THE DEVELOPMENT AND TESTING OF AN AUTOMATED BUILDING COMMISSIONING ANALYSIS TOOL (ABCAT)

A Thesis

by

JONATHAN M. CURTIN

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

August 2007

Major Subject: Mechanical Engineering

THE DEVELOPMENT AND TESTING OF AN AUTOMATED BUILDING COMMISSIONING ANALYSIS TOOL (ABCAT)

A Thesis

by

JONATHAN M. CURTIN

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

Approved by:

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

August 2007

Major Subject: Mechanical Engineering

ABSTRACT

The Development and Testing of an Automated Building

Commissioning Analysis Tool (ABCAT). (August 2007)

Jonathan M. Curtin, B.S., Binghamton University

Chair of Advisory Committee: Dr. David Claridge

More than $18 billion of energy is wasted annually in the U.S. commercial building sector. Retro-Commissioning services have proven to be successful with relatively short payback times, but tools that support the commissioning effort in maintaining the optimal energy performance in a building are just not readily available. The current work in the field of fault detection and diagnostics of HVAC systems, its cost, complexity and reliance on improved sensor technology, will require years until it can become the mainstay in building energy management. In the meantime, a simplified system is needed today that can be robust and universal enough to use in most types of buildings, address the main concerns of building owners by focusing on consumption deviations that significantly affect the bottom line and provide them some assistance in the remediation of these problems. This thesis presents the results of the development and testing of an advanced prototype of the Automated Building Commissioning Analysis Tool (ABCAT), which has detected three significant energy consumption deviations through four live building implementations. The ABCAT has also demonstrated additional functional benefits of tracking the savings due to retro-commissioning efforts, verifying billed utility data in addition to its primary function of detecting significant consumption faults. Although similar attempts have been made in FDD at the whole

building level, the simplification, flexibility, robustness and benefits of this new approach are expected to exhibit the characteristics that will be desired and desperately needed by industry professionals.

DEDICATION

To my Catica

ACKNOWLEDGEMENTS

I owe a huge debt of gratitude to Dr. David Claridge for his guidance, leadership, and friendship during these past few years as I have grown as a person and an engineer in ways I never could have imagined. The endless support through encouragement, advise, and motivation from Dr. Claridge, especially through those many times when it was most desperately needed, will not be forgotten. I would also like to thank and recognize the contributions of Dr. Jeff S. Haberl for and Dr. W. Dan Turner for their expert review and suggestions to improve this work, in addition to the positive influence they had on me inside and out of the classroom setting. To the ESL family and my fellow grad students in DOH 205: it has been a pleasure working in such a great environment with all of you, and I wish you all the best that life brings.

Additionally, the results of this project could not have been achieved without the outstanding multi-institutional support and dedication of many individuals throughout the country. I would like to recognize the effort of individuals from the test facilities as well as those involved in the program management and coordination to make this project a success. I would also like to express my gratitude to the State Technologies Advancement Collaborative (STAC) and the Technical Advisory Group (TAG), which was comprised of Daniel Choiniere, Daniel Dougherty, David Bornside, Eric Jeannette, George Mellen, Jerry Kettler, Jim Bochat, Jim Braun, Keith Marchando, Keith Rinaldi, Kent Browning, Michael English, Pete Keithly, Richard Kelso, Ron Gecsedi, Salvatore Renda, Saverio Grosso, and Srinivas Katipamula, for their valuable feedback throughout the course of the project and all others that have reviewed or commented on this work. I especially thank the following individuals for their various contributions:

Texas A&M University, Hui Chen, JJ Zhu, Homer Bruner and Jeremy Taylor

University of Nebraksa – Lincoln, Gang Wang and Minsheng Liu

Dorm Authority of the State of New York (DASNY), Bob McRae

Dome-Tech, Saverio Grosso and Chris Katz

NYSERDA, Kim Lenihan

IBM, Brian Birch and Baha Yousef

Austin Energy, Wayne Langehennig

PECI, Hannah Friedman, Marci Shuman, Aleisha Khan and Bill Koran

AIR Engineering, Jerry Kettler

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

Page

Page

Page

LIST OF TABLES

Page

CHAPTER I

INTRODUCTION

1.1 Background

Fault detection and diagnostics (FDD) has long been a player in such critical fields as aeronautics, automobiles and nuclear technologies, where the primary issues of safety and critically high reliability drove research. FDD in HVAC systems on the other hand, is just beginning to come of age, since safety typically is not of concern, reliability is important but typically not critical and the expected costs of implementing such tools are no longer believed to be overly preventative. Adding to the interest in this project is the fact that energy costs have increased, and therefore have created a greater potential for savings inspired by new research, accompanied with a drop in the costs of, and added reliability and sophistication in sensors and metering equipment. Advances in computing technology, processing speed and data storage have enabled the automation of FDD by removing the human or manual elements particularly from the data management and processing stages. Direct digital controls (DDC), standardized networking protocols like BACnet, energy information systems (EIS) and web-based technology are helping to shape buildings today with unlimited access to performance data. Despite all of these advancements in building technology, tools that support users in ensuring energy optimization and efficiency of building HVAC

This thesis follows the style of *HVAC&R Research* systems have not gained significant acceptance in the marketplace.

One of the difficulties in detecting degradation in the energy performance of building HVAC systems is that often it can go unseen at the comfort level. Occupant complaints are the industry's first and foremost fault indicators, but if occupants are satisfied it does not necessarily mean that the conditioning has been done in an energy efficient manner. Sometimes in the desire to promptly resolve a fault that causes an occupant complaint, temporary measures are taken to indirectly resolve a comfort problem, but this is often done at the detriment of energy efficiency. It is also common to see the inherent robustness of the HVAC system automatically respond to a fault by compensating with another part of the system. In both these situations, the true nature of the problem is masked, comfort is maintained, but with a hidden energy price tag. Another difficulty is that the detection of energy performance degradation from an analysis of energy bills alone usually is not possible, since the major contributing factors such as weather, schedules, occupancy, energy prices, billing period length and building system upgrades or construction variances from year to year tend to cloud the picture of easy direct comparisons.

Several studies have shown that HVAC operations in commercial buildings rarely are maintained close to their peak performance level. The Energy Systems Laboratory of Texas A&M University has tracked results of their Continuous Commissioning® (CC®)[1] process that has evolved out of their work with the Texas

[1] Continuous Commissioning® and CC® are Registered Trademarks of the Texas Engineering Experiment Station. Contact the Energy Systems Laboratory, Texas A&M University for further information.

LoanSTAR program. The average energy savings has been reported at levels greater than 20%, typically with payback periods of less than two years (Claridge et al. 2000). A broader, major study of 224 new and existing commercial buildings in 21 states across the country, commissioned by 18 different commissioning service providers, netted a median savings of 15% of whole building energy (Mills et al. 2005). Paybacks for existing construction were found to be better than that of new construction with medians of 0.7 and 4.5 years respectively. With these numbers applied to the entire U.S. commercial building energy sector, approximately $18 billion (15%) is wasted of the $125 billion market (EIA 2006). These estimates are with 2002 pricing and do not reflect the increase in prices over the past five years.

The persistence of savings obtained in commissioning has not been thoroughly studied, but a few research studies have explored the topic. Claridge et al. (2004) proposed the question of "Is Commissioning Once Enough?" They present the results of a study of the persistence of savings in ten university buildings (Turner et al. 2001) that averaged an increase of heating and cooling costs by 12.1% over a two year period post-commissioning. Major control changes and component failures in two of the ten buildings resulted in 75% of the measured increase. The problems in these two buildings were identified by tracking consumption in the building and comparing it to the baseline consumption, but the major increases were not identified until two years had passed, and hundreds of thousands of dollars in excess energy costs had already been forfeited. Clearly there exists a need for a simple, cost efficient automated system that can continuously monitor building energy consumption, alert operations personnel early upon the onset of problems and assist them in identifying the problem.

1.2 Purpose and Objectives

The purpose of this research is to develop the Automated Building Commissioning Analysis Tool (ABCAT), work originally initiated by Lee and Claridge (2003) , Lee et al. (2007), and Painter (2005), to an advanced prototype stage, along with demonstrating its effectiveness through four live building implementations, and five retrospective building implementations. The ABCAT is applied to the whole building energy level, rather than on an individual system (e.g., AHUs) or component (e.g., VAV boxes, coils, valves) which is the focus of many FDD tools today. The ABCAT whole building top-down approach simplifies the requirements for the tool to those already available for most buildings (i.e., hourly or daily averaged cooling, heating and electricity consumption, and hourly ambient weather conditions (temperature and relative humidity)). The goal of the ABCAT is to become a simplified, robust, marketable, cost effective alternative to the high priced, heavily sensor reliant existing tools that have failed to make significant market penetration. Summarized below are the specific developmental goals for the ABCAT in this project:

- Establish engineering and software requirements
- Commission each of the buildings selected as test beds to establish the base case
- Develop an interface protocol, within the budget, between ABCAT and at least one major control system to allow for some form of automated data exchange

- Establish and/or select metrics to express significant changes in building performance that normally are not detected or flagged which will lead to suboptimal performance.
- Add reporting routines with a user interface for manual data entry
- Modify the tool, using field data from three testbed sites in Texas and Nebraska and from the testers in New York

The implementation of the ABCAT in buildings of various size, shape, space utilization and HVAC system types tests the current capabilities of the ABCAT. The lessons learned from these implementations will help to shape the ABCAT in future developmental stages and bring it a step closer to end users in the marketplace. The following are the set testing objectives of the project:

- Building Types to be Tested
    - 1 Building served by the Texas A&M Central Plant
    - 1 High Performance building in Texas
    - 1 Highrise Commercial Building in Nebraska
    - 2 – 4 Building in NY
- Training and support to NY testers
- Provide summary of feedback on ABCAT testing and modifications, based on feedback

1.3 Literature Review

This literature review was drawn from various ASHRAE publications, proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings, the Journal of Solar Energy Engineering, the Energy and Buildings Journal, Annex Reports of the International Energy Agency (IEA), proceedings of the National Conference on Building Commissioning, proceedings of the Diagnostics for Commercial Buildings: Research to Practice Workshop, reports from nationally recognized laboratories, including: the Energy Systems Laboratory at Texas A&M University and the Pacific Northwest National Laboratory, along with a few select theses, books, web references and journal articles. These referenced sources cover topics related to the basics of fault detection and diagnostics in HVAC systems, model based methods, fault detection thresholds, fault diagnostics, previous attempts at whole building FDD and marketability and user considerations of FDD systems.

1.3.1 What Is FDD in HVAC

FDD in HVAC systems will generally consist of the following steps. First, correct or normal behavior and operation of a system or component must be known. With the expected performance known, if a deviation in an observed parameter occurs that is outside its normal, expected or tolerable range of operation, a fault is said to be detected. The diagnosis, or determination of the cause of the fault, is then undertaken by an analysis of any number of variables or conditions surrounding the fault. In an automated FDD system, additional steps include an evaluation, decision and action step, but automated systems will not be the focus of this research. Isermann (1984), Hyvarinen and Karki (1996) and Rossi and Braun (1997) all have described the FDD process in a similar fashion.

Several different approaches can be taken to determine the correct system behavior, some of which require previous operating data, while others may rely strictly upon the underlying physical relationships. Some of these different approaches include using *first principles models* - physical models governed by engineering fundamentals (Haves et al. 1996); *data driven models* – statistical regression (Haberl and Claridge 1987) or artificial neural networks (ANNs) (Lee et al. 1996) that learn to map inputs to outputs from a set of training data; rule-based systems (Haberl and Claridge 1987; House et al. 2001)– a set of IF-THEN rules used to navigate a knowledge base derived from experienced professionals or experts (*expert rules*) or derived with first principles considerations. These methods involve far greater detail and intricacies that are explained in Katipamula and Brambley (2005), where they state that often the clear distinction between methods becomes cloudy since some will incorporate parts of the others.

Perhaps the most traditional and fundamental fault detection method is limit checking (comparing a process variable with pre-set limits). Limit checking can be seen today in may building automation systems (BASs), providing simple alarm limits for variables. The difficulty comes in that some variables are dependent on operating states of the process, and therefore the limits would also have to be adaptive to the operating states. This method is usually reserved for steady or constant processes where detection of abrupt failures is required (Patton et al. 1995).

The research in the field of fault detection and diagnostics in HVAC systems has primarily focused on the sub-system or component level such as air handling units (Norford et al. 2002, Salsbury and Diamond 1999), variable air volume terminals (Xu and Haves 2002, Wang and Qin 2005), chillers (Wang and Cui 2006) or vapor compression air conditioners (Rossi and Braun 1997). Whole building level fault detection and diagnosis is an approach using measured building energy consumption to detect and diagnose building level energy consumption problems (Dodier and Kreider 1999; Breekweg et al. 2000a; Breekweg et al. 2000b; Facility Dynamics Engineering (n.d.); Katipamula et al. 1999; Haberl and Claridge 1987, Haberl et al. 1989). The detectable magnitude of whole building energy consumption faults using this approach is about five percent (Claridge et al. 1999).

1.3.2 Model Based Methods

Model based methods will be the focus of the FDD methods discussed in this research. Model based methods use mathematical models developed from a priori process information to predict a process variable, and evaluate *residuals* or the difference between the model output and the measurement. This process is referred to as *analytical redundancy* (Patton et al. 1995). The types of models used can generally be categorized into one of two types: either first principles driven or data driven models. First principles models, also referred to as *white-box* or quantitative models, are developed from the quantifiable relationships of the underlying physics involved, and are described as detailed or simplified depending upon their computational complexity and sophistication of the knowledge required to build them. Data driven models (ASHRAE 2005), also known as *black-box* or empirical, use techniques to mathematically relate inputs to output, without any concern for the physical relationship between the two. Examples of these data driven models include simple or multiple linear regression, multiple non-linear regression (Haberl and Claridge 1987), ANNs (Dodier and Kreider 1999), and the inverse bin method by Thamilseran (1999).

All of these modeling techniques have been used for FDD applications in HVAC, including the whole building level, but using a first principles model to predict energy consumption has the following advantages:

1. First principles models are based on actual representative physical characteristics of the building. The influences of various model variables are well understood and some are readily measured from actual building data.

2. First principles models can be used to identify more efficient operating strategies (Liu and Claridge 1998).

3. The affect of some faults on performance can be determined with simulation.

4. Retrofits or other major changes to the building can be accounted for with minor changes to the simulation program. Effectively the models can be created and/or modified without the need for training data, although training data will help to ensure the model accuracy.

5. There is better confidence that the first principles model will extrapolate well for operating conditions outside of those used to define the model (Reddy et al. 2003; Katipamula and Brambley 2005).

6. Also first principles models tend to have greater accuracy than that of black-box models (Katipamula and Brambley 2005), although this is not always true (Reddy et al. 2003).

Some of the disadvantages to using a first principles model include:

1. The physical inputs required for the model are not always readily available.

2. Even experienced model developers may find that the effort required to develop the model is significant.

3. The execution of the model may be computationally demanding.

4. The requirements for the collection and management of all the model input parameters in a real-time continuous implementation of a first principles model may be burdensome.

5. The model leaves room for user judgment in its configuration, which intrinsically leads to the potential for poor judgment to be used, particularly for inexperienced users.

The use of a first principles model in a whole building fault detection and diagnostic scheme shows great promise, but its feasibility is questionable unless the significance of the described disadvantages can be minimized. Detailed physical models (e.g. DOE-2, EnergyPlus) tend to be over-parameterized and can often require significant experience and time to provide an accurate representation of the building. Working in a real or semi-real-time environment adds additional complexity. *Calibrating* or tuning these detailed simulation models has also be shown to require significant effort (Kaplan et al. 1990; Bronson et al. 1992; Haberl and Bou-Saada 1998; Song 2006). Simplifying these physical models, as is done with ASHRAE's Simplified Energy Analysis Procedure (SEAP) (Knebel 1983), has repeatedly been shown to provide reasonable accuracy (Katipamula and Claridge 1992; Liu and Claridge 1995; Liu and Claridge 1998; Liu et al. 2004) without excessive complexity.

Such a model has been shown to be a manageable model for work in semi-real-time fashion and in a platform suitable for future embedment into a control system.

A manual systematic approach to calibrating first principles models with the signature techniques of Wei et al. (1998) has helped to minimize the expertise needed to calibrate a model. The approach, with the use of energy signatures, assists the user in clearly understanding the impact of various changes to the simulation parameters, as well as to help target the changes required for improved model accuracy. Song (2006) has recently built upon Wei's method by adding 25th, 50th and 75th percentiles to the calibration signatures, thus enhancing their graphical detail. Although the complexity that originally was involved in model calibration has been significantly reduced with the advent of this manual systematic approach, advances such as automated calibration may soon provide another great leap in calibration simplification. Recently, Baltazar (2006), improving upon the work of Lee (2002), has developed automated calibration techniques, testing them in SEAP models. Time and continued testing is needed to refine these methods before they are to the place where they can replace the manual systematic approaches previously described.

1.3.3 Fault Detection and Thresholds

Control charts have been a popular technique in establishing quality process control for more than half a century. Walter A. Shewhart was the pioneer in industry whose name is now synonymous with control charts - Shewhart Chart (Ryan 2000). The basic principle is that approximately 99.7% of samples of a normally distributed process variable under statistical control will be observed to be within the defined upper and lower control limits, which typically are set at ± 3 standard deviations from the process mean. These charts are the gold standard for detecting large sudden process mean shifts.

Accumulating the error from a process variable has been shown to be superior to the Shewhart Charts in detecting smaller sustained shifts (Ryan 2000). In the field of HVAC, Haberl and Vajda (1988) and later Haberl (1992) used this technique in analyzing both the cumulative energy and cost of the difference between measured and projected heating and cooling consumption. Schein and House (2003) applied what is referred to as the Cumulative Sum (CUSUM) control chart, a slight variation of the simple accumulation of residuals, to variable air volume (VAV) boxes to detect faults.

The Cumulative Sum (CUSUM) control chart provides an alternative to the Shewhart Chart and was introduced by Page (1954). Ryan (2000) defines both a positive and a negative cumulative sum as:

$$C_i^+ = \max\left[0, (z_i - k) + C_{i-1}^+\right] \quad (1.1)$$

$$C_i^- = \min\left[0, (z_i + k) + C_{i-1}^-\right] \quad (1.2)$$

where

C_i^+ = cumulative sum for positive errors for sample i,

C_i^- = cumulative sum for negative errors for sample i,

z_i = normalized process error = $\dfrac{x_i - \bar{x}}{\sigma}$,

x_i = process error at sampling time i,

$\bar{x}$ = estimate of the mean value of the process error,

σ = estimate of the standard deviation of the process error, and

k = sometimes called the reference parameter or slack parameter, is the minimum change (as multiple of σ) that will be detected in the CUSUM, and is typically chosen to be half the value of the mean shift one desires to detect.

The upper and lower CUSUM control limits, or decision intervals, that indicate a process is out of control are usually designated as h^+ and h^- and are multiples of σ. The application of the CUSUM in HVAC FDD applications has been rare. The system of Schein and House (2003) resets the CUSUM to 0 after each breaching of the control limit, which provides information as to the severity of the fault from the number of breaches and whether the fault is a growing or slowing problem by analyzing the time it takes between subsequent breaches of the control limits. The CUSUM is also valuable in that it has a built-in change point estimator by its design, where the start of the fault can be indicated by where the CUSUM first began to deviate from 0. Investigating system activity around that date may be important in the diagnosis of the fault.

1.3.4 Diagnostics

The diagnosis of faults is widely viewed as a more challenging and difficult process than fault detection. In methods using analytical redundancy, which usually consists of multiple residuals, each residual is evaluated as either greater than, less than or equal to expected performance. It is typical to analyze the pattern of residuals and classify the pattern according to an established "Rules for Diagnostic Classifier", such as the table shown on page 50, that describes the specific patterns of residuals for each fault condition considered. Grimmelius et al. (1995) used a fuzzy logic scoring system to evaluate each residual, while Rossi and Braun (1997) used crisply defined statistical thresholds to determine if they were greater than, less than or equal to expected performance.

1.3.5 Previous Attempts at Whole Building FDD

In the 80's, Haberl and Claridge (1987) were early pioneers who recognized the potential benefit of FDD at the whole building level, and implemented a prototype expert system for energy consumption analysis of a university recreation center. Consumption was predicted with multivariate linear regression techniques applied to historical measurements and compared with measured consumption on a regular short-term basis. If abnormal building consumption was detected by a statistical threshold deviation, this information was then passed to an expert system derived from the knowledge base of the authors and area maintenance personnel in the building. The expert system was highly detailed in its diagnostic capabilities due to the number of sub-meters throughout the facility and detailed inputs from manually recorded log files. IF-THEN rules were then tested in a decision tree to determine the cause. Although labor intensive at the time, the BEACON (Building Energy Analysis CONsultant) system showed promise in realizing 15% savings in energy consumption for the recreation center. A downside to the system was that its expert system was site-specific and not readily implementable in other buildings, and the consumption prediction techniques were statistically difficult mainly due to the identification of predictor variables in the regression and their intercorrelations.

Haberl et al. (1989) described a similar system that used PRISM – the Princeton Scorekeeping Method (Fels 1986), a steady-state three-parameter model to predict the energy consumption. PRISM regresses the energy consumption against heating and cooling degree days, yielding three-parameters (hence the name three-parameter model). PRISM includes a base level consumption, a balance point temperature and a slope. This system was implemented in an all-electric office building, and was successful in detecting prolonged equipment operation problems. A potential problem with the system is in its broad range applicability to commercial buildings. Haberl and Cho (2004) report how Rabl et al. (1992) and Kissock (1993) have shown that the three-parameter model often does not apply to the variable types of energy consumption seen in commercial buildings. Also the diagnostic capabilities of the system were fairly limited.

More recent attempts at whole building diagnostics include the tools PACRAT – Performance and Continuous Re-commissioning Analysis Tool (Facility Dynamics Engineering (n.d.)) and the Whole Building Diagnostician (WBD) (Dodier and Kreider 1999; Katipamula et al. 1999). For each tool, the analysis of whole building energy is only a portion or module of the complete system capability. Both tools use a multiple variable bin method to predict whole building energy consumption. PACRAT creates bins by hour of day, day of week and any third variable (typically ambient temperature). The bins of the WBD are typically defined by hour/day of week, temperature and relative humidity (Friedman and Piette 2001), but can be configured to any variable and any number of explanatory variables (Chassin et al. 2003). Baseline loads are categorized into these bins and later referenced in the prediction of consumption. A concern with this approach is that the amount of training data required is significant to provide a complete picture of the baseline consumption use. Like most black box or empirical models, they would not be able to predict consumption for conditions outside of those defined in the training data. Both PACRAT and the WBD provide automated real-time monitoring of whole building energy performance and include comparisons with measured performance, but from review of all known literature, no additional diagnostic information is generated by the tool other than the difference between expected and measured consumption in daily units of energy and cost.

Although the following examples may not be specifically in the form of a FDD tool per se, the monitoring and analysis of whole building energy has proven over and over again to be valuable in diagnosing faults in buildings. Haberl and Vajda (1988) and Claridge et al. (1996) document success stories of fault detection and ultimately of diagnosis thorough monitoring and analysis of whole building energy. Claridge et al. (1999) describe how the value provided by metering in Haberl and Vajda (1988) and (Haberl and Claridge 1987) were major factors in the implementation of the metering program of the Texas LoanSTAR Program ($98.6 million revolving loan program for energy retrofits) as insurance to ensure its success. “Preliminary Problem Diagnosis Using Measured Energy Data” became one of the first steps in the LoanSTAR O&M Methodology (Claridge et al. 1996). The LoanSTAR program identified the potential of using simplified first principles building energy models, calibrated (adjusted or tuned) to whole building energy, to calculate retrofit savings (Katipamula and Claridge 1992), and later developed techniques to identify component failures and optimization steps available with these calibrated models (Liu and Claridge 1995; Liu and Claridge 1998). Cho (2002) in his master’s thesis studied the persistence of commissioning measures over the period of five years in ten different buildings. Cho used calibrated simulations of these buildings to identify operational changes that were made that contributed to the loss of savings, but also investigated and documented specific control system changes that were known to have taken place.

Lee and Claridge (2003) describe the foundation of what was to become the ABCAT with the outlined steps for a whole building simulation fault detection procedure, which are still applicable to the fault detection of the current ABCAT version. This includes the use of a calibrated simplified first principles model for predicting consumption and an introduction of the benefits of the cumulative sum. A retrospective analysis was performed on a building where Lee and Claridge evaluated several graphical indicators on hourly, daily and monthly levels, and detected three significant schedule changes and two significant component failures with a time series visual analysis. Painter (2005) took the system of Lee and Claridge (2003) and demonstrated the feasibility of implementing an early prototype of the ABCAT in a "live" situation, developing a simple interaction and communication protocol for the three different software types: an early prototype of the ABCAT, the building energy simulation model (Airmodel) and trend data from the building energy management system.

1.3.6 Marketability and User Considerations

The Annex 34 (Computer Aided Evaluation of HVAC System Performance) of the IEA emphasized real building testing of several dozen FDD techniques that were developed earlier in Annex 25 (Real Time HEVAC Simulation). An assessment of these test situations (Dexter and Pakanen 2001) presents the lessons learned for the direction of future design, deployment and use of all types of HVAC FDD systems. Heinemeier et al. (1999) performed an analysis on market factors most critical to ensure market acceptance of the Whole Building Diagnostician, a prototype FDD tool at the time (Dodier and Kreider 1999; Katipamula et al. 1999). The study involved the creation of focus groups of various building related job functions, a brief presentation of the tool, questions and answers, and recorded feedback. Some common themes are seen when these tool evaluations are put to the test with real clients, such as: (1) users will want to be a part of the process and will be less willing to accept a tool that is completely out of their control, (2) skepticism must be overcome, and a customer's trust must be gained, (3) the system cannot require excessive specialization or require excessive operator time, and (4) false alarms seem to have a great influence over the acceptance of the tool.

Therefore, the approach taken in this thesis with ABCAT is not to replace the operator or technician with a diagnostic tool, but rather aid them in the course of evaluating system performance and diagnostics by narrowly classifying faults into a subset of possibilities. Keeping the tool simple by focusing at the whole building energy level allows for only significant faults to be detected, practically eliminating the chance of false alarms. Additionally, the importance and benefits of data visualization have been recognized by many others in this field (Haberl et al. 1996; Meyers et al. 1996; Haberl and Abbas 1998a; Haberl and Abbas 1998b). In order to provide added value in analysis and understanding of building energy performance, we looked to provide a unique approach to the graphical presentation of consumption data in ABCAT.

1.3.7 Literature Review Summary and the ABCAT Approach

A thorough review of the literature in the field of FDD in HVAC has shown that only a few of the past approaches have been successful in transitioning to marketable products, whether focused at the whole building, system or component level, and none have gained wide spread acceptance by building owners. The use of a simplified first principles model (ASHRAE's Simplified Energy Analysis Procedure (Knebel 1983)) to predict heating and cooling energy use at the whole building level with ABCAT, deviates from the black box models that have been used in other whole building FDD systems. The advantage expected from this approach is increased accuracy and greater robustness and flexibility to changes in the building by requiring less training data. The use of the CUSUM in the analysis of whole building energy is another new application in ABCAT, which focuses on the detection of small but sustained impacts on energy. Diagnostic classifiers in most systems add complexity and additional uncertainty as the number of observed and modeled variables increase as is required for the specificity of their diagnosis. The ABCAT approach is designed to gain maximum benefit from simplicity, by using only the cooling and heating[2] residuals along with the ambient temperature at which they occur to provide information that can lead to a prompt identification and resolution of a fault. By involving the user, keeping it simplified and focusing on faults that truly have a cost impact, this work takes into account the lessons learned from the real building trials of other tools. This work builds upon the prior work of Lee and Claridge (2003), Painter and Claridge (2007), and Painter (2005) with ABCAT, with additional field testing, a new building model that accounts for measured electricity consumption in the building load calculation, improved system user friendliness and graphics, and clearly defined fault detection and diagnostic schemes.

---

[2] The cooling and heating energy simulated in the ABCAT program is that of the airside systems (AHUs), which corresponds to the output of the primary cooling and heating equipment (e.g., chillers and boilers), but not the input energy consumed by the primary equipment (electric and gas). Generally speaking, the measured energy used in the ABCAT is the energy transferred by the hot water and chilled water to the AHUs, and does not include pumping energy or losses associated with the distribution of the hot water or chilled water from the boiler or chiller to the building. In lieu of measuring chilled and hot water energy, the output of the boilers and chillers may be obtained with an energy model using measured input energy and other key system parameters, although these models are not currently included in the program.

CHAPTER II
PROJECT APPROACH

2.1 Introduction

The FDD approach to be undertaken in this research will be applied to the whole building energy consumption level and is simplified to aid in the practicality of its implementation outside of the university and research lab setting. Whole building diagnostics have been somewhat overlooked as a main area of research focus in HVAC and building operations. This is likely due to the fact that terms whole building and diagnostics are somewhat contradictory, since diagnostics generally implies a detailed identification of a problem, while whole building is a broad encompassment of the building systems. The level of diagnostics to be provided in this whole building diagnostics approach will focus on providing key characteristics of the problem, which can limit the possible causes to several options. It may not have the detail to find a needle in a haystack, but instead is an attempt to effectively reduce the size of the haystack in which someone will have to look.

2.2 Initial Setup

The ABCAT is initially set up in a building through the following sequence of steps:

1. **Define a Baseline Consumption Period and Collect Baseline Measurements**

The baseline period should correspond to a time when the building mechanical systems are known to be operating correctly, typically post new building commissioning (Cx) or retro-commissioning (RCx). The length of baseline can be a minimum of four weeks if during the swing seasons where a wide range of outside air temperatures is experienced and heating and cooling systems are both operating. Required measurements include whole building heating (WB_{Heat}) whole building cooling (WB_{Cool}), whole building electric (WB_{Elec}), ambient outside air temperature and relative humidity or dew point temperature, all recorded in hourly intervals. Figure 1 describes the consumption monitoring that is required for the ABCAT. Ideally the WB_{Heat} and the WB_{Cool} would be obtained by Btu metering of chilled and hot water, but these values could also be obtained by modeling the chiller and boiler if interval meters exist that monitor chiller electric loads and natural gas consumption. A slight decrease in the ABCAT detection sensitivity would be expected in these cases due to this added modeling step and the associated uncertainties involved.

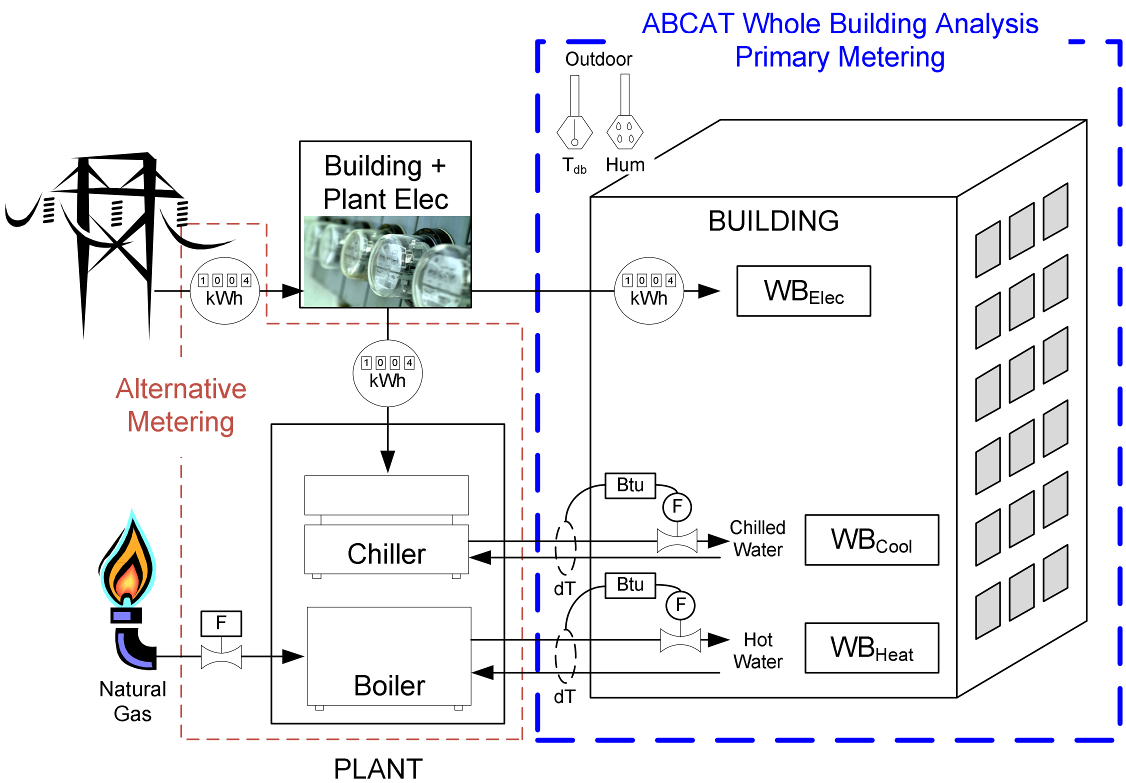

Figure 1. Consumption Metering Requirements for the ABCAT

2. **Obtain Building and Air Handling Unit System Details**

   The required information includes: floor area, exterior surface area type, orientation and U-values; AHU type, AHU air flow rates, outside air total or % of total flowrate, operating schedule, supply air temperature schedule, space set point temperatures, economizer settings, estimated occupancy and occupancy schedule, and economizer and humidifier operation details if they exist.

3. **Establish Initial Values of Inputs for the Simulation Model and Calibrate the Model**

   Generate an input file for simulation based on measured data and system information, and calibrate or tune the model inputs until desired accuracy is achieved

4. **Correct for Bias in Model**

   Provide a final adjustment to simulation model by calculating the mean bias error (MBE) and subtracting this amount from to the model so that the MBE of the model is zero for the baseline period. Even a small systematic bias in the simulation will decrease the sensitivity of the fault detection process.

5. **Program Regular Data Transfer to ABCAT**

   Develop a method by which the required measured inputs can regularly be updated and passed to the ABCAT program. In the current test facilities, Visual Basic for Applications programs link the ABCAT with consumption data files. The programs sort, fill missing data with linear interpolation when applicable, summarize and import the data into the ABCAT program in its required format.

Once the ABCAT is configured for the particular building through the steps described above, the program is ready for execution. Figure 2 is a process flow diagram which visually describes the following five steps in the ABCAT methodology:

1. **Import Measured Data**

   Evoke the program developed in step 5 of the initial setup steps above from the ABCAT program.

2. **Simulate Heating and Cooling Consumption**

The required inputs are passed to the energy simulation routine, where the heating and cooling consumption is simulated.

3. **Data Analysis**

The simulated consumption and measured consumption are passed to the data analysis routine that generates the building performance plots, compares and performs calculations on the two values, applies fault detection methods, and reports diagnostic and energy consumption statistics.

4. **Evaluation**

The user of the tool is to evaluate the data presented and determine whether or not a fault exists that requires action. The user plays an important role in defining fault triggers and manipulating the plotted data with easily adjustable parameters to suit their site specific preferences. Abnormal periods of consumption can sometimes be explained by irregular activities (i.e. shutdowns, holidays, snow days, power outages, etc) in the building, or by an incomplete or faulty measured data collection process. The user in this step applies their knowledge of the building to determine if any known but unaccounted for factors in the ABCAT model contributed to the fault. If no significant fault is identified, or if the faulty performance persisted only for a short period and is explainable, then no action is needed. If this is not the case, and action is required, then the process moves to the next step.

5. **Action**

The type of action taken will depend on whether the faulty condition observed is the result of a required change in operations or whether it was caused by a system or component failure or a change in control to a less than optimal setting. In the case of the latter, the user or other experts can use the diagnostic information provided by the ABCAT to help identify and correct the fault, and follow up observations should review a return to expected performance. If required changes in operation (such as work schedule changes or construction retrofits) are behind the observed deviations in energy performance, and the new energy performance in the building is considered to be “correct”, then the ABCAT simulation must be recalibrated to reflect the new building performance.

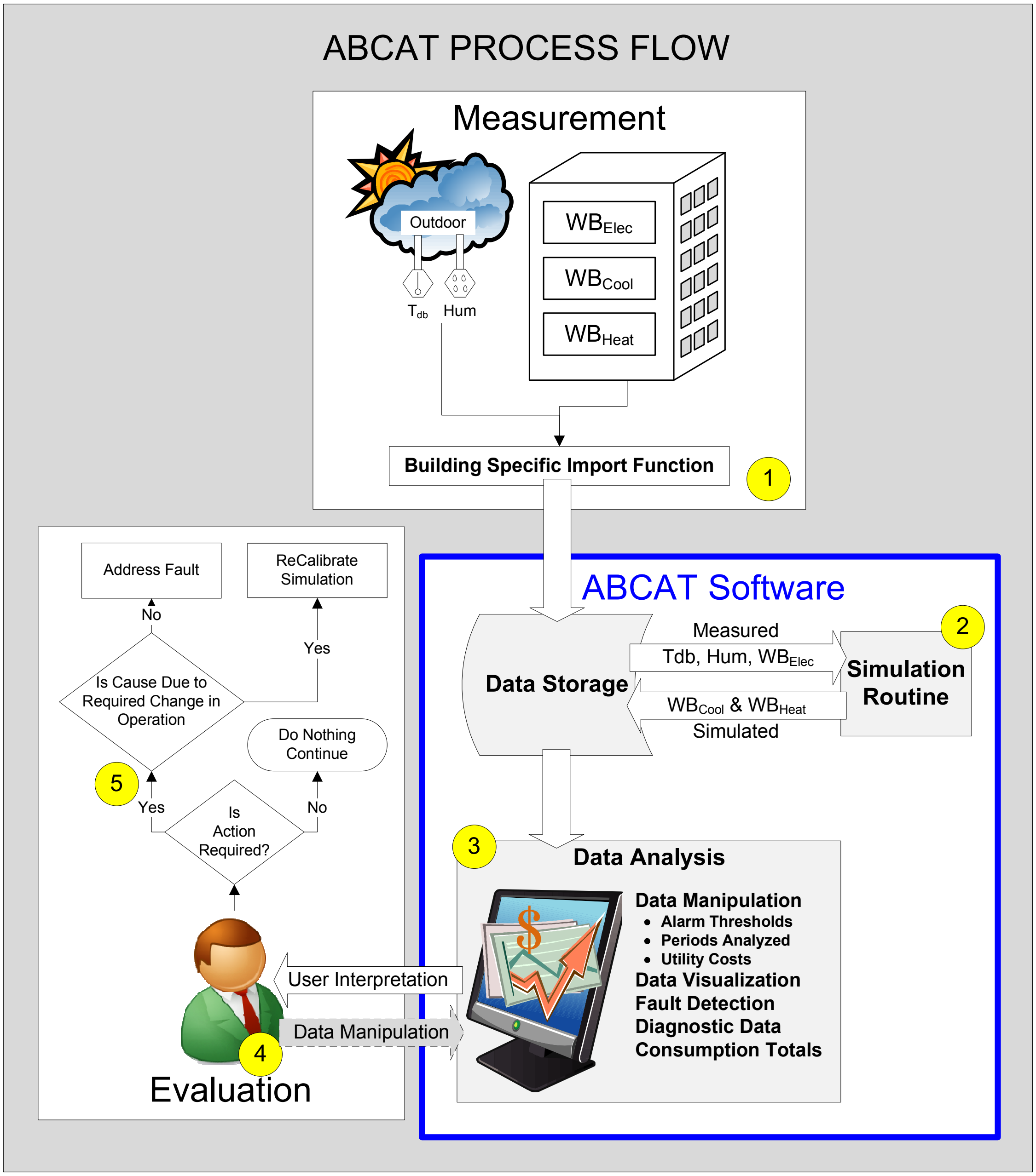

Figure 2. ABCAT Flow Diagram

2.3 Test Buildings Selected

Testing this type of FDD system in real buildings provides the most realistic and valuable type of feedback possible. Since the first half of 2005, ABCAT has been running in two live building installations. The first building is an 82,000 ft^2 dining services facility in College Station, TX, and the second is a 482,000 ft^2 computing services building in Austin, TX. Two additional office buildings were added as test sites in early 2007; one is 180,000ft^2 in Albany, NY and the second is a 190,000 ft^2 high rise in Omaha, NE. Although a second NY test facility was originally identified and targeted for installation of the ABCAT, difficulties in obtaining the required preliminary baseline consumption data prevented a successful deployment in this case.

In search of an alterative testing situation in lieu of a second NY building, the idea of applying the FDD scheme retrospectively was considered. The conditions required in our case for an informative retrospective test are such that the buildings must: (1) have been commissioned, (2) have sufficient post-commissioning measured consumption data by which to define a baseline, and sufficient continuous measured data from that point on, (3) have had a known significant degradation in energy performance that could be detected, (4) not have experienced any major capital retrofits during the period analyzed and (5) have additional information as to the nature or cause of the degradation in energy performance available to compare with the diagnostic results of ABCAT.

Cho (2002) in his master's thesis studied the persistence of commissioning measures over a period of five years in ten different buildings. Five of the ten buildings were considered candidates for testing with ABCAT. Cho used calibrated simulations of these buildings to identify operational changes that were made that contributed to the loss of savings, but also investigated and documented specific control system changes that were known to have taken place. These buildings are Harrington Tower, the Kleberg Center, Eller Oceanography-Meteorology Building, Veterinary Research Building and the Wehner Building on the Texas A&M University campus. They met all the conditions set forth above to be test subjects, and have therefore undergone a retrospective analysis with the ABCAT to substitute for the original project objective of implementing ABCAT in a second NY building.

The findings from both the live and retrospective building analysis with the ABCAT will be presented in this document.

2.4 Building Energy Model

2.4.1 Simplified Energy Analysis Procedure

The SEAP (Knebel 1983) will be used to predict the cooling and heating energy consumption for the buildings in the study. The strength of the model comes from its simplification. The major premise as described by Knebel is that “the net time dependent energy rate, added to or removed from the space during a given computational period, is equivalent to the average energy rate added or removed from the space times the duration of the computational period.” The model developed specifically for ABCAT encompasses these principles, and is briefly described below:

1. The simulation is run on a daily average basis, with daily inputs of ambient daily average temperature, relative humidity and whole building electricity consumption. The model allows for the specification of a fraction of the electricity consumption that is converted into heat gain within the building.

2. The building is represented as a two zone model. An exterior zone that is subjected to building envelope loads (solar transmission and conduction gains/losses), occupant, equipment and lighting, and ventilation loads. The interior zone is subjected to the same loads with the exception of envelope loads. Knebel (1983) recognized the importance of proper zoning of large buildings where cooling and heating may be experienced simultaneously in separate zones. Katipamula and Claridge (1992), Liu and Claridge (1995) along with others have shown the two zone building model to be an adequate simplification in modeling.

3. The key characteristics of the building and its HVAC systems that must be included in the model are the: (1) Envelope Area and Heat Transfer Coefficient, (2) Solar Radiation Load, (3) Internal Heat Gain from Equipment and Lighting (taken as fraction of measured electric load), (4) Deck Temperature Schedules, (5) Maximum and Minimum Air Flow Rates, (6) Outside Air Intake, (7) Occupancy Schedule and (8) AHU Operation Schedule. Liu et al. (2004) describe the steps for an initial value selection of these parameters in a model with similar input requirements as ABCAT.

4. Systems with similar functionality, outside air flow rates, minimum flow rates and loads may be consolidated into a single system.

5. The types of systems available for modeling include: Single Duct - Variable Air Volume or Constant Volume (SDVAV or SDCV) with terminal reheat, Single Zone Heating and Cooling (SZHC), Dual Duct Variable Air Volume or Constant Volume (DDVAV or DDCV) and Dual Fan Duct Dual Variable Air Volume (DFDDVAV).

6. The energy calculations of the systems follow the procedures outlined by Knebel (1983) but also include the following user specified options:

    a. Damper leakage in the terminal boxes of the dual-duct systems can be specified.

    b. Preheat and precooling coils can be specified to exist in the outside air ductwork (as the case of a dedicated outside air handling unit) or in the main air handling units.

7. Outlines of the program flow calculations are presented in Appendix A.

2.4.2 Measured Electric Load as Heat Gain

A true whole building level energy consumption analysis would include the actual consumption of electricity and its effect on space loads to simulate heating and cooling energy in buildings. The impact of electric gains in buildings on heating and cooling loads is significant. Calculating the loads in the building by using measured electric loads as opposed to fixed specified loads (that are normally used in most simulation programs) will result in simulated heating and cooling loads that respond well to daily or seasonal variations in production, occupancy or operational schedules which otherwise could be hard to predict with simple fixed weekday/weekend/holiday gain schedules.

The fraction of the whole building electric load that directly contributes to heat gains in the space is not necessarily easily determined. Direct sub-metering of interior lighting and plug loads would provide the best approximation of these loads, but this level of sub-metering is seldom available. Some electric loads that would not contribute to heat gain include: exterior lighting, mechanical cooling loads from chiller compressors, air cooled condensers, cooling towers, the AHU exhaust air heat-to-return portion of the lighting load seen in return air plenums, the latent heat of vaporization from electronic humidifiers, interior lighting that may be transmitter to the exterior, losses from mechanical equipment motors in exterior unconditioned spaces, and most exhaust fan power.

Some buildings have loading schedules that are extremely predictable and not very likely to change, and in this case it may be reasonable to specify electric gains in an energy simulation model. In other cases, it may be difficult to get a good measurement of the electric load that would contribute to gains, especially if sub-metering is not available. Because of these situations, it was considered important that the ABCAT simulation model also have the capabilities of specifying electric gains as an input, and it was therefore added to the simulation model.

The ABCAT has been constructed to allow for several manipulations of the measured whole building electric load to ensure that it is accounted for accurately in the simulation model. A fraction of the measured whole building electric gain that is to be assigned to heat gains in the space is specified in the input file. In addition, if multiple system types are defined in the simulation model, the fraction assigned to each system can be specified. Within a single system type, due to the two zone model (interior and exterior zones), a further subdivision of the gain for that particular system must be completed, and two fractions are required in the input file to divide the load by zone. Unless there are reasons not to do so, it is expected that an equal distribution of load per unit area of space would be the most reasonable in determining these fractions. Initial values of all of these fractions should be based on solid knowledge of the systems and equipment in the buildings. Fine tuning of these parameters should then occur in the calibration process.

2.4.3 Additional ABCAT Simulation Features

The following additional features are described in detail in Appendix A:

- Electric Humidification Load Estimation
- Leakage Flow Rates
- Simplified Thermal Mass Considerations

2.5 Model Calibration

For each building in which the ABCAT has been implemented, the model has been calibrated or tuned to match post-commissioning energy consumption which is expected to be representative of "correct" or optimal energy performance. The calibration procedure was aided at times by the method of calibrated signatures developed by Wei et al. (1998). The goal through calibration is minimizing the statistical measures of the Root Mean Square Error (RMSE), the Coefficient of Variation of the Root Mean Square Error (CV-RMSE), and the Mean Bias Error (MBE). These measures are those used by Kreider and Haberl (1994):

$$RMSE = \frac{\sqrt{\sum_{i=1}^{n} \left(y_{pred,i} - y_{meas,i}\right)^2}}{n} \tag{2.1}$$

$$CV - RMSE = \frac{\sqrt{\sum_{i=1}^{n} \left(y_{pred,i} - y_{meas,i}\right)^2}}{n \times \overline{y}_{meas}} \tag{2.2}$$

$$MBE = \frac{\sum_{i=1}^{n} \left(y_{pred,i} - y_{meas,i}\right)}{n \times \overline{y}_{meas}} \tag{2.3}$$

where

$y_{pred,i}$ = the predicted consumption value for sample i
$y_{meas,i}$ = the measured consumption value for sample i
$\overline{y}_{meas}$ = the mean of the measured consumption of the data set
n = the total number of data points

An important part of calibrating a simulation model is understanding the limits of accuracy and how an acceptable or adequate calibration is defined. An analysis of these results in Section 3.6 provides some insight in quantifying acceptable target accuracies for the calibration.

2.6 Executing the Simulation

The calibrated simulation model is run in a semi-continuous fashion, using the measured inputs of daily average electricity consumption, average daily ambient temperature and relative humidity, and the date to predict the heating and cooling requirements of the building. A detailed flow diagram of the ABCAT process through to the execution of the simulation is summarized in Figure 3. The predicted consumption is then compared with the measured consumption and the deviations analyzed as described in the following steps.

2.7 Fault Detection and Graphical Presentation

It is a basic premise of the work presented in this thesis that the types of faults most likely to avoid detection in buildings are the types that are difficult to detect on the daily level, but have a significant impact when allowed to continue for a period of weeks, months or sometimes years. Consequently, this thesis strongly emphasizes the cumulative effect of faults quantitatively, in an eye-catching and informative fashion that compels users to act.

