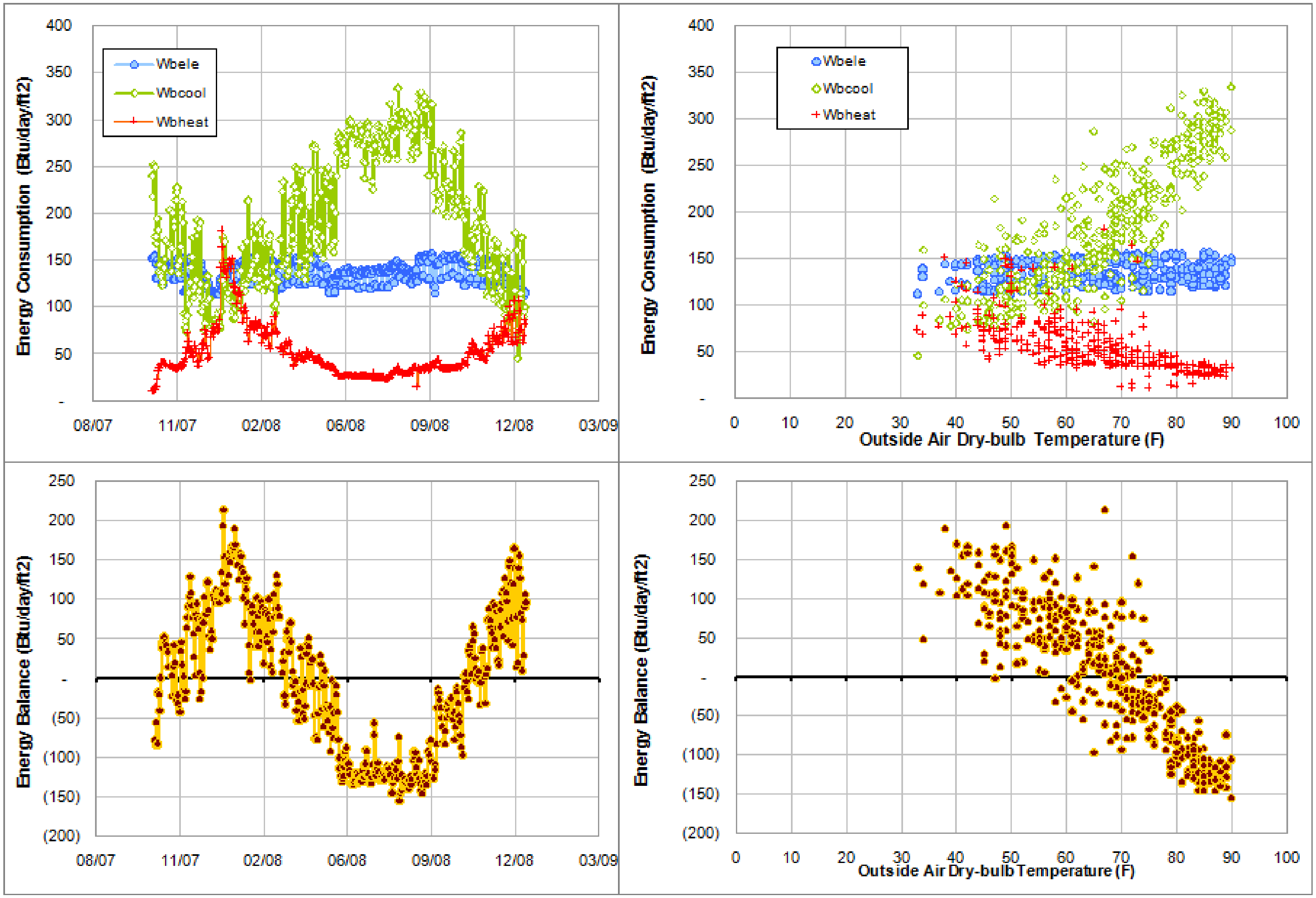


Figure D - 85. Energy balance plots for Zachry 2007-08 data.

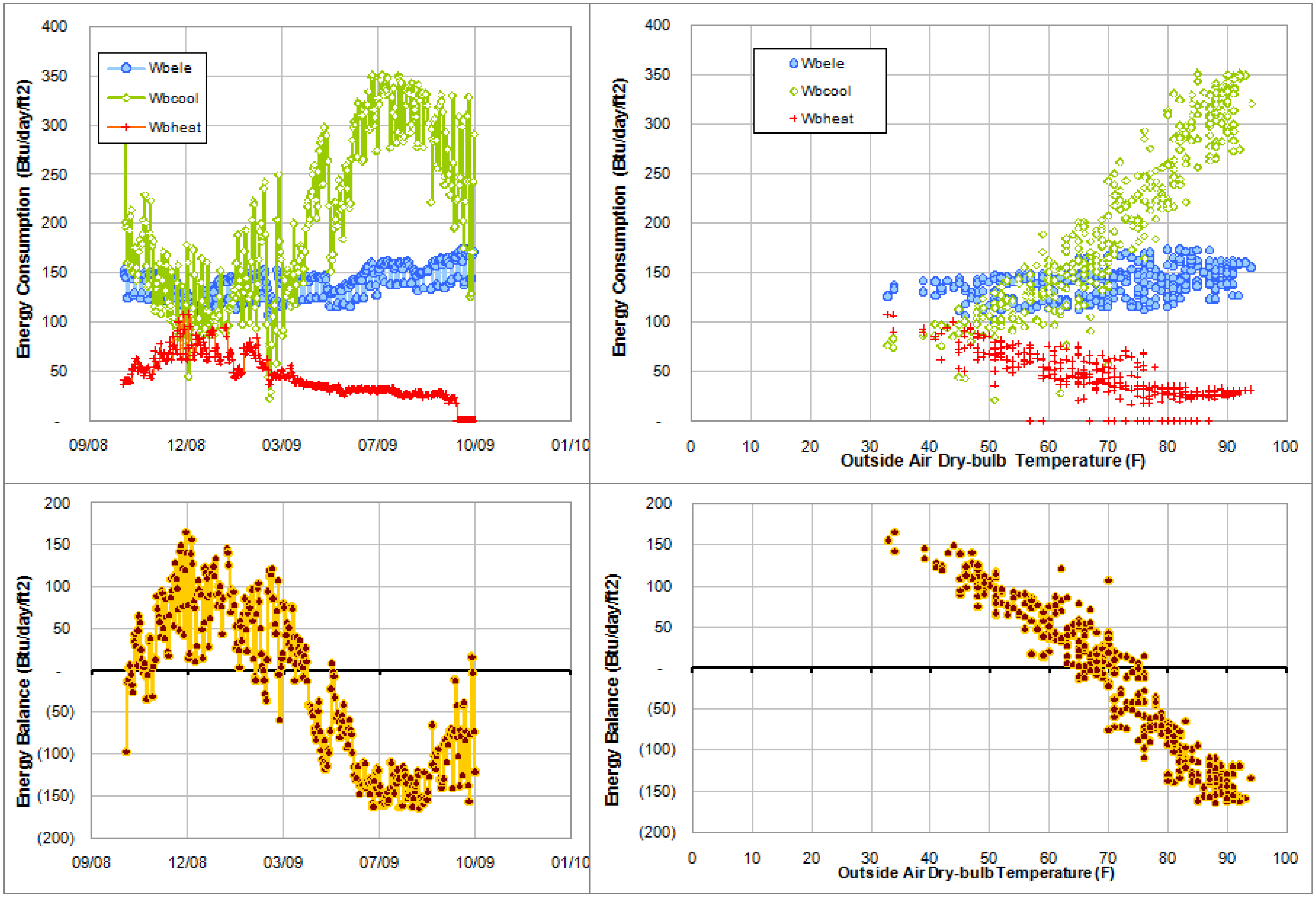
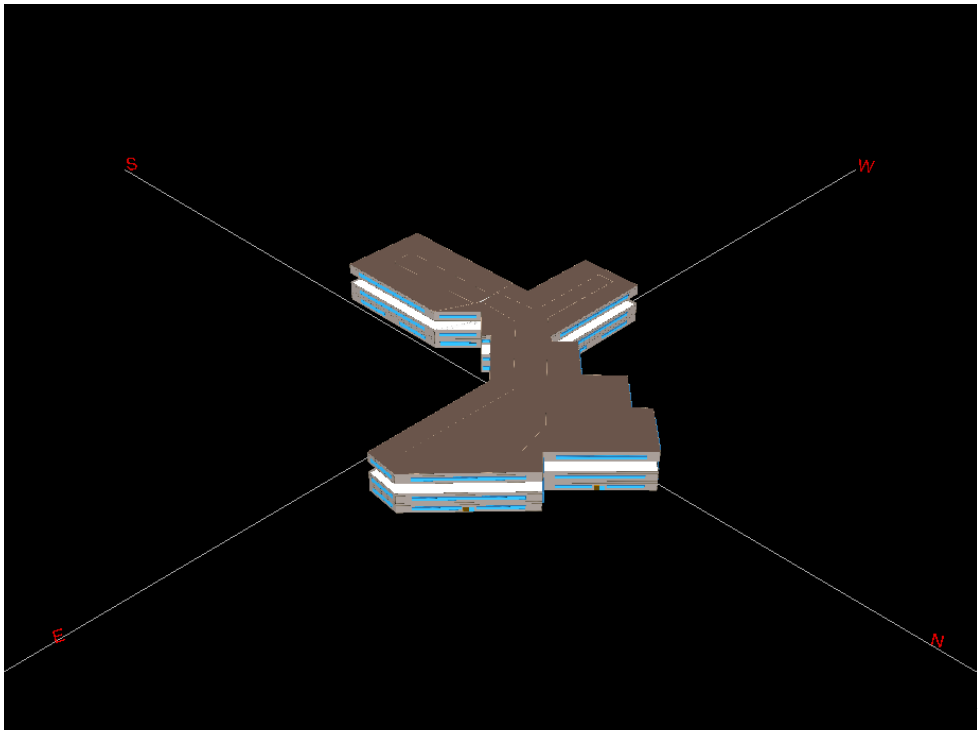


Figure D - 86. Energy balance plots for Zachry 2008-09 data.