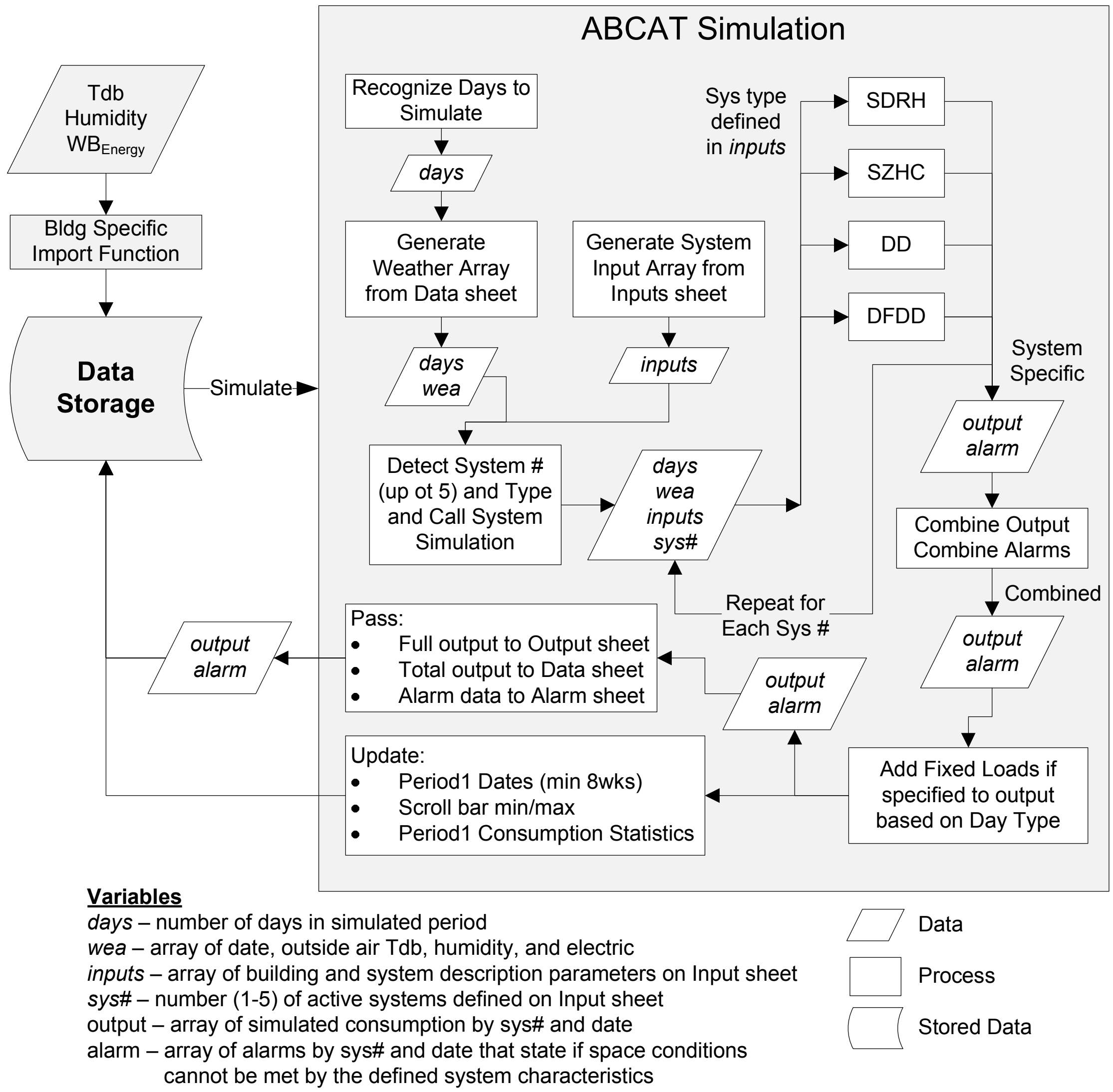

Figure 3. ABCAT Simulation Process Flow Diagram

Several metrics have been evaluated and established for detecting faults with the ABCAT. Two of the primary metrics are the Cumulative Cost Difference, previously used by Haberl and Vajda (1988) and the CUSUM technique. The Cumulative Cost Difference accumulates the cost of persistent deviations from measured consumption by adding the energy residuals to that of the total of the previous day and multiplying by an user specified utility cost. This presents the deviations in the universally understood language of dollars and cents. The CUSUM also enables the detection of small but persistent deviations of the energy residuals and additionally provides an estimator for indicating the start of the fault. From preliminary testing of the two current buildings with ABCAT installed, settings of $k = (.5 - 1)$ and h^+ and $h^- = (4 – 5)$ appear to provide reasonable sensitivity for fault detection. These parameters should be adjusted to minimize false alarms during the calibration period.

In the current state of development of the ABCAT, these metrics require user interpretation to detect faults. This work describes the advantages of, and results from, using them in the ABCAT test phases, but future work will be required to better quantify threshold determination, and appropriate integration of diagnostics, if a fully automated FDD process is desired.

A secondary goal of the ABCAT is to present data in forms that are uniquely informative and easy to interpret, while avoiding the time consuming and often cumbersome task of manipulating, managing and viewing thousands of data points. The current graphical layout of the ABCAT is detailed in Appendix B.

2.8 Fault Diagnostics

As a part of this project, a detailed methodology for fault detection and diagnosis was developed for SDVAV systems, and is described in Section 2.8.1. This approach was determined to be too complicated for direct implementation in the current version of ABCAT, but a simplified variant of this method is described in Section 2.8.2. The simplified diagnostic method shows promise in application to early ABCAT test cases and is undergoing additional testing.

2.8.1 Fault Detection and Diagnosis for Single Duct Air Handling Units[3]

2.8.1.1 System configuration assumptions

The conditioned area is served by single duct AHUs. The AHUs have a supply fan, a return fan and a cooling coil. Both the supply fan and return fan have a variable frequency drive (VFD). The relief air damper, return air damper and outside air damper are interlinked and the air handling unit has an economizer mode. The end users of the system are variable air volume (VAV) terminal boxes with a reheat coil. The cooling coil at AHUs receives chilled water, and the reheat coils at terminal boxes receive hot water from a central plant. The chilled water pump has a VFD and the hot water pump may or may not have a VFD. A preheat coil and humidifier are not used in this system.

---

[3] This section (2.8.1) is the work of Gang Wang and Mingsheng Liu of the University of Nebraska. The work of this section was completed in tandem with the additional work of this thesis under of the California Energy Commission, PIER Energy-Related Environmental Research Program, Contract No. 500-01-044

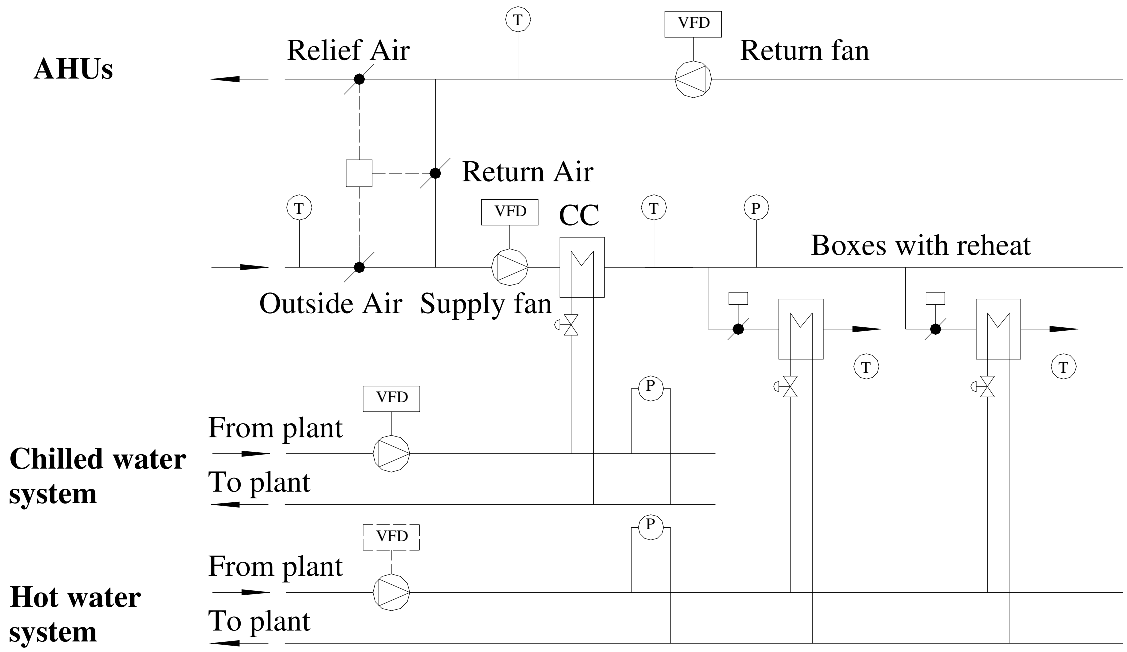

Figure 4. System Schematic

2.8.1.2 System control assumptions

Outside air control

- The outside air damper maintains a minimum position when outside air temperature is higher than the economizer outside air temperature setpoint.
- The outside air damper is fully open when the outside air temperature is between the AHU supply air temperature setpoint and the economizer outside air temperature setpoint.
- The outside air damper is modulated to maintain the supply air temperature at its setpoint until the outside air damper reaches the minimum position.

Cooling coil chilled water valve control

- The cooling coil chilled water control valve is modulated to maintain the supply air temperature at its setpoint

Supply fan speed control

- The supply fan speed is modulated to maintain the duct static pressure at its setpoint.

Return fan speed control

- The return fan speed is modulated to maintain the airflow difference between the supply and return fans or the building pressure at its setpoint.

Terminal box control

- The box control damper is modulated to maintain the space temperature at its setpoint until the terminal box airflow drops to a minimum airflow setpoint.
- The reheat coil hot water valve is modulated to maintain the space temperature at its setpoint when the terminal box airflow drops to a minimum airflow setpoint.

Chilled water system control

- The chilled water temperature is controlled by the chiller operation or determined by the district cooling system.
- The chilled water circulation pump speed is modulated to maintain the chilled water distribution pipe pressure differential at its setpoint.
- The chilled water system is shut down when the outside air temperature is lower than the supply air temperature setpoint.

Hot water system control

- The hot water temperature is controlled by the boiler operation or determined by the district heating system.
- The hot water circulation pump speed is modulated to maintain the hot water distribution pipe pressure differential at its setpoint if a VFD is installed on the hot water pump.
- The hot water system is shut down when the outside air temperature is higher than the economizer outside air temperature setpoint.

2.8.1.3 Information required

The fault diagnosis is based on the following system operational data.

<u>Outside conditions</u>

- Daily outside temperature hours in three different ranges (see Section 2.8.1.4)

<u>Measured energy consumption</u>

- Chilled water energy consumption

- Hot water energy consumption

Measured comfort conditions

- Return air temperature
- Return air humidity

Diagnostic variables

- Supply fan power or discharge air static pressure
- Chilled water power or chilled water pressure differential
- Hot water power or hot water pressure differential

2.8.1.4 Fault list

This study considers only AHU and primary system faults. However, these faults may also result in a terminal box malfunction. For example, high duct pressure may cause air leakage from the duct to conditioned space and a high hot water pressure differential or high hot water supply temperature may make the terminal box use more reheat energy than desired.

Cooling energy, chilled water pump energy, heating energy, hot water pump energy, fan energy and space temperature and humidity are compared in three outside temperature ranges.

- Outside air temperature is less than the supply air temperature setpoint, $T_{s,sp}$ (typically 55°F).
- Outside air temperature is higher than the AHU economizer outside air temperature setpoint, $T_{e,sp}$ (e.g. 65°F in Omaha, NE).
- Outside air temperature is between the supply air temperature setpoint and the AHU economizer outside air temperature setpoint.

a) Supply fan speed control

Fault:

- The fan speed has been overridden.
- The duct static pressure setpoint is set to too high or too low.
- The duct static pressure sensor has malfunctioned.

Explanation

- High duct air pressure increases duct air leakage and increases airflow and fan power. The air leakage may enter the conditioned space and effectively increase the terminal box minimum airflow.
- Low duct air pressure, which results in inadequate terminal box airflow.

Comparison of energy consumption and indoor comfort

Table 1 lists the symptoms of the fan speed control fault. The table describes the response of the various energy and comfort conditions listed in the column on the left, to the fault condition described in the top row of the table in each of the three outside air temperature ranges. The responses have been symbolically simplified to include greater, warmer or more humid (▲), less, colder, or dryer (▼), or unchanged (●)

Table 1. Symptoms of the Fan Speed Control Fault

Energy and comfort	High speed			Low speed		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	Off	▲	▲	Off	▼	▼
CW pump	Off	▲	▲	Off	▼	▼
Heating	▲	▲	Off	▼	▼	Off
HW pump	▲	▲	Off	▼	▼	Off
Fan	▲	▲	▲	▼	▼	▼
Space temperature	• or ▼	• or ▼	• or ▼	• or ▲	• or ▲	• or ▲
Space humidity	•	•	•	•	•	•

b) Pump speed control

I. <u>Chilled water pump</u>

Fault:

- The pump speed has been overridden.
- The pressure differential setpoint is too high or too low.
- The water pressure differential sensor has malfunctioned.

Explanation

- Low supply air temperature, which results from cooling coil chilled water valve leakage due to high pressure differential.

- High supply air temperature, which results from inadequate chilled water flow through the cooling coil due to low pressure differential.

Comparison of energy consumption and indoor comfort

Table 2 lists the symptoms of the chilled water pump speed control fault.

Table 2. Symptoms of the Chilled Water Pump Speed Control Fault

Energy and comfort	High speed			Low speed		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	Off	▲	•[1]	Off	▼	•
CW pump	Off	▲	▲	Off	▼	▼
Heating	N/a	▲	Off	N/a	▼	Off
HW pump	N/a	▲	Off	N/a	▼	Off
Fan	N/a	▼	▼	N/a	▲	▲
Space temperature	N/a	• or ▼	• or ▼	N/a	• or ▲	• or ▲
Space humidity	N/a	▼[2]	▼[2]	N/a	▲	▲

Note: 1. The low supply air temperature decreases the supply airflow or outside airflow, but increases the outside air dehumidification resulting in approximately the same cooling coil energy use.

2. Space humidity level is improved but the fresh air intake decreases.

II. <u>Hot water pump</u>

Fault:

- The pump speed has been overridden.
- The pressure differential setpoint is too high or too low.
- The water pressure differential sensor has malfunctioned.

Explanation

- Reheat coils may add excessive heat to the supply air at the terminal box due to high hot water pressure differential, which results from the high pump speed.
- Reheat coils my not provide enough heat to the supply air at the terminal box due to low hot water pressure differential, which results from the low pump speed.

Comparison of energy consumption and indoor comfort

Table 3 lists the symptoms of the hot water pump speed control fault.

Table 3. Symptoms of the Hot Water Pump Speed Control Fault

Energy and comfort	High speed			Low speed		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	Off	▲	N/a	Off	•	N/a
CW pump	Off	▲	N/a	Off	•	N/a
Heating	▲	▲	Off	▼	▼	Off
HW pump	▲	▲	Off	▼	▼	Off
Fan	▲	▲	N/a	•	•	N/a
Space temperature	• or ▲	• or ▲	N/a	▼	▼	N/a
Space humidity	•	•	N/a	•	•	N/a

c) Outside air control

I. <u>Minimum outside air control</u>

Fault:

- The outside air damper minimum position is set incorrectly
- The outside air damper has malfunctioned.

Explanation

- More warm and humid outside air enters the system when the outside air temperature is higher than the economizer outside air temperature setpoint.
- Less fresh outside air enters the system, which may cause indoor air quality problems.

Comparison of energy consumption and indoor comfort

Table 4 lists the symptoms of the minimum outside air control fault.

Table 4. Symptoms of the Minimum Outside Air Control Fault

Energy and comfort	More min outside air			Less min outside air[1]		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	N/a	N/a	▲	N/a	N/a	▼
CW pump	N/a	N/a	▲	N/a	N/a	▼
Heating	N/a	N/a	Off	N/a	N/a	Off
HW pump	N/a	N/a	Off	N/a	N/a	Off
Fan	N/a	N/a	• or ▲	N/a	N/a	•
Space temperature	N/a	N/a	• or ▲	N/a	N/a	•
Space humidity	N/a	N/a	• or ▲	N/a	N/a	•

Note: 1. The indoor air quality may be worse due to less fresh air.

II. <u>Economizer outside air control</u>

Fault:

- The mixed (or supply) air temperature setpoint is incorrect.
- The mixed air temperature sensor has malfunctioned.
- The outside air damper position has been overridden.
- The outside air damper has malfunctioned.

Explanation

- Mixed or supply air temperature is lower than its setpoint due to a high outside air intake ratio when the system operates in the economizer mode.
- Mixed or supply air temperature is higher than its setpoint due to a low outside air intake ratio when the system operates in economizer mode.

Comparison of energy consumption and indoor comfort

Table 5 lists the symptoms of the economizer outside air control fault.

Table 5. Symptoms of the Economizer Outside Air Control Fault

Energy and comfort	More outside air			Less outside air		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	Off	N/a	N/a	Off	N/a	N/a
CW pump	Off	N/a	N/a	Off	N/a	N/a
Heating	▲	N/a	N/a	▼	N/a	N/a

Table 5. Continued

Energy and comfort	More outside air			Less outside air		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
HW pump	▲	N/a	N/a	▼	N/a	N/a
Fan	▼	N/a	N/a	▲	N/a	N/a
Space temperature	• or ▼	N/a	N/a	• or ▲	N/a	N/a
Space humidity	• or ▼	N/a	N/a	• or ▲[1]	N/a	N/a

Note: 1. The space humidity level is improved.

III. <u>Economizer outside air temperature range</u>

Fault:

- The outside air temperature sensor has malfunctioned.
- The economizer outside air temperature is set incorrectly.

Explanation

- Economizer mode is enabled when the outside air temperature is still too high.
- Economizer mode is disabled when the outside air temperature is low enough.

Comparison of energy consumption and indoor comfort

Table 6 lists the symptoms of the economizer outside air temperature range fault.

Table 6. Symptoms of the Economizer Outside Air Range Fault

Energy and comfort	High economizer outside air temperature			Low economizer outside air temperature		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	N/a	•	▲	N/a	▲	•
CW pump	N/a	•	▲	N/a	▲	•
Heating	N/a	•	off	N/a	•	off
HW pump	N/a	•	off	N/a	•	off
Fan	N/a	•	• or ▲	N/a	•	•
Space temperature	N/a	•	• or ▲	N/a	•	•
Space humidity	N/a	•	• or ▲	N/a	•	•

d) Terminal box control

An individual terminal box operation fault is not covered in this study. The terminal box operation fault is indirectly related to the water pressure change in the hot water system and the air static pressure change in AHUs. The terminal box minimum airflow setpoint at local controllers also may be overlapped with an incorrect value from the central control system.

- A reheat coil fault may results from the hot water pump speed control fault.
- An airflow control damper fault may results from the fan speed control fault.
- Overlapped high minimum airflow setpoint results in the same symptoms as high fan speed.

e) Supply air temperature or cooling coil valve control

Fault:

- The supply air temperature setpoint is incorrect.
- The supply air temperature sensor has malfunctioned.
- The cooling coil valve has malfunctioned.
- The cooling coil valve position has been overridden.
- The chilled water system pressure differential is too high or too low due to a chilled water pump speed control fault.

Explanation

- Low supply air temperature.
- High supply air temperature.

Comparison of energy consumption and indoor comfort

Table 7 lists the symptoms of the cooling coil valve control fault.

Table 7. Symptoms of the Cooling Coil Valve Control Fault

Energy and comfort	Lower supply air temperature			High supply air temperature		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	Off	▲	•[1]	Off	▼	•
CW pump	Off	▲	▲	Off	▼	▼
Heating	N/a	▲	Off	N/a	▼	Off
HW pump	N/a	▲	Off	N/a	▼	Off

Table 7. Continued

Energy and comfort	Lower supply air temperature			High supply air temperature		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Fan	N/a	▼	▼	N/a	▲	▲
Space temperature	N/a	• or ▼	• or ▼	N/a	• or ▲	• or ▲
Space humidity	N/a	▼[2]	▼[2]	N/a	▲	▲

Note: 1. The low supply air temperature decreases the supply airflow or outside airflow, but increases the outside air dehumidification resulting in approximately the same cooling consumption.

2. Space humidity level is improved but the fresh air intake decreases.

f) Duct static pressure control

A duct static pressure control fault results from the fan speed control fault.

g) SA Sensor faults

- An outside air temperature sensor malfunction may result in an economizer outside temperature range fault.
- A mixed air or supply air temperature sensor malfunction may result in an outside air control fault when the outside air temperature is less than the supply air temperature setpoint and result in a cooling coil valve control fault when the outside air temperature is higher than the supply air temperature setpoint.
- A duct static pressure sensor malfunction may result in a fan speed control fault.
- A hot water pressure differential sensor malfunction may result in a hot water pump speed control fault
- A chilled water pressure differential sensor malfunction may result in a chilled water pump speed control fault.

h) Control valve fault

- A cooling coil valve malfunction results in a coiling coil valve control fault.
- A reheat coil valve malfunction, which is related to abnormal hot water pressure differential, results in a terminal box reheat coil valve control fault

i) Damper fault

- An outside air damper malfunction results in an outside air control fault.
- An airflow control damper malfunction at the terminal box, which is related to abnormal duct static pressure, results in a terminal airflow control fault.

j) Boiler and chiller schedule fault

I. <u>Chiller</u>

Fault:

- The chiller is on when outside air temperature is lower than the supply air temperature setpoint.

Explanation

- Economizer mode is enabled when outside air temperature is still too high.
- Economizer mode is disabled when outside air temperature is low enough.

Comparison of energy consumption and indoor comfort

Table 8 lists the symptoms of the chiller schedule fault.

Table 8. Symptoms of the Chiller Schedule Fault

Energy and comfort	chiller schedule fault		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	▲	N/a	N/a
CW pump	▲	N/a	N/a
Heating	▲	N/a	N/a
HW pump	▲	N/a	N/a
Fan	▼	N/a	N/a
Space temperature	• or ▼	N/a	N/a
Space humidity	▼	N/a	N/a

II. Boiler

Fault:

- The boiler is on when outside air temperature is higher than 65°F.

Explanation

- Reheat coils may provide excessive heat to the supply air at the terminal box.

Comparison of energy consumption and indoor comfort

Table 9 lists the symptoms of the boiler schedule fault.

Table 9. Symptoms of the Boiler Schedule Fault

Energy and comfort	Boiler schedule fault		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	N/a	N/a	▲
CW pump	N/a	N/a	▲
Heating	N/a	N/a	▲
HW pump	N/a	N/a	▲
Fan	N/a	N/a	▲
Space temperature	N/a	N/a	• or ▲
Space humidity	N/a	N/a	•

k) Boiler and chiller temperature control fault

I. Chiller

Fault:

- The chiller has malfunctioned.
- The chilled water temperature setpoint is incorrect.

Explanation

- Chilled water temperature may be higher or lower than the design value.

Comparison of energy consumption and indoor comfort

Table 10 lists the symptoms of the chilled water temperature control fault.

Table 10. Symptoms of the Chilled Water Temperature Control Fault

Energy and comfort	Low Temperature			High temperature		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	Off	▲	▲	Off	▼	▼
CW pump	Off	▼	▼	Off	▲	▲
Heating	N/a	• or ▲	Off	N/a	• o r ▼	Off
HW pump	N/a	• or ▲	Off	N/a	• or ▼	Off
Fan	N/a	• or ▼	• or ▼	N/a	• or ▲	• or ▲
Space temperature	N/a	• or ▼	• or ▼	N/a	• or ▲	• or ▲
Space humidity	N/a	• or ▼[1]	• or ▼[1]	N/a	• o r ▲	• or ▲

Note: 1. The space humidity level may be improved.

II. <u>Boiler</u>

Fault:

- The boiler has malfunctioned.
- The boiler water temperature setpoint is incorrect.

Explanation

- Hot water temperature may be higher or lower than the design value.

Comparison of energy consumption and indoor comfort

Table 11 lists the symptoms of the hot water temperature control fault.

Table 11. Symptoms of the Hot Water Temperature Control Fault

Energy and Comfort	High temperature			Low temperature		
	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$	$T_{oa} < T_{s,sp}$	$T_{s,sp} < T_{oa} < T_{e,sp}$	$T_{oa} > T_{e,sp}$
Cooling	Off	• or ▲	N/a	Off	•	N/a
CW pump	Off	• or ▲	N/a	Off	•	N/a
Heating	▲	▲	Off	▼	▼	Off
HW pump	▼	▼	Off	▲	▲	Off
Fan	• or ▲	• or ▲	N/a	•	•	N/a
Space temperature	• or ▲	• or ▲	N/a	• or ▼	• or ▼	N/a
Space humidity	•	•	N/a	•	•	N/a

2.8.2 Simplification of Fault Detection and Diagnosis for ABCAT

The method just described outlines a strategy for FDD, but the sensor requirements (4 per AHU plus 3 common to all systems), makes this technique too complex for the targeted simplicity of ABCAT. A similar but simpler approach can be taken to balance the ease of implementation with desired diagnostic capabilities.

Beneficial diagnostic information can be derived from the observed relationships between heating and cooling consumption deviations from that expected, along with the ambient conditions at which these deviations occur. The types of faults expected to be identified are general in nature and are expected to fall into one of the following categories:

1. Supply Air Flow Rate Fault
2. Chilled Water Pump Differential Pressure Fault
3. Hot Water Pump Differential Pressure Fault
4. Outside Air Flow Rate Fault
5. Supply Air Temperature Fault
6. Chilled Water or Hot Water Metering Fault
7. Chiller or Boiler Run-Time Fault

Each of these fault categories would have a subset of possible faults associated with it. Table 12 provides a proposed outline for this procedure which is a slight modification of Wang and Liu (2006) (Section 2.8.1), with the types of faults indicated on the left hand side, and their affect on cooling and heating consumption residuals (greater than ▲, less than ▼, or as expected ●) to the right. Each fault is divided into three temperature ranges based on ambient temperature: $T_{oa} < T_{sa,sp}$ (supply air temperature); $T_{s,sp} \leq T_{oa} \leq T_{e,sp}$ (temperature the economizer deactivates); $T_{oa} > T_{e,sp}$. In the system described, cooling not required when $T_{oa} < T_{s,sp}$ and heating is not required when $T_{oa} > T_{e,sp}$. The gray shaded cells with the striped background represent faults that are expected to cause significant problems with comfort in the buildings, and are therefore more likely addressed with corrective measures before a significant and persisting energy impact can be observed. The energy impact of these faults also is less heating and/or less cooling than expected, which, in general, is a less common problem.

Table 12. SDVAV w/Economizer Rules for Diagnostic Clarifier

Fault Type		Higher			Lower		
		$T < T_{s,sp}$	$T_{s,sp} < T < T_{e,sp}$	$T > T_{e,sp}$	$T < T_{s,sp}$	$T_{s,sp} < T < T_{e,sp}$	$T > T_{e,sp}$
1. Supply Air Flow Rate	Cooling	Off	▲	▲	Off	▼	▼
	Heating	▲	▲	Off	▼	▼	Off
2. CHW Pump DP	Cooling	Off	▲	●	Off	▼	●
	Heating	N/A	▲	Off	N/A	▼	Off
3. HW Pump DP	Cooling	Off	▲	N/A	Off	●	N/A
	Heating	▲	▲	Off	▼	▼	Off
4. Outside Air Flow Rate							
a. Minimum OA Flowrate	Cooling	N/A	N/A	▲	N/A	N/A	▼
	Heating	N/A	N/A	Off	N/A	N/A	Off
b. Economizing OA Flowrate	Cooling	Off	N/A	N/A	Off	▲	N/A
	Heating	▲	N/A	N/A	▼	●	N/A
c. Economizer Temperature	Cooling	N/A	●	▲	N/A	▲	●
	Heating	N/A	●	Off	N/A	●	Off
5. Supply Air Temperature	Cooling	Off	▼	●	Off	▲	Same
	Heating	N/A	▼	Off	▲ or ●	▲	Off
6. Metering							
a. Chilled Water Meter	Cooling	Off	▲	▲	Off	▼	▼
	Heating	●	●	Off	●	●	Off
b. Hot Water Meter	Cooling	Off	●	●	Off	●	●
	Heating	▲	▲	Off	▼	▼	Off
7. Scheduling		Longer			Shorter		
a. Chiller	Cooling	▲	▲	▲	▼	▼	▼
	Heating	▲	▲	▲	▼	▼	▼
b. Boiler	Cooling	▲	▲	▲	▼	▼	▼
	Heating	▲	▲	▲	▼	▼	▼

Notes: N/A - Not Applicable; Cooling Off When $T <_{s,sp}$; Heating Off When $T >_{e,sp}$

To determine how to categorize consumption data from each temperature zone, a user specified fixed threshold can be applied, such as $\pm 1\sigma$ centered on a zero residual for expected (●) conditions. If the majority of the points fall outside the $+1\sigma$ limit it will be considered ▲, or ▼ in the case of outside the -1σ limit.

If a fault with a specific pattern of heating and cooling is observed in only one temperature range, three or four of the fault categories may apply. As more data is gathered from one of the other ambient temperature ranges, the possibilities for a more deterministic diagnosis improve. The approach taken with the ABCAT is to readily provide the condition of the heating and cooling data in each of the outside air temperature ranges to users such that they can refer to fault tables made specifically for the systems and operating modes of the specific test building. Special considerations will have to be made for systems without economizers, systems that require year round heating and cooling or systems with mixed system types. Results from applying this diagnostic approach where applicable to the ABCAT test buildings in this study are presented in the following chapter.

CHAPTER III

PROJECT RESULTS

3.1 Initial Live Test Cases

Early testing of the ABCAT in the two Texas facilities provided a live learning scenario that helped to influence developments with the program particularly in the areas of fault detection, graphical presentation and diagnostic capabilities. Fortunately during this test period, the ABCAT was on-line in the buildings when two instances of abnormal energy consumption occurred (one in each building). Presented are the findings of these two test cases, which include the process by which the faults were determined to exist, and the investigative reasoning that led to the diagnosis in each case.

3.1.1 Sbisa Dining Hall (College Station, TX)

3.1.1.1 Building Description

Sbisa Dining Hall (Figure 5) is an 82,000 ft^2 single story building with a partial basement on the campus of Texas A&M University in College Station, TX. Its primary function is as a dining facility, although a small fraction of the building is dedicated to office space and a bookstore. A total of 19 AHUs, 12 on the main floor and seven in the basement supply the heating and cooling needs of the building. Four of these units are strictly for makeup air in the kitchen and are interlocked with individual fume hoods, two are SDVAV and the rest are SDCV with terminal reheat units. Three constant volume dedicated OAHUs provide pretreated makeup air for the majority of the AHUs. The schedule of the primary food service function of the facility generally follows the university class schedules, and shuts down for spring break, the winter semester break and various campus holidays, and operates for reduced hours over the summer session. Thermal energy is supplied to the building in the form of hot and chilled water from the central utility plant.

Figure 5. Sbisa Dining Hall

3.1.1.2 Data Collection and Processing

The thermal and electric energy consumption measurement, along with the EMCS sensor data are managed by the campus Energy Office. An automated routine retrieves and updates files in a server folder on a daily basis that provide the past seven days of thermal and electric energy as well as the ambient temperature and relative humidity data from EMCS sensors at the building. A remote desktop (host computer for the ABCAT program) on the same campus-wide network, is given IP address read-only logon permission to the specific folder on the server. The ABCAT was programmed to be automatically executed every three days to ensure that occasional network delays in updating the consumption files, or any communication errors with the server would not lead to incomplete data collection. This system provides the required data inputs for the ABCAT with no human intervention required.

3.1.1.3 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 02/02/2004 – 12/31/2004, the results of which are presented in Figure 6 and Table 13.

3.1.1.4 Initial Findings

SBISA Dining Hall Chilled Water Energy Consumption Fault Identified

Introduction

During the early spring of 2006 an unexpected increase in cooling energy consumption was detected, at an additional cost to the campus of approximately $950/week. The fault was determined to be the result of excessively low discharge air temperatures in two of the three dedicated OAHUs in the building. Several figures from the ABCAT tool are presented below to explain how, through use of the ABCAT,

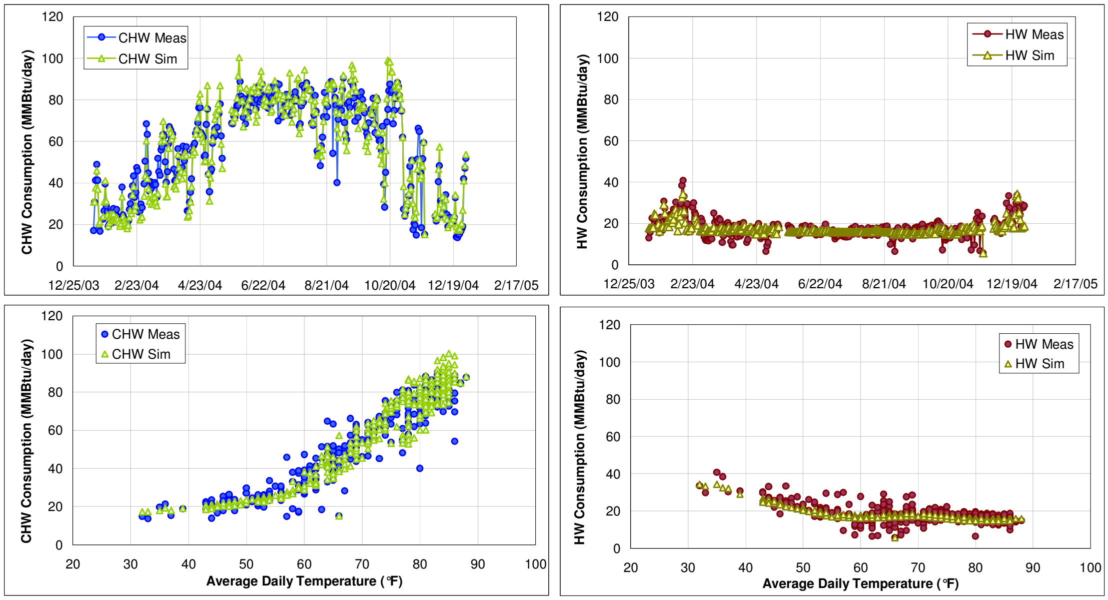

Figure 6. Time Series and OA Temperature Dependent Plots of the Measured and Simulated Cooling and Heating Consumption for the Period used to Calibrate the Sbisa Dining Hall Simulation.

Table 13. Calibration Statistics of the Sbisa Dining Hall

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	6.96	0.6	90.48	55.92	12.45%	MMBtu/day
HW:	3.36	-0.288	40.8	17.76	18.92%	MMBtu/day

the conclusion was drawn that this fault existed. Also described is how the ABCAT, along with the addition of some key trended control system data, assisted in narrowing down the likely cause of the fault. Note that all of the plotted data are presented as daily averages.

Fault Detection

Figure 7 displays the measured and simulated chilled water energy consumption for the period of 2/20/2006-6/4/2006, which spans the period during which this cooling energy consumption fault appeared.

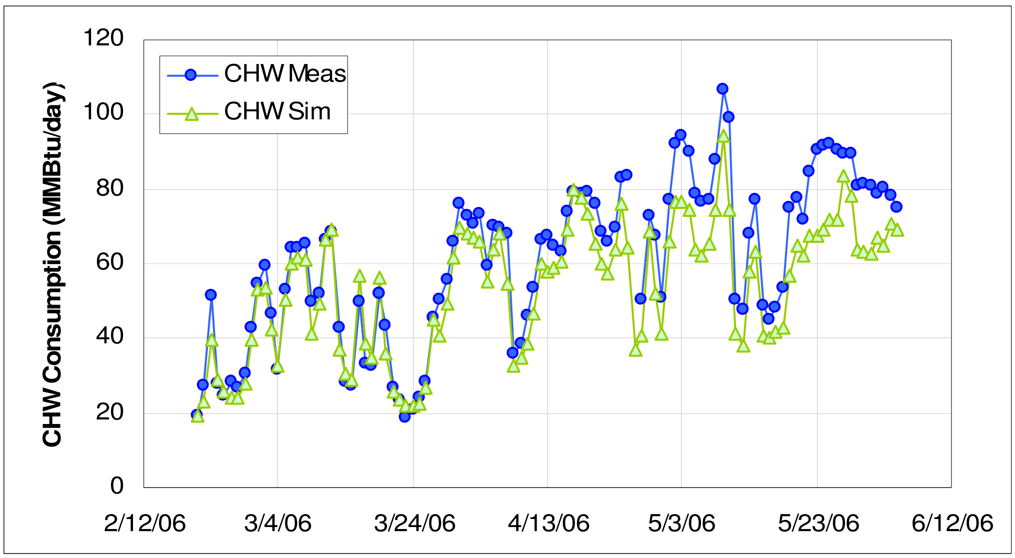

Figure 7. Measured and Simulated Chilled Water Energy Consumption 2/20/2006 – 6/4/2006

The significance of the daily deviation seen in Figure 7 may be difficult to gage unless it is also accumulated and compared with past performance. The cumulative effect of this increased consumption can be seen in Figure 8, where the daily difference between the measured and simulated consumption is multiplied by an estimated cooling energy cost of $13.437/MMBtu, and added to the previous day's total. This figure shows that costs had increased by nearly $9,500 over that expected for the 10 week period of time (3/27/2006 – 6/4/2006).

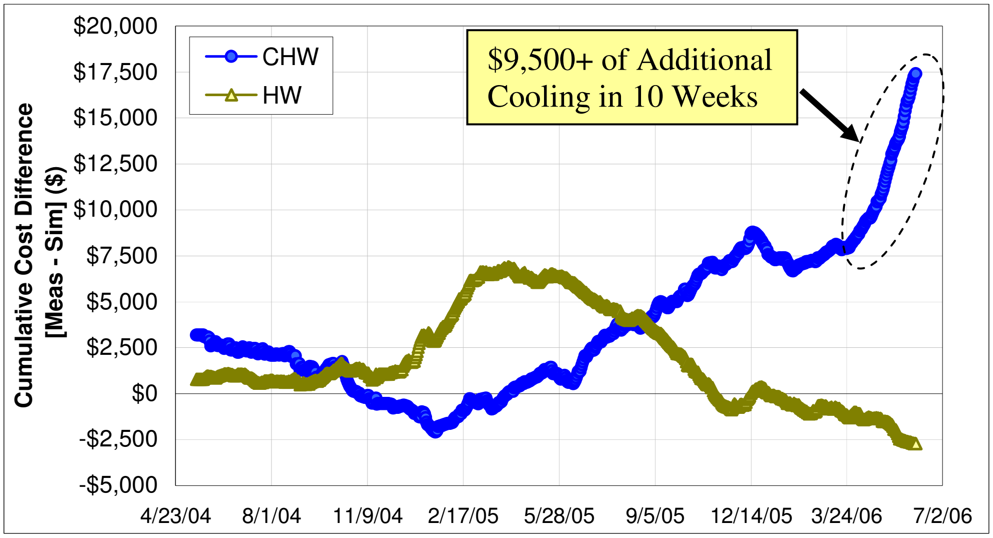

Figure 8. Cumulative Cost Difference (Assuming $13.437 and $17.650/MMBtu for CHW and HW respectively)

Figure 9 is a plot of the difference (Meas – Sim), as a percent of the maximum consumption during the baseline period (2004), which was 90.5 MMBtu/day. This means that a 10% difference in Figure 9 corresponds to a measured cooling energy consumption of 10% x 90.5 or 9.05 MMBtu/day greater than that which was simulated. This error plot shows that the seven day moving average of the percent difference had been within the +/-10% range for nearly the entire period of the plot (more than 2 years) except for the period starting around April 25th, 2006, and continuing through the beginning of June.

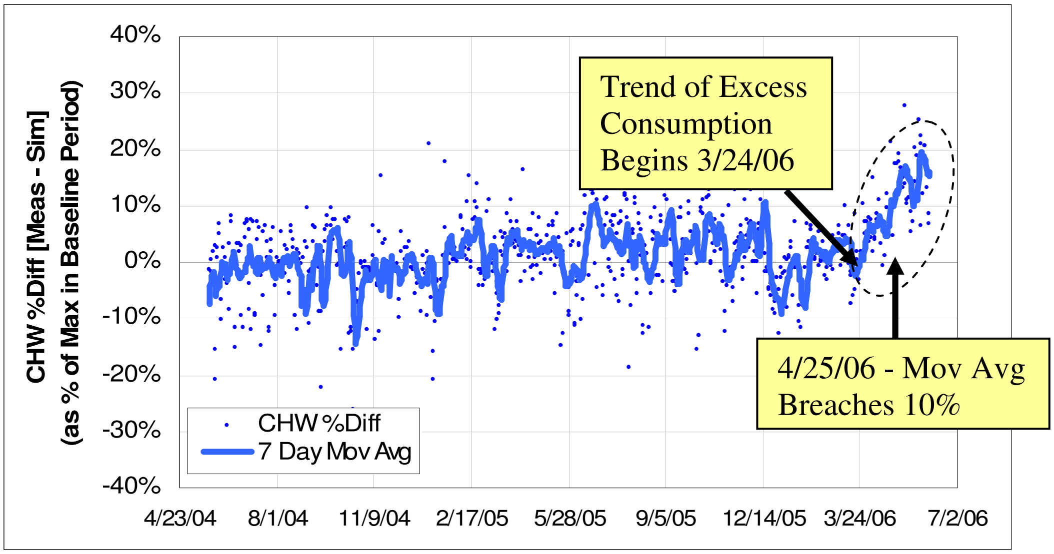

Figure 9. CHW % Difference Plot (10% Error → (Meas – Sim) of 9.05 MMBtu/day

Diagnosis

To assist in identifying the cause of the fault, Figure 10 compares the WB_{Elec} consumption for this period of increased cooling energy consumption, along side the WB_{Elec} from the same dates in 2005. The similarity of the two series in Figure 10 indicate that the cause of this increase in cooling energy is not likely related to an increased electric load in the building. Additionally, in referring back to Figure 8, it can be seen that the measured HW heating energy consumption did not vary from the simulation nearly as much as the CHW consumption, and actually was consistently slightly less than the simulated consumption since the beginning of 2006. This revealed that the increased cooling energy was not caused by an increase in heating energy consumption.

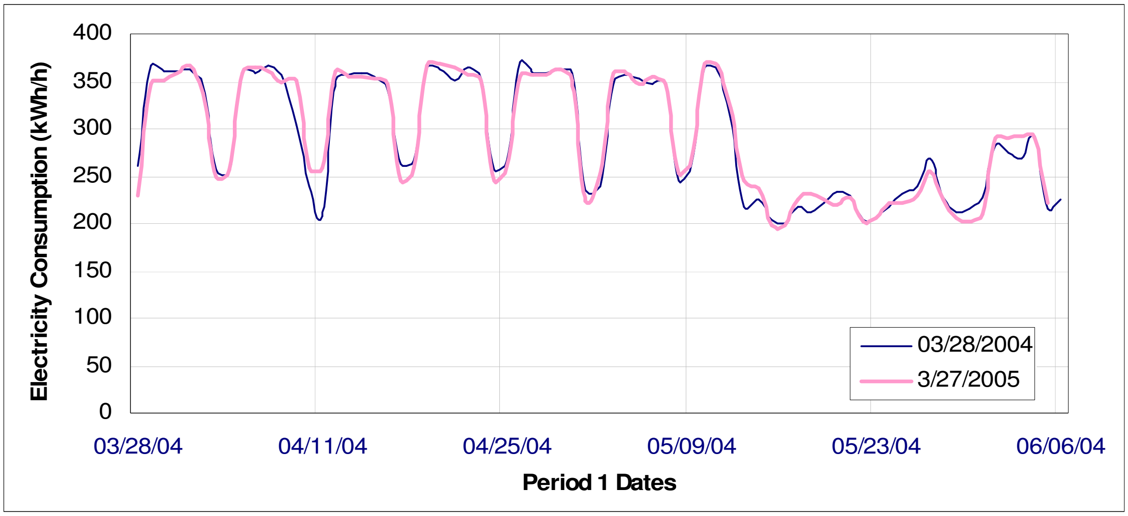

Figure 10. Electric Consumption for two 10 week periods 1 year apart; start dates of periods are 3/28/2005 and 3/27/2006

Further investigation into trended control data points has led to the discovery of exceptionally low discharge air temperatures (extended periods at < 50°F) in two of the three OAHUs (OAHUB1 and OAHU2) in the building. From analyses of the trend data it can be determined that these same operating conditions have been in place for an extended period of time (at least since November 2005), and therefore the change in discharge air temperature of these units does not coincide directly with the identified period of increased cooling consumption. But this does not mean that the two are unrelated. The average ambient dew point temperature in College Station does not tend to consistently rise above 50°F until late March/early April (Figure 11). This means that the low discharge air temperatures for the outside air handling units would not result in a significant increase in latent cooling loads until this spring time period had arrived.

Conclusion

This investigation surmised that the OAHU's discharge air temperature control set points were lowered some time in late September/early October 2005 during a time in which the outside dew point had already fallen well below its summer highs. Although the trended data is not available from that time period to prove this conjecture, there are other reasons to believe this is a latent cooling issue. First, if it was an increase in sensible cooling, either hot water reheat energy would have increased to compensate for the increased cooling, or a noticeable drop in space temperatures would have occurred. It was noted previously that heating energy use in the building was actually slightly lower than expected for this period. Also, since space temperatures were trended and investigated during this period and no significant changes were identified, we can confidently rule out an increase of sensible cooling as the determining factor in the excess consumption. Therefore it was recommended that the discharge air temperature schedules for OAHUB1 and OAHU2 be reset to higher levels that maintain adequate humidity control in the building, without adding a penalty from excessive latent cooling.

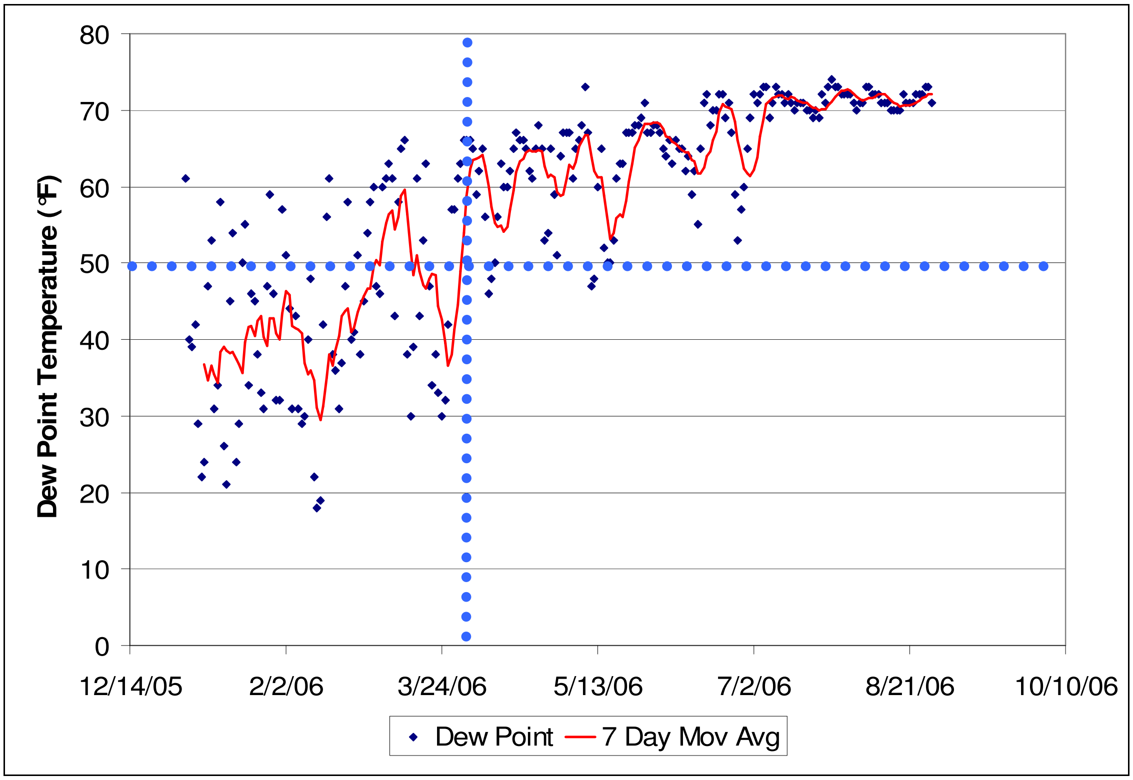

Figure 11. Jan – Aug 2006 Average Daily Dew Point Temperature in College Station, TX

3.1.2 Computing Services Building (Austin, TX)

3.1.2.1 Building Description

The Computing Services Building (Figure 12) in Austin, TX is a 2-story and half basement 482,000ft^2 facility consisting of computer test laboratories, offices, a kitchen and cafeteria. During the period of initial ABCAT monitoring of the facility, electric and thermal energy (in the form of chilled water and steam) were supplied to the facility from the district utility provider. A heat exchanger converted the heating energy of the steam to hot water for heating coil use in the air handling units. The steam was also required for steam kettle and dishwashing equipment in the cafeteria kitchen. RCx activities were performed on the building from October 2004 through February 2005, although most measures were implemented by the beginning of December 2005.

The interior zone air handling units in the building are primarily SDVAV units with economizers and mixed air preheat. The AHUs that serve exterior zones have separate hot deck units, making them DFDD units. The hot deck fans are activated when outside air temperatures drop below 50°F. The main air handling units' cooling is supplemented by more than a dozen chilled water cooled Liebert fan coil units which ensure proper cooling in several energy intense computer testing laboratories.