APPENDIX E

MODEL PARAMETER SETTINGS

The Wehner Building was simulated in accordance with IPMVP Option D using eQuest version 3.63. The model was calibrated to consumption data from 6/1/2008 to 5/31/2009. A screenshot of the model is shown in Figure E-1. The rectangular piece on the South end represents the new addition to the building that was constructed in 2002.



F

Figure E-1. Screenshot of the Wehner 2008-2009 simulation model.

Figures E-2, E-3, and E-4 show the calibrated accuracy of the model by comparing daily simulated chilled water, hot water, and electricity consumption values with their measured data counterparts.

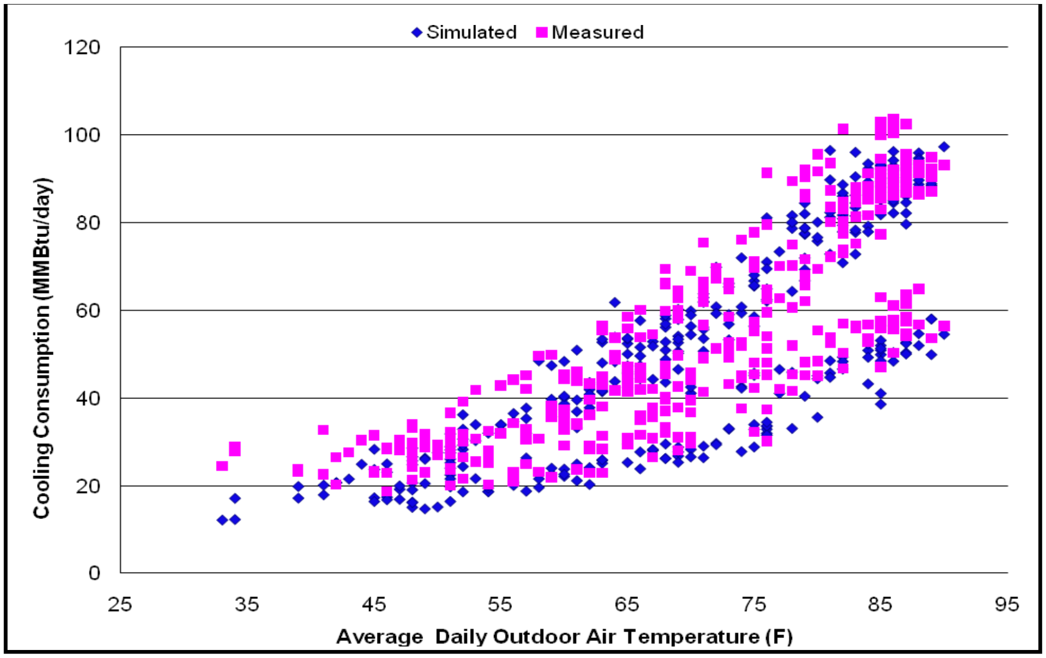


Figure E-2. Simulated and measured daily cooling consumption versus outdoor air temperature for the Wehner model.