Figure 12. Computing Services Building

3.1.2.2 Data Collection and Processing

The thermal consumption data is recorded and stored in the secure server database of the utility provider. A representative from the utility provider creates a weekly consumption data file that is sent as an email attachment to the remote user at Texas A&M University. The hourly electric data and ambient weather conditions (dry bulb temperature and relative humidity) are available and combined in a single file, downloadable with a secure sign-on to the utility provider website. The weather data provided is obtained from a local National Weather Service station in Austin.

3.1.2.3 Calibrated Simulation

The ABCAT simulation was originally calibrated to the baseline consumption period of 12/01/2004 – 11/30/2005, the results of which are presented in Figure 13 and Table 14.

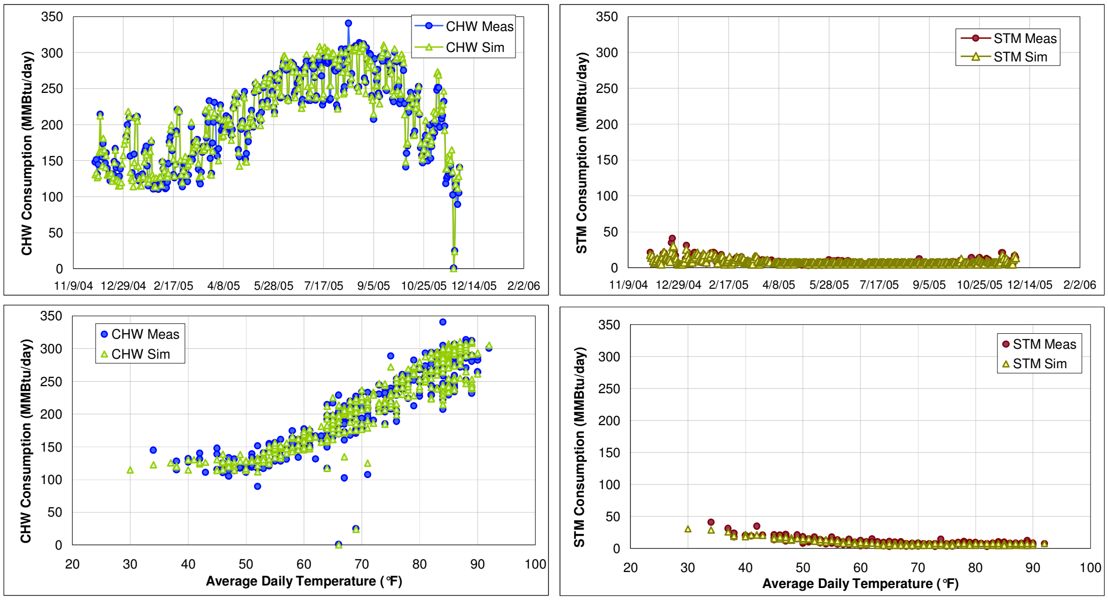

Figure 13. Time Series and OA Temperature Dependent Plots of the Measured and Simulated Cooling and Heating Consumption for the Period used to Calibrate the Computing Services Building Simulation.

Table 14. Calibration Statistics of the Computing Services Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	10.800	0.692	340.644	210.910	5.1%	MMBtu/day
STM:	1.693	0.213	40.943	8.347	20.3%	MMBtu/day

3.1.2.4 Initial Findings

Computing Services Building Cooling Consumption Fault Identified

Introduction

The ABCAT had been continuously monitoring the energy consumption from the Computing Services Building since May 2005. This monitoring resulted in the identification of a subtle change in chilled water energy consumption in the fall of

2005. It was determined that the situation was likely the result of changes in the metering equipment that were introduced to the system at the time of the last meter calibration in October of 2005. The following information and figures in this report will help explain how this conclusion was reached from the use of the ABCAT along with some follow up investigation with key building energy personnel.

Since the RCx measures implemented in the building were for the most part completed by November 2004, a period of one year starting December 2004 was established as a baseline for determining expected energy consumption. The ABCAT's energy simulation engine was calibrated to the energy consumption from this period.

Fault Identification

As the monitoring continued months past the end of this baseline period, several key observations were made. First, a significant decrease in CHW cooling energy was detected with the Cumulative Energy Difference plot of Figure 14. The magnitude of the daily difference was approximately 18 MMBtu/day on average (or about 10%) less than that expected.

In addition, the steam consumption in the building remained roughly as expected as can be seen by either Figure 14 or Figure 15. The steam energy consumed constitutes only a small fraction of the total energy use in the building, on average less than 3% of total energy. The cooling load dominated building, with variable speed drive HVAC units, and a separate hot deck fan and duct system, requires no HVAC related steam heating in the summer and winter heating only increases the contribution of steam to total building energy to approximately 7%. The cafeteria kitchen with a dishwasher and two steam kettles was the steady, year round principal consumer of steam in the building.

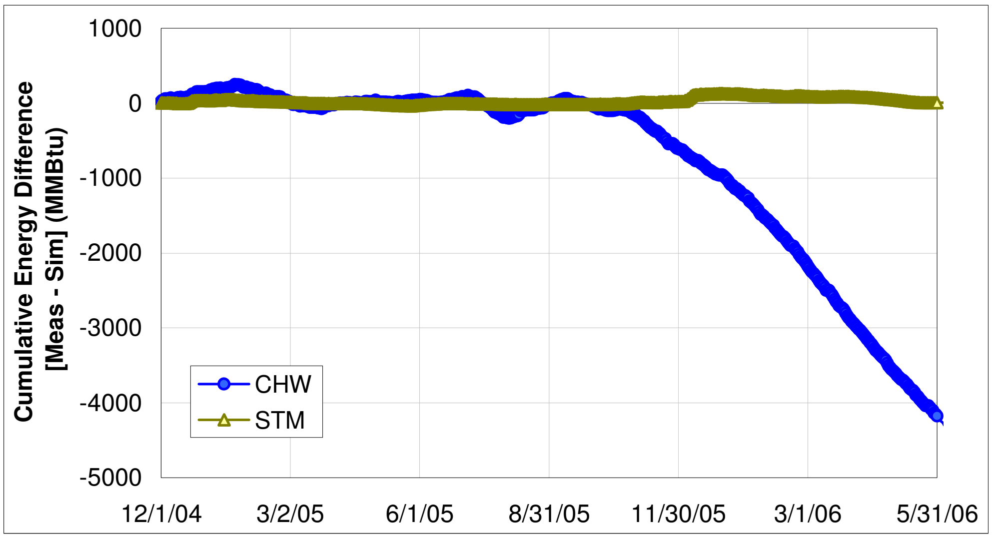

Figure 14. CHW and STM Cumulative Energy Difference for the period of 12/01/04 – 05/31/06

Finally, the electric load from the period December 2005 through May 2006 was on average about 100 kWh/h (341,200 Btu/hr in additional cooling load) greater than that of the same period the year previous (Figure 16). For a building with an average of approximately 2500 kWh/h or 5.0 W/ft^2, this is a modest increase of 4%.

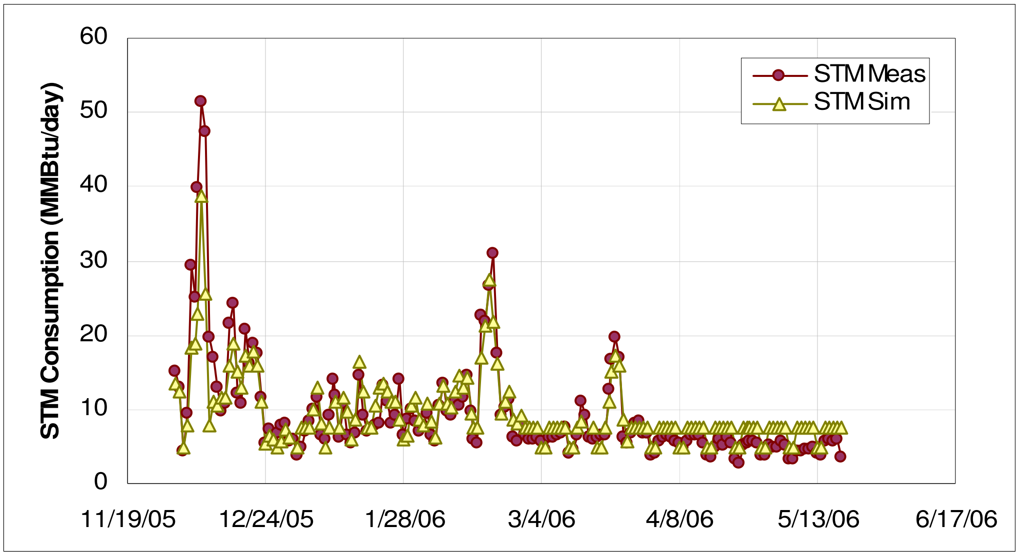

Figure 15. ABCAT Measured and Simulated Average Daily Steam Energy Consumption

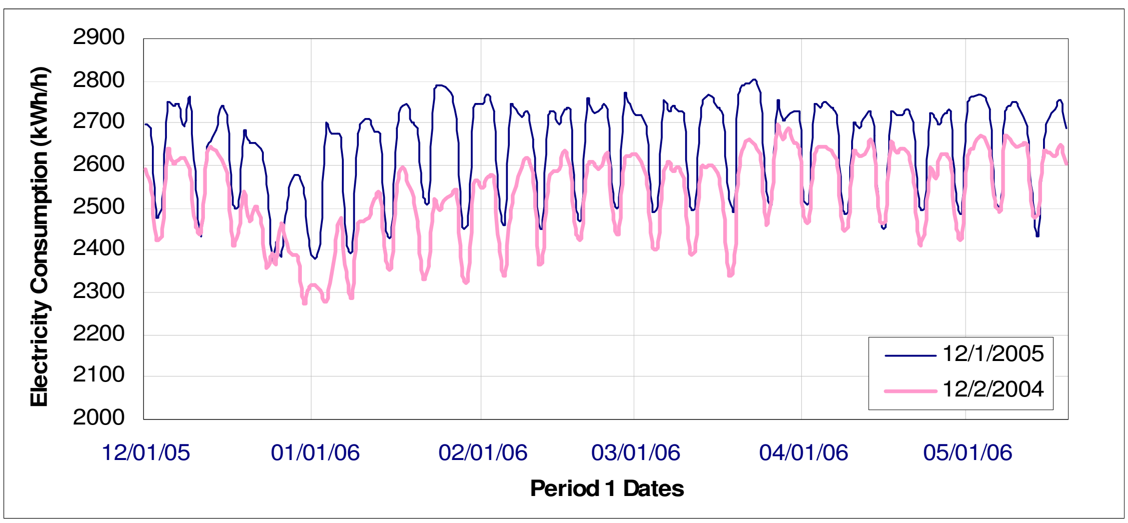

Figure 16. ABCAT Time Series Average Daily Electric

A 4% increase in electricity consumption in a computing services energy intensive building can be reasonably explained with changes in work load or production/service schedules. A slight retreat back to less than optimal lighting or equipment operation schedules could also have potentially contributed to the increased load. But explaining the significant cooling energy decrease during this time with increasing electricity consumption and heat gain in the building presented a perplexing situation.

Diagnosis

To analyze the situation, the first assumption made was that comfort conditions within the building did not drastically change during this period. With that said, a perfect explanation for the change in building energy consumption would be the addition of mechanical cooling and DX (direct expansion) units, which would offset the chilled water load while increasing electricity consumption. Key energy personnel of the building were asked if the installation of new DX equipment or activation of old dormant equipment could have caused these changes in consumption. They indicated the only DX units in the building are four 20 ton units which have not seen significant changes in their operation for years.

Also discussed during this meeting was the possibility that the increase in electric load could have been a result of the addition of parking lot lights or some other source which would not translate the electricity consumed into direct heat gain in the conditioned space. Again, the knowledgeable building personnel were not aware of any such changes. Even if this was the case, it would only explain an increase in electricity consumption not associated with increased cooling, but this would not explain the decrease in cooling observed.

Increased use of outside air and improved economizer operation could have explained the difference seen in the cooling consumption for days that were sufficiently cold, but the deviation spanned a period with a wide range of ambient temperatures, and the economizer function would not have been constantly used.

With the investigation providing no discernable solution, it became evident that the fault was likely unrelated to operational changes in the building, and the focus shifted towards the energy meter. Initially it was thought that since the utilities (steam, chilled water, and electricity) were provided by a utility company, the utility grade meters would be an unlikely source of error. An inquiry was sent to the utility provider asking if any metering changes or calibration had taken place toward the end of 2005. The response was:

> "… the [building] chilled water meters were last calibrated on 10/28/05. Two of the meters were very close when checked, but one meter (FT45T04) appeared to be reading a little high on flow in the lower half of its range. The calibration report noted that the calibration company had difficulty finding a location for the standard (comparison) flow meter where turbulence did not create high readings."

Although it was believed that the calibration change was minor and would not have been significant, findings from use of the ABCAT program have shown that this was not the case. Using the figures from the ABCAT to examine the period around 10/28/05 provides some additional support to this theory that the decrease in cooling consumption is directly tied to a metering problem. Although it may be difficult to distinguish a definite decrease in consumption from the inaccuracies or limitations of the simulation in the daily time series plot (Figure 17), there does seem to be a definite pattern of decreased consumption starting around this time evident in the cumulative energy difference plot (Figure 18). The cumulative energy difference plot takes the difference between the measured and simulated energy consumption on a daily basis and adds it to the result from the previous day. Assuming a cost of $10.00/MMBtu for the chilled water utility service, this translates into a cost savings of approximately $76,510.

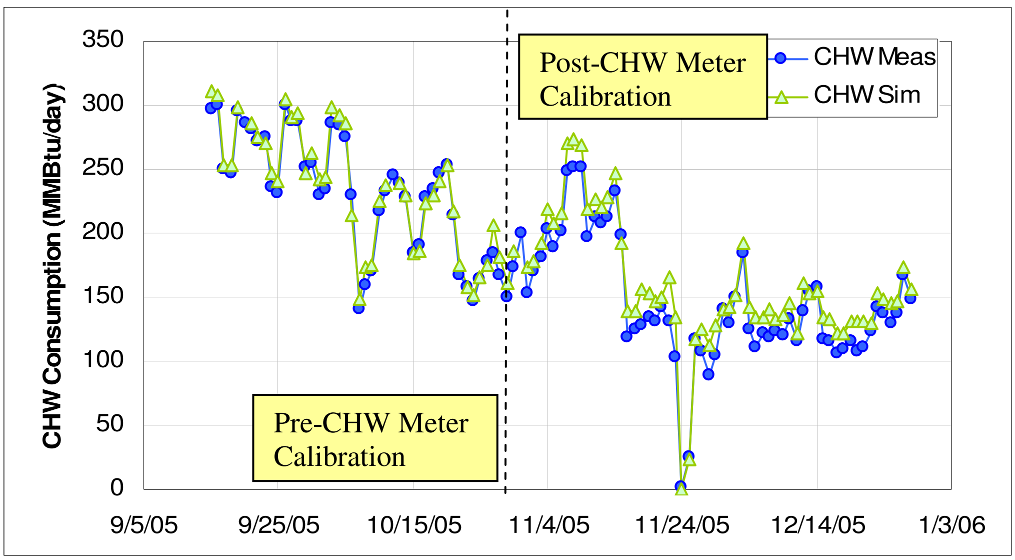

Figure 17. ABCAT Pre & Post CHW Meter Calibration Measured and Simulated Average Daily Chilled Water Energy Consumption

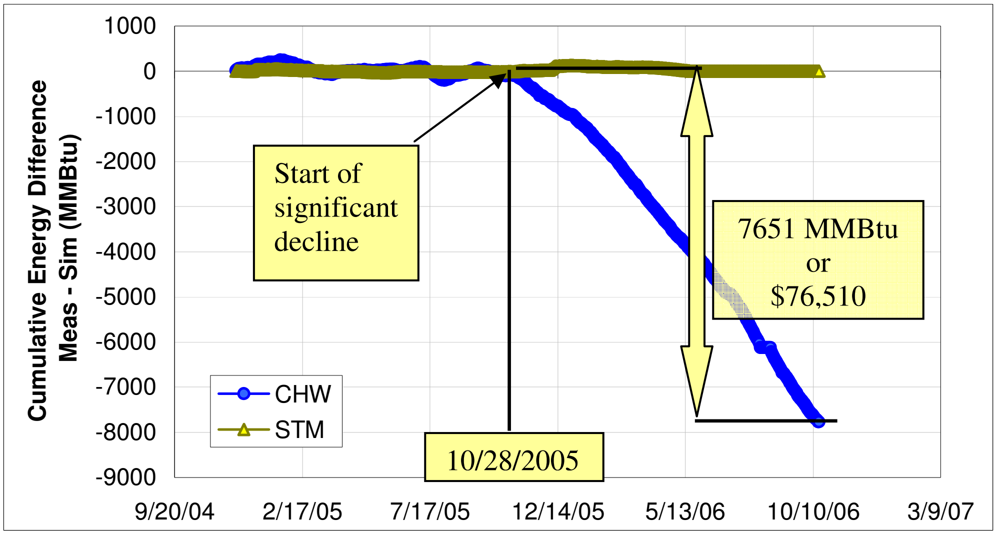

Figure 18. ABCAT Cumulative Energy Difference Meas – Sim (MMBtu) with Simulation Re-Calibrated to Period of 12/01/2004 to 10/27/2005

If the CHW meter calibration that took place on 10/28/2006 was indeed accurate, this opens the window to the possibility that the measurements prior to that date were high. To estimate the significance of the error in these chilled water measurements, the simulation had to be recalibrated to a new baseline period (post-CHW meter calibration), and the period from 10/28/2005 – 5/19/2006 was selected. This new simulation model was then applied to the period from 12/01/2004 – 10/27/2005. The result is shown in Figure 19.

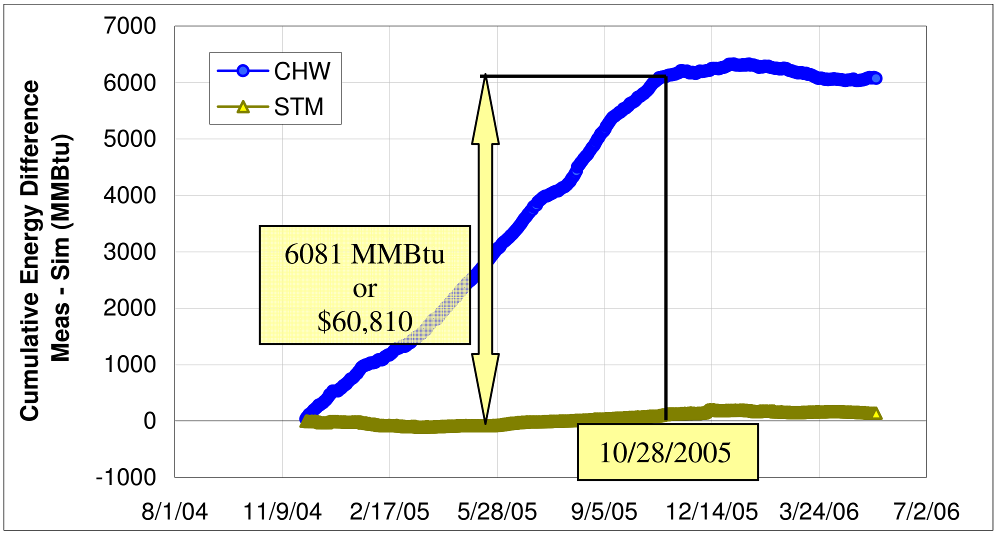

Figure 19. ABCAT Cumulative Energy Difference Meas – Sim (MMBtu) with Simulation Calibrated to Period 10/28/2005 to 5/19/2006

Conclusions

Monitoring the Computing Services Building with the ABCAT has resulted in the identification of a significant decrease in chilled water energy consumption. A follow up investigation with the utility provider revealed that the timing of the calibration of their chilled water meters coincided with the beginning of the period of decreased consumption. Discussions with energy personnel at the facility revealed that no major operating changed or retrofits occurred in the building during this time that could have also contributed to this decrease.

It is natural to assume that the most recent calibration of the chilled water meter is the most accurate measurement available. In this case, we have re-calibrated or "tuned" the simulation model of ABCAT to the period after this meter calibration took place (10/28/2006 – 5/19/2006) and then ran the model against the period prior to the meter calibration. It appears that for the period of 12/01/2006 to 10/27/2006 that the computing services facility may have been overcharged by the utility provider for chilled water energy in the tune of 6081 MMBtu or 507 Ton-hr (Figure 19).

There is also the possibility that the CHW meter calibration of 10/28/2006 was somehow flawed such that the measured consumption prior to this date is accurate. In this case, a simulation model calibrated to the period of 12/01/2004 to 10/27/2005 and applied to the period of 10/28/2005 to 10/16/2006 shows that CHW consumption is 7651 MMBtu or 638 Ton-hr less than that expected for the period (Figure 18).

The supporting evidence in this summary report indicates that this detected change in measured consumption is linked to the CHW meter calibration on 10/28/2005. Additional construction or operational changes cannot be ruled out as partial cause of this decrease in energy consumption, but the start date and the consistency of the detected difference throughout all seasons while the electric load in the building was increasing, strongly suggests a metering problem as the main culprit. It was recommended that a thorough review of the calibration reports be conducted to fully understand the modifications made and if they were suitable for the specific flow meter installations.

3.1.3 How the Early Test Cases of Sbisa and the Computing Services Building Shaped the ABCAT Development

The testing of the ABCAT in these two buildings, the identification of the faults and the diagnostic reasoning that followed, helped shape some specific ideas for the developmental direction of the ABCAT. Some of the keys points from these early test experiences are the following:

- Analysis of daily consumption data at the whole building level can provide enough detail to identify and troubleshoot faults that have a significant effect on energy consumption in buildings.

- Accumulated deviations from optimal performance provide the best indicator of significant faults that persist. In both buildings the faults detected were well below the +/-3 Std Dev (often used as fault thresholds in process control scenarios) and instead on the order of +/- 1.5 Std Dev. By themselves, on an individual daily basis, these points cannot distinguish themselves from a significant number of non-fault condition points that lie outside the +/- 1.5 Std Dev. Range.

- The cumulative consumption cost appears to be a good indicator of significance of a fault, communicating in a language ($) that is either significant to the user or can be used by the user to compel action.

- The value of ABCAT does not appear to lie in daily short-term observations, but rather in observations on the order of weeks to months.

- In both of the faults discussed, knowing the start date of the fault greatly assisted in diagnosing the cause.

- The advantage of using a first principles simulation model (with minimal training data required) in the ABCAT was seen because changes occurred in the Computing Services Building. The cooling meter calibration, the subsequent shutdown of the steam utility supply, and the installation of a natural gas boiler, all constitute a need to recalibrate the simulation model.

- The Computing Services Building benefited from using measured instead of specified electric gains in the simulation. The ABCAT provides a means to account in the simulation changes in electric gain levels (increase in this case), which results in predicted consumption that more accurately represents the current building operational needs.

3.2 ABCAT Layout

3.2.1 Interface

The ABCAT is laid out as any typical Microsoft Excel file, with multiple worksheets and chart sheets accessible by the colored tabs at the bottom of the screen. The Interface sheet, seen in Figure 20, is the gateway of communication between the user and the tool, and includes the following:

- The dates of the periods analyzed can be adjusted
- Various alarm thresholds can be modified to user preferred levels
- Utility cost information can be specified
- Folder and file locations can be setup for importing and saving data files
- The calibrated simulation statistical results for the baseline
- Consumption totals and diagnostic summary of the period analyzed

3.2.2 Charts

The ABCAT has three chart sheets, Meas&Sim, Meas&Sim(2) and Meas&Sim(3), that provide multiple performance plots per sheet of measured and simulated consumption for the period defined as Period 1 on the Interface sheet. The Period1&2 and Period1&2(2) chart sheets compare the measured consumption from the two periods defined on the Interface sheet as Period 1 and Period 2, also with multiple plots per sheet. An individual plot description and a detailed layout of the plots can be found in Appendix B. Two of these plots have been identified as key components in the ABCAT fault detection process and are highlighted below due to their significance.

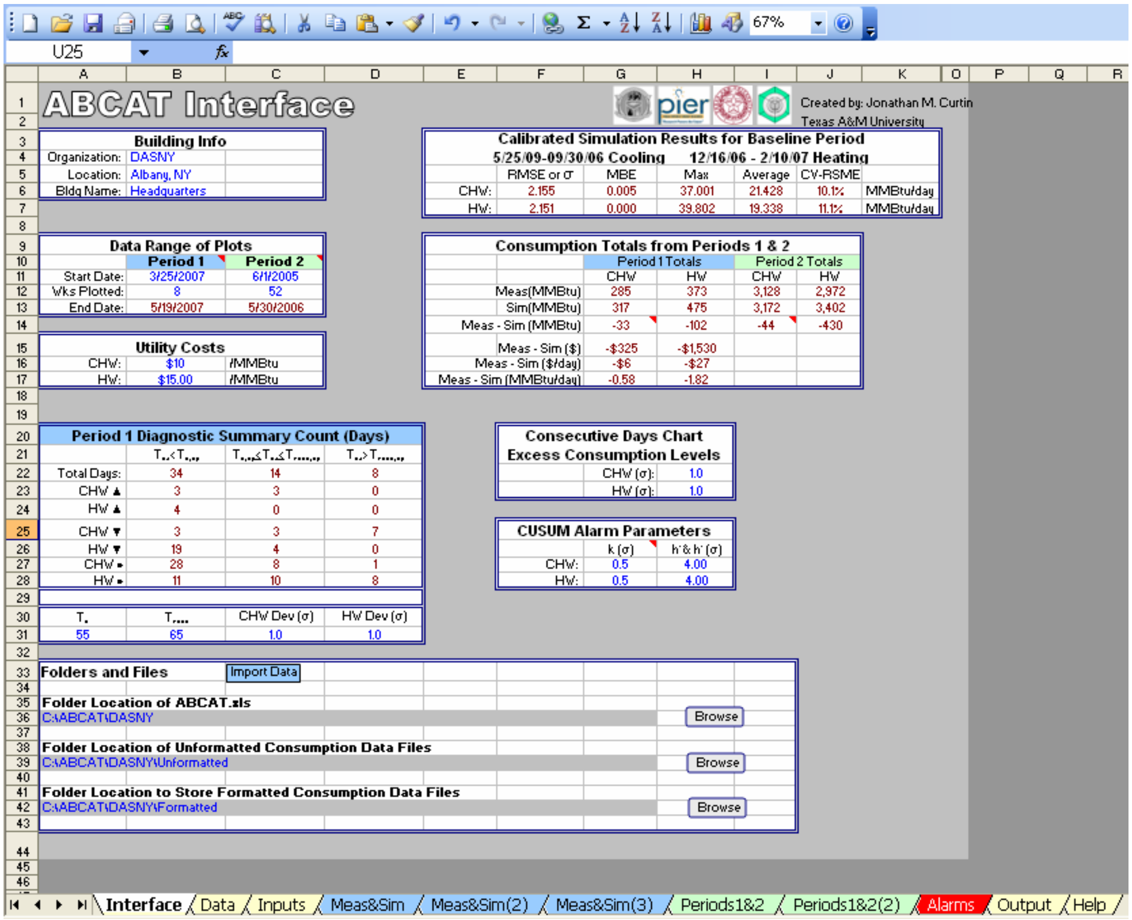

Figure 20. The ABCAT User Interface Sheet

The CHW Cumulative Cost (or Energy) Difference plot was clearly influential in detecting the faults in both the Computing Services Facilty and Sbisa; it also explains the problem in terms of dollars and cents which tends to compel users to act. But some key information regarding the fault cannot be easily determined from this plot. One detail that played a significant role in the diagnosis of the faults in these two cases was the starting time of the fault. This would also be important in performing an automated diagnostic analysis for the period in which the fault propagated. Without firm knowledge as to the start of the fault, the faulty period cannot clearly be defined. Both visual and analytical identification of the start of the fault in Figure 21 would be difficult to discern from the normal random fluctuations of the plot. The CUSUM alarm chart on the other hand, has a built-in change point estimator as previously described, by following the alarm back to where it last was equal to 0. Figure 21 - Figure 24 compare the CUSUM alarm charts with the cumulative excess CHW cost plots for the two fault cases.

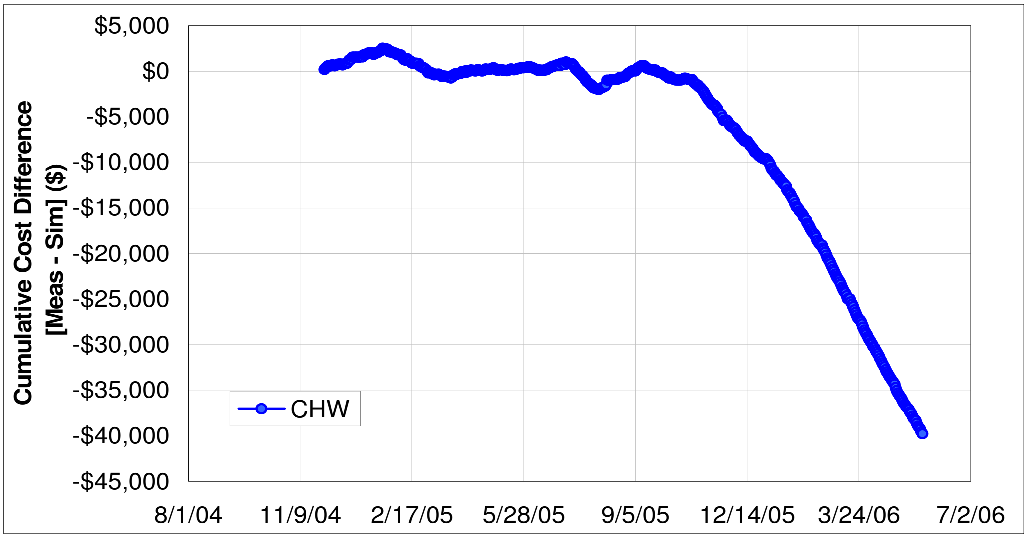

Figure 21. Computing Services Building Cumulative Excess CHW

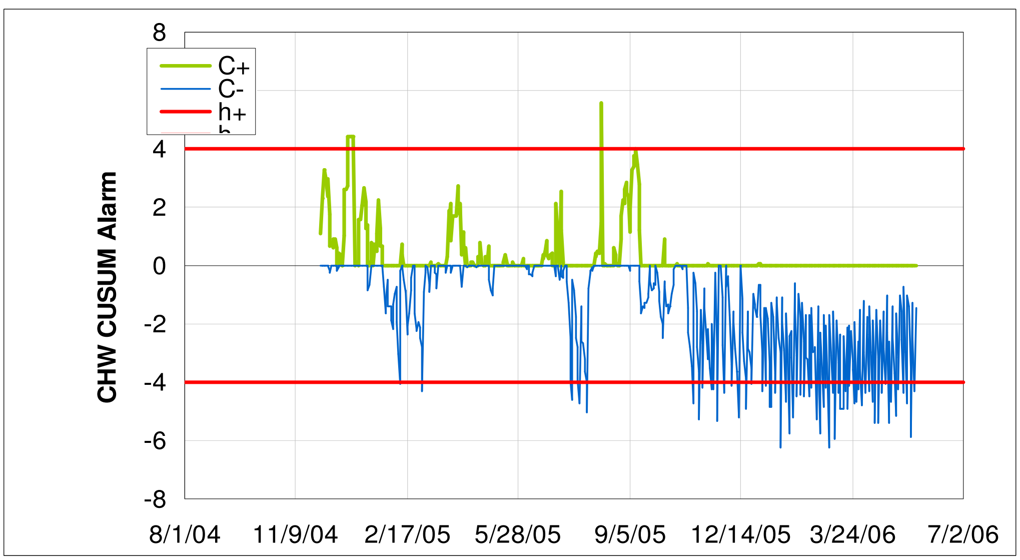

Figure 22. Computing Services Building CHW CUSUM Control Chart (k = 0.5, h = 4)

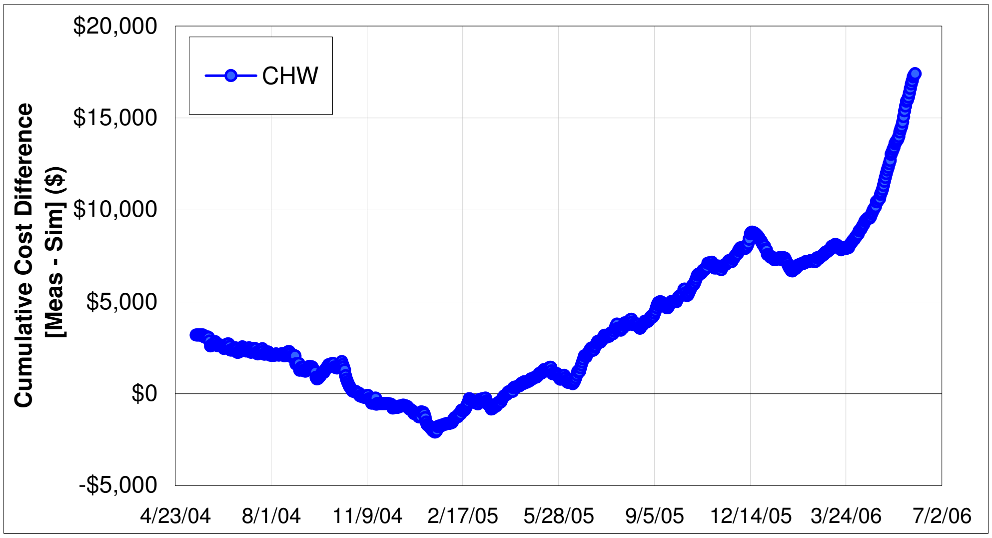

Figure 23. Sbisa CHW Cumulative Energy Difference

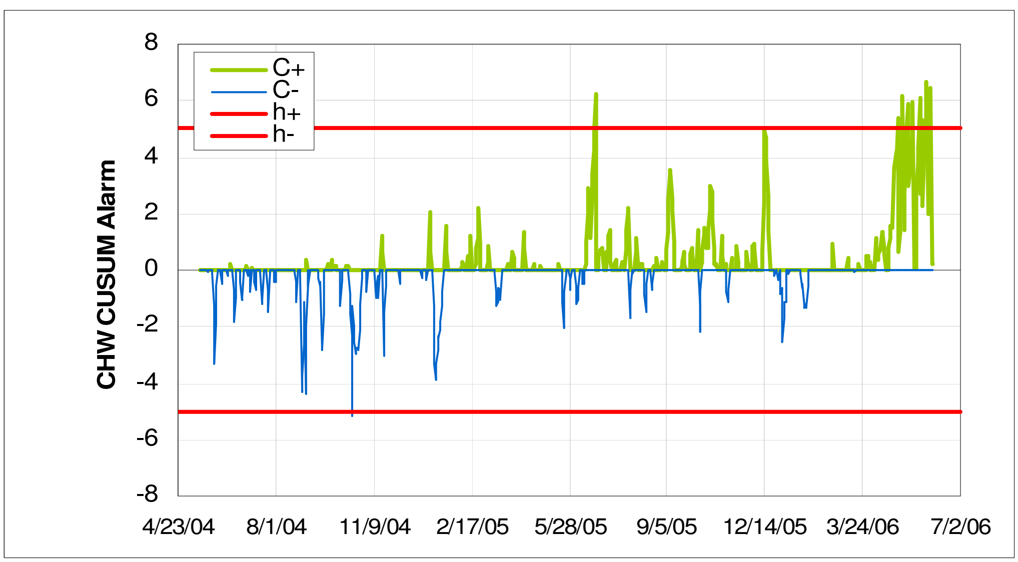

Figure 24. Sbisa CHW CUSUM Control Chart (k = 1, h = 5)

3.2.3 Features

- Quick day-type and date association for all plotted points

  As the number of days of data stored in the ABCAT increases, it becomes increasingly difficult to identify a single point on a plot, particularly on the plots where the x-axis is outside air temperature. An added feature of the ABCAT is the ability of the user to click twice on any data point in any chart, and the day of the week and date associated with that point will be displayed in a pop up window.

- Scroll through time with the scroll bars

  Move forwards and backwards throughout the entire date range of ABCAT data, using the endpoints of the scroll bar to move just a single day, or click the interior of the scroll bar to move one week per click.

- Daily data summarized and stored in the tool such that the simulation can run for any period without user concern of reprocessing or collecting required inputs.

  There are several foreseeable situations where the user of the ABCAT may want to rerun the simulation. Inevitably there will be vacation days or shutdown days that are not pre-programmed into the ABCAT, as well as days where some missing or incomplete consumption data has either caused a simulation result that is inaccurate or prevents the result from being calculated. Since the complete set of daily data required to execute the simulation is always available with the ABCAT, no special file generation is require to execute this step.

- Multiple Period Analysis

  Analyzing past periods of measured energy consumption became a natural early step when further insight into current energy consumption performance was desired. Functionality was then built into the ABCAT for this purpose of comparing two periods of measured data, which alone can be a simple graphical aid for an energy analyst, even without the simulation feature.

3.2.4 Additional Details

The intricate details of the design, layout and function of the rest of the ABCAT can be found in Appendices C and D.

3.3 Additional Activity at the Sbisa and the Computing Services Building Sites

3.3.1 Sbisa Additional Activity

A problem with the thermal meters in the fall of 2006 resulted in no consumption data being available until they were repaired several months later during the winter. After the accumulation of several months of new data, a comparison with the ABCAT simulation and the old consumption data was performed to determine if a recalibration of the simulation model was required. It appears that the heating consumption data is consistent with levels observed prior to the meter problem, but the new cooling consumption is significantly lower than that expected with the previous ABCAT model or from a comparison with the previous year's consumption data.

3.3.2 Computing Services Building Additional Activity

A Second Computing Services Building Cooling Consumption Fault Identified

Introduction

The Automated Building Commissioning Analysis Tool (ABCAT) has detected another deviation from expected energy consumption in the Computing Services Building. It appears to have originated at the time immediately following some Thanksgiving 2006 shutdown work. As opposed to the previous fault identified by the tool in October 2005, which resulted in measured cooling energy consumption less than expected, this fault has increased consumption above that predicted by the ABCAT. The fault magnitude is about 20 MMBtu/day on average and has continued through the end of the analysis period of this thesis (June 2006).

The ABCAT Adaptation to Building Operations

Several changes to the building operation and consumption patterns over the year and a half since the ABCAT was originally calibrated, have required periodic changes to the simulation model for its output to remain representative of the building. See Appendix E for details that describe the changes occurring in the building and the resulting changes made to the ABCAT during this time.

Fault Identification

The following series of figures from the ABCAT will present the tool's analysis of the building heating and cooling energy performance and describe the conditions that have indicated a fault occurred on or around 11/28/2006 and has persisted through the end of the analysis period of this thesis (June 2006). The conditions in the year prior to the fault, the fault period itself, and a comparison of the fault period during the same period in the year previous are included.

Figure 25 presents slightly more than one full year of measured and simulated cooling and heating (CHW and HW) consumption data, starting 10/28/2005 (the time of the last CHW meter calibration) and ending 11/27/2006, just prior to the start date of the new fault.

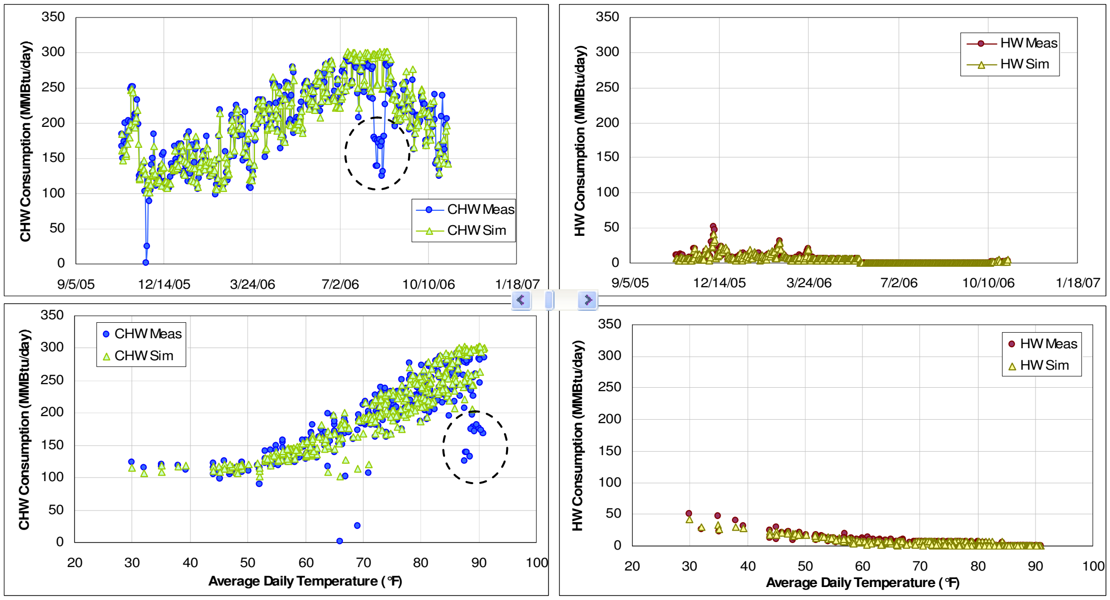

Figure 25. Building Cooling and Heating Time Series and Cooling and Heating versus Outside Air Temperature for One Year Starting 10/27/2006.

Figure 26 shows the cumulative energy difference between the measured and simulated consumption for this same period. A straight line on the chart would represent a perfect alignment between measured and simulated consumption. The small random fluctuations seen in Figure 26 represent regular random errors that will always exist due to the limitations of the simulation model. The dashed encircled areas of both Figure 25 and Figure 26 are during a period starting 8/9/2006, where a bypass valve on the chilled water line at the entrance to the building was mistakenly opened by a contractor and led to artificially high return water temperature and significantly lower measured consumption. Due to its magnitude, this fault was quickly recognized, investigated and corrected by the utility provider, without any assistance from the ABCAT. Although the ABCAT did not play a role in this fault's identification or resolution, the fault was clearly identifiable in the ABCAT with Figure 25 and Figure 26.

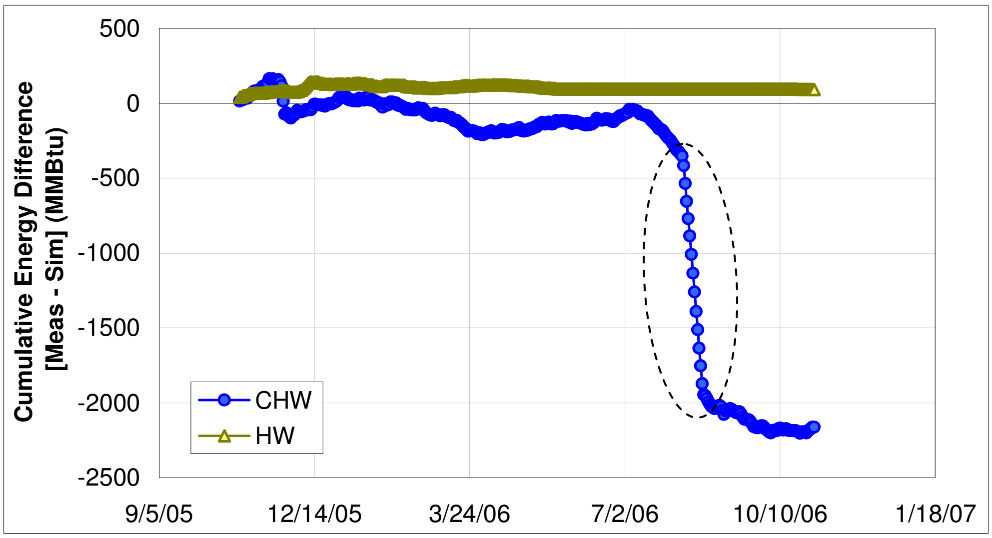

Figure 26. Cumulative Energy Difference for the Period 10/27/2006 – 11/27/2006

A new significant deviation in cooling consumption, which has its origins soon after Thanksgiving 2006, has now been detected with the ABCAT. This fault is most clearly presented in the Cumulative Energy Difference plot of Figure 27. The relatively linear behavior of the slope of the series encircled in Figure 27 is representative of a daily difference between measured and simulated consumption that is fairly constant throughout the entire period, at around 20 MMBtu/day. Except for a few outliers at the extreme of the cold ambient conditions, Figure 28 shows that the residuals (measured – simulated consumption), have weak dependence on ambient temperature for the period 11/28/2006 – 4/29/2007.

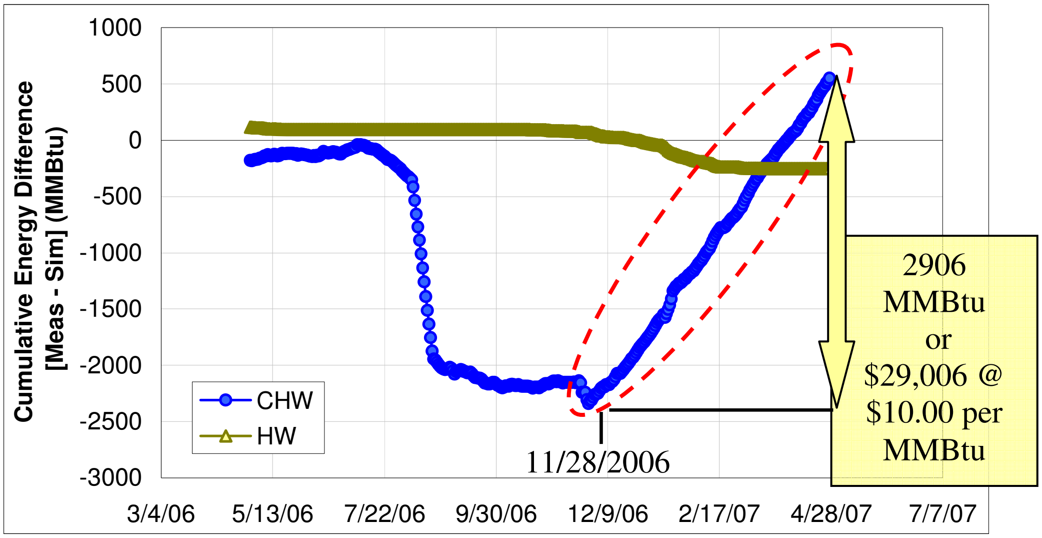

Figure 27. Cumulative Energy Difference for One Year Starting 04/29/2006.

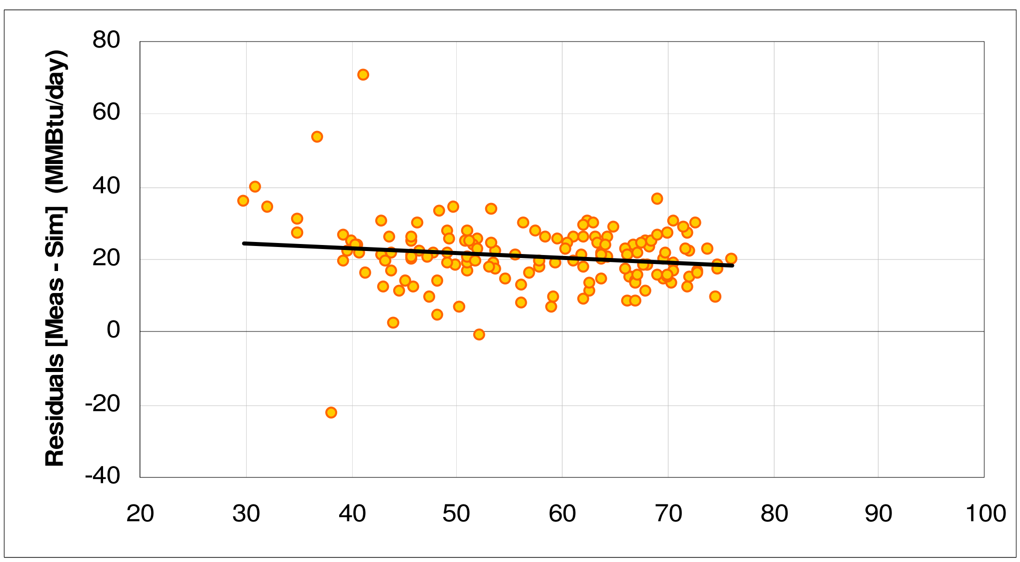

Figure 28. Cooling Energy Residuals (Meas – Sim) versus Outside Air Temperature and Linear Fit for the Fault Period 11/28/2006 – 04/29/2007

For a historical perspective, Figure 29 contrasts the measured cooling consumption in the current fault period with that from the same dates in the year previous. The current fault period consumption is clearly greater throughout the entire range of operation. The same comparison is performed with the average daily electricity consumption, Figure 30. Some items worth noting in Figure 30 are that the difference between weekday and weekend consumption has decreased in the most recent period (seen starting around 1/28/2007), and there has been a rise of about 200 kWh/h in consumption (seen starting around 3/28/2007) above that of the previous year.