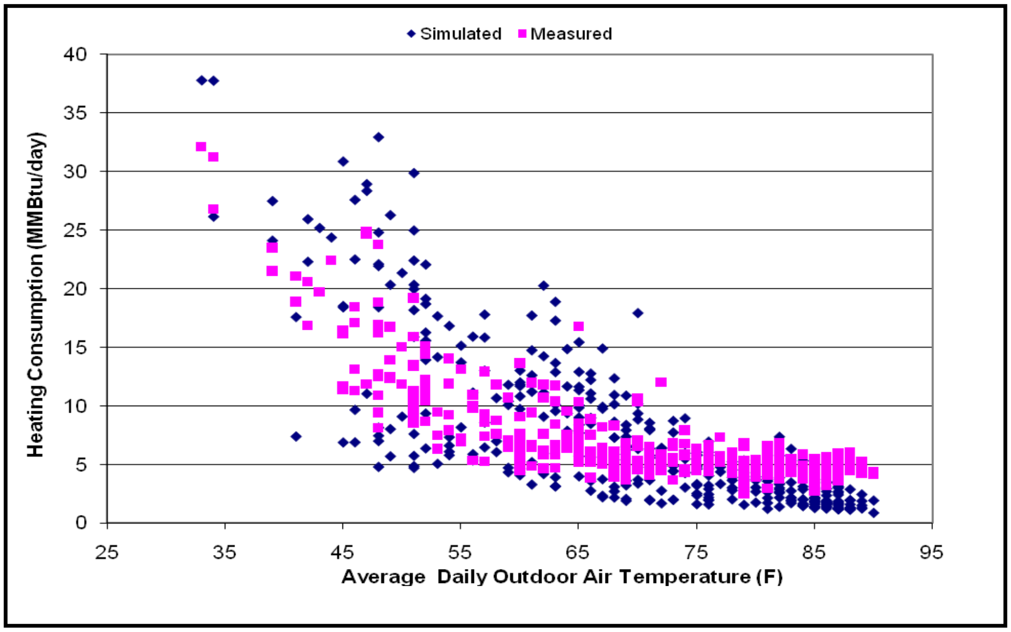


Figure E-3. Simulated and measured daily heating consumption versus outdoor air temperature for the Wehner model.

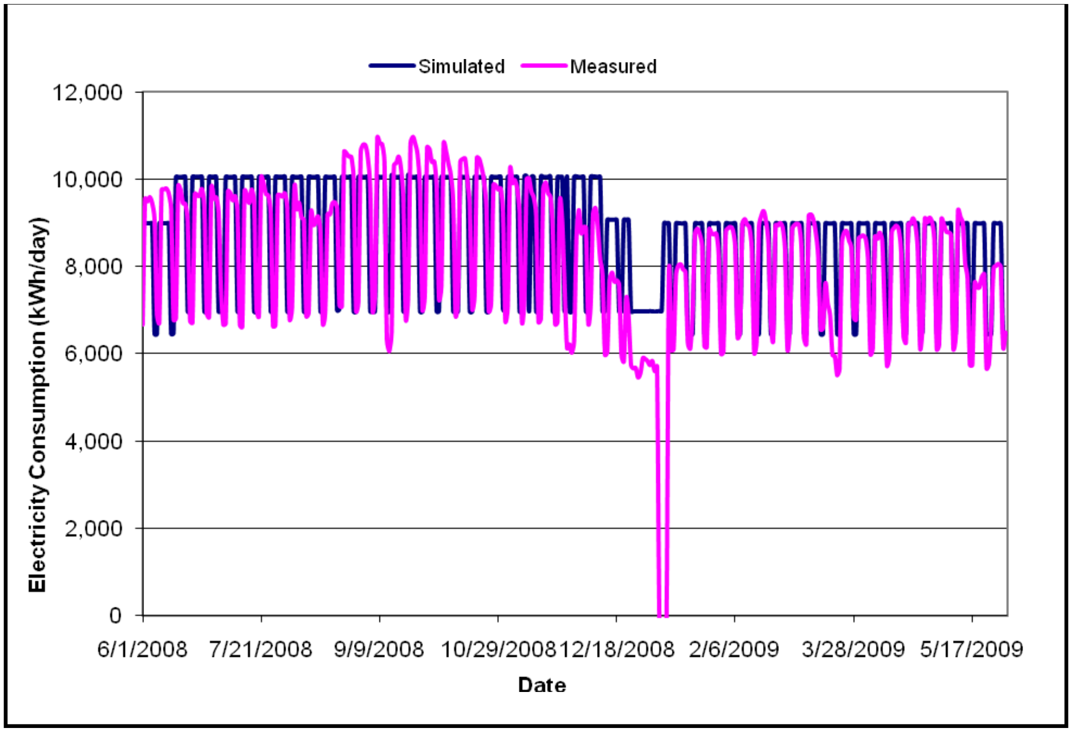


Figure E-4. Simulated and measured daily electricity consumption versus time for the Wehner model.

The accuracy of the model can be partly explained through its RMSE values, which for cooling was 12.517 and for heating was 4.399. The CV(RMSE) for cooling was 22.92% and for heating was 59.777%. The Mean Bias Error (MBE) for cooling was -2.831, and for heating was -0.067.

After calibration, the model was then altered to allow comparison with the baseline consumption for the building. The new section of the building was removed, and the model was simulated again using 1995 weather data obtained from NOAA. Hourly data gaps were filled in using linear interpolation. For periods of 6 consecutive hours of missing data or less, linear interpolation was employed using the data points just before and after the missing hours. For periods of missing data longer than 6 consecutive hours, the average of the same hour the day before and the day after was used to fill in each missing hour.

The total consumption simulated for the adjusted model could then be compared directly with the adjusted baseline consumption data for the building to determine savings.

The input files used for the 2008-2009 calibrated simulation model, the adjusted model, and the corrected hourly 1995 weather data used are available upon request.

VITA

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