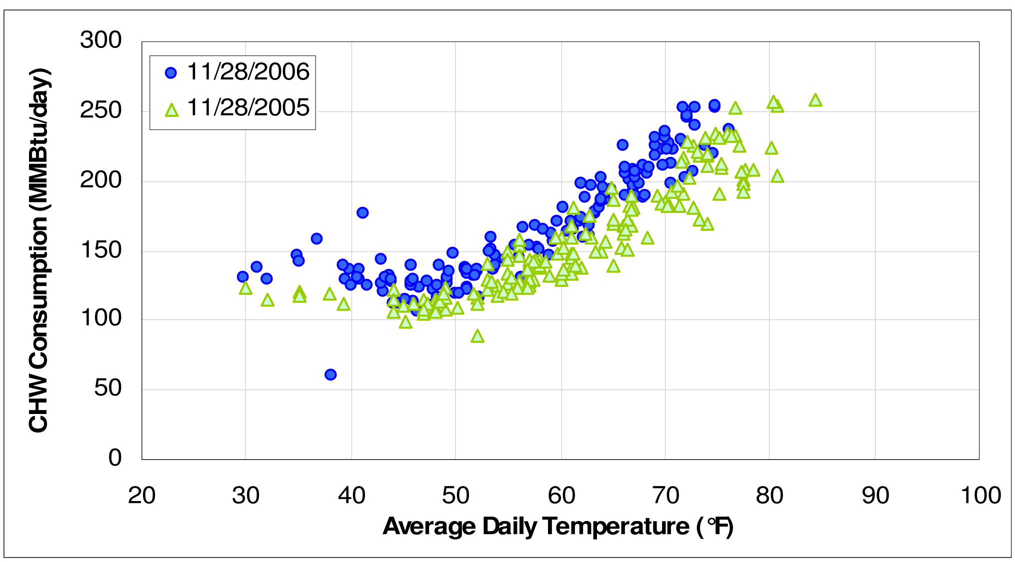

Figure 29. Cooling Energy Consumption versus Outside Air Temperature for the Fault Period 11/28/2006 – 04-29/2007 and the Same Period in the Previous Year 11/28/2005 – 04/29/2006 (The chart legend indicates the start dates of the periods)

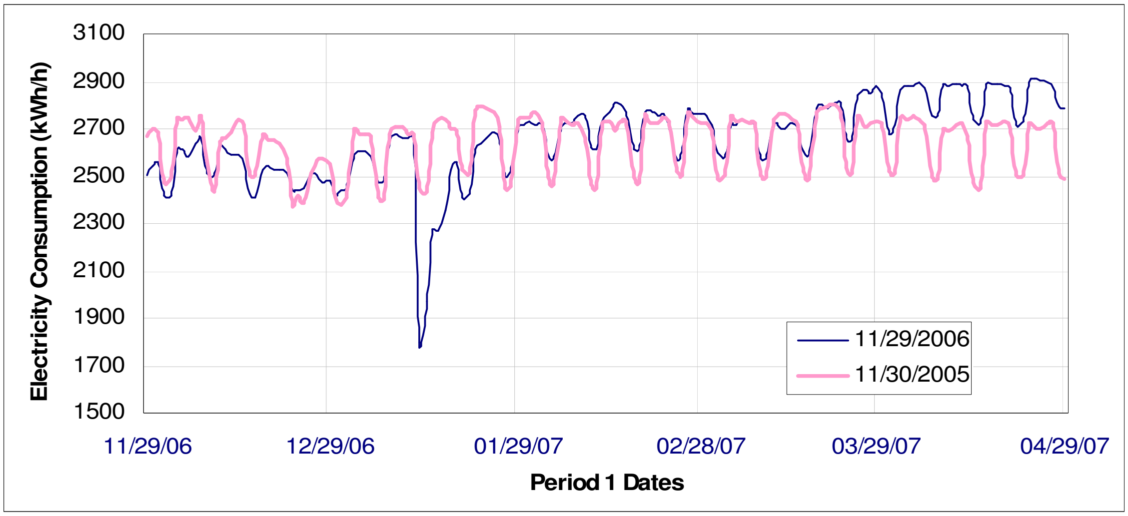

Figure 30. Time Series Average Daily Electric Consumption for the Fault Period 11/28/2006 – 04-29/2007 and the Same Period in the Previous Year 11/29/2005 – 04/30/2006 (The chart legend indicates the start dates of the periods)

An increase in electricity consumption is worth noting in a complete whole building energy analysis, but it does not explain the increase in cooling energy detected in the current fault period. A constant fraction of the measured electric consumption is used as electric gain inputs in the loads calculation of the ABCAT simulation engine, and therefore the simulated cooling loads, reflect this variation in electric loads.

The heating energy does not account for the increase in cooling detected. As Figure 31 shows, the measured heating consumption (determined by monthly gas bills and the boiler output model described in Appendix E) is even less than that simulated during this fault period. The heating is also fairly insignificant in scale when compared with the minimum 125 MMBtu/day measured cooling energy.

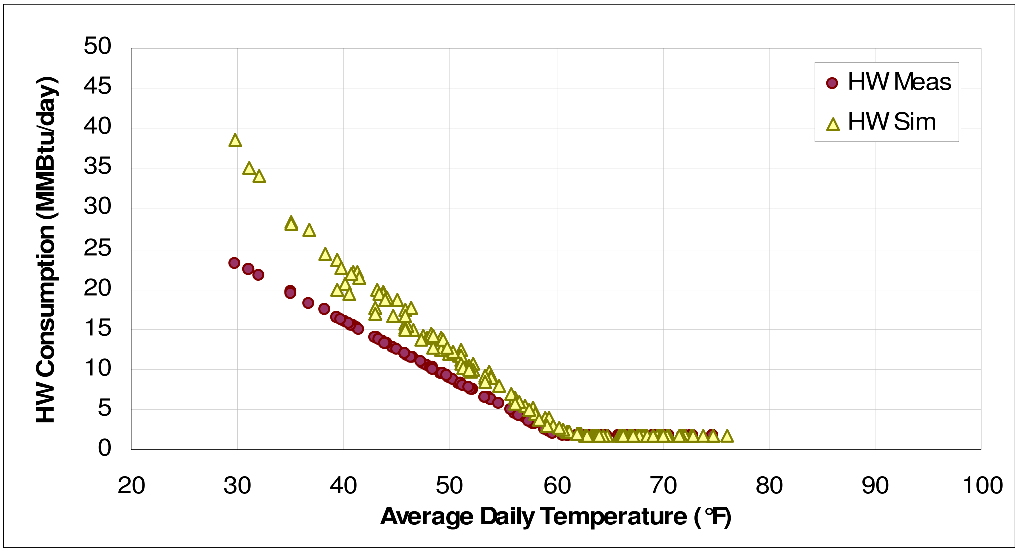

Figure 31. Measured and Simulated Heating Consumption for the Fault Period of 11/28/2006 – 04/29/2007

Conclusions

For a second time, the use of the ABCAT has detected a significant cooling energy consumption deviation from that expected in the computing services building. The deviation appears to be relatively constant throughout a wide range of ambient weather conditions from the late fall 2006 through early spring 2007. Excess heating consumption in the building has been ruled out as a possible cause since it has been shown to be slightly less than predicted by the ABCAT simulation for the same period. The electric consumption of the fault period analyzed is at times greater than that of the same time the previous year, but the electric load is an independent variable used in the ABCAT simulation, and therefore the simulated cooling consumption would reflect the increased electric gains in the building.

The fault condition described above is strikingly similar to the one identified in 2006, where again the deviation was rather steady and consistent throughout a wide ambient temperature range, the heating consumption did not suffer any drastic change on a comparable scale, and the magnitudes of both faults were approximately on the order of 20 MMBtu/day. The primary difference was that they were opposite in direction (i.e. the measured consumption was less than that simulated in the 10/27/05 fault, the measured consumption was greater than that simulated in the current fault period).

Due to the analysis provided, along with its similarity to the fault that was previously detected, it seems reasonable to believe that this deviation is likely related to another calibration or fault associated with the chilled water meters. Investigation revealed that 10/28/2005 was the last calibration of the meters. The approximate start of the fault (11/28/2006) and the period surrounding that day was investigated for indications of any scheduled maintenance, change in control settings or building operations, or possible error in the flow meter or chilled water temperature sensors that may have caused to this fault. No definitive diagnosis of the fault was determined by the time this thesis was written - June 2007.

3.4 Additional Live Test Sites Added in 2007

3.4.1 DASNY Corporate Headquarters (Albany, NY)

3.4.1.1 Building Description

The Dormitory Authority of the State of NY corporate headquarters building (Figure 32) is located just off the Hudson River in Albany, NY. It is a 180,000ft^2 six-story office building. The only part of the building that differs from the primary office function is the northern half of the first floor of the building that is dedicated storage space that is minimally heated in the winter and requires no cooling in the summer.

Two (2) 239 ton water-cooled screw chillers and five (5) 1000 MBtu condensing boilers generate chilled water and hot water for the building cooling and heating respectively. Two (2) SDVAV AHUs with mixed air preheat, economizers and terminal reheat serve each floor and are separated by north and south distinctions. Electric humidifiers are installed in 9 of the 12 AHUs and maintain a minimum 25% winter relative humidity in the building. Perimeter hot water radiant heating is operated at constant flow rates with the hot water temperature reset based on the outside air temperature. A hot water to glycol heat exchange provides the heating needs for the building's front sidewalk snowmelt system that operates when precipitation and temperatures create conditions for ice formation.

Figure 32. DASNY Corporate Headquarters Building

3.4.1.2 Data Collection and Processing

The thermal and electric energy consumption, along with building sensor data are maintained with the Continuum building automation system. The control system has been programmed to download a weekly file of the inputs that are critical to the ABCAT. Since network security issues prohibit remote internet access to the facility, the file is emailed on a weekly basis to the remote ABCAT user.

Due to the building specific equipment layout and metering capabilities, special considerations for data handling were required. The chiller electric load is monitored separately, and subtracted from the whole building electric load to arrive at the electric load used in the ABCAT simulation. A single Btu meter on the chilled water provides the measured whole building cooling. The measured whole building heating energy is determined from the metered natural gas, an assumed heat content of 1020 Btu/cf and condensing boiler efficiency of 95%, and subtracting the sub-metered consumption of the glycol snowmelt system.

3.4.1.3 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 12/16/2006-02/10/2007 for heating, and the pre-RCx period of 05/26/2006-10/01/2006 for cooling since no post-RCx cooling data is available at time of implementation. The results of the calibration are presented in Figure 33 and Table 15.

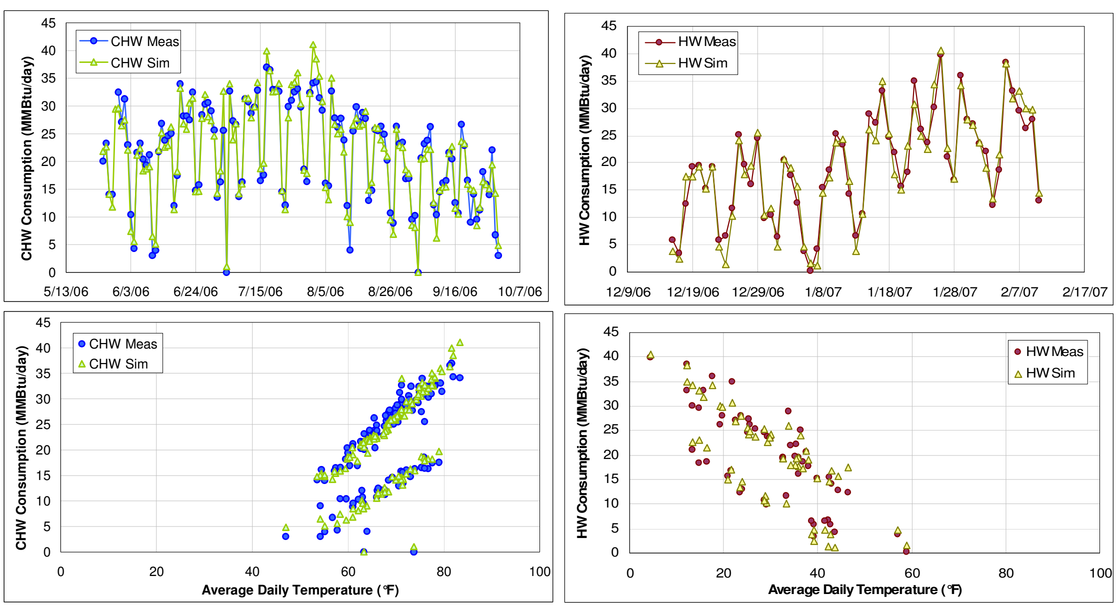

Figure 33. Time Series and OA Temperature Dependent Plots of the Measured and Simulated Cooling and Heating Consumption for the Period Used to Calibrate the DASNY Bldg Simulation

Table 15. Calibration Statistics of the DASNY Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	2.155	0.005	37.001	21.428	10.1%	MMBtu/day
HW:	2.151	0.000	39.802	19.338	11.1%	MMBtu/day

3.4.1.4 NY Training and Technology Transfer

A site visit ABCAT demonstration was provided by TEES in Albany for a group that included representatives from DASNY, NYSERDA, and several New York State commissioning agents. The tool has been transferred both to DASNY, and the building commissioning agent: Dome-Tech, for continued use over the remainder of the project. Some instructional/information manuals were also created and distributed with the tool. Both users were able to successfully install and have been operating the tool since the middle of March, 2007. Two small errors in the initial startup with these users, one with the data processing from the building BAS trend log and a second previously unknown programmed dependency on a particular Windows OS file extension setting, were both quickly identified and remedied. Continued remote support has been available for the participants although no additional issues requiring support have arisen in their continued use of the ABCAT. Several upgraded versions of the tool have been sent out to these users during this period as the debugging process continues and corrections are implemented, and/or as minor reporting or cosmetic changes are implemented.

3.4.1.5 Early Tracking

Preliminary results from the ABCAT in the DASNY building, as seen in Figure 34, show the effect of heightened energy awareness and implementation of commissioning measures throughout the ABCAT test period. The heating savings realized from the end of the calibration period (12/16/2006) through 6/2/2007 is approximately $3,250.

3.4.2 OPPD Energy Plaza East Building

3.4.2.1 Building Description

The OPPD Energy Plaza East building (Figure 35) is a 190,000ft^2 10-story office building with a basement located in Omaha, NE. The building has a large sky-lit six story high atrium that divides the East and West buildings of the plaza.

The atrium is conditioned with a SZHC AHU with economizer. The remainder of the building is served by four (4) SDVAV AHUs with exterior zone terminal reheat and economizers. On both sides of the building, a unit in the penthouse and a unit in the basement feed a common header duct which connects each of the 4 units with all 10 floors.

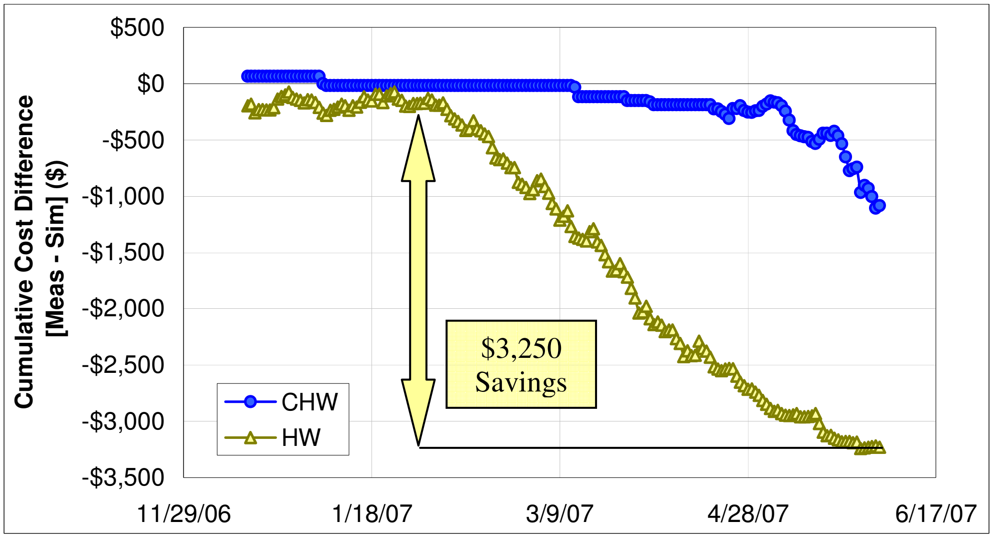

Figure 34. DASNY Cumulative Cost Difference ($15/MMBtu Heating, $10/MMBtu Cooling)

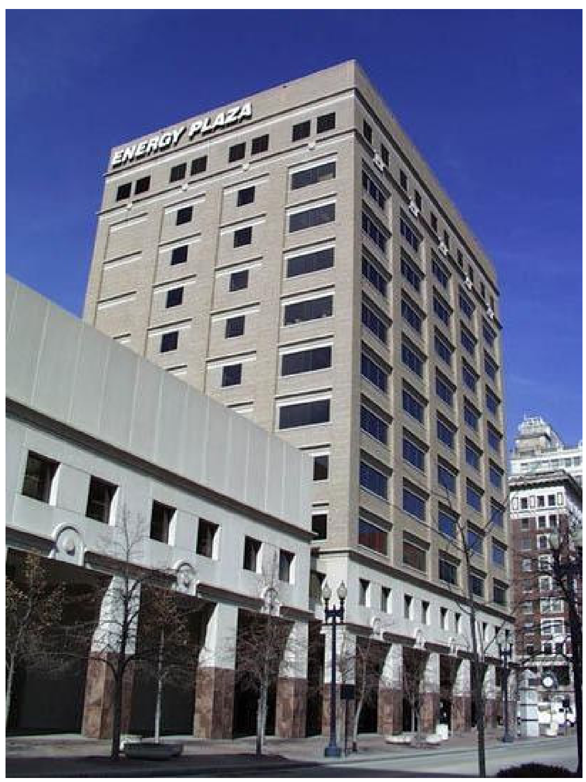

Figure 35. OPPD Energy Plaza East Building

3.4.2.2 Data Collection and Processing

The BAS of the building did not have thermal energy monitoring capabilities, so thermal energy meters were installed in the building. The meters consisted of a chilled water flow station that uses logged pump power and differential pressure to calculate flow, and a hot water flow station that uses the logged pump differential pressure to calculate flow. Temperature sensors are secured to supply and return pipe surfaces under the insulation, and logged in conjunction with the flow stations inputs, and the combined data is processed into hourly energy consumption for the building.

3.4.2.3 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 08/15/2006-02/02/2007 for cooling and 10/17/2006-02/02/2007 for heating, the results of which are presented in Figure 36 and Table 16.

3.4.2.4 Early Tracking

Continued testing in the OPPD building confirms the findings from an engineer involved in collecting the consumption data, that the heating consumption suffered a significant decline from its expected values starting around 2/4/2007. This is identified as Fault #1 on the plots of Figure 37 and Figure 38. Investigation of the measured flow and differential temperature data revealed that a malfunctioning hot water return temperature sensor was the culprit. Following the resolution of the return water temperature sensor problem, a second fault plagued the data collection efforts in the building. A dead battery was found in one of the hot water system flow station data loggers. Fault #2 labeled on Figure 37 and Figure 38 describes the affected period of hot water data collection. Figure 38 also shows that the simulated cooling consumption tracked the measured consumption fairly well, due to the relatively flat response of the cooling cumulative cost difference plot.

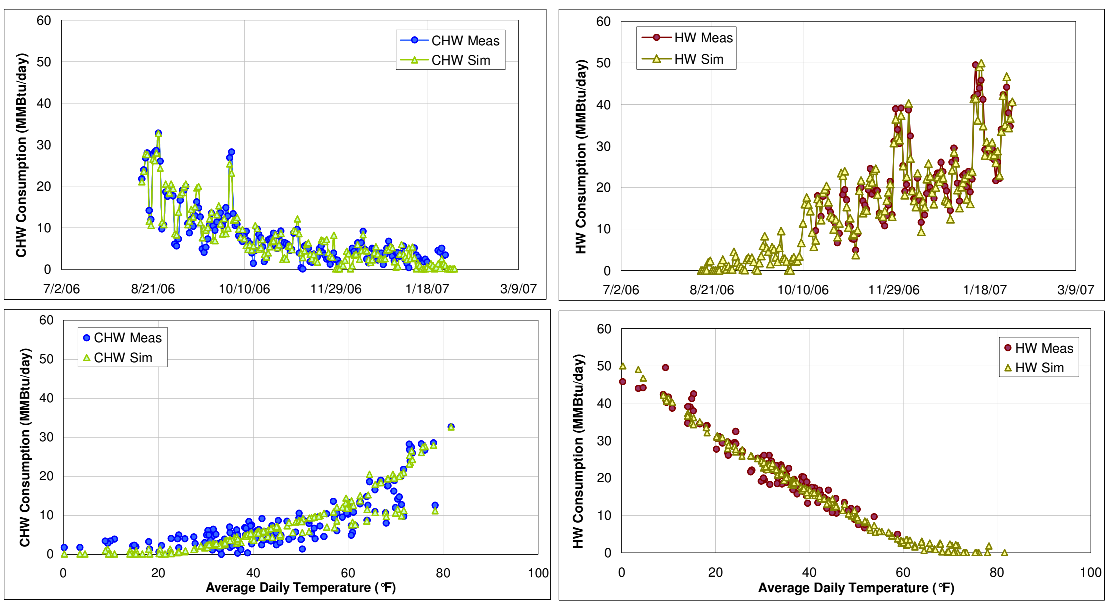

Figure 36. Time Series and OA Temperature Dependent Plots of the Measured and Simulated Cooling and Heating Consumption for the Period used to Calibrate the OPPD Bldg Simulation

Table 16. Calibration Statistics of the OPPD Energy Plaza East Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	2.355	0.000	32.748	8.133	29.0%	MMBtu/day
HW:	2.454	0.000	49.502	22.152	11.1%	MMBtu/day

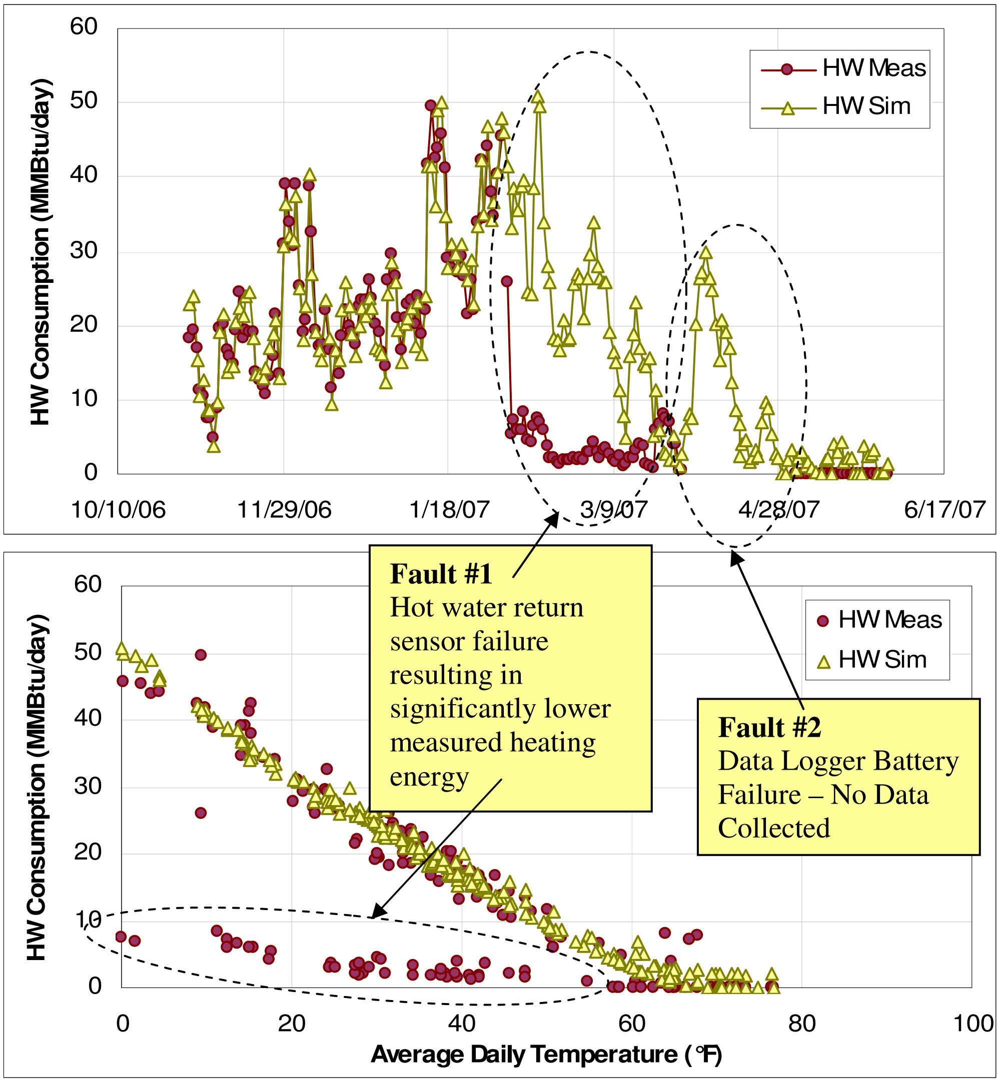

Figure 37. OPPD Energy Plaza Hot Water Time Series and Temperature Dependent Plots

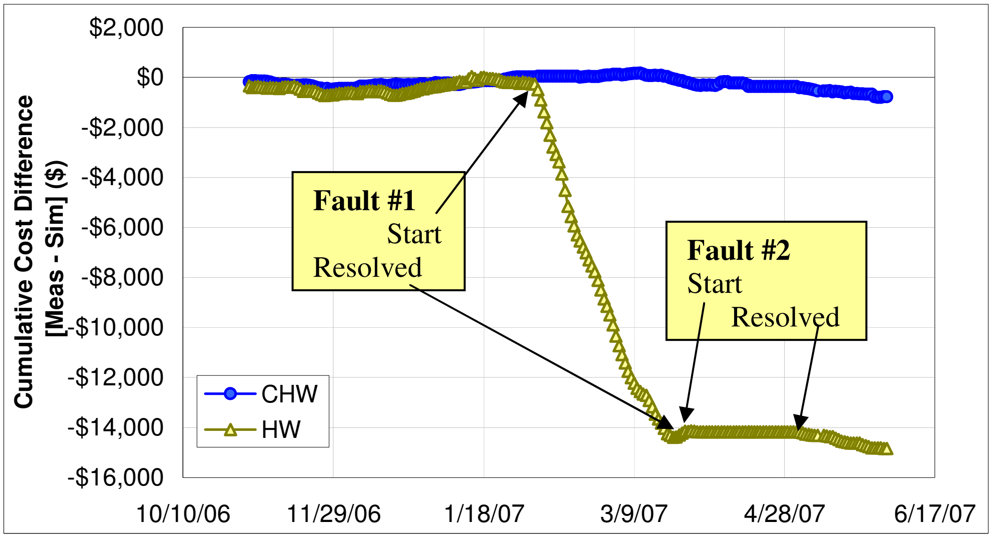

Figure 38. OPPD Energy Plaza Cumulative Cost Difference ($15/MMBtu Heating, $10/MMBtu Cooling)

3.5 Retrospective Testing

Due to difficulties in obtaining the preliminary baseline consumption data required for the implementation of the ABCAT in a second New York building, the focus of the project shifted to a multiple building retrospective test. Five buildings on the Texas A&M University campus which had previously been studied in a commissioning persistence study (for the years of 1996 – 2000), had fairly complete consumption data sets, historical documentation as to commissioning measures implemented, documentation of some control system set point changes during the commissioning process and the end of the period analyzed. It was expected that an analysis with the ABCAT of a span of more than 15 building years, would provide some immediate feedback into the fault detection and diagnostic approaches used with the tool.

The results of this retrospective implementation of the ABCAT were mixed. The combination of data quality issues and a lack a detailed performance history from the building throughout the period of the analysis, prohibited a detailed analysis of the faulty consumption periods identified. Therefore, the following descriptions of the retrospective test are limited to a description of the buildings and their calibrated simulations, along with a brief summary of the five building retrospective analysis and the number and magnitude of the faults detected.

3.5.1 Wehner Building (College Station, TX)

3.5.1.1 Building Description

The Wehner Building (Figure 39) on the campus of Texas A&M University in College Station, TX, is home to the university's school of business. For the period this analysis covers, the building included 192,000 ft^2 of conditioned space on four floors consisting of offices, classrooms and computer labs. Thermal energy is supplied to the building in the form of hot and chilled water from the central utility plant. The building has (6) DDVAV AHUs that serve the 2^{nd} – 4^{th} floors, each with a separate constant volume outside air pretreat unit, and (3) SDVAV AHUs serving the 1^{st} floor. None of the AHUs have economizers.

Figure 39. Wehner Building

3.5.1.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 01/01/1997 – 07/31/1997, the results of which are presented in Figure 40 and Table 17.

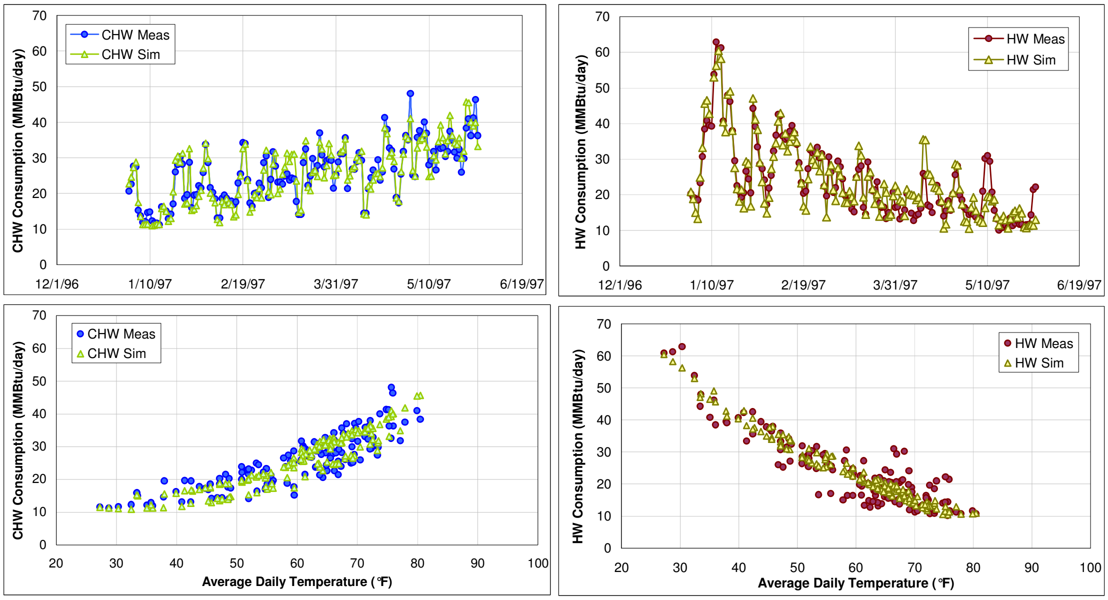

Figure 40. Time Series and OA Temperature Dependent Plots of the Measured and Simulated Cooling and Heating Consumption for the Period used to Calibrate the Wehner Bldg Simulation

Table 17. Calibration Statistics of the Wehner Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	2.735	0.000	48.072	25.623	10.7%	MMBtu/day
HW:	4.116	0.000	62.839	23.782	17.3%	MMBtu/day

3.5.2 Kleberg Center (College Station, TX)

3.5.2.1 Building Description

The Kleberg Center (Figure 41) on the campus of Texas A&M University in College Station, TX, is home to the university's animal and food science center. The building has 165,000 ft^2 of conditioned space, four stories and a basement. Space is utilized as offices, classrooms, and laboratories, and there is also a large four story center atrium. Thermal energy is supplied to the building in the form of hot and chilled water from the central utility plant. The building has two large SDVAV AHUs with large fresh air requirements to maintain proper makeup air for significant laboratory exhaust flows. Additionally, two smaller SDCV AHUs condition some lecture/teaching rooms on the first floor.

Figure 41. Kleberg Center

3.5.2.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 11/01/1996-07/31/1997 excluding 12/16/1996-02/04/1997 & 03/15/1997-04/08/1997 for both cooling and heating and excluding 5/11/1997-07/31/1997 for heating only. The results of the calibration are presented in and Figure 42 and Table 18.

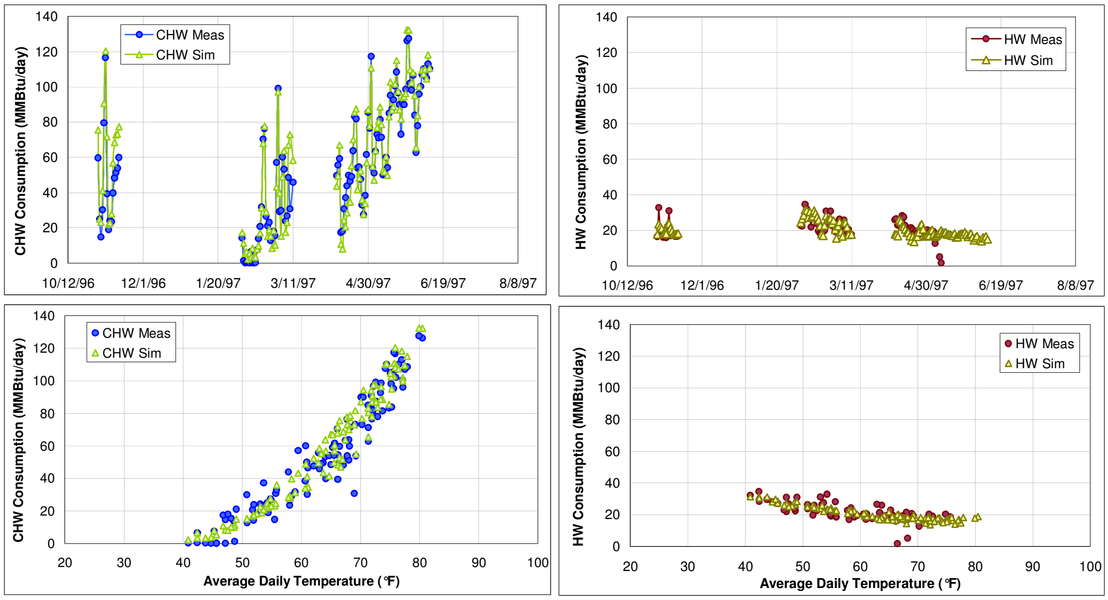

Figure 42. Time Series and OA Temperature Dependent Plots of the Measured and Simulated Cooling and Heating Consumption for the Period used to Calibrate the Kleberg Center Simulation

Table 18. Calibration Statistics of the Kleberg Center

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	10.101	0.000	166.300	81.238	12.4%	MMBtu/day
HW:	4.352	0.000	34.618	21.443	20.3%	MMBtu/day

3.5.3 Eller Oceanography and Meteorology (College Station, TX)

3.5.3.1 Building Description

The Eller Oceanography and Meteorology Building (Figure 43) on the campus of Texas A&M University in College Station, TX, is a high-rise 14 story building with a basement and with 180,000ft^2 of conditioned space. The building is comprised of multiple office, classroom and laboratory spaces. Thermal energy is supplied to the building in the form of hot and chilled water from the central utility plant. The majority of the building is served by (4) DDVAV AHUs, that operate at high discharge pressures with the use of two parallel fans. None of the AHUs have economizer capabilities.

Figure 43. Eller O&M Building

3.5.3.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 03/19/1997 – 08/31/1997, the results of which are presented in Figure 44 and Table 19.

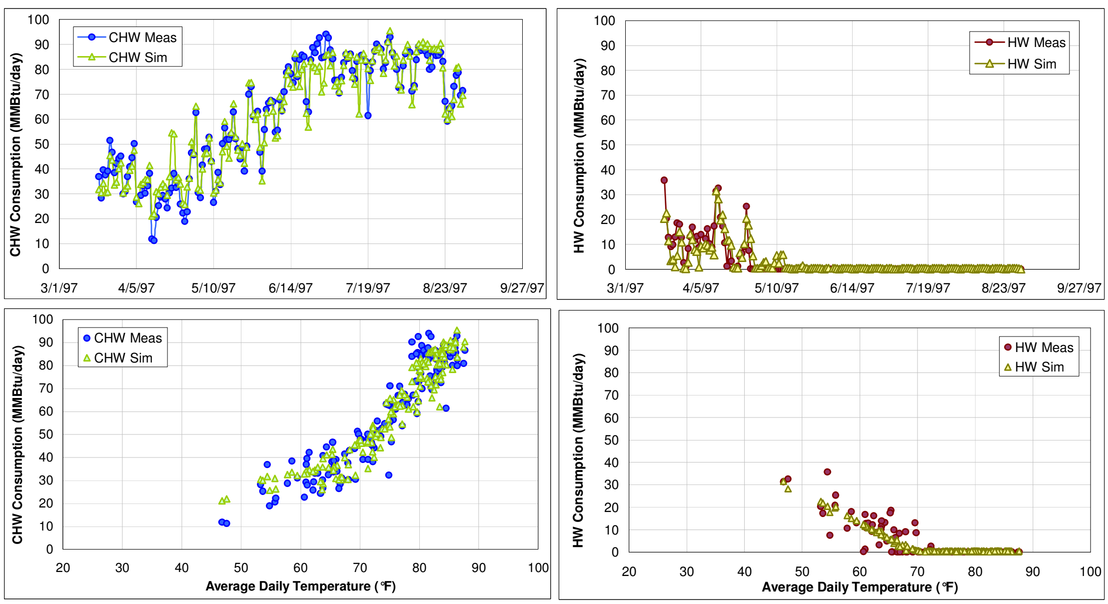

Figure 44. Time Series and OA Temperature Dependent Plots of the Measured and Simulated Cooling and Heating Consumption for the Period used to Calibrate the Eller O&M Bldg Simulation

Table 19. Calibration Statistics for the Eller O&M Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	4.980	0.000	94.094	61.489	8.1%	MMBtu/day
HW:	3.266	0.000	35.787	2.969	110.0%	MMBtu/day

3.5.4 Veterinary Research Building (College Station, TX)

3.5.4.1 Building Description

The Veterinary Research Building (Figure 45) on the campus of Texas A&M University in College Station, TX, is a 5 story building with 115,000ft^2 of conditioned space. The building is comprised primarily of laboratories, but also contains classrooms and offices. Thermal energy is supplied to the building in the form of hot and chilled water from the central utility plant. The majority of the building is served by (5) SDVAV AHUs, (4) of which operate with 100% outside air.

Figure 45. Veterinary Research Building

3.5.4.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 01/01/1998 – 07/10/1998, the results of which are presented in Figure 46 and Table 20.

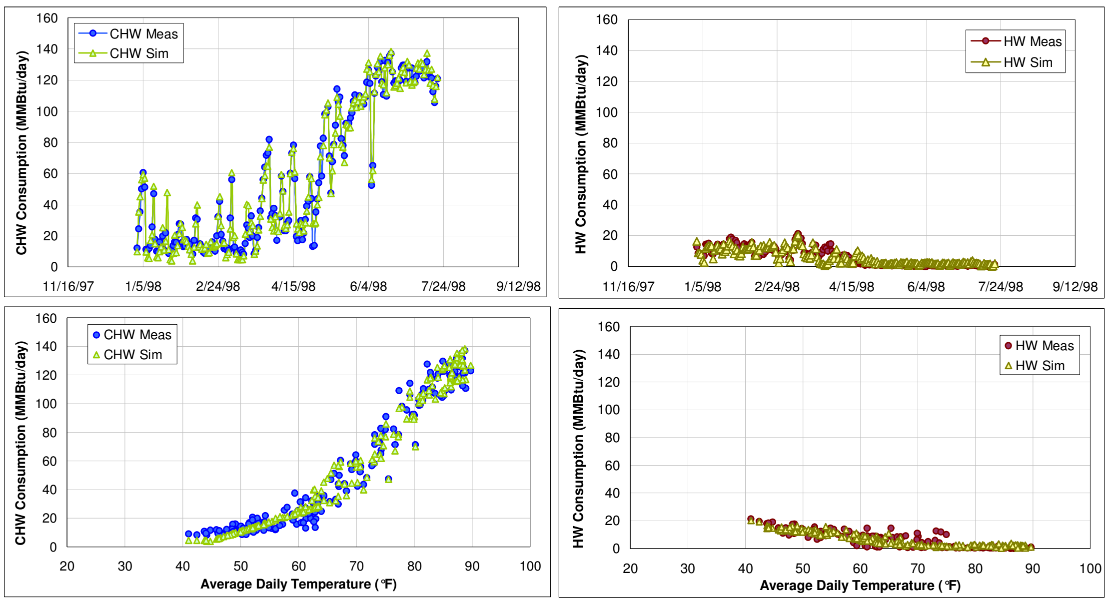

Figure 46. Time Series and OA Temperature Dependent Plots of the Measured and Simulated Cooling and Heating Consumption for the Period used to Calibrate the Veterinary Research Bldg Simulation

Table 20. Calibration Statistics for the Veterinary Research Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	5.008	0.000	137.039	59.173	8.5%	MMBtu/day
HW:	2.993	0.000	21.249	5.921	50.5%	MMBtu/day

3.5.5 Harrington Tower (College Station, TX)

3.5.5.1 Building Description

Harrington Tower (Figure 47) on the campus of Texas A&M University in College Station, TX, is a 8 story building with 131,000ft^2 of conditioned space. The building is comprised of multiple office, classroom and computer laboratory spaces. Thermal energy is supplied to the building in the form of hot and chilled water from the central utility plant. The majority of the building (floors 2 – 8) is served by (1) DDVAV AHU with an economizer. The 1st floor is served by (3) separate SDVAV AHUs.

Figure 47. Harrington Tower

3.5.5.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 08/16/1996 – 08/31/1997, the results of which are presented in Figure 48 and Table 21.

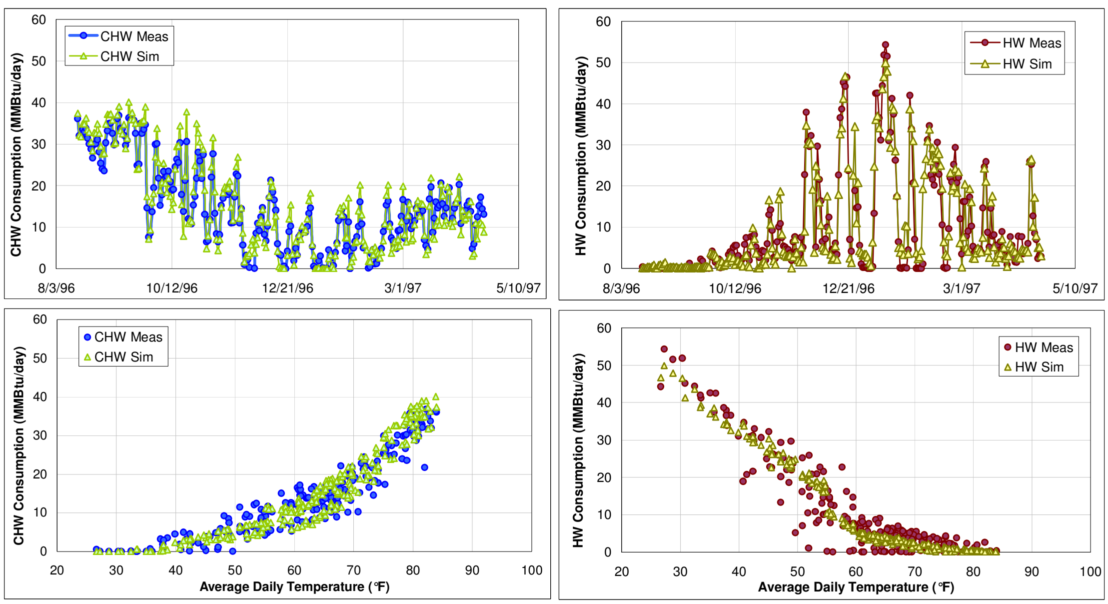

Figure 48. Time Series and OA Temperature Dependent Plots of the Measured and Simulated Cooling and Heating Consumption for the Period used to Calibrate the Harrington Tower Simulation

Table 21. Calibration Statistics for the Harrington Tower

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	2.540	0.000	40.700	20.654	12.3%	MMBtu/day
HW:	3.407	0.000	54.332	6.711	50.8%	MMBtu/day

3.5.6 Summary of the Retrospective Test

In the five buildings tested there were 24 faults that were detected with deviations greater than +/- one standard deviation (as determined from the statistics of the calibrated simulation) that persisted for the period of at least one month. These fault magnitudes, calculated as min, max, and median percentages of the average annual simulated consumption were 11.1%/107%/25.6% for the 13 CHW faults, and 39.0%/210%/106% for the 11 HW faults. The combination of incomplete metering data, suspect metering data, along with a lack of sufficient detailed performance knowledge surrounding the periods of the faults, prevented a successful application of the diagnostic methodology in these cases. Nonetheless, these retrospective tests provided an opportunity to test the simulation capabilities of the ABCAT in five additional buildings of varying type and function.

3.6 Model Accuracy Analysis

An important part of calibrating a simulation model is understanding the limits of accuracy and how an acceptable or adequate calibration is defined. In an attempt to provide additional insight into this subject, the calibration statistics from the test buildings in this project are compiled in Appendix F. In each building, the utility (cooling or heating) with the greater average consumption in the calibration period had the lower CV-RMSE, which was also < 15% in all cases, but the range of the opposite service CV-RMSEs was highly variable from 11%-110% (Figure 49).

It must be noted that a direct comparison of the nine building CV-RMSEs may not be appropriate because of the variable lengths of the calibration periods in each case. Rachlin et al. (1986) analyzed the affect of missing seasonal measured data on the stability of PRISM estimates. They conclude that 12 consecutive monthly readings are ideal for PRISM estimates, and point to the need for cautious interpretation of results when more than three consecutive months of data in the span of a year is missing. In the case of the simulations performed in this thesis, undue seasonal weight may be given in the cases with less than a year of full data. Table 22 summarizes the calibration period dates and their lengths to help avoid misinterpretation.

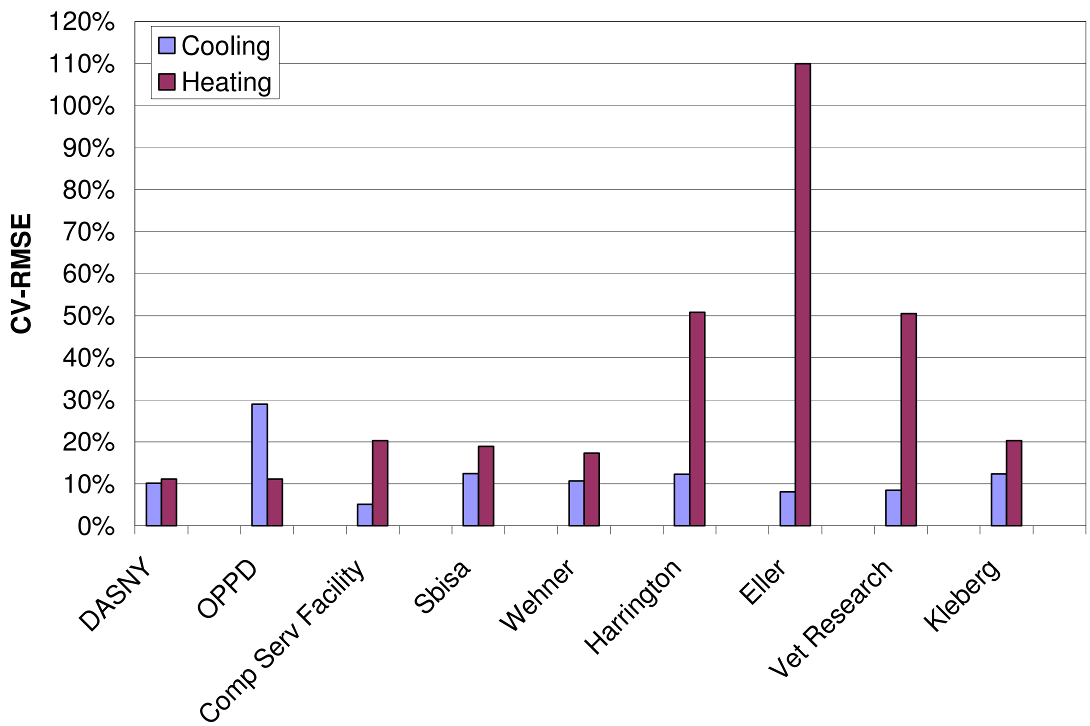

Figure 49. Final CV-RSME Achieved in Nine ABCAT Calibrated Simulations

Table 22. Calibration Period Dates and Length for Nine Buildings

Bldg	Utility	Calibration Period	Weeks
DASNY	CHW	05/26/06-10/01/06	18.3
	HW	12/16/06-02/10/07	8.0
OPPD	CHW	08/15/06-02/02/07	24.4
	HW	10/17/06-02/02/07	15.4
Comp Serv Facility	CHW	12/01/04-11/30/05	52.0
	STM		
Sbisa	CHW	02/02/04-12/31/04	47.6
	HW		
Wehner	CHW	01/01/97-07/31/97	30.1
	HW		

Bldg	Utility	Calibration Period	Weeks
Harrington	CHW	08/16/96-08/31/97	54.3
	HW		
Eller	CHW	03/19/97-08/31/97	24.4
	HW		
Vet Research	CHW	01/01/98-07/10/98	27.1
	HW		
Kleberg	CHW	11/01/96-07/31/97	38.9
	HW	11/01/96-12/15/96 &	16.0
		02/05/97-03/14/97 &	
		04/09/97-05/10/97	

Also compared in Appendix F are the results of the four-parameter change-point (4P-CP) model (Ruch and Claridge 1992) using the software EModel (Kissock et al. 1993) with that obtainable with the ABCAT simplified energy analysis procedure (SEAP) model for these same buildings. The SEAP model in these cases had a lower CV-RMSE in 12 of the 18 cases. These results provide some insight into quantifying acceptable target accuracies for the calibration.

3.7 Analysis of Comments and Feedback

In the developmental process of the ABCAT, informal comments and feedback from users, potential users, the Technical Advisory Group (TAG) and the State Technologies Advancement Collaborative (STAC) management members and others were received. This section summarizes the feedback and generally consists of comments that were repeated or supported by multiple participants. Also included are responses to some of the comments or statements clarifying the current status or approach used in the tool. Although no statistical significance can be assigned to this feedback due to the small number of participants involved and no formal collection methodology, this feedback has nonetheless been beneficial in implementing upgrades to the tool, and setting the course for future developmental and testing steps.

3.7.1 General Approach

A common theme that has resonated almost universally through all those involved in testing or evaluating the ABCAT is that there is interest and a market for ***simple*** energy monitoring and fault detection and diagnostic tools. Over-complication of a tool can immediately lead to reservations from any potential user that is not about to quit his day job to learn how to operate and continually manage the tool. The main focus throughout the continued developmental process was maximizing the benefit with simplicity. The participants expressed support for an adequate modeling system, like the SEAP model, that can vastly simply the setup and input requirements typically encountered in detailed hourly simulation models like DOE-2 and Energy-Plus.

Although the original plan was to provide training on the complete setup and operation of the tool, it later became clear that in the ABCAT's current form, the beta testers would derive little if any benefit from such a step. It was also the opinion of several potential users, after given a brief description of the calibration details, that they would have reservations in tackling this step on their own. At least in the near future, an expert user and expert technical support will be needed in the initial setup/configuration of the tool, as is the case with most of the FDD systems of this nature.

Several positive remarks were associated with the presentation of the cumulative cost different chart in the ABCAT. A common problem in responding to known mechanical system problems in buildings is the disconnect or lack of clarity between the fault and its cost to the facility. The participants believed that this fault metric would provide a motive for users to act, and help the user in providing justification if higher level approval for action is required. It was also stated that detection, and clearly expressing the significance of faults carries a greater weight than diagnostics, since experts will be able to find the fault if called upon, but a fault not known to exist cannot be addressed.

The diagnostic methodology presented in this thesis is still in its developmental infancy, and most of the participants had little to say, or were unsure of the benefit of these developed diagnostics. One comment presents a question for future development… "Do you put the expert in the tool or leave the expert in the field?" The question remains as to what extent on-site diagnostics can be supplemented by the ABCAT, and the tradeoffs of cost, complexity and the diagnostic benefits will have to be considered in determining the direction of future development.

3.7.2 Summary of NY Pilot Feedback

The tool was found to be "very helpful and beneficial for tracking energy consumption on a higher level" and "good for both building owners and operators", although it was stated that the tool cannot take the place of on-site diagnostics. On weekly time intervals the required consumption data was imported into the tool, and it was perceived by one user that the optimal time interval for using the tool is weekly.

Microsoft Excel as the host program was considered “Good” as far as file size, speed of execution, graphical capabilities, data storage general file layout, familiarity and ease of operation were concerned. A preference was expressed for greater clarity with labels on the Interface sheet for user manipulated fields, consumption period totals for both defined periods on the Interface sheet, and a linking to greater granularity (hourly) than daily data. One user expressed interest in a lesson to calibrate the tool.

3.7.3 Software Layout and Performance

With the use of Microsoft Excel as a host to the ABCAT, speed of execution, program flow and the size of the program were concerns. The feedback showed a preference for a laptop/desktop application rather than one residing on a server. The program is currently a laptop/desktop application, with a file size small enough for emailing or download. The current version of ABCAT stores data summarized on a daily basis within its main Microsoft Excel file. Recommendations for linking to Microsoft Access were made, which could strengthen data storage capabilities, and allow for storage of smaller time interval and supporting data that would not be feasible to manage within Excel alone. The familiarity of most users with the general function of Excel was seen as a bonus. As far as speed is concerned, simulation of a year’s worth of data occurs on the order of several seconds with a Pentium 3.3 GHz processor computer with 1.0 Gb of RAM. Importing data to the ABCAT from the test building consumption files was found to take from 2 - 10 seconds depending upon the specific sorting code and period length of the data.

3.7.4 Graphical Presentation

Several helpful comments directed toward the graphical presentation of the tool are listed below and commented on where addressed in the current version of the ABCAT:

- Positive response to the following features
    - Scroll bar for zooming
    - Pop-up windows for day type and date when clicking on data points
    - Multiple plots per chart sheet

- Recommended changes and additions
    - Add day typing
    - Highlight most recent data on plots
    - Data summary tables
        - Implemented in most recent update to the ABCAT
    - Improve "cleanliness" of charts – remove tick marks and redundant time scale labels in top-bottom charts, eliminate chart area border, possibly remove gridlines or make lighter
        - Partially addressed in most recent update to the ABCAT
    - Provide checks to make sure charts look good at most common monitor resolutions and investigate the disabling of autoscaling features
    - Fix plot y-axis scales particularly when using the scroll feature
        - This could be programmed or added as a manual step in the initial setup instruction documentation of the ABCAT.
    - Look to add zoom-box scaling or separate scaling feature in addition to scroll bars on chart sheets
    - Remove redundant plots or the user may want to add own charts or replace charts
        - The "overloading" of the program with performance plots was by initial design, knowing that different users would have different preferences. Providing instructions and options for users to delete and/or rearrange the views they do not find valuable or create and add new plotted series seems to be a logical next step in development. These instructions have been completed and included in Appendix D.

3.7.5 Continued Testing

Throughout the course of many presentations and discussions involving the tool, there has been interest expressed by NYSERDA for continued developmental and expanded testing in New York, as well as a desire by two building researchers in the Netherlands and Germany to have the ABCAT installed in buildings they are investigating.

CHAPTER IV

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The ABCAT has been shown to be a valuable energy tracking tool, identifying three periods in the live building implementations where significant energy consumption changes occurred that otherwise went undetected by the building energy management personnel. These faults were on the order of magnitude of 16.5%, -9.3%, and 9.5% (as % of average annual consumption) for the cases of the Sbisa Dining Hall fault and the first and second faults of the Computing Services Building respectively. The magnitudes of 24 faults identified in the retrospective test calculated as min, max, and median percentages of the average annual simulated consumption were 11.1%/107%/25.6% for the 13 CHW faults, and 39.0%/210%/106% for the 11 HW faults. In each of these cases it was the accumulation of daily differences between measured and simulated consumption that provided the clearest indication of the fault.

The methodology applied also has shown that it is not being prone to false positives, or false alarms. In long-term multi-year implementations, both in the real-time testing and retrospective analyses, the cumulative difference plot often simply verified that energy operations were well within acceptable limits for many extended periods. In the retrospective testing in particular, in four of the five buildings for cooling, and in one of the five building for heating, the maximum cumulative energy difference was less than 7.5% of the total consumption for the entire test period that ranged from three to five years depending on the building. This attests to the long-term stability of the methodology for buildings where energy consumption patterns remain essentially unchanged.

A simple diagnostic methodology has been developed which builds upon some of the diagnostic reasoning found helpful in determining the cause of two of the three faults identified in this study. This approach does not intend to replace the value of the BAS or onsite personnel, but instead intends to provide informed persons with some key characteristics of the fault, particularly the relationship between outside air temperature, the heating residuals, and the cooling residuals. A retrospective implementation of the ABCAT in five buildings was expected to provide additional testing of this diagnostic methodology, but instead primarily highlighted the importance of data quality. Most of the faults identified during the 15+ building years of retrospective study were found to be the result of, or were unable to have the diagnostic methodology applied because of, metering errors in the cooling or heating data.

The retrospective cases, in addition to three of the four live building implementations, all suffered from various degrees of data monitoring failures, whether due to equipment failure, system changes and/or improper setup procedures. The potential future success of the ABCAT is strongly tied to the ability of future users to obtain accurate and reliable measurements. A strong emphasis in sound engineering practices of installation, data management, calibration and data prescreening must accompany the ABCAT to ensure verification of data quality, and the likelihood for success in implementing the tool.

The simulation model built specifically for ABCAT has undergone testing in nine buildings with various AHU types, function, climate types, and schedules. Analytical testing of the model against the results of ASHRAE research project 865-RP has also been presented in this research. Although these results from early testing are favorable, larger scale deployment tests, and continued testing will be required before strong conclusions can be made about the robustness of the ABCAT simulation model.

Although the developed simulation model was able to predict the baseline heating and cooling energy of the nine building of this study to comparable levels of accuracy (Appendix F), it must be noted that the ABCAT simulation model is a simplified model, and it will not be suitable for use in all buildings. Buildings that are small and/or dominated by solar loads, buildings that have highly irregular operating or occupancy schedules, and building that experience complex dynamic behavior with large and frequent temperature swings will be especially difficult to model.

Performance of the ABCAT energy simulations on the daily level provides an adequate level of accuracy for buildings whose AHUs operate at least 18 hours per day. The developed simplified thermal mass approximation added to the modeling capabilities of the ABCAT, has demonstrated in the case of the DASNY building to provide an alternative to daily inputs, and accounts for the dynamic effects in the building by dividing the day into periods of HVAC run-time and down-time. The ABCAT FDD sensitivity would gain to benefit from simulations executed on an hourly basis with hourly input data, if the levels of accuracy achievable and the simulation complexity did not significantly vary from the current ABCAT model. The current status of complexity in the setup of detailed hourly simulation models is in contradiction to the fundamental goals of simplification and marketability of the ABCAT.

In addition to the originally targeted goals of tracking and ensuring energy optimization in commissioned buildings, through the course of implementing and testing the ABCAT, several other added benefits or alternative functional approaches have been identified. These include use as a commissioning savings tracking tool, a simple whole building energy analysis tool (even without the simulated consumption), and use providing verification of or filling of missing metered or billing data, both important for customers and district utility providers.

As was done in the DASNY building, implementing the tool early in the RCx process can provide a method by which to track savings from commissioning measures. Further testing of the ABCAT in this fashion can also provide essentially reverse diagnostic training, where the opposite of the observed response following the implementation of a commissioning measure would represent the fault response if that measure were undone.

One of the most sobering lessons that can be taken away from this project is that thermal energy metering is not an exact science, and even utility grade metering can be subject to errors. For any customer of energy utilities, whether district heating and cooling plants or simply natural gas providers, the ABCAT can be used as a basis to verify the plausibility of billing data. In the case of metered data failures, the ABCAT can provide a means by which to fill the missing data, which could be beneficial for utility providers.

4.2 Recommendations

The results of this project help to shed light on the steps that will be required for ABCAT to gain acceptability in the marketplace where most other programs of its kind have failed. The following recommendations have been strongly influenced by the developmental experiences, as well as the opinions of various reviewers, advisors and the testers:

Additional Testing

- The ABCAT is an advanced prototype and not ready for large scale deployment. In addition to the recommended developmental steps discussed below, a second phase of real building implementations at a larger scale (10+ buildings) is expected as a natural next step towards the eventual realization of a commercial program. Interest has already been expressed for expanded testing in New York partnered with NYSERDA, and by building researchers in Germany and the Netherlands.

- It seems apparent that extensive setup training for users of the ABCAT would be largely wasted if the user will only be involved in a single installation. But there is a basic level of the simulation inputs that should be understood by the user. Providing supporting tools and documented instruction for calibration or recalibration are likely needed to simplify this process for the occasional user. Baseline changes through changes in operation, occupancy schedules, calibration of metering equipment, or faults determined to be acceptable could be frequent occurrences in some buildings, and would require modifications to the simulation model.

- Train additional expert users of the tool that will continue to be involved in multiple installations and can provide expert feedback for advanced development.

Data Transfer and Storage

- As experienced in this project, data collection procedures specific to a building can often can have their own unique issues that need to be addressed. These can include the handling of: missing data points, repetitive data points, slightly asynchronous date/time stamps for multiple fields, and different markers for missing data, which can result from the control systems and retrieval methods, the experience level or programming preference of the database administrator, network or software limitations or other unknown problems. Strong preliminary efforts in managing this data properly are a crucial first step in ensuring a successful implementation of the ABCAT.

  - Investigate the possibility of taking advantage of inexpensive existing tools with strong data management capabilities, like the Universal Translator.
  - Develop a generic protocol for importing data into the ABCAT, perhaps limited to integration with control systems that can provide spreadsheet output, since most can.
- Investigate integration with Microsoft Access or an other database to implement a direct link to more granular data than daily.

Fault Detection and Diagnostics

- Test the sensitivity of the tool with simulation and experimental implementation of faults, analyzing time to detect, size and/or type of fault detectable with noise levels added that are comparable to that observed in the real building simulations of this project.

- Initial exploratory work has shown that a condition known as heteroscedasticity, or non-constant variance, in the calibrated simulation residuals when plotted against outside air temperature may lead to the need for adaptive fault thresholds based on outside air temperature. Defining when this condition is significant and how thresholds should take this into consideration can be an area of future study.

- Techniques can also be investigated in strengthening the diagnostic methodology for giving partial membership to the classes of: less than (▼), the same (●), or greater than (▲) in a fuzzy logic approach. Additionally, identifying strong indications of simultaneous heating and cooling, or clear indications that a deviation in either the heating or cooling is independent of the other could be achieved by accounting for the relative magnitudes of the cooling and heating deviations in the diagnostic methodology.

Software Development

- Short-Term
    - Continue to expand the functionality of the simulation model to accurately represent the variety of operational conditions, building, and system types expected to be encountered in the field, while continuing to focus on simplification and clarity of the model inputs.

    - Check for compatibility with Microsoft Excel version 2007 and Microsoft Vista OS. Upgrade as necessary.

    - Implement recommendations on graphical improvements as stated in section 3.7.4.

- Long -Term

- Bring onboard software engineer/specialists to improve performance with streamlined programming.

- Develop new and/or advance existing methods for providing automated, semi-automated, or other simplified calibration techniques.

4.3 Benefits to State Technologies Advancement Collaborative (STAC) Member States

The ABCAT has demonstrated on a small scale that it can bridge the gap in proactive energy management between the manual comparison of monthly energy bills, and FDD tools for HVAC systems that are: heavily reliant on sensors, expensive, require large training (historical) data and are overly sophisticated for typical users. The ABCAT identifies and displays the cost impact of significant (+5%) energy consumption faults in buildings that often go undetected, or are not acted upon because the energy or cost significance is underestimated. With wide scale deployment of an inexpensive, simplified tool such as the ABCAT to commissioning service providers, building owners or engineers, the long-term persistence of savings from building commissioning can be realized with continuous energy tracking. The ABCAT may also aid in the promotion of building commissioning services by presenting building owners with a tool to monitor continued savings. The results of this project lay the foundation for extending the energy benefits of building commissioning such that states can meet their goals for energy conservation and optimization in buildings. Continued testing and development of the ABCAT will be required before these large scale goals can be accomplished.

REFERENCES

ASHRAE. 2005. *2005 ASHRAE Handbook - Fundamentals*. Atlanta: American Society of Heating and Air Conditioning Engineers, Inc.

Baltazar Cervantes, J. C. 2006. Development of an automated methodology for calibration of simplified air-side HVAC system models and estimation of potential savings from retrofit/commissioning measures. Ph.D. Dissertation. Texas A&M University, College Station.

Breekweg, M. R. B., P. Gruber and O. Ahmed. 2000a. Development of a generalized neural network model to detect faults in building energy performance - Part I, *ASHRAE Transactions*, 106 (1): 61-73.

Breekweg, M. R. B., P. Gruber and O. Ahmed. 2000b. Development of a generalized neural network model to detect faults in building energy performance - Part II, *ASHRAE Transactions*, 106 (1): 74-93.

Bronson, D. J., S. B. Hinchey, J. S. Haberl and D. L. O'Neal. 1992. Procedure for calibrating the DOE-2 simulation program to non-weather-dependent measured loads, *ASHRAE Transactions*, 98(1): 636-652.

Chassin, D., T. Carlon, K. Growri and N. Bauman. 2003. Project 2.6 - Enhancement of the Whole-Building Diagnostician, Pacific Northwest National Laboratory PNNL-14383, August.

Cho, S. 2002. The persistence of savings obtained from commissioning of existing buildings. *M.S. Thesis*. Texas A&M University, College Station.

Claridge, D. E., C. H. Culp, M. Liu, S. Deng, W. D. Turner and J. S. Haberl. 2000. Campus-wide Continuous Commissioning[SM] of university buildings, *Proceedings ACEEE Summer Study on Energy Efficiency in Buildings*, 3(1): 3.101-3.112.

Claridge, D. E., M. Liu and W. D. Turner. 1999. Whole building diagnostics. *Diagnostics for Commercial Buildings: Research to Practice Workshop, Pacific Energy Center, San Francisco*.

Claridge, D. E., M. Liu, Y. Zhu, M. Abbas and A. Athar. 1996. Implementation of Continuous Commissioning in the Texas LoanSTAR Program: "Can you achieve 150% of estimated retrofit savings" revisited. *Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings,* 4(1): 4.59-4.67

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: Journal of the Association of Energy Engineering*, 101(4): 7-19.

Dexter, A. L. and J. Pakanen, Eds. 2001. *Demonstrating Automated Fault Detection and Diagnosis Methods in Real Buildings*. IEA Annex 34 Final Report. VTT Building Technology, Espoo, Finland.

Dodier, R. H. and J. F. Kreider. 1999. Detecting whole building energy problems, *ASHRAE Transactions*, 105(1): 579-592.

Energy Information Administration. 2006. Annual Energy Review 2005.

Facility Dynamics Engineering. (n.d.). PACRAT, http://facilitydynamics.com/pacrat.html, March 2006.

Fels, M. F. 1986. PRISM: An Introduction, *Energy and Buildings*, 9(1,2): 5-18.

Friedman, H. and M. A. Piette. 2001. Comparison of emerging diagnostic tools for large commercial HVAC systems. *Proceedings of the 9th National Conference on Building Commissioning, Cherry Hill, NJ*. May 9-11, 2001.

Grimmelius, H. T., J. K. Woud and G. Been. 1995. On-line failure diagnosis for compression refrigeration plants, *International Journal of Refrigeration*, 18(1): 31-41.

Haberl, J. S. 1992. The use of a monthly whole-campus energy analysis for evaluating a third party energy service agreement, *Proceedings ACEEE Summer Study on Energy Efficiency in Buildings*, 3(1): 3.95-3.110.

Haberl, J., R. Sparks and C. Culp. 1996. Exploring new techniques for displaying complex building energy consumption data, *Energy and Buildings*, 24(1): 27-38.

Haberl, J. S. and M. Abbas. 1998a. Development of graphical indices for viewing building energy data. I, *Transactions of the ASME. Journal of Solar Energy Engineering*, 120(3): 156-61.

Haberl, J. S. and M. Abbas. 1998b. Development of graphical indices for viewing building energy data. II, *Transactions of the ASME. Journal of Solar Energy Engineering*, 120(3): 162-167.

Haberl, J. S. and T. E. Bou-Saada. 1998. Procedures for calibrating hourly simulation models to measured building energy and environmental data, *Transactions of the ASME. Journal of Solar Energy Engineering*, 120(3): 193-204.

Haberl, J. S. and S. Cho. 2004. Literature Review of Uncertainty of Analysis Methods (Inverse Model Toolkit), Energy Systems Lab ESL-TR-04/10-03, October 2004.

Haberl, J. S. and D. E. Claridge. 1987. Expert system for building energy consumption analysis: Prototype results, *ASHRAE Transactions*, 93(1): 979-998.

Haberl, J. S., L. K. Norford and J. V. Spadaro. 1989. Diagnosing building operational problems, *ASHRAE Journal*, 31(6): 20-30.

Haberl, J. S., N. Saman and T. Bou-Saada. 2002. Air-Side Accuracy Tests for Four HVAC Systems: Dual Duct Constant Volume (DDCAV), Dual Duct Variable Volume (DDVAV), Constant Volume with Reheat (CAVRH), Variable Volume with Reheat (VAVRH), Four Pipe Fan Coil Unit (FC), Four Pipe Induction Unit (FI), and Single Zone (SZ) Systems, Energy Systems Lab ESL-TR-01/02-02, Revised June 2002.

Haberl, J. S. and E. J. Vajda. 1988. Use of metered data analysis to improve building operation and maintenance: Early results from two federal complexes. *Proceedings of the ACEEE Summer Study on Energy Efficiency in Building, Asilomar, California*.

Haves, P., T. I. Salsbury and J. A. Wright. 1996. Condition monitoring in HVAC subsystems using first principles models. *ASHRAE Transactions* 102(1): 519-527.

Heinemeier, K. H., R. M. Richardson and K. Kulathumani. 1999. User and market factors that influence diagnostic tool development. *Diagnostics for Commercial Buildings: Research to Practice Workshop, Pacific Energy Center, San Francisco*.

House, J. M., H. Vaezi-Nejad and J. M. Whitcomb. 2001. An expert rule set for fault detection in air-handling units. *ASHRAE Transactions* 107(1): 858-871.

Hyvarinen, J. and S. Karki, Eds. 1996. *Building Optimization and Fault Diagnosis Source Book*. Technical Research Center (VTT), Espoo, Finland.

Isermann, R. 1984. Process fault detection based on modeling and estimation methods - A survey, *Automatica*, 20(4): 387-404.

Kaplan, M., J. McFerran, J. Jansen and R. Pratt. 1990. Reconciliation of a DOE2.1C model with monitored end-use data for a small office building, *ASHRAE Transactions*, 96(1): 994-1000.

Katipamula, S. and M. R. Brambley. 2005. Methods for fault detection, diagnostics, and prognostics for building systems - A review, Part I, *HVAC and R Research*, 11(1): 3-25.

Katipamula, S. and D. E. Claridge. 1992. Monitored air handler performance and comparison with a simplified system model, *ASHRAE Transactions*, 98(2): 341-350.

Katipamula, S., R. G. Pratt, D. P. Chassin, Z. T. Taylor, K. Gowri and M. R. Brambley. 1999. Automated fault detection and diagnostics for outdoor-air ventilation systems and economizers: methodology and results from field testing, *ASHRAE Transactions*, 105(1): 555-567.

Kissock, K., T. A. Reddy, J. S. Haberl and D. E. Claridge. 1993. EModel: A new tool for analyzing building energy use data. *Proceedings of the National Industrial Energy Technology Conference, Houston, TX.*

Knebel, D. E. 1983. *Simplified Energy Analysis Using the Modified Bin Method.* Atlanta, American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Kreider, J. F. and J. S. Haberl. 1994. Predicting hourly building energy use: the great energy predictor shootout - overview and discussion of results, *ASHRAE Transactions*, 100(2): 1104-1118.

Lee, S. U. 2002. Automatic calibration of a building energy performance model and remote fault detection for Continuous Commissioning using a global optimization program. M.S. Thesis. Texas A&M University, College Station.

Lee, S. U. and D. E. Claridge. 2003. Field tests of whole building simulation for HVAC system fault detection, draft report, Texas A&M University Energy Systems Laboratory, July 2003.

Lee, S.U., F. Painter and D. Claridge 2007. Whole building commercial HVAC systems simulation for use in energy consumption fault detection. Accepted: *ASHRAE Transactions* 113(1).

Lee, W.-Y., C. Park, J. M. House and G. E. Kelly. 1996. Fault diagnosis of an air-handling unit using artificial neural networks. *ASHRAE Transactions* 102(1): 540-549.

Liu, M. and D. E. Claridge. 1995. Application of calibrated HVAC system models to identify component malfunctions and to optimize the operation and control schedules. *International Solar Energy Conference, Maui, HI.*

Liu, M. and D. E. Claridge. 1998. Use of calibrated HVAC system models to optimize system operation, *Transactions of the ASME. Journal of Solar Energy Engineering*, 120(2): 131-138.

Liu, M., L. Song, G. Wei and D. E. Claridge. 2004. Simplified building and air-handling unit model calibration and applications, *Journal of Solar Energy Engineering, Transactions of the ASME*, 126(1): 601-609.

Meyers, S., E. Mills, A. Chen and L. Demsetz. 1996. Building data visualization for diagnostics, *ASHRAE Journal*, 38(6): 63-73.

Mills, E., N. Bourassa, M. A. Piette, H. Friedman, T. Haasl, T. Powell and D. Claridge. 2005. The cost-effectiveness of commissioning, *HPAC Heating, Piping, AirConditioning Engineering*, 77(10): 20-24.

Norford, L.K., J.A. Wright, R.A. Buswell, D. Luo, C.J. Klaassen, and A. Suby. 2002. Demonstration of fault detection and diagnosis methods for air handling units (RP-1020), *HVAC&R Research*, 8(1): 41-71.

Page, E. S. 1954. Continuous inspection schemes, *Biometrika*, 41(1): 100-115.

Painter, F. 2005. ABCAT: Automated Building Commissioning Analysis Tool development and implementation on a commercial grade building. (Draft of Thesis). Thesis not completed. Texas A&M University, College Station.

Patton, R. J., J. Chen and S. B. Nielsen. 1995. Model based methods for fault diagnosis: some guide-lines. *Transactions of the Institute of Measurement and Control* 17(2): 73-83.

Rachlin, J., M.F. Fels, and R.H. Socolow. 1986. The stability of PRISM estimates, *Energy and Buildings*, 9(1,2): 149-157.

Reddy, T. A., J. S. Haberl and J. S. Elleson. 1999. Engineering uncertainty analysis in the evaluation of energy and cost savings of cooling system alternatives based on field-monitored data (RP-1004), *ASHRAE Transactions*, 105(2): 1047-1057.

Reddy, T. A., D. Niebur, K. Anderson, P. Pericolo and G. Cabrera. 2003. Evaluation of the suitability of different chiller performance models for on-line training applied to automated fault detection and diagnosis (RP-1139), *HVAC&R Research*, 9(4): 385-414.

Rossi, T. M. and J. E. Braun. 1997. Statistical, rule-based fault detection and diagnostic method for vapor compression air conditioners, *HVAC&R Research*, 3(1): 19-37.

Ruch, D. and D. E. Claridge. 1992. Four-parameter change-point model for predicting energy consumption in commercial buildings, *Journal of Solar Energy Engineering, Transactions of the ASME*, 114(2): 77-83.

Ryan, T. P. 2000. *Statistical Methods for Quality Improvement*. 2nd Edition, New York, Wiley and Sons.

Salsbury, T. and R. Diamond. 2000. Performance validation and energy analysis of HVAC systems using simulation, *Energy and Buildings*, 32(1): 5-17.

Schein, J. and J. M. House. 2003. Application of control charts for detecting faults in variable-air-volume boxes, *ASHRAE Transactions*, 109(2): 671-682.

Song, S. (2006). Development of new methodologies for evaluating the energy performance of new commercial buildings. Ph.D. Dissertation. Texas A&M University, College Station.

Thamilseran, S. (1999). An inverse bin method to measure the savings from energy conservation retrofits in commercial buildings. Ph.D. Dissertation. Texas A&M University, College Station.

Turner, W. D., D. E. Claridge, S. Deng, S. Cho, M. Liu, T. Hagge, C. J. Darnell and H. J. Bruner. 2001. Persistence of savings obtained from Continuous Commissioning^{SM}. *Proceedings of the 9th National Conference on Building Commissioning, Cherry Hill, NJ*.

Wang, G. and M. Liu (2006). Fault detection and diagnosis for single duct air handling units. Unpublished draft report, University of Nebraska, Lincoln.

Wang, S. and J. Cui. 2006. A robust fault detection and diagnosis strategy for centrifugal chillers, *HVAC&R Research*, 12(3): 407-428.

Wang, S. and J. Qin. 2005. Sensor fault detection and validation of VAV terminals in air conditioning systems, *Energy Conversion and Management*, 46(15-16): 2482-2500.

Wei, G., M. Liu and D. E. Claridge. 1998. Signatures of heating and cooling energy consumption for typical AHUs. *Proceedings of the Eleventh Symposium on Improving Building Systems in Hot and Humid Climates, Fort Worth, TX*.

Xu, P. and P. Haves. 2002. Field testing of component level model based fault detection methods for mixing boxes and VAV fan systems. *California Energy Commission PIER Program*.

GLOSSARY

4P-CP	Four Parameter – Change Point
ABCAT	Automated Building Commissioning Analysis Tool
AHU	Air Handling Unit
Analytical Redundancy	Model based method of analyzing residuals
ANN	Artificial Neural Network
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
BAS	Building Automation Systems
Black box model	Empirical or Data driven models
Calibrate	When used in reference to a simulation model, it is the process of adjusting the inputs to the model such that the generated consumption more accurately represents measured consumption
Cf	Cubic Foot
CHW	Chilled Water or Chilled Water (cooling) energy consumption
CUSUM	Cumulative Sum
CV-RMSE	Coefficient of Variation of the Root Mean Squared Error
Cx	New Building Commissioning
DASNY	Dorm Authority of the State of New York
Data driven models	Models that learn to map inputs to outputs from a set of training data
DD	Dual Duct
DDCV	Dual Duct Constant Volume
DDVAV	Dual Duct Variable Air Volume
DFDD	Dual Fan Dual Duct
DFDDCV	Dual Fan Dual Duct Constant Volume
DFDDVAV	Dual Fan Dual Duct Variable Air Volume
DOE	Department of Energy
DX	Direct Expansion
EMCS	Energy Management and Control System
EIS	Energy Information Systems
Expert rules	Knowledge base derived from experienced professionals or experts
FDD	Fault Detection and Diagnostics
First Principles Models	Physical models governed by engineering fundamentals
HVAC	Heating Ventilating and Air Conditioning
HW	Hot Water or Hot Water (heating) energy consumption
IEA	International Energy Agency
MBE	Mean Bias Error
MMBTU	Million BTU
OAHU	Outside Air Handling Unit

PACRAT	Performance and Continuous Re-commissioning Analysis Tool
PRISM	Princeton Scorekeeping Method
Residuals	Difference between the model output and the measurement
RCx	Retro-Commissioning
RMSE	Root Mean Squared Error
SDCV	Single Duct Constant Volume
SDRH	Single Duct with terminal ReHeat
SDVAV	Single Duct Variable Air Volume
SEAP	Simplified Energy Analysis Procedure
STAC	State Technologies Advancement Collaborative
SZHC	Single Zone Heating and Cooling
TAG	Technical Advisory Group
VAV	Variable Air Volume
VFD	Variable Frequency Drive
WB_{Cool}	Whole Building Cooling
WBD	Whole Building Diagnostician
WB_{Elec}	Whole Building Electric
WB_{Heat}	Whole Building Heating
White box models	First principles models

APPENDIX A

SIMULATION MODEL DETAILS

A.1. System Diagrams

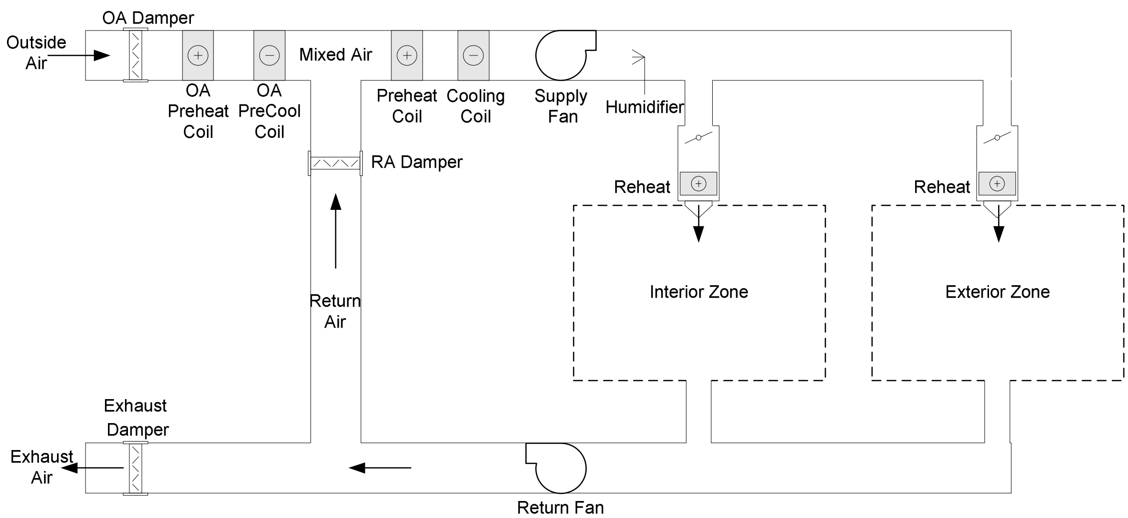

Figure 50. Single Duct with Terminal Reheat (SDRH) System Diagram

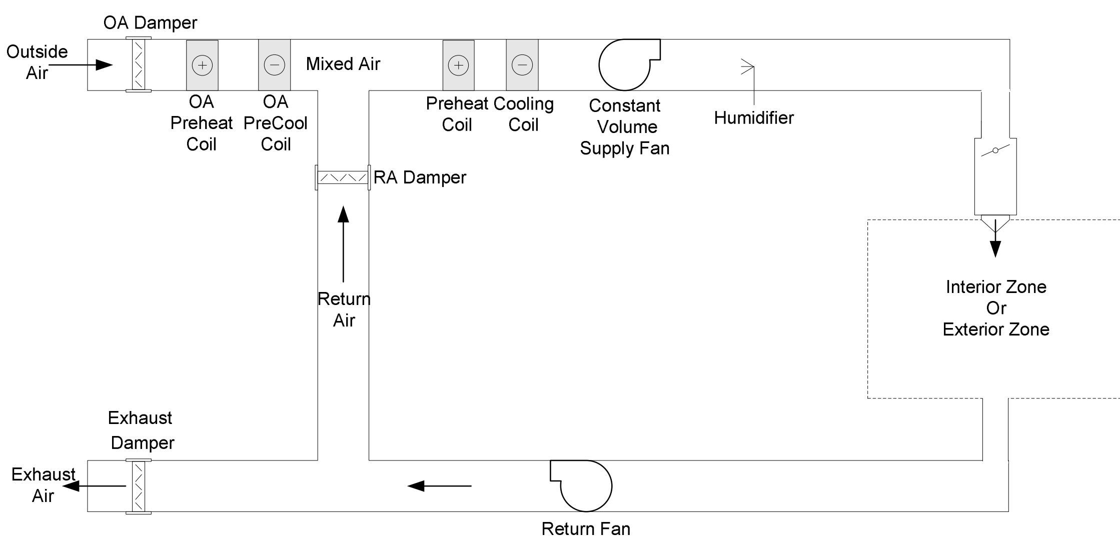

Figure 51. Single Zone Heating and Cooling (SZHC) System Diagram

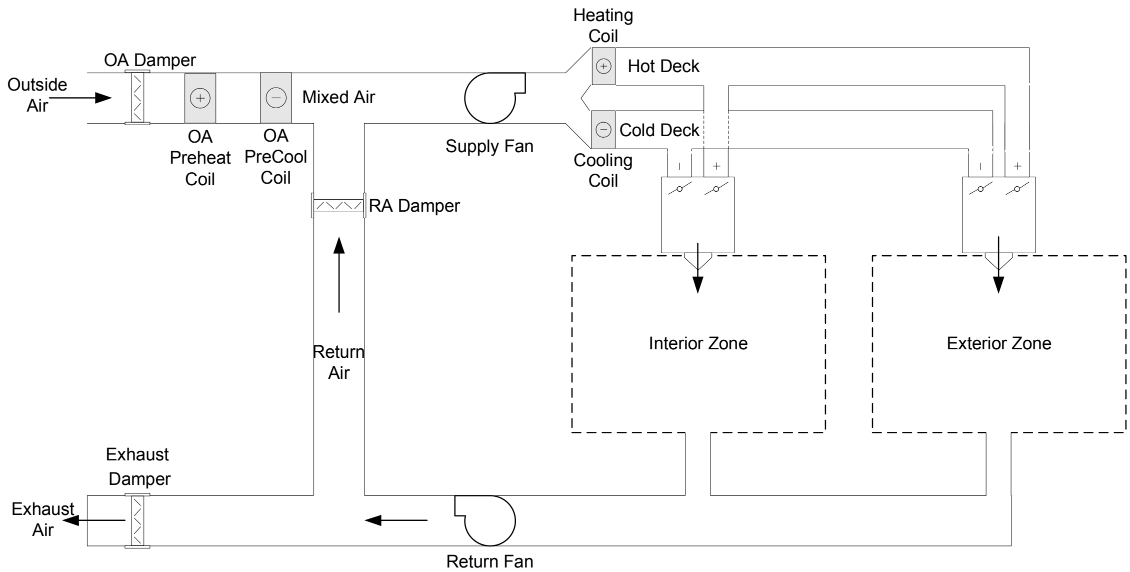

Figure 52. Dual Duct (DD) System Diagram

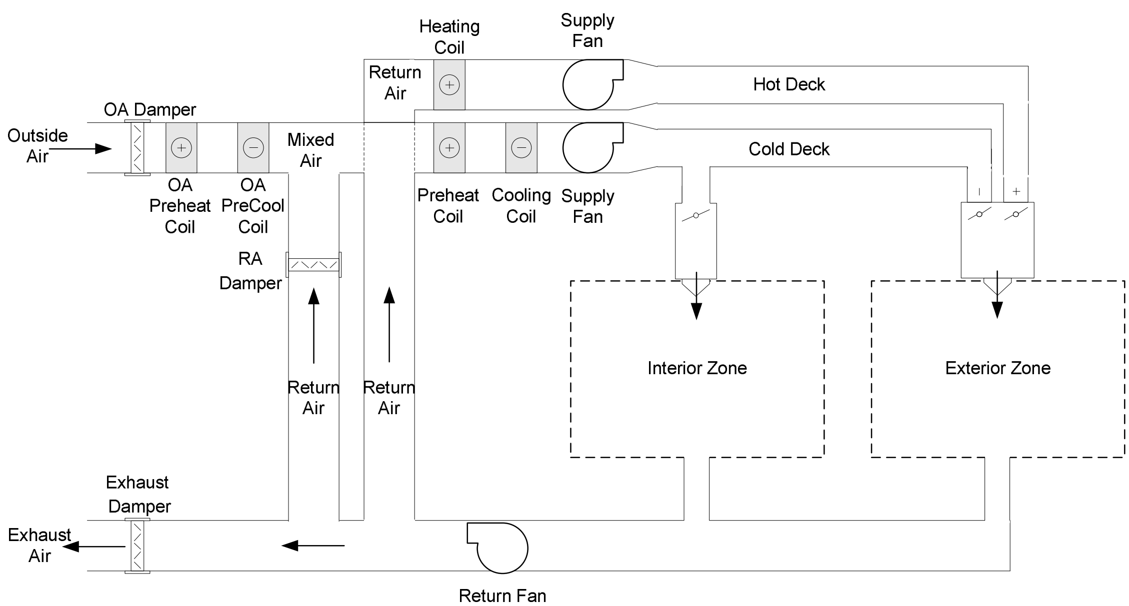

Figure 53. Dual Fan Duct Dual (DFDD) System Diagram

A.2. Operational Equations for System Models

The following set of four system calculations assume that zone set point temperatures, outside air temperature and relative humidity, system design and minimum flow rates, design fan static, fan efficiency, and coil discharge temperatures have been previously established.

A.2.1. SDRH

1.	Air flow rate (cfm) for interior and exterior zones: Variable Air Volume:	$V_i = \frac{q_{is}}{1.08(T_i - T_{CL})}$ $V_e = \frac{q_{es}}{1.08(T_e - T_{CL})}$
	Constant Volume:	$V_i = V_{iD}$ $V_e = V_{eD}$
2.	Supply air temperature (°F) for interior and exterior zones if CV systems:	$T_{iS} = T_i - \frac{q_{iS}}{1.08 \times V_i}$ $T_{eS} = T_e - \frac{q_{eS}}{1.08 \times V_e}$
3.	Total Air Flow Rate (cfm):	$V_T = V_i + V_e$
4.	Rated Supply Fan Heat Gain (Btu/hr):	$q_{SfRated} = \frac{V_T \times P_{SfT} \times 0.7457 \times 3412}{6346 Eff_f}$
	Part Load Ratio:	$PLR = \frac{V_T}{V_{iD} + V_{eD}}$
	Actual Supply Fan Heat Gain (Btu/hr):	$q_{Sf} = \begin{pmatrix} 0.00153 + 0.0052 PLR + \\ 1.1086 PLR^2 - 0.1164 PLR^3 \end{pmatrix} \times q_{SfRated}$
	Differential Temperature Across Supply Fan (°F):	$dT_{Sf} = \frac{q_{Sf}}{1.08 V_T}$
5.	Cooling coil leaving air conditions: Temperature (°F):	$T_{CL} = T_{Cset} + dT_{Sf}$
	Wet Coil Humidity Ratio (lb_m/lb_{da}): (Assuming 90% saturated)	$w_{CLwet} = \frac{0.62198 \times 0.9 P_{CLws}}{P_{atm} - 0.9 P_{CLws}}$
6.	Reheat energy (Btu/hr) Variable Air Volume:	$q_{iRH} = 1.08 \times V_i \times (T_i - T_{Cset}) - q_{iS}$ $q_{eRH} = 1.08 \times V_e \times (T_e - T_{Cset}) - q_{eS}$
	Constant Volume:	$q_{iRH} = 1.08 \times V_i \times (T_{iS} - T_{Cset})$ $q_{eRH} = 1.08 \times V_e \times (T_{eS} - T_{Cset})$

7.	Rated Return Fan Heat Gain (Btu/hr):	$q_{RfRated} = \frac{V_T \times P_{RfT} \times 0.7457 \times 3412}{6346 Eff_f}$
	Part Load Ratio:	$PLR = \frac{V_T}{V_{iD} + V_{eD}}$
	Actual Return Fan Heat Gain (Btu/hr):	$q_{Rf} = \begin{pmatrix} 0.00153 + 0.0052 PLR + \\ 1.1086 PLR^2 - 0.1164 PLR^3 \end{pmatrix} \times q_{RfRated}$
	Differential Temperature Across Return Fan (°F):	$dT_{Rf} = \frac{q_{Rf}}{1.08 V_T}$
8.	Return Air Temperatures (°F) from interior and exterior zones and Return Air Temperature (°F) after return air fan:	$T_{iR} = T_i$ and $T_{eR} = T_e$ $T_R = \frac{(T_{iR} \times V_i + T_{eR} \times V_e)}{V_T} + dT_{Rf} + dT_{Rduct}$
9.	Outside Air Pretreat Coil Leaving Air Temperature (°F):	
	If $T_{OAPHset} > T_{OA}$:	$T_{OAL} = T_{OAPHset}$
	Else:	$T_{OAL} = T_{OA}$
10.	Outside Air Volume Ratio and Flow Rate:	
	If there is an economizer:	$X_{OA} = Max\left(X_{OAEconMin}, \frac{T_{CL} - T_R}{T_{OAL} - T_R} \right)$
	If X_{OA} calculated exceeds $X_{OAEconMax}$:	$X_{OA} = X_{OAEconMax}$
	If there is no economizer and fixed percentage outside air control:	$X_{OA} = \frac{V_{OAD}}{V_{iD} + V_{eD}}$
	If there is no economizer and fixed volume outside air control:	$X_{OA} = \frac{V_{OAD}}{V_T}$
	Outside Air Flow Rate (cfm):	$V_{OA} = X_{OA} \times V_T$

11.	If an electric humidifier exists:	
	Return Air Humidity Ratio at Minimum RH Set Point (lb_m/lb_{da}):	$w_{R1} = \dfrac{0.62198 \dfrac{RH_{spMin}}{100} \times P_{Rws}}{P_{atm} \dfrac{RH_{spMin}}{100} \times P_{Rws}}$
	Humidification Load (lbs/hr):	$humidload = \left(w_{R1} - w_{oa}\right) \times \dfrac{60\,\min/hr}{13.5\,ft^3/lb} \times V_{oa}$
	Latent Heat of Vaporization (kW):	$E_{fg} = humidload \times \dfrac{1120\,Btu/lb}{3412\,Btu/kW}$
	If measured electric gains were used in load calculations, subtract E_{fg} from measured electric gains, recalculate loads, and return to step 1. Repeat until the change from E_{fg} from one pass to the next is less than 0.01.	
12.	Heating and Cooling Loads of outside air pretreatment coils:	
	Wet Precool Coil Leaving Air Humidity Ratio (lb_m/lb_{da}):	$w_{OAL} = \dfrac{0.62198 \times 0.9 P_{OAPCws}}{P_{atm} - 0.9 P_{OAPCws}}$
	OA Preheat Coil Heating Load (Btu/hr):	$q_{OAPH} = 1.08 V_{OA}\left(T_{OAPHset} - T_{OA}\right)$
	OA Precool Coil Sensible Cooling Load (Btu/hr):	$q_{OAPCS} = 1.08 V_{OA}\left(T_{OA} - T_{OAPCset}\right)$
	OA Precool Coil Sensible Cooling Load (Btu/hr):	$q_{OAPCL} = 4840 V_{OA}\left(w_{OA} - w_{OAL}\right)^{+}$
13.	Mixed Air Temperature (°F):	$T_{MA} = T_R + X_{OA}\left(T_{OAL} - T_R\right)$

14. Intermediate Return and Mixed Air Humidity Ratios (lb_m/lb_{da}) for dry and wet cooling coil conditions:	$w_{iRdry} = w_{OAL} + \frac{q_{iL}}{4840 \times X_{OA} V_i}$ $w_{eRdry} = w_{CLwet} + \frac{q_{eL}}{4840 \times V_e}$ $w_{Rdry} = \frac{(w_{iRdry} \times V_i + w_{eRdry} \times V_e)}{V_T}$ $w_{MAdry} = w_{Rdry} + X_{OA}(w_{OAL} - w_{Rdry})$ $w_{iRwet} = w_{CLwet} + \frac{q_{iL}}{4840 \times V_i}$ $w_{eRwet} = w_{CLwet} + \frac{q_{eL}}{4840 \times V_e}$ $w_{Rwet} = \frac{(w_{iRwet} \times V_i + w_{eRwet} \times V_e)}{V_T}$ $w_{MAwet} = w_{Rwet} + X_{OA}(w_{OAL} - w_{Rwet})$
15. Final Return Air Humidity Ratio (lb_m/lb_{da}): Final Mixed Air Humidity Ratio (lb_m/lb_{da}):	$w_R = Min(w_{Rdry} + w_{Rwet})$ $w_{MA} = Min(w_{MAdry} + w_{MAwet})$
16. Final Space Relative Humidity (%) in interior and exterior zones:	$RH_i = \frac{w_i \times 100}{w_{isat}\left[1 - \left(1 - \frac{w_i}{w_{isat}}\right) \times \frac{P_{iws}}{P_{atm}}\right]}$ $RH_e = \frac{w_e \times 100}{w_{esat}\left[1 - \left(1 - \frac{w_e}{w_{esat}}\right) \times \frac{P_{ews}}{P_{atm}}\right]}$
17. Preheat Coil Heating Load (Btu/hr): Cooling Coil Sensible Cooling Load (Btu/hr): Cooling Coil Latent Cooling Load (Btu/hr):	$q_{PH} = Max\left(1.08 V_T (T_{HL} - T_{MA})^+, 1.08 V_T (T_{CL} - T_{MA})^+\right)$ $q_{CS} = 1.08 V_T (T_{CE} - T_{CL})$ $q_{CL} = 4840 V_T (w_{MA} - w_{CLwet})$ if $w_{MA} > w_{CLwet}$
18. Total Heating Load (Btu/hr): Total Cooling Load (Btu/hr):	$q_{HT} = q_{iRH} + q_{eRH} + q_{PH} + q_{OAPH}$ $q_{CT} = q_{CS} + q_{CL} + q_{OAPCS} + q_{OAPCL}$

A.2.2. SZHC

1.	Air flow rate (cfm) for interior and exterior zones: Constant Volume Only:	$V_e = V_{eD}$
2.	Supply air temperature (°F) for interior and exterior zones:	$T_{eS} = T_e - \frac{q_{eS}}{1.08 \times V_e}$
3.	Total Air Flow Rate (cfm):	$V_T = V_e$
4.	Rated Supply Fan Heat Gain (Btu/hr):	$q_{SfRated} = \frac{V_T \times P_{SfT} \times 0.7457 \times 3412}{6346 Eff_f}$
	Part Load Ratio:	$PLR = \frac{V_T}{V_{iD} + V_{eD}}$
	Actual Supply Fan Heat Gain (Btu/hr):	$q_{Sf} = \begin{pmatrix} 0.00153 + 0.0052 PLR + \\ 1.1086 PLR^2 - 0.1164 PLR^3 \end{pmatrix} \times q_{SfRated}$
	Differential Temperature Across Supply Fan (°F):	$dT_{Sf} = \frac{q_{Sf}}{1.08 V_T}$
5.	Cooling coil leaving air conditions: Temperature (F):	$T_{CL} = T_{eS} - dT_{Sf}$
	Wet Coil Humidity Ratio (lb_m/lb_{da}): (Assuming 90% saturated)	$w_{CLwet} = \frac{0.62198 \times 0.9 P_{CLws}}{P_{atm} - 0.9 P_{CLws}}$
6.	Rated Return Fan Heat Gain (Btu/hr):	$q_{RfRated} = \frac{V_T \times P_{RfT} \times 0.7457 \times 3412}{6346 Eff_f}$
	Part Load Ratio:	$PLR = \frac{V_T}{V_{eD}} = 1$
	Actual Return Fan Heat Gain (Btu/hr):	$q_{Rf} = \begin{pmatrix} 0.00153 + 0.0052 PLR + \\ 1.1086 PLR^2 - 0.1164 PLR^3 \end{pmatrix} \times q_{RfRated}$
	Differential Temperature Across Return Fan (°F):	$dT_{Rf} = \frac{q_{Rf}}{1.08 V_T}$
7.	Return Air Temperatures (°F) from interior and exterior zones and Return Air Temperature (°F) after return air fan:	$T_{eR} = T_e$ $T_R = \frac{(T_{eR} \times V_e)}{V_T} + dT_{Rf} + dT_{Rduct}$
8.	Outside Air Pretreat Coil Leaving Air Temperature (°F): If $T_{OAPHset} > T_{OA}$: Else:	 $T_{OAL} = T_{OAPHset}$ $T_{OAL} = T_{OA}$

9. Outside Air Volume Ratio and Flow Rate:	
If there is an economizer:	$X_{OA} = Max\left(X_{OAEconMin}, \frac{T_{CL} - T_R}{T_{OAL} - T_R}\right)$
If X_{OA} calculated exceeds $X_{OAEconMax}$:	$X_{OA} = X_{OAEconMax}$
If there is no economizer and fixed percentage outside air control:	$X_{OA} = \frac{V_{OAD}}{V_{eD}}$
If there is no economizer and fixed volume outside air control:	$X_{OA} = \frac{V_{OAD}}{V_T}$
Outside Air Flow Rate (cfm):	$V_{OA} = X_{OA} \times V_T$
10. If an electric humidifier exists:	
Return Air Humidity Ratio at Space RH Set Point (lb_m/lb_{da}):	$w_{R1} = \frac{0.62198 \frac{RH_{spMin}}{100} \times P_{Rws}}{P_{atm} \frac{RH_{spMin}}{100} \times P_{Rws}}$
Humidification Load (lbs/hr):	$humidload = (w_{R1} - w_{oa}) \times \frac{60 \min/hr}{13.5 ft^3/lb} \times V_{oa}$
Latent Heat of Vaporization (kW):	$E_{fg} = humidload \times \frac{1120 Btu/lb}{3412 Btu/kW}$
If measured electric gains were used in load calculations, subtract E_{fg} from measured electric gains, recalculate loads, and return to step 1. Repeat until the change from E_{fg} from one pass to the next is less than 0.01.	
11. Heating and Cooling Loads of outside air pretreatment coils:	
Wet Precool Coil Leaving Air Humidity Ratio (lb_m/lb_{da}):	$w_{OAL} = \frac{0.62198 \times 0.9 P_{OAPCws}}{P_{atm} - 0.9 P_{OAPCws}}$
OA Preheat Coil Heating Load (Btu/hr):	$q_{OAPH} = 1.08 V_{OA}(T_{OAPHset} - T_{OA})$
OA Precool Coil Sensible Cooling Load (Btu/hr):	$q_{OAPCS} = 1.08 V_{OA}(T_{OA} - T_{OAPCset})$
OA Precool Coil Sensible Cooling Load (Btu/hr):	$q_{OAPCL} = 4840 V_{OA}(w_{OA} - w_{OAL})^+$
12. Mixed Air Temperature (°F):	$T_{MA} = T_R + x_{OA}(T_{OAL} - T_R)$

13.	Intermediate Return and Mixed Air Humidity Ratios (lb_m/lb_{da}) for dry and wet cooling coil conditions:	$w_{eRdry} = w_{CLwet} + \frac{q_{eL}}{4840 \times V_e}$ $w_{Rdry} = \frac{(w_{eRdry} \times V_e)}{V_T}$ $w_{MAdry} = w_{Rdry} + X_{OA}(w_{OAL} - w_{Rdry})$ $w_{eRwet} = w_{CLwet} + \frac{q_{eL}}{4840 \times V_e}$ $w_{Rwet} = \frac{(w_{eRwet} \times V_e)}{V_T}$ $w_{MAwet} = w_{Rwet} + X_{OA}(w_{OAL} - w_{Rwet})$
14.	Final Return Air Humidity Ratio (lb_m/lb_{da}): Final Mixed Air Humidity Ratio (lb_m/lb_{da}):	$w_R = Min(w_{Rdry} + w_{Rwet})$ $w_{MA} = Min(w_{MAdry} + w_{MAwet})$
15.	Final Space Relative Humidity (%) in interior and exterior zones:	$RH_e = \frac{w_e \times 100}{w_{esat}\left[1 - \left(1 - \frac{w_e}{w_{esat}}\right) \times \frac{P_{ews}}{P_{atm}}\right]}$
16.	Heating Coil Heating Load (Btu/hr): Cooling Coil Sensible Cooling Load (Btu/hr): Cooling Coil Latent Cooling Load (Btu/hr):	$q_H = 1.08 V_T (T_{CL} - T_{MA})^+$ $q_{CS} = 1.08 V_T (T_{MA} - T_{CL})^+$ $q_{CL} = 4840 V_T (w_{MA} - w_{CLwet})$ if $w_{MA} > w_{CLwet}$
17.	Total Heating Load (Btu/hr): Total Cooling Load (Btu/hr):	$q_{HT} = q_{PH} + q_{OAPH}$ $q_{CT} = q_{CS} + q_{CL} + q_{OAPCS} + q_{OAPCL}$

A.2.3. DD

1. Air Flow Rates of Interior Zone only, identical approach for Exterior Zone flows:

If $q_{iS} > 0$: $T_{iS} = T_{CL}$, $V_{iCideal} = \dfrac{q_{is}}{1.08(T_i - T_{iS})}$

Else $q_{iS} < 0$: $T_{iS} = T_{HL}$, $V_{iHideal} = \dfrac{q_{is}}{1.08(T_i - T_{iS})}$

If $V_{iMin} > (V_{iCideal}$ or $V_{iHideal})$ $T_{iS} = T_i - \dfrac{q_{is}}{1.08 V_{iMin}}$

$$V_{iC} = \frac{V_{iMin}(T_{iS} - T_{HL})}{(T_{CL} - T_{HL})} \text{ , } V_{iH} = \frac{V_{iMin}(T_{iS} - T_{CL})}{(T_{HL} - T_{CL})}$$

Leakage Flow Rates: $V_{iLeakage} = leakage\_rate \times V_i$

If $V_{iH} < V_{iLeakage}$

$$V_{iHLeakage} = V_{iLeakage} - V_{iH}$$

$$V_{iCadder} = \frac{V_{iHLeakage} \times (T_{HL} - T_i)}{(T_i - T_{CL})}$$

Else: $V_{iHLeakage} = 0$, $V_{iCadder} = 0$

If $V_{iC} < V_{iLeakage}$

$$V_{iCLeakage} = V_{iLeakage} - V_{iC}$$

$$V_{iHadder} = \frac{V_{iCLeakage} \times (T_i - T_{CL})}{(T_{HL} - T_i)}$$

Else: $V_{iCLeakage} = 0$, $V_{iHadder} = 0$

Int Cold Deck Flow (cfm): $V_{iC} = V_{iCideal} + V_{iCadder} + V_{iCLeakage}$

Int Hot Deck Flow (cfm): $V_{iH} = V_{iHideal} + V_{iHadder} + V_{iHLeakage}$

Total Int Zone Flow (cfm): $V_i = V_{iC} + V_{iH}$

Total Cold Deck Flow (cfm): $V_{Tcd} = V_{iC} + V_{eC}$

Total Hot Deck Flow (cfm): $V_{Thd} = V_{iH} + V_{eH}$

Total Flow (cfm): $V_T = V_{Tcd} + V_{Thd}$

2.	Rated Supply Fan Heat Gain (Btu/hr):	$q_{SfRated} = \frac{V_T \times P_{SfT} \times 0.7457 \times 3412}{6346 Eff_f}$
	Part Load Ratio:	$PLR = \frac{V_T}{V_{iD} + V_{eD}}$
	Actual Supply Fan Heat Gain (Btu/hr):	$q_{Sf} = \begin{pmatrix} 0.00153 + 0.0052 PLR + \\ 1.1086 PLR^2 - 0.1164 PLR^3 \end{pmatrix} \times q_{SfRated}$
	Differential Temperature Across Supply Fan (°F):	$dT_{Sf} = \frac{q_{Sf}}{1.08 V_{Tcd}}$
3.	Cooling coil leaving air conditions:	
	Temperature (°F):	$T_{CL} = T_{Cset}$
	Wet Coil Humidity Ratio (lb_m/lb_{da}): (Assuming 90% saturated)	$w_{CLwet} = \frac{0.62198 \times 0.9 P_{CLws}}{P_{atm} - 0.9 P_{CLws}}$
4.	Heating coil leaving air conditions:	
	Temperature (°F):	$T_{HL} = T_{Hset}$
5.	Rated Return Fan Heat Gain (Btu/hr):	$q_{RfRated} = \frac{V_T \times P_{RfT} \times 0.7457 \times 3412}{6346 Eff_f}$
	Part Load Ratio:	$PLR = \frac{V_T}{V_{iD} + V_{eD}}$
	Actual Return Fan Heat Gain (Btu/hr):	$q_{Rf} = \begin{pmatrix} 0.00153 + 0.0052 PLR + \\ 1.1086 PLR^2 - 0.1164 PLR^3 \end{pmatrix} \times q_{RfRated}$
	Differential Temperature Across Return Fan (°F):	$dT_{Rf} = \frac{q_{Rf}}{1.08 V_T}$
6.	Return Air Temperatures (°F) from interior and exterior zones and Return Air Temperature (°F) after return air fan:	$T_{iR} = T_i$ and $T_{eR} = T_e$ $T_R = \frac{(T_{iR} \times V_i + T_{eR} \times V_e)}{V_T} + dT_{Rf} + dT_{Rduct}$
7.	Outside Air Pretreat Coil Leaving Air Temperature (°F):	
	If $T_{OAPHset} > T_{OA}$:	$T_{OAL} = T_{OAPHset}$
	Else:	$T_{OAL} = T_{OA}$

8.	Outside Air Volume Ratio and Flow Rate:		
	If there is an economizer:	$X_{OA} = Max\left(X_{OAEconMin}, \frac{T_{CL} - dT_{Sf} - T_R}{T_{OAL} - T_R} \right)$	
	If X_{OA} calculated exceeds $X_{OAEconMax}$:	$X_{OA} = X_{OAEconMax}$	
	If there is no economizer and fixed percentage outside air control:	$X_{OA} = \frac{V_{OAD}}{V_{iD} + V_{eD}}$	
	If there is no economizer and fixed volume outside air control:	$X_{OA} = \frac{V_{OAD}}{V_T}$	
	Outside Air Flow Rate (cfm):	$V_{OA} = X_{OA} \times V_T$	
9.	Heating and Cooling Loads of outside air pretreatment coils:		
	Wet Precool Coil Leaving Air Humidity Ratio (lb_m/lb_{da}):	$w_{OAL} = \frac{0.62198 \times 0.9 P_{OAPCws}}{P_{atm} - 0.9 P_{OAPCws}}$	
	OA Preheat Coil Heating Load (Btu/hr):	$q_{OAPH} = 1.08 V_{OA} \left(T_{OAPHset} - T_{OA} \right)$	
	OA Precool Coil Sensible Cooling Load (Btu/hr):	$q_{OAPCS} = 1.08 V_{OA} \left(T_{OA} - T_{OAPCset} \right)$	
	OA Precool Coil Sensible Cooling Load (Btu/hr):	$q_{OAPCL} = 4840 V_{OA} \left(w_{OA} - w_{OAL} \right)^{+}$	
10.	Mixed Air Temperature (°F):	$T_{MA} = T_R + X_{OA} \left(T_{OAL} - T_R \right)$	
	Preheat Coil Leaving Air Temperature (°F):	$T_{PH} = Max\left(T_{MA}, T_{CL} - dT_{Sf} \right)$	
	Hot Deck Coil Entering Temp (°F):	$T_{HE} = T_{PH} + dT_{Sf}$	
	Cold Deck Coil Entering Air Temp (°F):	$T_{CE} = T_{PH} + dT_{Sf}$	

11. Intermediate Return and Mixed Air Humidity Ratios (lb_m/lb_{da}) for dry and wet cooling coil conditions:	$X_C = \frac{V_{Tcd}}{V_T}$, $X_H = \frac{V_{Thd}}{V_T}$, $X_R = 1 - X_{OA}$ $X_{eC} = \frac{V_{eC}}{V_e}$, $X_{eH} = \frac{V_{eH}}{V_e}$ $X_{iC} = \frac{V_{iC}}{V_i}$, $X_{iH} = \frac{V_{iH}}{V_i}$ $w_{iRdry} = w_{OAL} + \frac{q_{iL}}{4840 \times X_{OA} V_i}$ $w_{eRdry} = w_{OAL} + \frac{q_{eL}}{4840 \times X_{OA} V_e}$ $w_{Rdry} = w_{OAL} + \frac{q_{iL} + q_{eL}}{4840 \times X_{OA} V_T}$ $w_{MAdry} = w_{Rdry} + X_{OA}(w_{OAL} - w_{Rdry})$ $w_{iRwet} = \frac{\left(X_{iC} \times w_{CLwet} + X_{iH} \times X_{OA} \times w_{OA} + \frac{q_{iL}}{4840 \times V_i} \right)}{(1 - X_{iH} \times X_R)}$ $w_{eRwet} = \frac{\left(X_{eC} \times w_{CLwet} + X_{eH} \times X_{OA} \times w_{OA} + \frac{q_{eL}}{4840 \times V_e} \right)}{(1 - X_{eH} \times X_R)}$ $w_{Rwet} = \frac{(w_{iRwet} \times V_i + w_{eRwet} \times V_e)}{V_T}$ $w_{MAwet} = w_{Rwet} + X_{OA}(w_{OAL} - w_{Rwet})$
12. Final Return Air Humidity Ratio (lb_m/lb_{da}): Final Mixed Air Humidity Ratio (lb_m/lb_{da}):	$w_R = Min(w_{Rdry} + w_{Rwet})$ $w_{MA} = Min(w_{MAdry} + w_{MAwet})$
13. Final Space Relative Humidity (%) in interior and exterior zones:	$RH_i = \frac{w_i \times 100}{w_{isat}\left[1 - \left(1 - \frac{w_i}{w_{isat}}\right) \times \frac{P_{iws}}{P_{atm}}\right]}$ $RH_e = \frac{w_e \times 100}{w_{esat}\left[1 - \left(1 - \frac{w_e}{w_{esat}}\right) \times \frac{P_{ews}}{P_{atm}}\right]}$

14.	Preheat Coil Heating Load (Btu/hr):	$q_{PH} = 1.08V_T(T_{CL} - dT_{Sf} - T_{MA})^+$
	Hot Deck Heating Load (Btu/hr):	$q_{hd} = 1.08V_{Thd}(T_{HL} - T_{HE})^+$
	Cold Deck Coil Sensible Cooling Load (Btu/hr):	$q_{CS} = 1.08V_{Tcd}(T_{CE} - T_{CL})$
	Cold Deck Coil Latent Cooling Load (Btu/hr):	$q_{CL} = 4840V_T(w_{MA} - w_{CLwet})$ if $w_{MA} > w_{CLwet}$
15.	Total Heating Load (Btu/hr):	$q_{HT} = q_{hd} + q_{PH} + q_{OAPH}$
	Total Cooling Load (Btu/hr):	$q_{CT} = q_{CS} + q_{CL} + q_{OAPCS} + q_{OAPCL}$

A.2.4. DFDD

1. Air Flow Rates:

Int Zone CD Flow (cfm):	$V_{iC} = \dfrac{q_{is}}{1.08(T_i - T_{Cset})}$
Ext Zone Ideal CD Flow (cfm):	$V_{eCideal} = \dfrac{q_{es}}{1.08(T_e - T_{Cset})}$
If $T_{OA} > T_{HDonoffTemp}$ Exterior Zone Hot Deck Flow (cfm):	$V_{eH} = 0$
Else: Ext Zone Ideal Hot Deck Flow (cfm):	$V_{eHideal} = \dfrac{1.08V_{eCideal}(T_e - T_{Cset}) - q_{es}}{1.08(T_{Hset} - T_e)}$
If $V_{eC} = V_{emin}$ and $V_{eHideal} < V_{\_eHmin}$ Added CD Flow to Compensate for HD Min Flow (cfm):	$V_{eCadder} = \dfrac{(V_{eH\min} - V_{eHideal}) \times (T_{Hset} - T_e)}{(T_e - T_{Cset})}$, $V_{eH} = V_{eH\min}$
If $V_{eC} > V_{emin}$	$V_{eCadder} = \dfrac{V_{eH\min} \times (T_{Hset} - T_e)}{(T_e - T_{Cset})}$, $V_{eH} = V_{eH\min}$
Ext Cold Deck Flow (cfm):	$V_{eC} = V_{eCideal} + V_{eCadder}$
Total Cold Deck Flow (cfm):	$V_{Tcd} = V_{iC} + V_{eC}$
Total Hot Deck Flow (cfm):	$V_{Thd} = V_{eH}$
Total Flow (cfm):	$V_T = V_{Tcd} + V_{Thd}$
Ext Zone Total Flow (cfm):	$V_e = V_{eH} + V_{eC}$

2.

Rated Cold Deck Supply Fan Heat Gain (Btu/hr):	$q_{SfRated} = \dfrac{V_T \times P_{SfT} \times 0.7457 \times 3412}{6346 Eff_f}$
Part Load Ratio:	$PLR = \dfrac{V_T}{V_{iD} + V_{eD}}$
Actual Supply Fan Heat Gain (Btu/hr):	$q_{Sf} = \begin{pmatrix} 0.00153 + 0.0052PLR + \\ 1.1086PLR^2 - 0.1164PLR^3 \end{pmatrix} \times q_{SfRated}$
Differential Temperature Across Supply Fan (°F):	$dT_{Sf} = \dfrac{q_{Sf}}{1.08V_{Tcd}}$

3. Cooling coil leaving air conditions:

Temperature (°F):	$T_{CL} = T_{Cset} - dT_{Sf}$
Wet Coil Humidity Ratio (lb_m/lb_{da}): (Assuming 90% saturated)	$w_{CLwet} = \dfrac{0.62198 \times 0.9P_{CLws}}{P_{atm} - 0.9P_{CLws}}$

4. Rated Hot Deck Fan Heat Gain (Btu/hr):	$q_{Sf2Rated} = \dfrac{V_T \times P_{SfT} \times 0.7457 \times 3412}{6346 Eff_f}$
Part Load Ratio:	$PLR = \dfrac{V_T}{V_{iD} + V_{eD}}$
Actual Supply Fan Heat Gain (Btu/hr):	$q_{Sf2} = \begin{pmatrix} 0.00153 + 0.0052PLR + \\ 1.1086PLR^2 - 0.1164PLR^3 \end{pmatrix} \times q_{Sf2Rated}$
Differential Temperature Across Supply Fan (°F):	$dT_{Sf2} = \dfrac{q_{Sf2}}{1.08V_{hd}}$
5. Heating coil leaving air conditions:	
Temperature (°F):	$T_{HL} = T_{Hset} - dT_{Sf2}$
6. Rated Return Fan Heat Gain (Btu/hr):	$q_{RfRated} = \dfrac{V_T \times P_{RfT} \times 0.7457 \times 3412}{6346 Eff_f}$
Part Load Ratio:	$PLR = \dfrac{V_T}{V_{iD} + V_{eD}}$
Actual Return Fan Heat Gain (Btu/hr):	$q_{Rf} = \begin{pmatrix} 0.00153 + 0.0052PLR + \\ 1.1086PLR^2 - 0.1164PLR^3 \end{pmatrix} \times q_{RfRated}$
Differential Temperature Across Return Fan (°F):	$dT_{Rf} = \dfrac{q_{Rf}}{1.08V_T}$
7. Return Air Temperatures (°F) from interior and exterior zones and Return Air Temperature (°F) after return air fan:	$T_{iR} = T_i$ and $T_{eR} = T_e$ $T_R = \dfrac{(T_{iR} \times V_{iC} + T_{eR}(V_{eC} + V_{eH}))}{V_T} + dT_{Rf} + dT_{Rduct}$
8. Outside Air Pretreat Coil Leaving Air Temperature (°F):	
If $T_{OAPHset} > T_{OA}$:	$T_{OAL} = T_{OAPHset}$
Else:	$T_{OAL} = T_{OA}$

9.	Outside Air Volume Ratio and Flow Rate:	
	If there is an economizer:	$X_{OA} = Max\left(X_{OAEconMin}, \frac{T_{CL} - T_R}{T_{OAL} - T_R}\right)$
	If X_{OA} calculated exceeds $X_{OAEconMax}$:	$X_{OA} = X_{OAEconMax}$
	If there is no economizer and fixed percentage outside air control:	$X_{OA} = \frac{V_{OAD}}{V_{iD} + V_{eD}}$
	If there is no economizer and fixed volume outside air control:	$X_{OA} = \frac{V_{OAD}}{V_i + V_e}$
	Outside Air Flow Rate (cfm):	$V_{OA} = X_{OA} \times V_{Tcd}$
10.	Heating and Cooling Loads of outside air pretreatment coils:	
	Wet Precool Coil Leaving Air Humidity Ratio (lb_m/lb_{da}):	$w_{OAL} = \frac{0.62198 \times 0.9 P_{OAPCws}}{P_{atm} - 0.9 P_{OAPCws}}$
	OA Preheat Coil Heating Load (Btu/hr):	$q_{OAPH} = 1.08 V_{OA} (T_{OAPHset} - T_{OA})$
	OA Precool Coil Sensible Cooling Load (Btu/hr):	$q_{OAPCS} = 1.08 V_{OA} (T_{OA} - T_{OAPCset})$
	OA Precool Coil Sensible Cooling Load (Btu/hr):	$q_{OAPCL} = 4840 V_{OA} (w_{OA} - w_{OAL})^{+}$
11.	Mixed Air Temperature (°F):	$T_{MA} = T_R + X_{OA} (T_{OAL} - T_R)$

12. Intermediate Return and Mixed Air Humidity Ratios (lb_m/lb_{da}) for dry and wet cooling coil conditions:	$X_C = \frac{V_{Tcd}}{V_T}$, $X_H = \frac{V_{Thd}}{V_T}$, $X_R = 1 - X_{OA}$ $X_{eC} = \frac{V_{eC}}{V_{eH}}$, $X_{eH} = \frac{V_{eH}}{V_e}$ $w_{iRdry} = w_{OAL} + \frac{q_{iL}}{4840 \times X_{OA} V_{iC}}$ $w_{eRdry} = \frac{\left(X_{eC} \times X_{OA} \times w_{OAL} + \frac{q_{eL}}{4840 \times V_e} \right)}{(1 - X_{eC} \times (1 - X_{OA}) - X_{eH})}$ $w_{Rdry} = \frac{(w_{iRdry} \times V_{iC} + w_{eRdry} \times V_e)}{V_T}$ $w_{MAdry} = w_{Rdry} + X_{OA}(w_{OAL} - w_{Rdry})$ $w_{iRwet} = w_{CLwet} + \frac{q_{iL}}{4840 \times V_{iC}}$ $w_{eRwet} = \frac{\left(X_{eC} \times w_{CLwet} + \frac{q_{eL}}{4840 \times V_e} \right)}{(1 - X_{eH})}$ $w_{Rwet} = \frac{(w_{iRwet} \times V_{iC} + w_{eRwet} \times V_e)}{V_T}$ $w_{MAwet} = w_{Rwet} + X_{OA}(w_{OAL} - w_{Rwet})$
13. Final Return Air Humidity Ratio (lb_m/lb_{da}): Final Mixed Air Humidity Ratio (lb_m/lb_{da}):	$w_R = Min(w_{Rdry} + w_{Rwet})$ $w_{MA} = Min(w_{MAdry} + w_{MAwet})$
14. Final Space Relative Humidity (%) in interior and exterior zones:	$RH_i = \frac{w_i \times 100}{w_{isat}\left[1 - \left(1 - \frac{w_i}{w_{isat}}\right) \times \frac{P_{iws}}{P_{atm}}\right]}$ $RH_e = \frac{w_e \times 100}{w_{esat}\left[1 - \left(1 - \frac{w_e}{w_{esat}}\right) \times \frac{P_{ews}}{P_{atm}}\right]}$

15.	Preheat Coil Heating Load (Btu/hr):	$q_{PH} = 1.08V_T\left(T_{CL} - T_{MA}\right)^+$
	Hot Deck Heating Load (Btu/hr):	$q_{hd} = 1.08V_{eH}\left(T_{Hset} - T_R\right)^+$
	Cold Deck Coil Sensible Cooling Load (Btu/hr):	$q_{CS} = 1.08V_{Tcd}\left(T_{CE} - T_{CL}\right)$
	Cold Deck Coil Latent Cooling Load (Btu/hr):	$q_{CL} = 4840V_T\left(w_{MA} - w_{CLwet}\right)$ if $w_{MA} > w_{CLwet}$
16.	Total Heating Load (Btu/hr):	$q_{HT} = q_{hd} + q_{PH} + q_{OAPH}$
	Total Cooling Load (Btu/hr):	$q_{CT} = q_{CS} + q_{CL} + q_{OAPCS} + q_{OAPCL}$

A.3. Nomenclature for System Models and ABCAT Code

Table 23. ABCAT Variable Nomenclature

Variable	Definition	Units
$Cool_{postHVAC}$	Cooling required for PreHVAC Period	Btu/hr
$Cool_{preHVAC}$	Cooling required for PreHVAC Period	Btu/hr
dT_{Rduct}	Return duct differential temperature	°F
dT_{Rf}	Return air fan temperature rise	°F
dT_{Rf}	Return fan differential temperature	°F
dT_{Sf}	Supply air fan temperature rise	°F
dT_{Sf}	Supply fan differential temperature	°F
dT_{Sf2}	Supply fan 2 (in dual fan system) differential temperature	°F
Eff_f	fan efficiency	
E_{fg}	Latent heat of vaporization	Btu/lb
$Elec_{HVAC}$	Elec load for HVAC period	kWh/h
$Elec_{PostHVAC}$	Elec load for PostHVAC period	kWh/h
$Elec_{PreHVAC}$	Elec load for PreHVAC period	kWh/h
$Heat_{postHVAC}$	Heating required for PostHVAC Period	Btu/hr
$Heat_{preHVAC}$	Heating required for PreHVAC Period	Btu/hr
Humidload	Humidification load	lbs/hr
HVAC Period	HVAC unit runtime period	hr
P_{atm}	atmospheric pressure	psi
P_{CLws}	Cooling coil Leaving water vapor saturation pressure	psi
P_{fT}	fan Total pressure	in H_2O
PLR_f	fan part load ratio	
PostHVAC Period	Period from HVAC shut down time to midnight	hr
PreHVAC Period	Period from start of day to HVAC start time	hr
q_{CL}	Cooling coil Latent load	Btu/hr
q_{CS}	Cooling coil Sensible load	Btu/hr
q_{CT}	Cooling coil Total load	Btu/hr

Table 23. Continued

Variable	Definition	Units
q_{eL}	exterior zone Latent load	Btu/hr
q_{eRH}	exterior zone ReHeat coil load	Btu/hr
q_{eS}	exterior zone Sensible load	Btu/hr
q_{H}	Heating coil load	Btu/hr
q_{HT}	Total Heating load	Btu/hr
q_{iL}	interior zone Latent load	Btu/hr
q_{iRH}	interior zone ReHeat coil load	Btu/hr
q_{iS}	interior zone Sensible load	Btu/hr
q_{OAL}	Outside Air Latent load	Btu/hr
q_{OAPCl}	Outside Air PreCool coil latent cooling load	Btu/hr
q_{OAPCs}	Outside Air PreCool coil sensible cooling load	Btu/hr
q_{OAPH}	Outside Air PreHeat coil heating load	Btu/hr
q_{OAS}	Outside Air Sensible load	Btu/hr
$q_{OccHVAC}$	Occupant gains for HVAC period	Btu/hr
$q_{OccpostHVAC}$	Occupant gains for PostHVAC period	Btu/hr
$q_{OccpreHVAC}$	Occupant gains for PreHVAC period	Btu/hr
q_{PH}	Preheat coil heating load	Btu/hr
q_{R}	Return air heat gain	Btu/hr
q_{Rf}	Return fan heat gain	Btu/hr
q_{Sf}	Supply fan heat gain	Btu/hr
q_{Sf2}	Supply fan 2 (if dual fan system) heat gain	Btu/hr
$q_{SolarHVAC}$	Solar gains for HVAC period	Btu/hr
$q_{SolarpostHVAC}$	Solar gains for PostHVAC period	Btu/hr
$q_{SolarpreHVAC}$	Solar gains for PreHVAC period	Btu/hr
RH_e	exterior zone relative humidity	%
RH_i	interior zone relative humidity	%
T_{CE}	Cooling coil Entering air dry bulb temperature	°F
T_{CL}	Cooling coil Leaving air dry bulb temperature	°F
T_{csb}	cooling setback temperature	°F

Table 23. Continued

Variable	Definition	Units
T_{Cset}	Cooling coil set point temperature	°F
T_e	exterior zone temperature	°F
T_{eR}	exterior zone Return air dry bulb temperature	°F
T_{eS}	exterior zone Supply air dry bulb temperature	°F
ThermalMassLoad	Load required to bring combined Air/Mass temperature at start up of HVAC system (T_{m2}), back to the set point temperature. This load is averaged across the entire runtime period of the HVAC system.	Btu/hr
T_{hsb}	heating setback temperature	°F
T_{Hset}	Heating coil set point temperature	°F
t_{HVAC}	Current day's length of HVAC period	hr
T_i	interior zone temperature	°F
T_{iR}	interior zone Return air dry bulb temperature	°F
T_{iS}	interior zone Supply air dry bulb temperature	°F
T_{m1}	Air/Mass temperature at start of day	°F
T_{m2}	Air/Mass temperature at start of HVAC sys	°F
T_{m3}	Air/Mass temperature when HVAC sys shuts down, set equal to set point temperature	°F
T_{m4}	Air/Mass temperature at end of day	°F
T_{MA}	Mixed Air dry bulb temperature	°F
T_{OA}	Outside Air dry bulb temperature	°F
$T_{OA,\ HVAC}$	OA temp for HVAC period	°F
$T_{OA,\ PostHVAC}$	OA temp for PostHVAC period	°F
$T_{OA,\ PreHVAC}$	OA temp for PreHVAC period	°F
T_{OAL}	Outside Air pretreat coil Leaving dry bulb temperature	°F
$T_{OAPCset}$	Outside Air PreCool coil set point temperature	°F
$T_{OAPHset}$	Outside Air PreHeat coil set point temperature	°F
T_{PH}	PreHeat coil leaving air dry bulb temperature	°F
$t_{PostHVAC}$	Current day's length of PostHVAC period	hr

Table 23. Continued

Variable	Definition	Units
$t_{PostHVACPrevday}$	Estimated length of previous day's PostHVAC period	hr
$t_{PreHVAC}$	Current day's length of PreHVAC period	hr
T_R	Return air dry bulb temperature	°F
T_S	Supply air dry bulb temperature	°F
V_e	exterior zone supply air volume	ft^3/min
$V_{eCadder}$	Dual duct exterior zone additional Cold deck flow required to overcome hot deck leakage	ft^3/min
$V_{eCLeakage}$	Dual duct exterior zone Cold deck Leakage flow rate	ft^3/min
V_{eD}	exterior zone Design supply air volume	ft^3/min
$V_{eHadder}$	Dual duct exterior zone additional Hot deck flow required to overcome cold deck leakage	ft^3/min
$V_{eHLeakage}$	Dual duct exterior zone Hot deck Leakage flow rate	ft^3/min
$V_{eLeakage}$	Dual duct exterior zone Leakage flow rate	ft^3/min
V_i	interior zone supply air volume	ft^3/min
V_{iC}	interior zone Cooling air flow rate	ft^3/min
$V_{iCadder}$	Dual duct interior zone additional Cold deck flow required to overcome hot deck leakage	ft^3/min
$V_{iCLeakage}$	Dual duct interior zone Cold deck Leakage flow rate	ft^3/min
V_{iD}	interior zone Design supply air volume	ft^3/min
V_{iH}	interior zone Heating air flow rate	ft^3/min
$V_{iHadder}$	Dual duct interior zone additional Hot deck flow required to overcome Cold deck leakage	ft^3/min
$V_{iHLeakage}$	Dual duct interior zone Hot deck Leakage flow rate	ft^3/min
$V_{iLeakage}$	Dual duct interior zone Leakage flow rate	ft^3/min
V_{OA}	Outside Air volume	ft^3/min
V_T	Total supply air volume	ft^3/min
V_T	Total supply air flow rate	ft^3/min
V_{Tcd}	Total cold deck supply air flow rate	ft^3/min
V_{TD}	Total Design supply air volume	ft^3/min

Table 23. Continued

Variable	Definition	Units
V_{Thd}	Total hot deck supply air flow rate	ft^3/min
w_{CE}	Cooling coil Entering air humidity ratio	lb_w/lb_a
w_{CL}	Cooling coil Leaving air humidity ratio	lb_w/lb_a
w_{CLwet}	Cooling coil Leaving air humidity ratio if wet	lb_w/lb_a
w_{eRdry}	exterior zone Return air humidity ratio if dry	lb_w/lb_a
w_{eRwet}	exterior zone Return air humidity ratio if wet	lb_w/lb_a
w_{iRdry}	interior zone Return air humidity ratio if dry	lb_w/lb_a
w_{iRwet}	interior zone Return air humidity ratio if wet	lb_w/lb_a
w_{MA}	Mixed Air humidity ratio	lb_w/lb_a
w_{MAdry}	Mixed Air Return air humidity ratio if dry	lb_w/lb_a
w_{OA}	Outside Air humidity ratio	lb_w/lb_a
w_{OAL}	Outside Air humidity ratio Leaving the precool coil	lb_w/lb_a
w_R	Return air humidity ratio	lb_w/lb_a
w_{R1}	preliminary Return air humidity ratio if humidifier is used	lb_w/lb_a
w_S	Supply air humidity ratio	lb_w/lb_a
X_{EsysHG}	Fraction of measured Electric load that contibutes to Heat Gain in the system being simulate. Total of all systems should be maximum 1. Not a factor if gain levels are specified.	
X_{OA}	fractional Outside Air volume	
$X_{OAEconMax}$	Maximum Outside Air Economizer fraction	
$X_{OAEconMin}$	Minimum Outside Air Economizer fraction	

A.4. ABCAT Additions to the Simplified Energy Analysis Procedure

A.4.1. Electric Humidification Load Estimation

If an electric humidifier is specified in a system, a humidification loop is initiated in the program, and an initial pass through the system calculations is performed with the loads only including the originally specified electric gains. The humidification load, both in lbs/hr of moisture and the latent heat of vaporization is calculated by:

$$humidload(lbs/hr) = \frac{(w_{R1} - w_{OA}) \times 60\frac{\min}{hr} \times V_{OA}}{13.5\frac{ft^3}{lb}}$$

$$E_{fg}(kW) = \frac{humidload \times 1120\frac{Btu}{lb}}{3412kW}$$

The E_{fg} is subtracted from the electric gains previously used in the loads calculation, and the program loops back to the system calculations using the new load. The loop is exited when the change from loop to loop in the humidifier electric load meets a specified convergence criterion. This option currently exists only in the SDRH system type.

A.4.2. Leakage Flow Rates

In the simulation program, considerations for the unavoidable leakage through terminal box dampers are included for the DD and DFDD system types. For the DD system type, the leakage flow rate as a fraction of the ideal (no leakage) total system flow is a specified simulation parameter. When either the required hot deck or cold deck flow rate is less than this volume, the flows are increased to this minimum level, which results in a required increase in flow of the opposite deck to compensate.

For the DFDD system type, both the hot deck and cold deck have separate minimum flow settings. If the required calculated flow rate for either deck is less than this level, the flow is adjusted up to this level, which results in a required increase in flow of the opposite deck to compensate.

A.4.3. Simplified Thermal Mass Considerations

A simple lumped capacitance thermal model has been added to the simulation for all system types, and is explained in the following details. An added level of data organization/processing is required to incorporate this model as a part of the ABCAT simulation. The prerequisite data processing is first explained, followed by the lumped capacitance thermal model.

1. Daily Data Processing Requirements
   a. The heating and cooling energy is simulated and the building combined air/mass temperature is observed for each of following three periods:

      i. PreHVAC – the time from midnight until the HVAC unit is scheduled to start
      ii. HVAC – the HVAC unit runtime period
      iii. PostHVAC – the time from HVAC unit shut down to midnight

      Additional details into how the occupancy, solar and electric loads in the building are managed so that they correspond with these periods are described below.

   b. Occupancy gains are calculated for the three periods (preHVAC, HVAC and postHVAC) based on the ft^2/occ inputs for occupied and unoccupied periods and the defined schedule of these periods. The schedule for the occupied and unoccupied periods may be different from the HVAC operation schedule. If there is an overlap in the defined schedules, the occupancy load is averaged within the HVAC scheduled periods. For example, if the occupancy schedule was for a total of 10 hrs and started 1 hr after the HVAC units and ended 1 hr before they shut down, the occupancy gains for the HVAC period would be the average of 10hrs of the occupied levels and 2hrs of the unoccupied levels. The preHVAC and postHVAC period loads would be the specified unoccupied period loads only.

c. Solar gains are calculated for the three periods of preHVAC, HVAC and postHVAC based on linear interpolation between Jan/July gains based on ambient temperature, assuming a 12hr solar day from 6am to 6pm, and averaged in the same fashion as the occupancy gains to the schedule of the HVAC unit. There is no solar contribution to loads in the conditioned space prior to 6am or after 6pm.

d. Electric lighting/equipment gains are calculated for the three periods of preHVAC, HVAC and postHVAC based on the WBE(preocc/occ/postocc) averages in the weather file and the hourly criteria used to divide them among periods, along with the defined operating schedule of the AHUs (like in the occupancy and solar loads). The ElecRise and ElecFall inputs for each day type (Wkday, Sat, Sun, Vac) in the input file are to match the criteria used in dividing up the measured electric inputs into the preocc/occ/postocc periods. The electric gain levels can be specified rather than measured for the periods defined by the ElecRise and ElecFall inputs, and averaged in the same fashion as the occupancy gains and solar gains to the schedule of the HVAC unit. For electric loads that are specified, the ClockElec inputs for each day type in the input file are factors applied to specified gain in the HVAC period only. The gains also default to the specified values if any of the measured period gains are blank.

2. Thermal Mass Considerations – Air and Mass combined temperature is observed for the three periods of preHVAC, HVAC and postHVAC for each system

e. Air-Mass combined temperature at the time when AHUs shut down (T_{m3}) is assumed to equal the setpoint temperature

f. The ΣUA and Capacitance are calculated

g. The Air-Mass temperature at midnight (T_{m1}) is either available from the previous day, or it is estimated from the knowledge of the current day's preHVAC temperature, electric and occupancy gains, along with the length of the previous day's postHVAC time determined earlier. x_EsysHG is the fraction of the Whole Building Elec that is assigned to the particular system being simulated (defined in the input file).

$$T_{m1} = \left(T_{m3} - \left(T_{oa,\Pr eHVAC} + \frac{1}{UA} \times \left(\begin{array}{l} Elec_{\Pr eHVAC} \times x_{EsysHG} \times 3412 + \\ \dot{q}_{OccpreHVAC} + \dot{q}_{SolarpreHVAC} \end{array} \right) \right) \right) \times e^{-\frac{UA \times t_{postHVAC \Pr evday}}{C}} + \left(T_{oa,\Pr eHVAC} + \frac{1}{UA} \times \left(\begin{array}{l} Elec_{\Pr eHVAC} \times x_{EsysHG} \times 3412 + \\ \dot{q}_{OccpreHVAC} + \dot{q}_{SolarpreHVAC} \end{array} \right) \right)$$

h. If the T_{m1} temperature drops below or rises above the setback temperatures then the temperature is set equal to the setback temperature.

i. The Air-Mass temperature at the startup of the AHUs (T_{m2}) is calculated in a similar fashion as:

$$T_{m2} = \left(T_{m1} - \left(T_{oa,\Pr eHVAC} + \frac{1}{UA} \times \left(\begin{array}{l} Elec_{\Pr eHVAC} \times x_{EsysHG} \times 3412 + \\ \dot{q}_{OccpreHVAC} + \dot{q}_{SolarpreHVAC} \end{array} \right) \right) \right) \times e^{-\frac{UA \times t_{preHVAC}}{C}} + \left(T_{oa,\Pr eHVAC} + \frac{1}{UA} \times \left(\begin{array}{l} Elec_{\Pr eHVAC} \times x_{EsysHG} \times 3412 + \\ \dot{q}_{OccpreHVAC} + \dot{q}_{SolarpreHVAC} \end{array} \right) \right)$$

j. If T_{m2} temperature drops below or rises above the setback temperatures then the temperature is set equal to the setback temperature. If it does cross either of these thresholds, the time spent at/across these thresholds is observed as well as the heating/cooling needed to keep the Air-Mass at the setback temperature:

$$Heat_{\Pr eHVAC} = UA \times \left(T_{hsb} - T_{oa,\Pr eHVAC} \right) - \left(Elec_{\Pr eHVAC} \times x_{EsysHG} \times 3412 + \dot{q}_{OccpreHVAC} + \dot{q}_{SolarpreHVAC} \right)$$

$$Cool_{\Pr eHVAC} = UA \times \left(T_{oa,\Pr eHVAC} - T_{csb} \right) + \left(Elec_{\Pr eHVAC} \times x_{EsysHG} \times 3412 + \dot{q}_{OccpreHVAC} + \dot{q}_{SolarpreHVAC} \right)$$

k. If the AHUs don't run at all for a particular day, T_{m3} is set equal to T_{m1}

l. The space temperature is either set to the heating or cooling setpoint based on the ambient temperature. The ThermalMassLoad is calculated to as:

$$ThermalMassLoad = (T_{m2} - T_h) \times C$$
$$ThermalMassLoad = (T_{m2} - T_c) \times C$$

where T_h and T_c are the heating and cooling setpoint temperatures, and this represents the energy required to bring the Air-Mass from its setback temperature to the setpoint. This load is later distributed into the load calculations for the AHUs.

m. T_{m4} (midnight of current day) Air-Mass temperature is calculated in the same fashion as the others:

$$T_{m4} = \left(T_{m3} - \left(T_{oa,PostHVAC} + \frac{1}{UA} \times \begin{pmatrix} Elec_{PostHVAC} \times x_{EsysHG} \times 3412 + \\ \dot{q}_{OccpostHVAC} + \dot{q}_{SolarpostHVAC} \end{pmatrix} \right) \right) \times e^{-\frac{UA \times t_{posttHVAC}}{C}} + \left(T_{oa,PostHVAC} + \frac{1}{UA} \times \begin{pmatrix} Elec_{PostHVAC} \times x_{EsysHG} \times 3412 + \\ \dot{q}_{OccpostHVAC} + \dot{q}_{SolarpostHVAC} \end{pmatrix} \right)$$

n. If T_{m4} temperature drops below or rises above the setback temperatures then the temperature is set equal to the setback temperature. If it does cross either of these thresholds, the time spent at/across these thresholds is observed as well as the heating/cooling needed to keep the Air-Mass at the setback temperature:

$$Heat_{PostHVAC} = UA \times (T_{hsb} - T_{oa,PostHVAC}) - (Elec_{PostHVAC} \times x_{EsysHG} \times 3412 + \dot{q}_{OccpostHVAC} + \dot{q}_{SolarpostHVAC})$$
$$Cool_{PostHVAC} = UA \times (T_{oa,PostHVAC} - T_{csb}) + (Elec_{PostHVAC} \times x_{EsysHG} \times 3412 + \dot{q}_{OccpostHVAC} + \dot{q}_{SolarpostHVAC})$$

o. T_{m4} and the current date are saved as variables to be passed to the next day of the simulation. If it is determined that the days are arranged chronologically, than T_{m4} will be used as the Air-Mass starting point for the next day, otherwise it is estimated as described earlier.

A.5. ABCAT Model Accuracy Tests with ASHRAE RP-865

As of June 2007, the ABCAT is an advanced prototype tool only. Rigorous testing and troubleshooting of its simulation model was not a primary objective in this thesis. For informational purposes only, the ABCAT simulation was executed for the described case conditions of ASHRAE RP-856 for the SDCV, SDVAV, DDCV, DDVAV, and SZ system types as per Haberl et al. 2002, and the results are provided in Table 24. No claims of accuracy of adequacy of the ABCAT simulation model are made through the presentation of this data. One known deviation of the ABCAT simulation with the analytical models is that the ABCAT assumes constant air density in all its calculations.

Table 24. Energy Totals from Various Simulation Techniques and System Types (Btu/hr)

	SDCV				SDVAV			
	CoolSen	**CoolLat**	**CoolTot**	**HeatTot**	**CoolSen**	**CoolLat**	**CoolTot**	**HeatTot**
Case1								
ABCAT	**0**	**0**	**0**	**64372**	**0**	**0**	**0**	**67156**
PSU1	0	0	0	64825				
PSU2	0	0	0	64932				
TAMU	0	0	0	64961	0	0	0	66867
BLAST	0	0	0	65039				
DOE 2	0	0	0	60995	0	0	0	64959
Case2								
ABCAT	**4064**	**0**	**4064**	**24976**	**0**	**0**	**0**	**23696**
PSU1	4146	0	4146	25693				
PSU2	3129	0	3129	24797				
TAMU	4083	0	4083	25716	0	0	0	23525
BLAST	3139	23	3162	24862				
DOE 2			3676	28047			0	20322
Case3								
ABCAT	**22856**	**0**	**22856**	**15188**	**5072**	**0**	**5072**	**0**
PSU1	23010	0	23010	16053				
PSU2	21780	0	21780	14978				
TAMU	22952	0	22952	16078	5042		5042	0
BLAST	21832	280	22112	15069				

Table 24. Continued

	SDCV				SDVAV			
	CoolSen	**CoolLat**	**CoolSen**	**CoolLat**	**CoolSen**	**CoolLat**	**CoolSen**	**CoolLat**
DOE 2			21344	15569			4731	0
Case4								
ABCAT	**34520**	**26600**	**61119**	**7592**	**25430**	**25615**	**51045**	**0**
PSU1	35158	22612	57770	8534				
PSU2	33357	24535	57892	7371				
TAMU	34728	23209	57937	8560	24839	22053	46892	0
BLAST	33434	26113	59547	7476				
DOE 2			57090	6611			44344	0
Case5								
ABCAT	**32036**	**0**	**32036**	**15188**	**14252**	**0**	**14252**	**0**
PSU1	33327	0	33327	16053				
PSU2	32148	0	32148	14978				
TAMU	33350	0	33350	16078	14312	0	14312	
BLAST	30963	474	31437	15069				
DOE 2			30648	15115			14648	
Case6								
ABCAT1	**30416**	**19608**	**50024**	**15188**	**12632**	**16748**	**29380**	**0**
PSU1	30490	17108	47598	16085				
PSU2	29284	8675	37959	14978				
TAMU	30541	16911	47452	16110	12548	13993	26541	0
BLAST	29352	9645	38997	15069				
DOE 2				15075			16053	0

Table 24. Continued

	DDCV				DDVAV			
	CoolSen	**CoolLat**	**CoolTot**	**HeatTot**	**CoolSen**	**CoolLat**	**CoolTot**	**HeatTot**
Case1								
ABCAT	**0**	**0**	**0**	**64372**	**0**	**0**	**0**	**67062**
PSU1	0	0	0	64825	0	0	0	66817
PSU2	0	0	0	64932	0	0	0	66778
TAMU	0	0	0	64962	0	0	0	66851
BLAST	0	0	0	65039	0	0	0	66858
DOE 2	0	0	0	71435	0	0	0	68449
Case2								
ABCAT	**2749**	**0**	**2749**	**23662**	**0**	**0**	**0**	**23696**
PSU1	2708	0	2708	24269	0	0	0	23563
PSU2	2116	0	2116	23785	0	0	0	23533
TAMU	2672	0	2672	24309	0	0	0	23579
BLAST	2123	0	2123	23846	0	0	0	23580
DOE 2			3028	26560	0	0	0	24670
Case3								
ABCAT	**18360**	**0**	**18360**	**10693**	**5072**	**0**	**5072**	**0**
PSU1	17732	0	17732	10850	5039	0	5039	0
PSU2	17524	0	17524	10722	5001	0	5001	0
TAMU	17724	0	17724	10873	5042	0	5042	0
BLAST	17549	225	17774	10786	5026	0	5026	0
DOE 2			17453	11542			4404	0
Case4								
ABCAT	**31126**	**24797**	**55923**	**4198**	**25430**	**25172**	**50601**	**0**
PSU1	30410	20874	51284	3960	25195	21808	47003	0
PSU2	30149	22270	52419	4163	24762	22990	47752	0
TAMU	30088	21439	51527	3972	24839	22053	46892	0
BLAST	30108	24176	54284	4221	24921	24335	49256	0
DOE 2			49848	3179			38908	0
Case5								
ABCAT	**25735**	**0**	**25735**	**8887**	**14252**	**0**	**14252**	**0**
PSU1	25748	0	25748	8594	14303	0	14303	0
PSU2	25866	0	25866	8695	14318	0	14318	0
TAMU	25761	0	25761	8609	14312	0	14312	0
BLAST	24889	380	25269	8994	14157	192	14349	0
DOE 2			24147	885			14289	0
Case6								
ABCAT1	**24433**	**17217**	**41651**	**9206**	**12632**	**16572**	**29204**	**0**
PSU1	23466	14823	38289	9173	12593	5389	17982	0
PSU2	23561	7138	30699	9255	12750	13938	26688	0
TAMU	23570	14645	38215	9187	12548	13993	26541	0
BLAST	23593	7942	31535	9311	12373	6171	18544	0
DOE 2			27957	9767			13697	0

Table 24. Continued

	SZ Zone 1				SZ Zone 2			
	CoolSen	**CoolLat**	**CoolTot**	**HeatTot**	**CoolSen**	**CoolLat**	**CoolTot**	**HeatTot**
Case1								
ABCAT	**0**	**0**	**0**	**28093**	**0**	**0**	**0**	**36346**
PSU1								
PSU2								
TAMU	0	0	0	28444	0	0	0	36544
BLAST								
DOE 2			0	26140			0	28479
Case2								
ABCAT	**0**	**0**	**0**	**9509**	**0**	**0**	**0**	**11470**
PSU1								
PSU2								
TAMU	0	0	0	9887	0	0	0	11768
BLAST								
DOE 2	0	0	0	11806			0	12523
Case3								
ABCAT	**6647**	**0**	**6647**	**0**	**4278**	**0**	**4278**	**0**
PSU1								
PSU2								
TAMU	2923		2923	0	3916		3916	0
BLAST								
DOE 2			2156	0			3559	0
Case4								
ABCAT	**12427**	**9338**	**21765**	**0**	**14434**	**12926**	**27360**	**0**
PSU1								
PSU2								
TAMU	7270	12024	19294	0	14031	9703	23734	0
BLAST								
DOE 2			16590	0			20218	0
Case5								
ABCAT	**6995**	**0**	**6995**	**0**	**9786**	**0**	**9786**	**0**
PSU1								
PSU2								
TAMU	7649	0	7649	0	9549		9549	
BLAST								
DOE 2			6369	0			9034	
Case6								
ABCAT1	**6347**	**4058**	**10405**	**0**	**8814**	**6328**	**15141**	**0**
PSU1								
PSU2								
TAMU	5924	2109	8033	0	7229	4150	11379	
BLAST								
DOE 2			6185	0			8105	

APPENDIX B

GRAPHICAL PRESENTATION TO AID IN WHOLE BUILDING DIAGNOSTICS

B.1. Introduction to the ABCAT Graphics

Despite the automated data collection, fault detection and diagnostic functions of the Automated Building Commissioning Analysis Tool (ABCAT), manual data analysis will remain an important part of evaluating the energy performance of a building. A secondary goal of the ABCAT is to present data in forms that are uniquely informative and easy to interpret, while avoiding the time consuming and often cumbersome task of manipulating, managing and viewing thousands of data points.

The ABCAT users, depending upon job function, experience level, education and desired goals, will have different preferences as how to best view the building performance data. In this developmental stage, we desire to gain user feedback as to which graphical presentation techniques will be most valuable in a revised final version. Currently a total of seventeen plots are presented on five different worksheets in the ABCAT program. A single sample of each plot is displayed in this document along with a brief description of interpretive techniques to assist users in drawing beneficial conclusions. All of the quantities plotted in the charts are daily total or daily averages of:

1.) measured whole building consumption of heating, cooling or electricity
2.) simulated heating and cooling energy consumption or

3.) various calculations resulting from the use 1, 2 or a combination of both.

Hot Water (HW) will be used throughout this document as the source of heating energy, while Chilled Water (CHW) is assumed as the primary cooling energy source.

The current version of the ABCAT is a Microsoft Excel file with five chart sheets dedicated to the graphical presentation of data. Each chart sheet contains multiple charts. The sheet names and corresponding charts are organized as described below, both in the ABCAT program as well as in this document:

This is the layout of the 18 plots currently in the ABCAT program, on 5 different chart sheets.

1	2
3	4

Sheet: Meas&Sim

5&6	7
8	9

Meas&Sim(2)

10	11
12	13

Meas&Sim(3)

	14	
	15	

Period1&2

16	
17	18

Period1&2(2)

B.2. ABCAT Sheet Name: Meas&Sim

B.2.1. Chart #1 Time Series Cooling Energy

See section B.2.2 below.

B.2.2. Chart #2 Time Series Heating Energy

These plots display the measured and simulated average daily cooling consumption and measured and simulated average daily heating consumption respectively. During periods of normal consumption, the plot should show a clear ability of the simulated value to follow the peaks and valleys of the measured consumption as factors of occupancy, heat gains or weather conditions vary. Major changes in system performance will result in significant deviations between the simulated and measured values. Single or short-term occurrences of these deviations that are readily corrected are likely anomalies in building performance that could not be simulated (i.e. shutdowns, testing of equipment or temporary control set point changes for maintenance purposes). If these differences are observed over an extended period of time, or occur on regular basis, it may be a sign of deteriorating system performance.

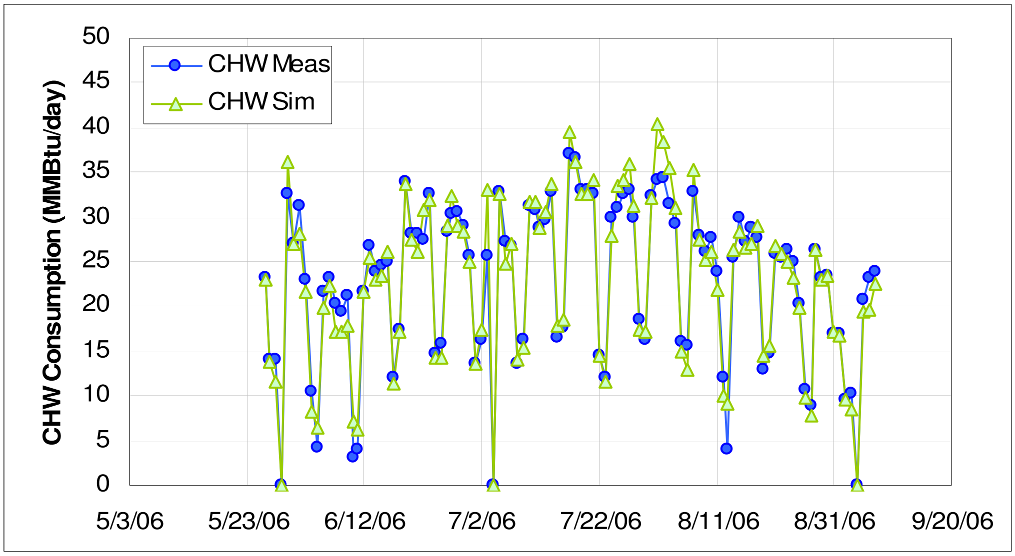

Figure 54. Time Series Cooling Energy Consumption (MMBtu/day)

It is also important to understand the coupled effect that cooling and heating energy often have upon one another. Due to the inherent nature of HVAC systems, non-ideal operations due to such things as leaking valves, imperfect control sequences, sensors accuracy and time constants, almost always exist to some level. Only a small percentage of the time will these errors actually have an effect at the comfort level, since HVAC systems typically have capabilities to compensate for these errors (e.g. downstream coils), but usually at the unnecessary cost of simultaneous heating and cooling. It is often seen that for a given set of conditions, the variance about the mean measured consumption at those conditions will be similar in magnitude for both cooling and heating. This means that if the measured cooling energy typically varies by +/- 5 MMBtu/day from the simulation for a given set of conditions, the heating may vary by the same amount from its simulated value. Now if the measured cooling energy is generally two, three or more times greater than the heating energy, as is often the case in warm climates, this variation will often lead to a less accurate heating simulation. When using these charts, it is important to understand the expected accuracy of the simulation as it pertains to both the heating and cooling energy.

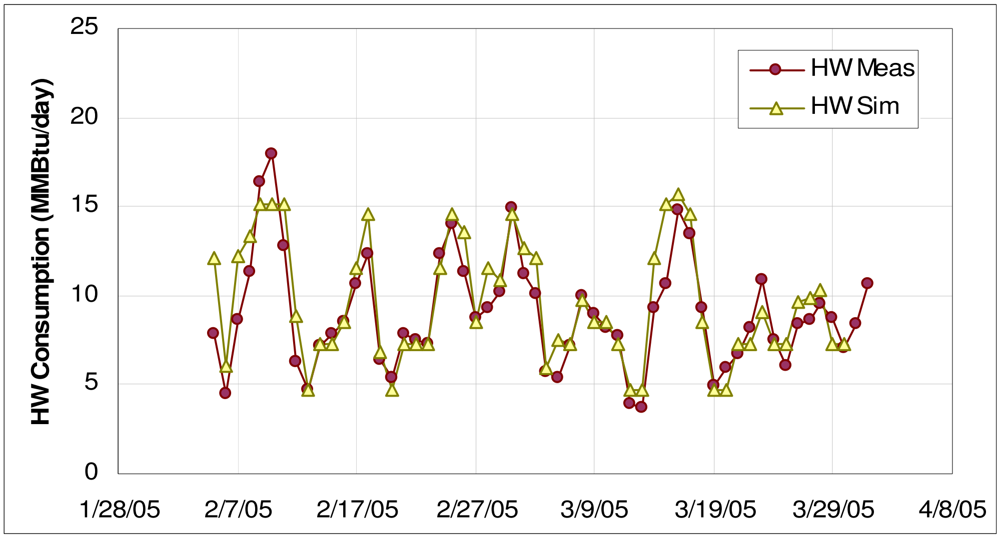

Figure 55. Time Series Heating Energy Consumption (MMBtu/day)

B.2.3. Chart #3 Cooling Energy versus Outside Air Temperature

Plotting cooling energy consumption versus outside air temperature displays the temperature dependence of the cooling energy. If base load cooling requirements (minimum cooling requirements independent of temperature) exist in the building, the CHW energy will be seen to flatten off at low temperatures, otherwise one should see a constant sloping trend towards zero consumption at low temperatures. Since only sensible cooling requirements generally exist at outside air temperatures less than approximately 55°F, the variation in energy consumption is typically much smaller than that at higher temperatures. As the absolute humidity of the outside air increases at average outside air temperatures generally above 55°F, latent cooling requirements are introduced and can be seen graphically with an increased steepness in the slope of the trend. Also, the variability of the humidity levels in the outside air at these higher temperatures contributes to the greater variation in consumption at a specific temperature.

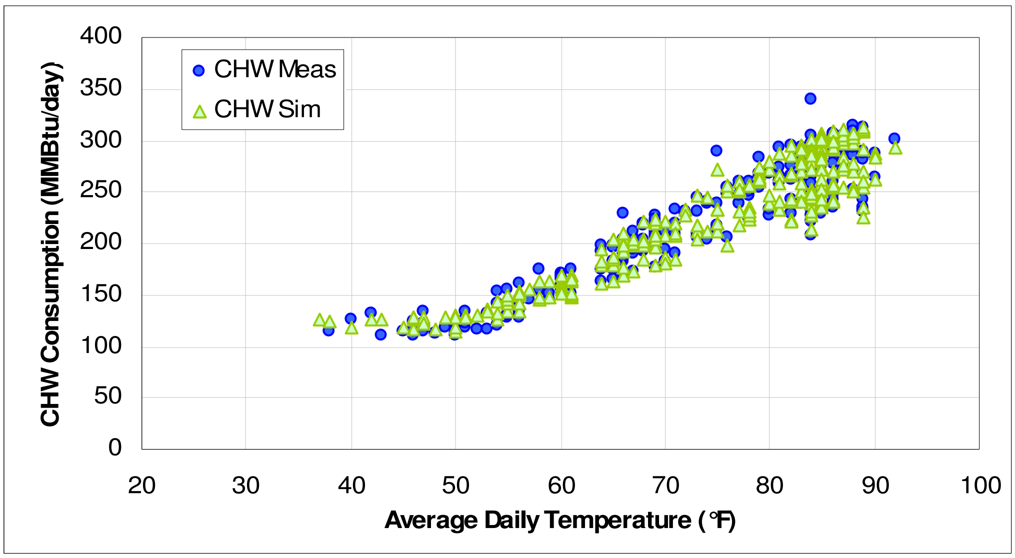

Figure 56. Cooling Energy Consumption (MMBtu/day) versus Outside Air Temperature

If economizers are operational within the building, a clear reduction in energy consumption should be seen as temperatures drop to the range of 60 - 65°F and below. If the economizers are capable to handle the entire building cooling load, the cooling should go to zero as temperatures drop to less than approximately 55°F.

If energy consumption patterns for unoccupied periods (weekends/holidays) are significantly lower than the occupied periods, one will see two distinct patterns in consumption, usually of the same shape but offset down in the unoccupied periods.

When comparing the measured consumption with the simulated in this plot, significant differences may be visually detected, along with the corresponding temperature range where these differences occur. Certain operational deficiencies may cause an unexpected increase or decrease in consumption only within specific temperature ranges, while others may affect consumption throughout all outside air conditions. This plot will help the user to understand if the measured and simulated data align well, or in the case where they do not, it should explain whether or not the difference has a temperature dependency.

B.2.4. Chart #4 Heating Energy versus Outside Air Temperature

Plotting heating energy consumption versus outside air temperature displays the temperature dependence of the heating energy. If heating consumption exists at temperatures greater than the indoor design condition, it is likely due to either base load process heating requirements that exist in the building (i.e. heating of domestic hot water), required reheat in constant volume AHU’s or some hot water fault (i.e. leaking valves, excessive pump pressure).

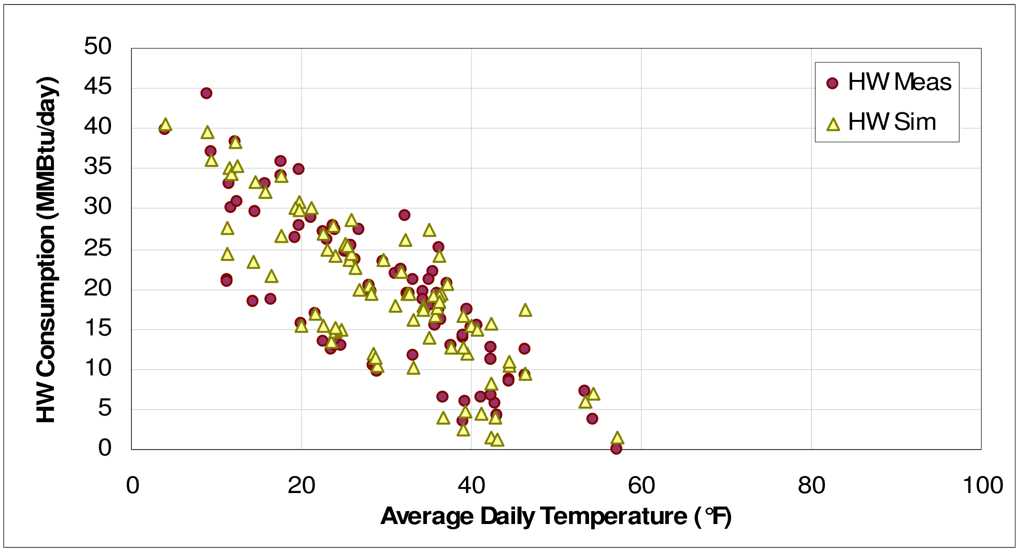

Figure 57. Heating Energy Consumption (MMBtu/day) versus Outside Air Temperature

If energy consumption patterns for unoccupied periods (weekends/holidays) are significantly lower than the occupied periods, one will see two distinct patterns in consumption, usually of the same shape but offset down in the unoccupied periods.

If boilers are shutdown, or heating systems are valved off seasonally, the heating consumption should go to zero at higher temperatures that signify the start of this period.

When comparing the measured consumption with the simulated in this plot, significant differences may be visually detected, along with the corresponding temperature range where these differences occur. Certain operational deficiencies may cause an unexpected increase or decrease in consumption only within specific temperature ranges, while others may affect consumption throughout all outside air conditions. This plot will help the user to understand if the measured and simulated data align well, or in the case where they do not, it should explain whether or not the difference has a temperature dependency.

B.3. ABCAT Sheet Name: Meas&Sim(2)

B.3.1. Chart #5 Time Series Cumulative Energy Difference

See section B.3.2 below.

B.3.2. Chart #6 Time Series Cumulative Cost Difference ($)

The Excess Energy Consumption plot takes the consumption residuals (Measured – Simulated) for each day and adds that value to that from the previous day. The zero point is typically defined at the beginning of the baseline period, but could be adjusted by the user if desired. Any reading in time of the excess energy and/or the excess costs will always be in reference to the zero point.

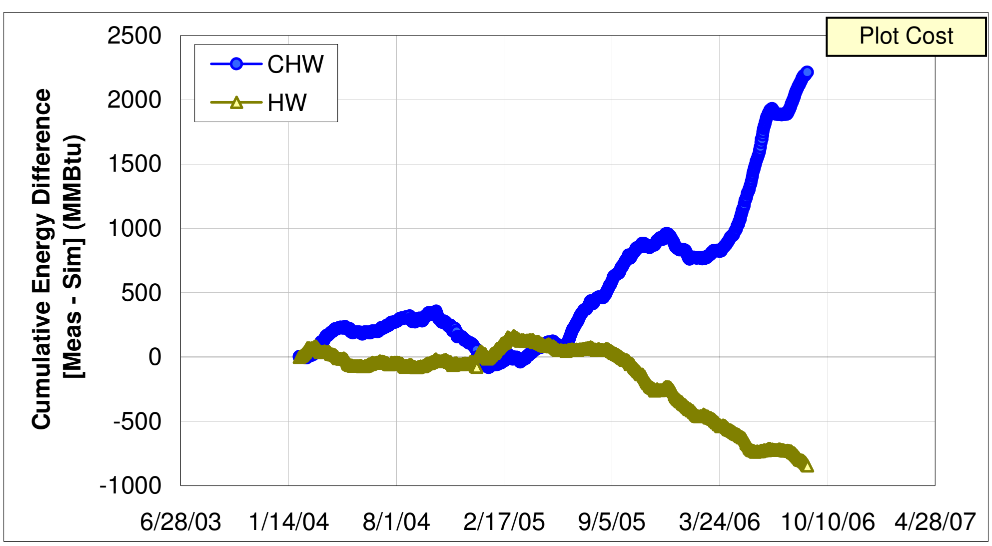

Figure 58. Time Series Cumulative Energy Difference (MMBtu)

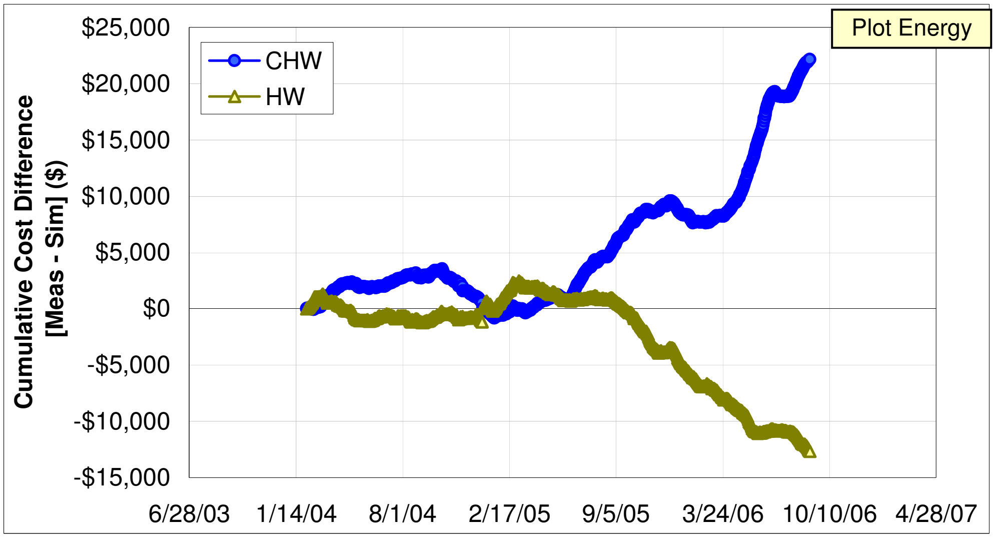

Figure 59. Time Series Cumulative Cost Difference ($)

A zero slope would indicate the measured and simulated values perfectly coincide. Positive slopes will be seen in periods where the measured values are consistently greater than the simulated, and vice versa for negative slopes. Increasing steepness of the slope, whether positive or negative indicates an increasing deviation between the measured and simulated values. The Excess Costs plot is simply generated by multiplying the excess energy consumption values by the cost for the particular energy source (CHW or HW) as defined on the *ABCAT Interface* sheet (see section B.8). The button in the upper right hand corner of the plot allows the user to switch between the two plots while in the ABCAT program.

B.3.3. Chart #7 Time Series Electricity Consumption (kWh/h)

The Electricity Consumption plot typically will display clear distinctions between weekday and weekend/holiday consumption. Occupancy, equipment schedules and cooling requirements are generally the three main variables affecting electric consumption. If the ratio of weekend to weekday consumption remains relatively constant, it is a good sign that equipment shutdown schedules are being maintained. For facilities/buildings that have several different operating schedules, as do college campuses (semester sessions, spring break, summer and holiday breaks), one should be able to clearly identify the dates of these periods from this plot due to the typically associated decrease in electric consumption.

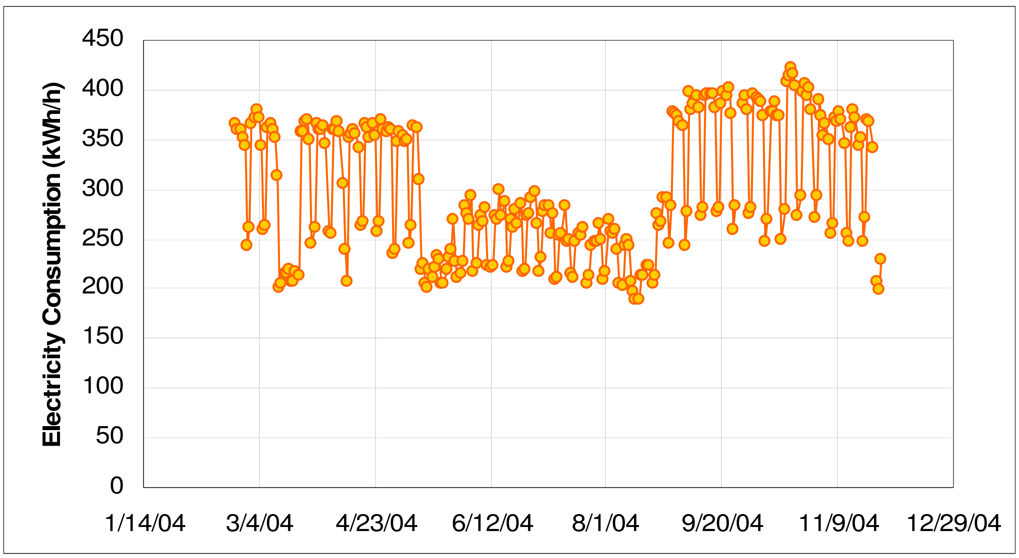

Figure 60. Time Series Electricity Consumption (kWh/h)

B.3.4. Chart #8 Time Series Cooling % Difference

See section B.3.5 below.

B.3.5. Chart #9 Time Series Heating % Difference

This Cooling & Heating % Difference plot displays the difference between the measured and simulated consumption, normalized by the maximum measured average daily consumption value for that particular energy source (CHW or HW) during the baseline period.

$$Error(\%) = \frac{Measured - Simulated}{Max\ Measured_{in\ baseline\ period}} \times 100(\%)$$

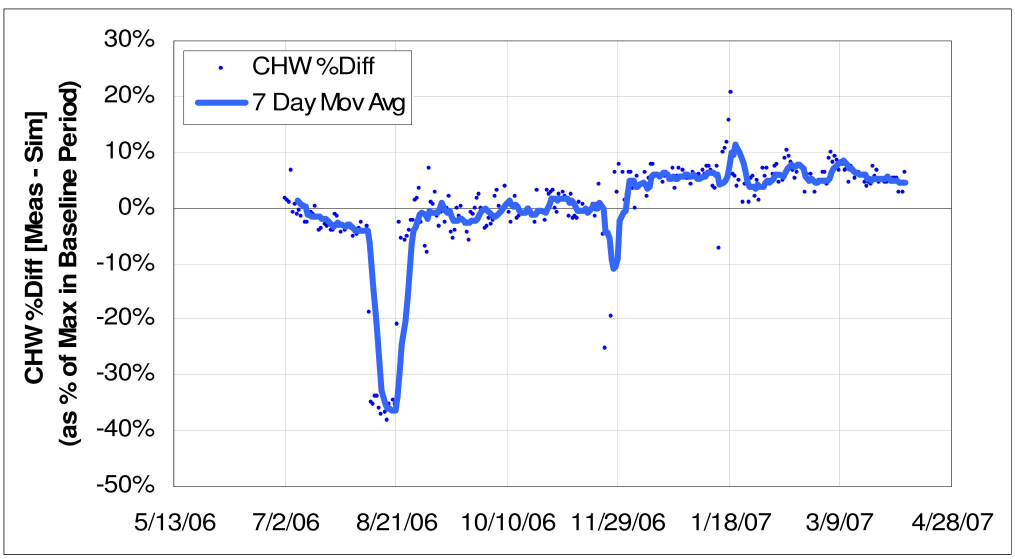

Figure 61. Time Series Cooling % Difference [Meas – Sim] (As a % of Max Measured in Baseline Period)

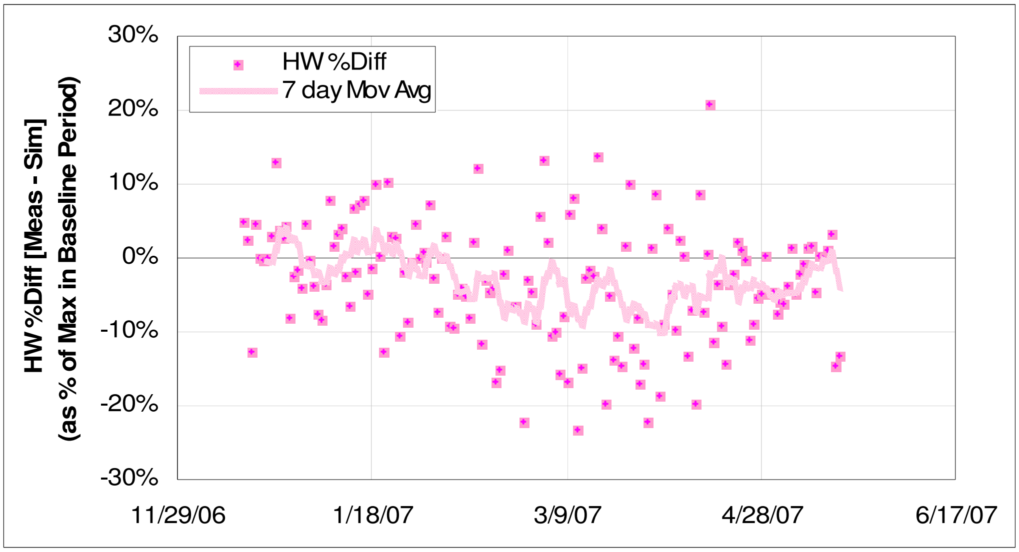

Figure 62. Time Series Heating % Difference [Meas – Sim] (As a % of Max Measured in Baseline Period)

Positive *%Diff* indicate excessive consumption while negative *%Diff* indicate less than expected consumption. For a maximum CHW consumption in the baseline period of 50 MMBtu/day, a 10% difference on this plot would correspond to a residual (Meas – Sim) of 5 MMBtu/day. For a maximum HW consumption in the baseline period of 40 MMBtu/day, a -10% error on this plot would correspond to a residual of -4 MMBtu/hr. A seven day moving average line is added to the plot to assist in the trend visualization.

B.4. ABCAT Sheet Name: Meas&Sim(3)

B.4.1. Chart #10 Consecutive Days

Threshold levels for what is considered “a day in excess” can be defined by the user on the *ABCAT Interface* sheet (see section B.8), in terms of the standard deviation. If the difference between the measured and simulated consumption for the particular energy source (CHW or HW) for a day exceeds the threshold, 1 day is plotted on this chart. For each consecutive day, another 1 day will be added if the consumption continues to exceed the threshold. The opposite will occur (with negative days) if the difference is less than the negative of the threshold value. Either trend will reset the consecutive days to zero if the difference falls within +/- the threshold. This is designed to allow the user to set a threshold that defines when significant deviations in measured consumption occur and easily distinguish between a single occurrence, and a distinct persistent pattern. For days where data may be missing, the plot will remain unchanged from that of the previous day.

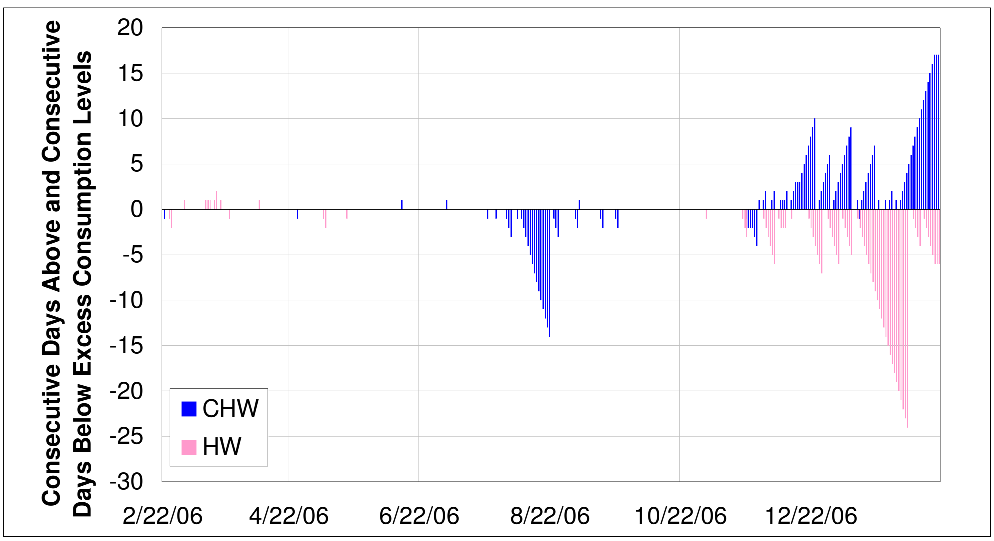

Figure 63. Consecutive Days Above and Consecutive Days Below Excess Consumption Levels

B.4.2. Chart #11 CHW Cumulative Sum Alarm

Control charts have been a popular technique in establishing quality process control for more than half a century. Walter A. Shewhart was the pioneer in industry whose name is now synonymous with control charts (Shewhart Chart). The basic principle is that approximately 99.7% of samples of a normally distributed process variable under statistical control will be observed to be within the defined upper and lower control limits, which typically are set at +/- 3 sigma from the process mean. These charts are the gold standard of detecting large sudden process mean shifts. The Cumulative Sum (CUSUM) control chart (Figure 64) provides an alternative to the Shewhart Chart and was introduced by Page[4]. The CUSUM control chart, as the name suggests, accumulates the error from a process variable, which makes the charts superior to the Shewhart Charts in detecting smaller sustained shifts. Ryan[5] defines both a positive and a negative cumulative sum as:

$$C_i^+ = \max\left[0, (z_i - k) + C_{i-1}^+\right] \qquad C_i^- = \min\left[0, (z_i + k) + C_{i-1}^-\right]$$

where

C_i^+ = cumulative sum for positive errors for sample i,

C_i^- = cumulative sum for negative errors for sample i,

z_i = normalized process error = $\frac{x_i - \bar{x}}{\sigma}$,

x_i = process error at sampling time i,

$\bar{x}$ = estimate of the mean value of the process error,

σ = estimate of the standard deviation of the process error, and

k = sometimes called the reference parameter or slack parameter, is the minimum change (as multiple of σ) that will be detected in the CUSUM, and is typically chosen to be half the value of the mean shift one desires to detect.

The upper and lower CUSUM control limits, or decision intervals, that indicate a process is out of control are usually designated as h+ and h- and are multiples of σ.

---

[4] Page, E.E. 1954. Continuous Inspection Schemes. *Biometrika* 41(1): 100-115

[5] Ryan, T.P. 2000. Statistical Methods for Quality Improvement. 2nd Edition, NY, Wiley and Sons.

The application of the CUSUM in HVAC FDD applications has been rare, but Schein and House[6] applied such a scheme to variable air volume (VAV) boxes to detect faults. Their system resets the CUSUM to 0 after each breaching of the control limit, which provides information as to the severity of the fault from the number of breaches and whether the fault is a growing or slowing problem by analyzing the time it takes between subsequent breaches of the control limits. The CUSUM is also valuable in that it has a built-in change point estimator by its design, where the start of the fault can be indicated by where the CUSUM first began to deviate from 0. Investigating system activity around that date may be important in the diagnosis of the fault.

Values of k and h can be specified by the user on the *ABCAT Interface* sheet (see section B.8). Preliminary testing has shown that values of k between (0.5 – 1) and h around 4 have shown to be relatively good indicators, although this will likely vary greatly due to building specific circumstances and energy simulation accuracy. A smaller value of k will in the plot will detect and accumulate smaller errors. The values of k and h should be adjusted to the user/building specific alarm sensitivity desired. One method to adjust these values such that only a minimal number (or zero) of alarm thresholds (h) are breached in the baseline calibration period.

---

[6] Schein, J. and J.M. House. 2003. Application of Control Charts for Detecting Faults in Variable-Air-Volume Boxes. *ASHRAE Transactions* 109(2): 671-682.

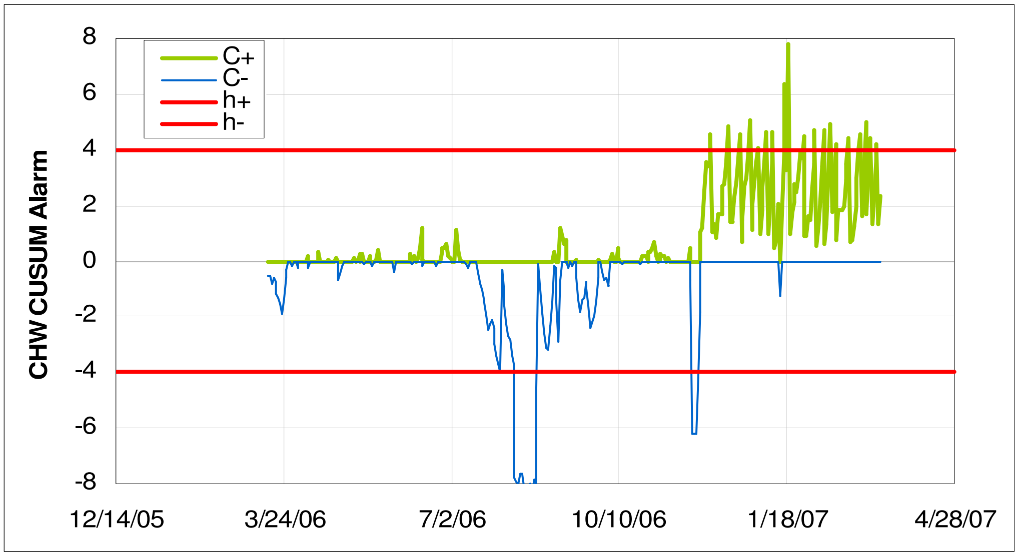

Figure 64. CHW Cumulative Sum Alarm

B.4.3. Chart #12 Diagnostic Summary Count

Beneficial diagnostic information can be derived from the observed relationships between heating and cooling consumption deviations from that expected, along with the ambient conditions at which these deviations occur. The Diagnostic Summary Count (Days) table (Figure 65), charts the number of days of Period 1 (defined on the *ABCAT Interface* sheet) that fall into several categories. The different categories are separated into three daily average outside air temperature ranges, $T_{oa} < T_{s,sp}$ (supply air temperature); $T_{s,sp} \leq T_{oa} \leq T_{e,sp}$ (temperature the economizer deactivates); $T_{oa} > T_{e,sp}$. For each outside air temperature range, the total days and days where the thermal energy consumption (CHW and HW) are greater than ▲, less than ▼, or within the limits ● of the deviation stated (CHW Dev and HW Dev) are counted and fill the table appropriately. Table 25 from the *ABCAT Interface* sheet, provides the source data for Figure 65.

Table 25 and Figure 65 can be used in conjunction with a predefined diagnostic fault table (Table 26) to provide some general insight as to the possible causes.

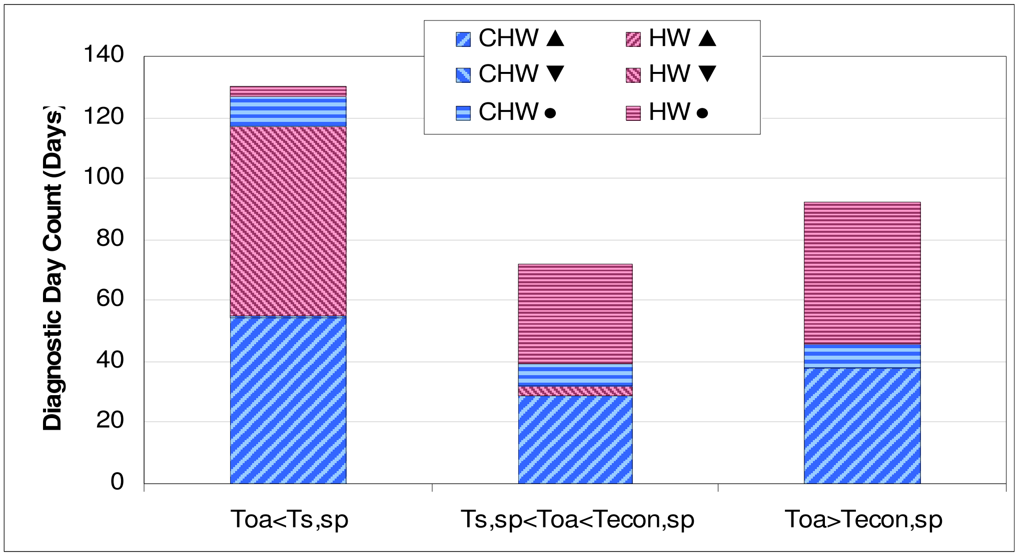

Figure 65. Diagnostic Summary Count (Days)

Table 25. Diagnostic Summary Count

Period 1 Diagnostic Summary Count (Days)			
	$T_{oa}<T_{s,sp}$	$T_{s,sp}<T_{oa}<T_{econ,sp}$	$T_{oa}>T_{econ,sp}$
Total Days:	65	36	46
CHW ▲	54	29	38
HW ▲	0	0	0
CHW ▼	1	0	0
HW ▼	62	3	0
CHW ●	10	7	8
HW ●	3	33	46
T_s	T_{econ}	CHW Dev (σ)	HW Dev (σ)
55	65	1.0	1.0

The types of faults expected to be identified are general in nature and are expected to fall into one of the following categories:

8. Supply Air Flow Rate Fault
9. Chilled Water or Hot Water Pump Differential Pressure Fault
10. Outside Air Flow Rate Fault
11. Supply Air Temperature Fault
12. Chilled Water or Hot Water Metering Fault
13. Chiller or Boiler Run-Time Fault

Table 26 provides a proposed outline for this procedure which is a slight modification of Wang and Liu (2006), with the types of faults indicated on the left hand side, and the expected response seen in cooling and heating consumption. Each fault is divided by the three temperature ranges based on ambient temperature. The gray shaded cells represent faults that are expected to cause significant problems with comfort in the buildings, and are therefore more likely addressed with corrective measures before a significant and persisting energy impact can be observed. The energy impact of these faults also is less heating and/or less cooling than expected, which, in general, is a less common problem and not necessarily in line with the goals of ABCAT. The rest of the color coding of the chart is provided to highlight the similar response of heating and cooling.

Table 26. SDVAV w/Economizer Rules for Diagnostic Classifier

Fault Type		Higher			Lower		
		$T < T_{s,sp}$	$T_{s,sp} < T < T_{e,sp}$	$T > T_{e,sp}$	$T < T_{s,sp}$	$T_{s,sp} < T < T_{e,sp}$	$T > T_{e,sp}$
1. Supply Air Flow Rate	Cooling	Off	▲	▲	Off	▼	▼
	Heating	▲	▲	Off	▼	▼	Off
2. CHW Pump DP	Cooling	Off	▲	●	Off	▼	●
	Heating	N/A	▲	Off	N/A	▼	Off
3. HW Pump DP	Cooling	Off	▲	N/A	Off	●	N/A
	Heating	▲	▲	Off	▼	▼	Off
4. Outside Air Flow Rate							
a. Minimum OA Flowrate	Cooling	N/A	N/A	▲	N/A	N/A	▼
	Heating	N/A	N/A	Off	N/A	N/A	Off
b. Economizing OA Flowrate	Cooling	Off	N/A	N/A	Off	▲	N/A
	Heating	▲	N/A	N/A	▼	●	N/A
c. Economizer Temperature	Cooling	N/A	●	▲	N/A	▲	●
	Heating	N/A	●	Off	N/A	●	Off
5. Supply Air Temperature	Cooling	Off	▼	●	Off	▲	Same
	Heating	N/A	▼	Off	▲ or ●	▲	Off
6. Metering							
a. Chilled Water Meter	Cooling	Off	▲	▲	Off	▼	▼
	Heating	●	●	Off	●	●	Off
b. Hot Water Meter	Cooling	Off	●	●	Off	●	●
	Heating	▲	▲	Off	▼	▼	Off
7. Scheduling		Longer			Shorter		
a. Chiller	Cooling	▲	▲	▲	▼	▼	▼
	Heating	▲	▲	▲	▼	▼	▼
b. Boiler	Cooling	▲	▲	▲	▼	▼	▼
	Heating	▲	▲	▲	▼	▼	▼

Notes: N/A - Not Applicable; Cooling Off When $T <_{s,sp}$; Heating Off When $T >_{e,sp}$

Sample of Reasoning Applied in Generation of Table 26

1. High Supply Air Flow Rate Fault
    a. In the low temperature range, the economizer function should maintain the required supply air temperature, and there will be no need for the chiller to start up, and cooling will remain OFF.
    b. In the low temperature range, ▲ heating by reheat will be required.
    c. In the mid temperature range, the economizer should be using 100% OA, and excess supply air flow will require ▲ cooling.
    d. In the mid temperature range, ▲ heating by reheat will be required, with a magnitude likely greater than that of the additional cooling stated in step c above. In analyzing only the portion of the flow that is extra: the reheat must first reverse the additional cooling of this flow by reheating the air back from the supply air temperature to the OA temperature, but then it must also heat this added flow up to the room temperature to avoid over cooling the conditioned space.
    e. In the high temperature range, maintaining the supply air temperature will require ▲ cooling. Higher flows will draw in higher levels of outside air and could also increase latent cooling requirements in addition to the sensible cooling. If no reheat exists at these higher temperatures, then comfort conditions will certainly be affected.
    f. In the high temperature range, if the HW and/or boiler system is shutdown, no heating consumption (OFF) will be seen. Otherwise reheat in the amount close to the cooling increase should be seen.

The results of the Diagnostic Summary Count table can be reclassified into the terms of Table 26 with some simple reasoning such as … if the majority of the points fall outside the +threshold limit it will be considered More, Less in the case of outside the -threshold limit, or Same if in between the +/- thresholds.

As one can see, if a fault with a specific pattern of heating and cooling is observed in only one temperature range, three or four of the fault categories may apply. As more data is gathered from one of the other ambient temperature ranges, the possibilities for a more deterministic diagnosis improve.

Table 26 is an example of a specific system type and is not representative of all buildings and all systems. Fault tables like must generated for the systems and operating modes found in each individual building running the ABCAT. Special considerations will have to be made for systems without economizers, systems that require year round heating and cooling or systems with mixed system types.

B.4.4. Chart #13 HW Cumulative Sum Alarm

See the CHW Cumulative Sum Alarm description above in chart B.4.2.

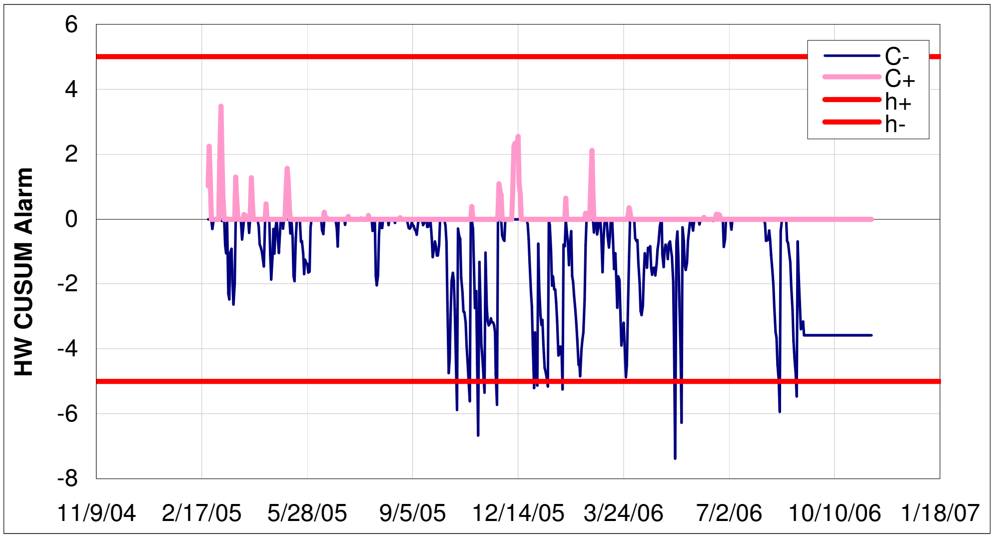

Figure 66. HW Cumulative Sum Alarm

B.5. ABCAT Sheet Name: Periods1&2

B.5.1. Chart #14 Two Period Time Series Average Daily Outside Air Temperature

See section B.5.2 below.

B.5.2. Chart #15 Two Period Time Series Electricity Consumption

These two plots together are designed to assist the user in comparing the past electricity consumption of the building for two different periods of time. The start dates (displayed in legend) for periods 1 and 2 are to be defined by the user on the *ABCAT Interface* sheet, along with the duration (in weeks) of the periods to be plotted. The x-axes of the two plots correspond to the dates of period 1 only. The dates corresponding to points of the period 2 curve can be determined from the start date in the legend, and clicking twice on any point of the curve. It is visually advantageous to use a scrollbar of either period to shift one of the plots by up to several days as necessary until similar day types align, as seen below with the alignment of the rise and fall of transitions from and to weekends with the two series.

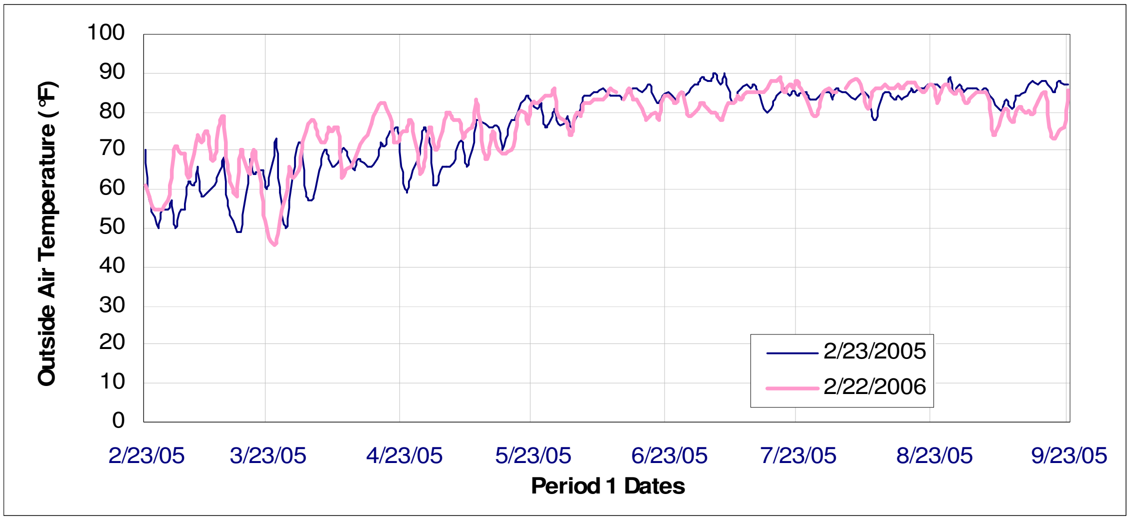

Figure 67. Two Period Time Series Average Daily Outside Air Temperature (°F)

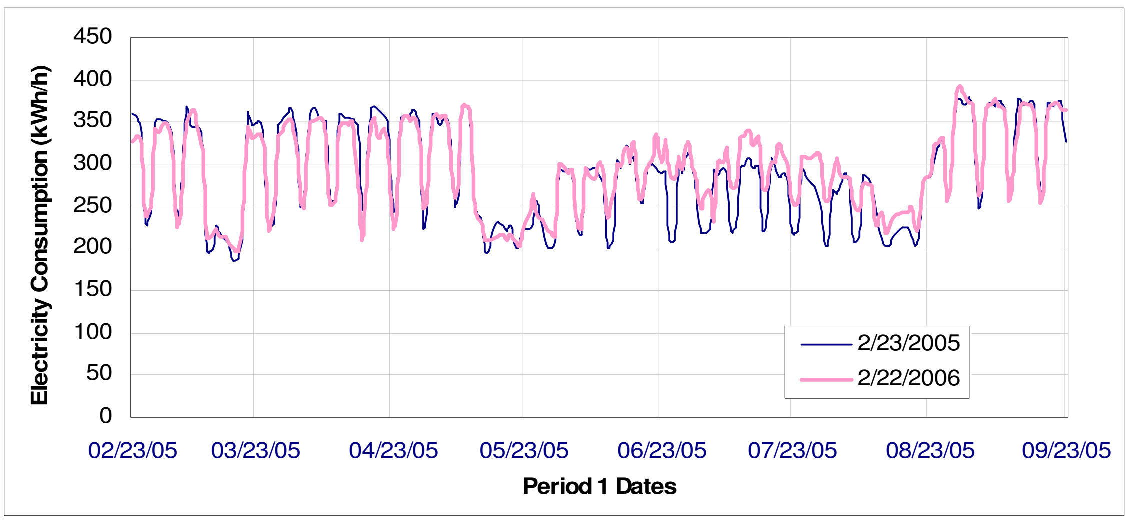

Figure 68. Two Period Time Series Electricity Consumption (kWh/h)

If the building operations had not changed significantly from the one period to the next, one would expect the respective electricity consumptions would align well, that is, unless there are temperature dependent differences. The temperature comparison can be easily made by using the two plots together.

Changes in electricity consumption that cannot be explained by temperature may be the result of the following: deviations from optimal pump and fan variable speed control, changes in building occupancy, changes in the unoccupied period duty cycling schedule or an increase/decrease in equipment and/or lighting loads.

B.6. ABCAT Sheet Name: Periods1&2(2)

B.6.1. Chart #16 Two Period Cooling versus Outside Air Temperature

See section B.6.2 below.

B.6.2. Chart #17 Two Period Heating versus Outside Air Temperature

These plots are similar to Charts #B.2.3 & #B.2.4 on the *Meas&Sim(2)* sheet except that these compare two periods of measured consumption, rather than measured and simulated data. The start dates (displayed in legend) for periods 1 and 2 are to be defined by the user on the *ABCAT Interface* sheet, along with the duration (in weeks) of the periods to be plotted. For additional detail on interpretation of the plots see the previous section on Charts #B.2.3 & #B.2.4.

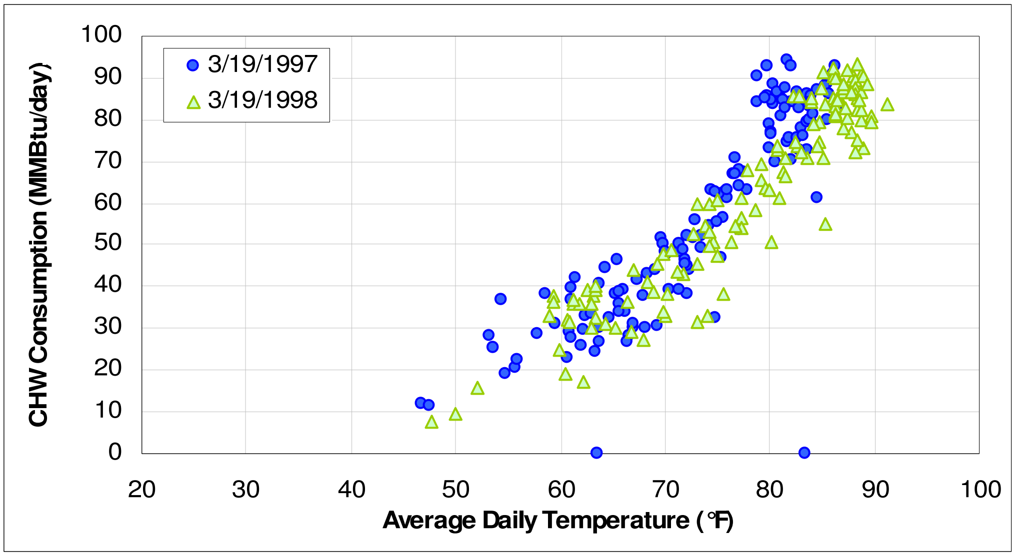

Figure 69. Cooling Consumption (MMBtu/day) versus Outside Air Temperature

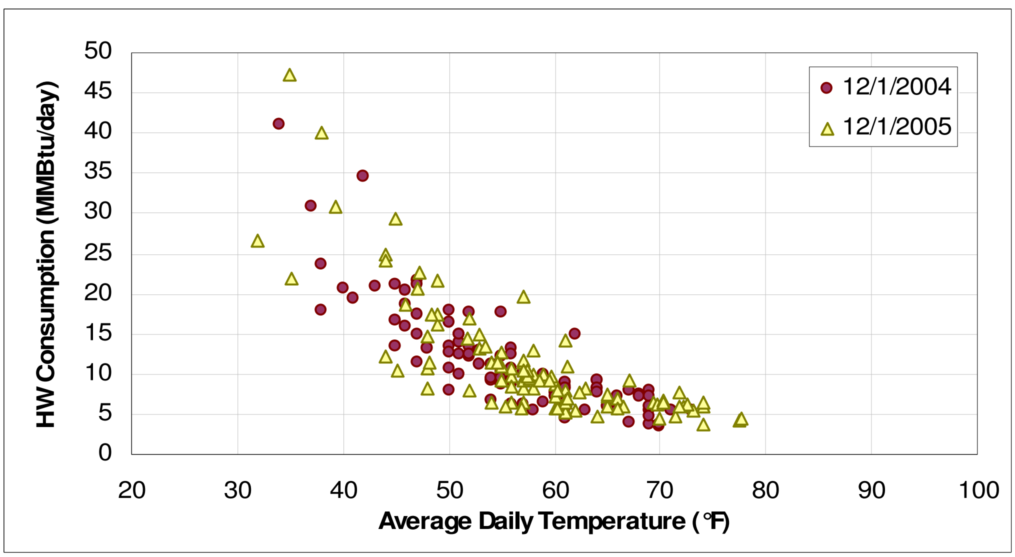

Figure 70. Heating Consumption (MMBtu/day) versus Outside Air Temperature

B.6.3. Chart #18 Average Daily Electric versus Outside Air Temperature

This plot will display the temperature dependency of electricity consumption for the two periods of measured consumption. The start dates (displayed in legend) for periods 1 and 2 are to be defined by the user on the *ABCAT Interface* sheet, along with the duration (in weeks) of the periods to be plotted. Several separate bands of consecutively lower consumption typically are apparent that represent weekday, weekend and/or holiday/vacation periods. Buildings with electric heat and mechanical refrigeration equipment may require special interpretative considerations. Flat profiles throughout the temperature range would generally be expected from constant volume HVAC systems. Positive sloping profiles can indicate the difference between peak and minimum HVAC related electricity consumption in VFD systems if you take the difference between the electricity at the highest and lowest temperatures in the range.

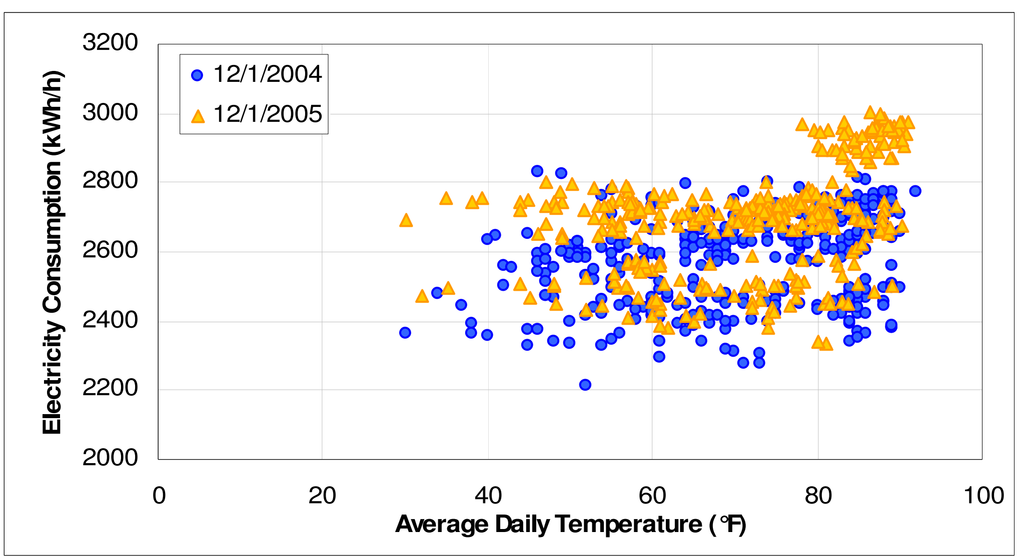

Figure 71. Average Daily Electric (kWh/h) versus Outside Air Temperature

B.7. Optional Plotting Capabilities

The ABCAT user can also take advantage of the fact that the above described plots are fully editable as far as color, gridlines and other formatting; but more importantly, the series plotted can also be defined by the user. Appendix D describes how one could perform a new calculation on the performance data and add that new series to a chart. There are also several ready to implement series, such as CHW or HW residuals and CHW or HW cumulative consumption, that could replace any of the existing plotted series by simply changing the source data name on the chart. Again, Appendix D describes this step in further detail.

B.8. ABCAT Interface

Figure 72 is a snapshot of the User Interface Screen of the ABCAT tool and is labeled to correspond with the descriptive numbered items found on the following pages.

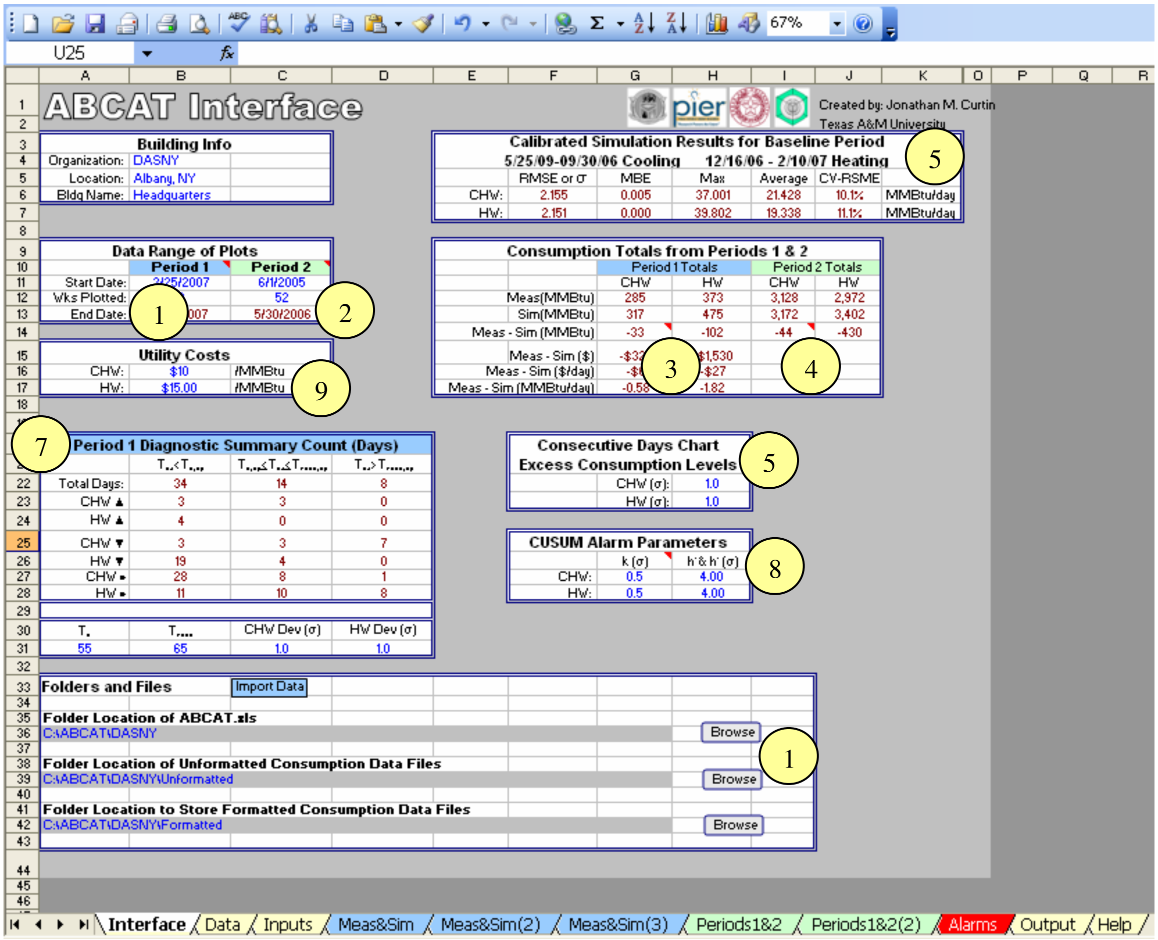

Figure 72. The ABCAT User Interface Screen Shot

1. To view plots of measured versus simulated data for a specific time period, enter the start date and number of weeks of data to plot in the boxes labeled Period1. The three tabs labeled "Meas&Sim" present the plotted measured and simulated data for Period1.

2. To compare measured data from two different periods of time, enter the start dates and period lengths for the two periods in the cells labels Period1 and Period2. The two tabs labeled "Periods1&2" will display the plotted data from the two periods.

3. The Period 1 Consumption Totals table presents the totalized chilled water and hot water consumption for the period defined and provides some basic difference calculations on these totals.

4. The Period 2 Consumption Totals table presents the totalized chilled water and hot water consumption for the period defined and provides some basic difference calculations on these totals.

5. The Consecutive Day Chart Excess Consumption Level thresholds defined here are the limits used to determine a "day in excess" on the Chart in Section B.4.1.

6. Calibrated Simulation statistical accuracy results from baseline periods. These parameters are uses in several calculations.

7. The Diagnostic Summary Count (Days) table, which tallies the number of days of the period that fall into each category of the table. The different categories are separated into three daily average outside air temperature ranges, $T_{oa} < T_{s,sp}$ (supply air temperature); $T_{s,sp} \leq T_{oa} \leq T_{e,sp}$ (temperature the economizer deactivates); $T_{oa} > T_{e,sp}$. For each outside air temperature range, the total days and days where the thermal energy consumption (CHW and HW) are greater than ▲, less than ▼, or within the limits ● of the deviation stated (CHW Dev and HW Dev in terms of the standard deviation) are counted and fill the table appropriately. These results are presented on the Chart in Section B.4.3.

8. CUSUM Alarm parameters for uses in the CUSUM Alarm Charts. The parameters k and h (both in terms of the standard deviation) for the CUSUM Alarm Charts (CHW – Section B.4.2 , HW – Section B.4.4) can be updated in this location. Smaller k's result in smaller deviations included in the CUSUM chart, and the setting for h determines when the chart resets to 0.

9. The cost of cooling (CHW) and heating (HW) energy can be manually input in this Utility Costs section. This affects the output of the Chart in Section B.3.2 - Time Series Cumulative Cost Difference ($).

10. Define folder location for data files and the ABCAT file.

APPENDIX C

ABCAT USERS MANUAL

C.1. Initial Setup Requirements

1. The main ABCAT file (ABCAT_Bldgname.XLS) can be renamed if desired, but it cannot have a space in its new name.

2. Macros have to be enabled through your security settings of Microsoft Excel (Tools - Macros - Security - Medium) in EXCEL to take full advantage of all options available. When opening the ABCAT file, if your Macro security settings are set to medium, you will be asked if you want to enable macros. Select "enable macros" to enable the full functionality of ABCAT.

3. On the *Interface* sheet of the ABCAT file, select the Browse buttons in the Folders and Files section to select the folder location for the ABCAT file, the unformatted consumption files and the formatted consumption files.

****Steps 4 & 5 are specific to the DASNY building**

4. This version of ABCAT is currently configured to read unformatted consumption files with the name "DASNYweeklyconsumption.xls". For the weekly file received through email, one needs to save the file to the unformatted consumption folder specified with the name "DASNYweeklyconsumption.xls".

5. After the weekly consumption file is downloaded, one can go to the *Data* Sheet and click on the "Import Data" button on the top left hand part of the page, which will import the data from the "DASNYweeklyconsumption.xls" file into the DATA SHEET.

6. Clicking the "Auto Run" button on the *Data* Sheet will run the energy simulation for any days that have measured consumption data but no simulated data.

7. The "Manual Run" button on the *Data* Sheet will allow the user to select a date in the first column of the sheet, and will prompt the user for the number of days for which they would like to run the simulation.

C.2. Interface Sheet

1. To view plots of measured versus simulated data for a specific time period, enter the start date and number of weeks of data to plot in the boxes labeled Period1. The three tabs labeled *Meas&Sim* present the plotted measured and simulated data for Period1.

2. To compare measured data from two different periods of time, enter the start dates and period lengths for the two periods in the cells labels Period1 and Period2. The two tabs labeled *Periods1&2* will display the plotted data from the two periods.

3. The Period 1 Consumption Totals table presents the totalized chilled water and hot water consumption for the period defined and provides some basic difference calculations on these totals.

4. The Period 2 Consumption Totals table presents the totalized chilled water and hot water consumption for the period defined and provides some basic difference calculations on these totals.

5. The Consecutive Day Chart Excess Consumption Level thresholds defined here are the limits used to determine a "consecutive days above or consecutive days below excess consumption levels ", on the sheet *Meas&Sim(3)*.

6. Calibrated Simulation statistical accuracy results from baseline periods. These parameters are uses in several calculations.

7. The Diagnostic Summary Count (Days) table, which tallies the number of days of the period that fall into each category of the table. The different categories are separated into three daily average outside air temperature ranges, $T_{oa} < T_{s,sp}$ (supply air temperature); $T_{s,sp} < T_{oa} < T_{e,sp}$ (temperature the economizer deactivates); $T_{oa} > T_{e,sp}$. For each outside air temperature range, the total days and days where the thermal energy consumption (CHW and HW) are greater than ▲, less than ▼, or within the limits ● of the deviation stated (CHW Dev and HW Dev in terms of the standard deviation) are counted and fill the table appropriately. These results are presented in the Diagnostic Count chart on sheet *Meas&Sim(3)*.

8. CUSUM Alarm parameters for uses in the CUSUM Alarm Charts. The parameters k and h (both in terms of the standard deviation) for the CUSUM Alarm Charts on sheet *Meas&Sim(3)*, can be updated in this location. Smaller k's result in smaller deviations included in the CUSUM chart, and the setting for h determines when the chart resets to 0.

9. The cost of cooling (CHW) and heating (HW) energy can be manually input in this Utility Costs section. This affects the output of the Time Series Cumulative Excess Cooling & Heating Costs ($) on sheet *Meas&Sim(2)*, previously described in this document.

10. The Files and Folders section has been explained in the Initial Setup Requirements section C.1 above.

C.3. Data Sheet

1. This sheet stores the measured and simulation consumption values as well as the results of several calculations performed with this data.

2. Columns A thru N on this sheet are described as follow:

    a. Columns A-C: Date, Average Daily Outside Air Temperature, Average Daily Dew Point Temperature (or Relative Humidity)

    b. Columns D-F: Measured Daily Chilled Water, Hot Water and Whole Building Elec

    c. Columns G-H: Average Preoccupied Period Outside Air Temperature and Whole building Elec

    d. Columns I-K: Average Occupied Period Outside Air Temperature, Dewpoint Temperature (or Relative Humidity) and Whole Building Elec

    e. Columns L-M: Average Postoccupied Period Outside Air Temperature and Whole Building Elec

    f. Columns N-O: Daily Simulated Chilled Water and Hot Water Consumption

    g. The remaining columns are the results of calculations performed upon the data in columns A-O with user specific inputs on the “Interface” sheet.

C.4. Inputs Sheet

1. System Information

a. System No. – Up to 5 different systems can be simulated at the same time, with each column B – F corresponding the inputs for systems numbered 1 – 5

b. Simulated – Enter a 1 in this cell for the system if you desire it to be included in the simulation, otherwise enter 0 to exclude it from the simulation. This way, one can easily view the simulated results from all or just one system which can aid in troubleshooting or understanding.

c. SysType – Three system types are currently available to simulate. These include 1. SDRH (Single Duct Reheat), 2. SDHC (Single Duct Heating and Cooling), and 3. DFDD (Dual Fan Dual Duct).

   i. Single Duct Reheat (SDRH) – This system type can be used to simulate both constant speed and variable speed units.

   ii. Single Zone Heating and Cooling (SZHC) – This system is to simulate a single zone only, so the % Interior Zone Area (x_iA) must be set equal to either 1 or 0

   iii. Dual Fan Dual Duct (DFDD) – This system allows the user to define a temperature at which the hot deck fan can shutoff (HD_onoffTemp)

   iv. Dual Duct (DD) – This sytem type can be used to simulate both constant speed and variable speed units

d. Tdewpoint_or_RH – specifies whether the ambient humidity measurement in the Occupied Period column of the "Data" sheet on the workbook is Dewpoint temperature (F) – (0) or Relative Humidity (%) – (1)

2. Total Floor Area and % Interior Zone Area

   a. A_T - Total Floor Area (ft^2) for each system specified in the simulation
   b. x_iA - Fraction of the system area that is considered the interior or core zone (not subjected to envelope gains/losses)

3. Thermal Mass Definition

   a. SWR – Surface Weight Ratio (lb/ft^2), typical values depending on construction type will usually range from (30 – light) to (130 – heavy). A single node Air-Mass lumped capacitance model is included in the simulation that seeks to simply represent and account for thermal storage effects in the building. A value of 0 entered for SWR tells the simulation to skip the thermal storage calculations.

4. Heating and Cooling Set Point and Night Setback Temperatures

    a. T_h – heating set point temperature (°F)

    b. T_c – cooling set point temperature (°F)

    c. T_hsb – heating setback temperature (°F)

    d. T_csb – cooling setback temperature (°F)

5. Humidification Settings

    a. Humidification – Does an electronic humidifier exist? No – (0); Yes – (1). If so, the electric load required for the latent heat of vaporization of the water is calculated and subtracted from the whole building electric load to avoid considering this load as heat gain.

    b. RH_spMin – minimum RH set point

6. Occupancy Schedules (0 – 24) hrs - This schedule is used in conjunction with the Occupied and Unoccupied period occupancy density inputs (14.) below to consider the heat gain from occupants for each of these periods.

    a. WkdayOccStart – Starting time of the occupied period

    b. WkdayOccEnd – Ending time of the occupied periods

    c. Same inputs follow for Saturday, Sunday and Vacation Periods.

7. HVAC Schedules (0 – 24) hrs

    a. WkdayHVACStart – Starting time of the HVAC system

    b. WkdayHVACEnd – Ending time of the HVAC system

    c. Same inputs follow for Saturday, Sunday and Vacation Periods.

8. Volumetric Flow Rates: Total, Outside Air, Minimum, Leakage, Infiltration

    a. V_eDsqft – Exterior Zone Design CFM/ft^2

b. V_iDsqft – Interior Zone Design CFM/ft^2

c. V_OAeDsqft – Exterior Zone Outside Air Design CFM/ft^2

d. V_OAiDsqft – Interior Zone Outside Air Design CFM/ft^2

e. OA_Control – Controls whether the outside air is controlled at a constant percentage (0) of total flow or a constant flow level (1)

f. V_eMinsqft – Exterior Zone Minimum CFM/ft^2 (equal to V_eDsqft for constant volume systems)

g. V_iMinsqft – Interior Zone Minimum CFM/ft^2 (equal to V_eDsqft for constant volume systems)

h. V_eHDsqft – Exterior Zone Hot Deck Design CFM/ft^2 (affects DFDD-SysType 3 only)

i. V_eHminsqft or V_leak(%) – V_eHminsqft is the Exterior Zone Hot Deck Minimum CFM/ft^2 (affects DFDD-SysType 3 only). V_leak (%) is the hot deck or cold deck flow that will inevitably leak as a percentage of the total flow in the Dual Duct System (DD-SysType 4 only)

j. V_inf – infiltration rate (NOT YET ACTIVE)

9. Hot Deck (DFDD only), RH in the interior zone? No - (0); Yes - (1); Return Duct Temp Rise

   a. HD_onoffTemp – Temperature at which the Hot Deck Fan is turned on (affects DFDD-SysType 3 only)

   b. Z_iRH – Enter a 1 if the system has reheat in the interior zones (affects DFDD-SysType 1 only). Otherwise enter a 0. If no reheat exists in the interior zones than there is the possibility that the system in the simulation may be overcooled if minimum flow settings or discharge air settings are not suitable to meet the load in the space.

   c. dT_Rduct – The temperature rise of the Return Air through the Return Air Duct back to the air handling unit

10. Economizer: yes/no (1/0), Temperature Set Points, Outside Air Fractions

a. Econ – Enter 1 if a temperature economizer exists, or 0 if there is no economizer

b. Econ_TH – Economizer High Temperature limit, the temperature above which the economizer deactivates, and dampers return to their minimum setting

c. Econ_TL – Economizer Low Temperature limit, the temperature below which the economizer deactivates, and dampers return to their minimum setting

d. x_OAEconMax – The maximum fraction of outside air capable by the air handling unit.

e. x_OAEconMin – The minimum fraction of outside air capable by the air handling unit. If an economizer is specified to exist, this input overrides the previous inputs for outside air levels V_OAeDsqft and V_OAiDsqft.

11. Envelope Areas and U-Values

a. A_Wall – Area of exterior envelope roof or wall (ft^2)

b. A_Win – Window area (ft^2)

c. U_Wall – U-value of exterior envelope ($Btu/ft^2{}^\circ Fhr$)

d. U_Win – U-value of window area ($Btu/ft^2{}^\circ Fhr$)

12. Supply Fan Efficiency and Total Pressure

a. Eff_f – Fan efficiency for all system fans 0 – 1

b. P_SfT – Supply Fan Total Pressure in.w.g.

c. P_Sf2T – Hot Deck Supply Fan Total Pressure in.w.g. (affects DFDD-SysType 3 and DD – SysType 4 only)

d. P_RfT – Return Fan Total Pressure in.w.g.

13. Solar Transmission – the solar gains used in the simulation will be from an linear interpolation of the inputs below at the day's measured ambient temperature

a. T_Jan – ambient temperature (°F) in January corresponding to solar load calculation

b. T_July - ambient temperature (°F) in July corresponding to solar load calculation

c. q_Jan – solar heat gain for January conditions at the ambient temperature - T_Jan (Btu/hr)

d. q_ July – solar heat gain for July conditions at the ambient temperature - T_July (Btu/hr)

14. Area per Occupant – used in conjunction with Occupancy Schedules (6.) above to determine loads from occupants

a. A_eOcc – exterior zone occupied period occupant density [Area(ft^2)/person]

b. A_iOcc – interior zone occupied period occupant density [Area(ft^2)/person]

c. A_eUnocc – exterior zone unoccupied period occupant density [Area(ft^2)/person]

d. A_iUnocc – interior zone unoccupied period occupant density [Area(ft^2)/person]

15. Lighting and Equipment Heat Gain

a. Elec – Either measured electric loads are used as inputs to the simulation (0) or electric loads are to be specified (1) from the inputs below

b. E_eSqftOcc – exterior zone occupied period electric gains (W/ft^2)

c. E_iSqftOcc – interior zone occupied period electric gains (W/ft^2)

d. E_eSqftUnocc – exterior zone occupied period electric gains (W/ft^2)

e. E_iSqftUnocc – interior zone occupied period electric gains (W/ft^2)

f. x_EsysHG – fraction of the overall measured electric load that contributes to heat gain in the system simulated. If 0.9 or (90%) is determined a reasonable estimate for overall conversion of electric power to load in the space, the sum of x_EsysHG across all systems simulated must equal 0.9. For example, in a 100,000ft^2 building, say the building has 2 system types, each one serving 50,000ft^2. If the load was distributed equally across the two systems, each one would have 0.45 as an input for x_EsysHG.

g. x_EiHG – fraction of the electric loads described above that contribute to Heat Gain in the interior zone. Unless a specific reason exists for it to be otherwise, x_EiHG should likely equal the interior zone fraction x_iA.

h. x_EeHG – fraction of the electric loads described above that contribute to Heat Gain in the exterior zone. Unless a specific reason exists for it to be otherwise, x_EeHG should likely equal (1 – x_iA), and should sum to 1 with x_EiHG.

16. Coil Set Point Temperature Schedules – coil discharge air temperature set points are to be linearly interpolated for conditions between the set points below, or equal to the end points stated if above or below the temperature range described. To disable any coil (if it doesn't exist in the system) set the set point temperature to conditions well above (for cooling) and well below (for heating) any entering air conditions one likely expects to see in practice. For the SDHC (SysType-2), one can disable the cooling control completely to simulate a Heating Only unit by setting T_Cset1 and T_Cset2 equal to 0.

a. T_Cset1 – cooling coil set point temperature corresponding to low ambient temperature T_C1

b. T_C1 – low ambient temperature condition for T_Cset1

c. T_Cset2 - cooling coil set point temperature corresponding to high ambient temperature T_C2

d. T_C2 - high ambient temperature condition for T_Cset2

e. T_Hset1 - heating coil set point temperature corresponding to low ambient temperature T_H1

f. T_H1 – low ambient temperature condition for T_Hset1

g. T_Hset2 – heating coil set point temperature corresponding to high ambient temperature T_H2

h. T_H2 – high ambient temperature condition for T_H2

i. T_OAPCset1 – outside air pre-treat cooling coil set point temperature corresponding to low ambient temperature T_OAPC1

j. T_OAPC1 - low ambient temperature condition for T_OAPCset1

k. T_OAPCset2 - outside air pre-treat cooling coil set point temperature corresponding to high ambient temperature T_OAPC2

l. T_OAPC2 - high ambient temperature condition for T_OAPCset2

m. T_OAPHset1 – outside air pre-treat heating coil set point temperature corresponding to low ambient temperature T_OAPH1

n. T_OAPH1 - low ambient temperature condition for T_OAPHset1

o. T_OAPHset2 - outside air pre-treat heating coil set point temperature corresponding to high ambient temperature T_OAPH2

p. T_OAPH2 - high ambient temperature condition for T_OAPHset2

17. Electric Load and HVAC Operation Fractions based on day type

a. WkdayElecRise (or Sat/Sun/Vac) – is to correspond to the time when the electric load begins to rise in the building and the start of the measured electric load for the occupied period.

b. WkdayElecFall (or Sat/Sun/Vac) – is to correspond to the time when the electric load begins to fall in the building and the end of the measured electric load for the occupied period

c. ClockElec_wkday (or Sat/Sun/Vac) – factor that adjusts the occupied period specified electric heat gains so that different occupied level gains can be specified for different day types. This is applicable whether the electric loads are specified or measured.

d. ClockHVAC_wkday (or Sat/Sun/Vac) – factor that adjusts the daily total cooling and heating. Only in special circumstances exist would one ever need to have this other than equal to 1.

18. Vacation Periods Defined

a. Vacation_Period1 (thru 7) – up to 7 vacation periods defined by (month – day) start and end dates. Each period must be contained within the same year, no Dec – Jan crossovers are allowed.

19. Additional Fixed Loads that cannot be readily simulated – can be used to add loads in special circumstances or to adjust the simulation results to eliminate bias error by day type

    a. NonSim_Cooling_wkday (or Sat/Sun/Vac) – adds value specified to simulated daily cooling consumption.

    b. NonSim_Heating_wkday (or Sat/Sun/Vac) – adds value specified to simulated daily heating consumption

C.5. Meas&Sim (3 Chart Sheets)

1. These 3 chart sheets provide various performance plots using the measured and simulated consumption data for the period described on the *Interface* sheet as period 1. Additional details and descriptions of the plots on these sheets can be found in Appendix B.

2. To see the date that corresponds to any data point plotted:
   First: Single-Click on the data point series
   Next: Single-Click on the specific data point of interest

3. To easily move the start date of the period analyzed in any plot forward or backward in time, use the scrollbars that are provided with the plot. This does not change the length of the period plotted, which can only be changed on the *Interface* sheet.

4. The top-left plot on the *Meas&Sim(2)* chart sheet allows the user to switch between viewing Cumulative Energy Difference (MMBtu) and Cumulative Cost Difference ($) by clicking on the button in the top-right corner of the plot.

C.6. Periods1&2 (2 Chart Sheets)

1. These 2 chart sheets provide various performance plots using the measured consumption data only for the two periods described on the *Interface* sheet as period 1 and period 2. Additional details and descriptions of the plots on these sheets can be found in Appendix B.

2. To see the date that corresponds to any data point plotted:
   First: Single-Click on the data point series
   Next: Single-Click on the specific data point of interest

3. To easily move the start date of the period analyzed in any plot forward or backward in time, use the scrollbars that are provided with the plot. This does not change the length of the period plotted, which can only be changed on the *Interface* sheet.

C.7. Alarm Sheet

1. This sheet will list various alarms for each run of the ABCAT simulation that may indicate that there is some problem with the inputs to the simulation. It will list the date, the outside air temperature, the system # and a brief description of the problem. For example, an alarm may be triggered if the specified airflows or supply air temperatures of a system are inadequate to meet the load in the space. The sheet will be cleared of all previous alarms for each subsequent run of the ABCAT simulation.

C.8. Output Sheet

1. Columns for the output sheet are arranged as follows:

    a. Date
    b. Average Daily Temperature (F)
    c. Occupied Period Relative Humidity (%)
    d. Total Building Cooling (MMBtu/day)
    e. Total Building Heating (MMBtu/day)
    f. Total Building Simulated Average Daily Electric (kwh/h)
    g. System 1 Cooling (MMBtu/day)
    h. System 1 Heating (MMBtu/day)
    i. System 1 Simulated Average Daily Electric (kwh/h)
    j. System 2 Cooling (MMBtu/day)
    k. System 2 Heating (MMBtu/day)
    l. System 2 Simulated Average Daily Electric (kwh/h)
    m. System 3 Cooling (MMBtu/day)
    n. System 3 Heating (MMBtu/day)
    o. System 3 Simulated Average Daily Electric (kwh/h)
    p. System 4 Cooling (MMBtu/day)
    q. System 4 Heating (MMBtu/day)
    r. System 4 Simulated Average Daily Electric (kwh/h)
    s. System 5 Cooling (MMBtu/day)
    t. System 5 Heating (MMBtu/day)
    u. System 5 Simulated Average Daily Electric (kwh/h)

APPENDIX D

ABCAT PROGRAM DETAILS

D.1. Named Ranges

Instead of fixed ranges used as source data for charts, ABCAT has multiple defined named ranges that are dynamic in that they respond to the changes in the period1 and period2 data ranges and the sliding action of the scroll bars. These are input as chart source values in the form of [=ABCATFilename.xls!NamedRange]. All the named ranges used in the ABCAT are presented in Table 27 along with their formula which uses the OFFSET function, the syntax of which is described below. Users can also create their own named range, by selecting the Insert > Name > Define menus from any worksheet of the ABCAT. This allows the user to perform new calculations on the performance data (by adding a formula to a new column to the right on the Data sheet), plot, and manipulate the data using the same controls as used for all the exiting plots.

Table 27. Microsoft Excel Named Ranges Used in the ABCAT

Named Range	Formula
CHW_ECI	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,29,Interface!$C$10*7,1)
CHW_Error	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,19,Interface!$C$10*7,1)
CHW_meas	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,3,Interface!$C$10*7,1)
CHW_meas2	=OFFSET(Data!$A$3,Interface!$C$11-Data!$A$3-2000+Interface!$L$2,3,Interface!$C$12*7,1)

Table 27. Continued

Named Range	Formula
CHW_resid	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,15,Interface!$C$10*7,1)
CHW_resid2	=OFFSET(Data!$A$3,Interface!$C$11-Data!$A$3-2000+Interface!$L$2,15,Interface!$C$12*7,1)
CHW_sim	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,13,Interface!$C$10*7,1)
CHWcMinus	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,32,Interface!$C$10*7,1)
CHWcPlus	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,31,Interface!$C$10*7,1)
consec_days_chw	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,25,Interface!$C$10*7,1)
consec_days_hw	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,26,Interface!$C$10*7,1)
Cum_CHW_Cost	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,17,Interface!$C$10*7,1)
Cum_CHW_Energy	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,21,Interface!$C$10*7,1)
Cum_CHW_Energy2	=OFFSET(Data!$A$3,Interface!$C$11-Data!$A$3-2000+Interface!$L$2,21,Interface!$C$12*7,1)
Cum_CHW_EnergySim	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,23,Interface!$C$10*7,1)
Cum_CHW_Resid	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,27,Interface!$C$10*7,1)
Cum_HW_Cost	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,18,Interface!$C$10*7,1)
Cum_HW_Energy	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,22,Interface!$C$10*7,1)
Cum_HW_Energy2	=OFFSET(Data!$A$3,Interface!$C$11-Data!$A$3-2000+Interface!$L$2,22,Interface!$C$12*7,1)
Cum_HW_EnergySim	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,24,Interface!$C$10*7,1)
Cum_HW_Resid	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,28,Interface!$C$10*7,1)
dates	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,0,Interface!$C$10*7,1)
dates2	=OFFSET(Data!$A$3,Interface!$C$11-Data!$A$3-2000+Interface!$L$2,0,Interface!$C$12*7,1)
HW_ECI	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,30,Interface!$C$10*7,1)
HW_Error	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,20,Interface!$C$10*7,1)
HW_meas	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,4,Interface!$C$10*7,1)
HW_meas2	=OFFSET(Data!$A$3,Interface!$C$11-Data!$A$3-2000+Interface!$L$2,4,Interface!$C$12*7,1)
HW_resid	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,16,Interface!$C$10*7,1)

Table 27. Continued

Named Range	Formula
HW_resid2	=OFFSET(Data!$A$3,Interface!$C$11-Data!$A$3-2000+Interface!$L$2,16,Interface!$C$12*7,1)
HW_sim	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,14,Interface!$C$10*7,1)
HWcMinus	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,35,Interface!$C$10*7,1)
HWcPlus	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,34,Interface!$C$10*7,1)
kw	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,5,Interface!$C$10*7,1)
kw2	=OFFSET(Data!$A$3,Interface!$C$11-Data!$A$3-2000+Interface!$L$2,5,Interface!$C$12*7,1)
oat	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,1,Interface!$C$10*7,1)
oat2	=OFFSET(Data!$A$3,Interface!$C$11-Data!$A$3-2000+Interface!$L$2,1,Interface!$C$12*7,1)
period1_startdate	=OFFSET(Data!$A$3,Interface!$C$9-Data!$A$3-2000+Interface!$L$1,0,1,1)
period2_startdate	=OFFSET(Data!$A$3,Interface!$C$11-Data!$A$3-2000+Interface!$L$2,0,1,1)

OFFSET Syntax

OFFSET (reference, rows, cols, height, width)

Reference – base location of the Offset. ABCAT - Cell A3 on the Data sheet.

Rows – rows above or below the reference. ABCAT – Period1 start date on the interface sheet minus Cell A3 on the Data sheet minus 2000 plus Cell L1 on the Interface sheet, or Period2 start date on the interface sheet minus Cell A3 on the Data sheet minus 2000 plus Cell L2 on the Interface sheet. The chart scroll bars are linked to the Cell L1 on the Interface sheet (Cell L2 for the second scroll bar on the Periods1&2 sheets). Since the scroll bar control minimum value cannot be less than 0, when the periods plotted are changed, Cells L1 & L2 are set to 2000, the 2000 is subtracted from this field so that backwards scrolling reduces this Rows value in the named ranges.

Cols – number of columns to the right to offset from the reference cell.

Height – height, in number of rows for the returned reference range. ABCAT – equals seven times the number of weeks of data plotted.

Width – the width in columns for the returned reference range. ABCAT – one in all cases.

D.2. Formulas

D.2.1. Interface Sheet

Table 28. User Interface Sheet Spreadsheet Cell Formulas

Col	Row	Formula
L	1	Linked to Scroll Bars 1.1 – 1.5
L	2	Linked to Scroll Bars 2.1 – 2.2
H	10	=F10-G10
I	10	=H10*G25
J	10	=I10/SUM(B21:D21)
K	10	=H10/SUM(B21:D21)
H	11	=F11-G11
I	11	=H11*G26
J	11	=H11/SUM(B21:D21)
K	11	=I11/SUM(B21:D21)
B	26	=B21-B22-B24
C	27	=C21-C22-C24
D	28	=D21-D22-D24
B	26	=B21-B23-B25
C	27	=C21-C23-C25
D	28	=D21-D23-D25
L	37	= 0
M	37	=H21
N	37	=-H21
L	38	= 1
M	38	=H21
N	38	=-H21
L	39	= 0
M	39	=H22
N	39	=-H22
L	40	= 1
M	40	=H22
N	40	=-H22

D.2.2. Data Sheet

Table 29. Data Sheet Spreadsheet Cell Formulas

Col	Row	Formula
A	3	= A4- 1
P – AK	3	Blank
P	4	=IF(A4="","",IF(OR(N4="",D4=""),#N/A,(D4-N4)))
Q	4	=IF(A4="","",IF(OR(O4="",E4=""),#N/A,(E4-O4)))
R	4	=IF(A4="","",IF(ISERROR(P4),R3,P4*Interface!$G$25+R3))
S	4	=IF(A4="","",IF(ISERROR(Q4),S3,Q4*Interface!$G$26+S3))
T	4	=IF(A4="","",IF(P4="",#N/A,(D4-N4)/(Interface!$H$16)))

Table 29. Continued

Col	Row	Formula
U	4	=IF(A4="","",IF(Q4="",#N/A,(E4-O4)/(Interface!$H$17)))
V	4	=IF(A4="","",IF(D4="",V3,D4+V3))
W	4	=IF(A4="","",IF(E4="",W3,E4+W3))
X	4	=IF(A4="","",IF(N4="",X3,N4+X3))
Y	4	=IF(A4="","",IF(O4="",Y3,O4+Y3))
Z	4	=IF(A4="","",IF(ISERROR(P4),Z3,IF(AND(P4>Interface!$C$15*Interface!$F$16,Z3<=0),1,IF(AND(P4>Interface!$C$15*Interface!$F$16,Z3>0),Z3+1,IF(AND(P4<-Interface!$C$15*Interface!$F$16,Z3>=0),-1,IF(AND(P4<-Interface!$C$15*Interface!$F$16,Z3<0),Z3-1,0))))))
AA	4	=IF(A4="","",IF(ISERROR(Q4),AA3,IF(AND(Q4>Interface!$C$16*Interface!$F$17,AA3<=0),1,IF(AND(Q4>Interface!$C$16*Interface!$F$17,AA3>0),AA3+1,IF(AND(Q4<-Interface!$C$16*Interface!$F$17,AA3>=0),-1,IF(AND(Q4<-Interface!$C$16*Interface!$F$17,AA3<0),AA3-1,0))))))
AB	4	=IF(A4="","",IF(ISERROR(P4),AB3,P4+AB3))
AC	4	=IF(A4="","",IF(ISERROR(Q4),AC3,Q4+AC3))
AD	4	=IF(A4="","",IF(OR(N4="",D4=""),#N/A,D4/N4))
AE	4	=IF(A4="","",IF(OR(O4="",E4=""),#N/A,E4/O4))
AF	4	=IF(ISERROR(P4),AF3,IF(OR(AF3>Interface!$H$21,AF3<-Interface!$H$21), MAX(0,AH4-Interface!$G$21+0),MAX(0,AH4-Interface!$G$21+AF3)))
AG	4	=IF(ISERROR(P4),AG3,IF(OR(AG3>Interface!$H$21,AG3<-Interface!$H$21), MIN(0,AH4+Interface!$G$21+0),MIN(0,AH4+Interface!$G$21+AG3)))
AH	4	=P4/(Interface!$F$16)
AI	4	=IF(ISERROR(Q4),AI3,IF(OR(AI3>Interface!$H$22,AI3<-Interface!$H$22), MAX(0,AK4-Interface!$G$22+0),MAX(0,AK4-Interface!$G$22+AI3)))
AJ	4	=IF(ISERROR(Q4),AJ3,IF(OR(AJ3>Interface!$H$22,AJ3<-Interface!$H$22), MIN(0,AK4+Interface!$G$22+0),MIN(0,AK4+Interface!$G$22+AJ3)))
AK	4	=Q4/(Interface!$F$17)

Additional Formulas: Formulas for cells P4 – AK4 are copied down through row 2000.

APPENDIX E

ABCAT AUSTIN RECALIBRATION DETAILS

In October 2005, the measured cooling energy consumption of the building began to consistently deviate from the ABCAT simulated consumption (measured < simulated), as was previously reported. Following some investigation, it was found that the time the deviation was first detected coincided with a calibration of the chilled water meters by Austin Energy. During the calibration, one of the three meters was found to be reading high flow, and was corrected. This seemed to reasonably explain the cause of the detected reduction in measured cooling consumption.

The change in measured cooling consumption as a result of the meter calibration required a redefining of the baseline consumption used in the ABCAT program. The period of 10/27/2005 – 05/19/2006 was selected as the new baseline, and the ABCAT simulation was recalibrated to the heating and cooling consumption from this period. The end of this period, 5/19/2006, was also significant in that the steam service from Austin Energy was permanently shutdown.

For the period of 5/20/2006 – 10/13/2006, the ABCAT simulation was adjusted slightly to account for the shutdown of the steam service. Although there is no required HVAC related steam consumption in the summer, there was some minimum steam consumption in the cafeteria kitchen equipment as well as through pipe losses. The change out of steam consuming kitchen equipment to electric equipment allowed for the shutdown of the steam service. The ABCAT simulation was adjusted by simply removing a fixed 6.0 MMBtu/day weekday and 4.8 MMBtu/day weekend base load from the heating simulation inputs. Assuming that 100% of these loads contributed directly to cooling loads in the building, the same magnitude adjustments were made in the cooling simulation inputs.

New natural gas service was introduced to the building on 10/14/2006, which provided yet another condition to account for with the ABCAT. Hourly or daily interval readings on the gas meter were not available, and Btu monitoring of the hot water system was not yet active, so an analysis of the monthly natural gas consumption was performed to estimate daily consumption for use in the ABCAT. A boiler heating energy output model was developed by regressing the total gas consumption from each of the billed periods against the average outside air temperatures of the periods with a four parameter change-point model. Daily consumption was obtained from the model with the average daily outside air temperature and assumptions of constant energy content of 1020 Btu/cf and average boiler efficiency of 90%. Domestic hot water heating consumption provides another minimal base load consumption of approximately 1.63 MMBtu/day, which was added as fixed loads for both the heating and cooling simulations of the ABCAT.

APPENDIX F

SUMMARY OF CALIBRATED SIMULATION STATISTICS

The compiled statistical results of nine calibrated simulations are presented in this section to aid in answering the question of when the simulation sufficiently calibrated, and also address this issue of adequacy of the ABCAT simulation model by comparison it against a 4P-CP model that regresses consumption against outside air temperature.

Presented first in Table 30, are the statistical results of the calibrated simulation of the nine buildings analyzed in this study. Caution must be taken in their interpretation because of the varying period lengths and seasonal representation of the calibration periods (see Section 3.6). Figure 73 displays the CV-RMSE of these nine building periods. In each building, the utility (CHW or HW) with the greater average consumption has the lower CV-RMSE, which is also < 20%. The two of the three cases where the HW CV-RMSE was greater than 50% occurred in buildings where the ratio of the CHW average to the HW average was approximately equal to 10:1 or greater. The third case, Harrington Tower, this ratio is about 3:1. Clearly the relationship between the heating and cooling average consumption has an effect on the minimum CV-RMSE achievable through calibration. This can be explained by the often interrelated consumption activities of CHW and HW, and how variations of a certain size in the larger of the two in magnitude, can often result in the same size variations in the smaller of the two.

Table 30. Statistical Results of the Nine ABCAT Calibrated Simulations

Bldg	Utility	Calibration Period	Weeks	RMSE	MBE	Max	Avg	CV-RMSE
DASNY	CHW	05/26/06-10/01/06	18.3	2.16	0.01	37	21.43	10.10%
	HW	12/16/06-02/10/07	8.0	2.15	0	39.8	19.34	11.10%
OPPD	CHW	08/15/06-02/02/07	24.4	2.36	0	32.75	8.13	29.00%
	HW	10/17/06-02/02/07	15.4	2.45	0	49.5	22.15	11.10%
Comp Serv Facility	CHW	12/01/04-11/30/05	52.0	10.8	0.69	340.64	210.91	5.10%
	STM			1.69	0.21	40.94	8.35	20.30%
Sbisa	CHW	02/02/04-12/31/04	47.6	6.96	0.6	90.48	55.92	12.45%
	HW			3.36	-0.288	40.8	17.76	18.92%
Wehner	CHW	01/01/97-07/31/97	30.1	2.74	0	48.07	25.62	10.70%
	HW			4.12	0	62.84	23.78	17.30%
Harrington	CHW	08/16/96-08/31/97	54.3	2.54	0	40.7	20.65	12.30%
	HW			3.41	0	54.33	6.71	50.80%
Eller	CHW	03/19/97-08/31/97	24.4	4.98	0	94.09	61.49	8.10%
	HW			3.27	0	35.79	2.97	110.00%
Vet Research	CHW	01/01/98-07/10/98	27.1	5.01	0	137.04	59.17	8.50%
	HW			2.99	0	21.25	5.92	50.50%
Kleberg	CHW	11/01/96-07/31/97	38.9	10.1	0	166.3	81.24	12.40%
	HW	11/01/96-12/15/96 & 02/05/97-03/14/97 & 04/09/97-05/10/97	16.0	4.35	0	34.62	21.44	20.30%

Data Frequency Analyzed: Daily

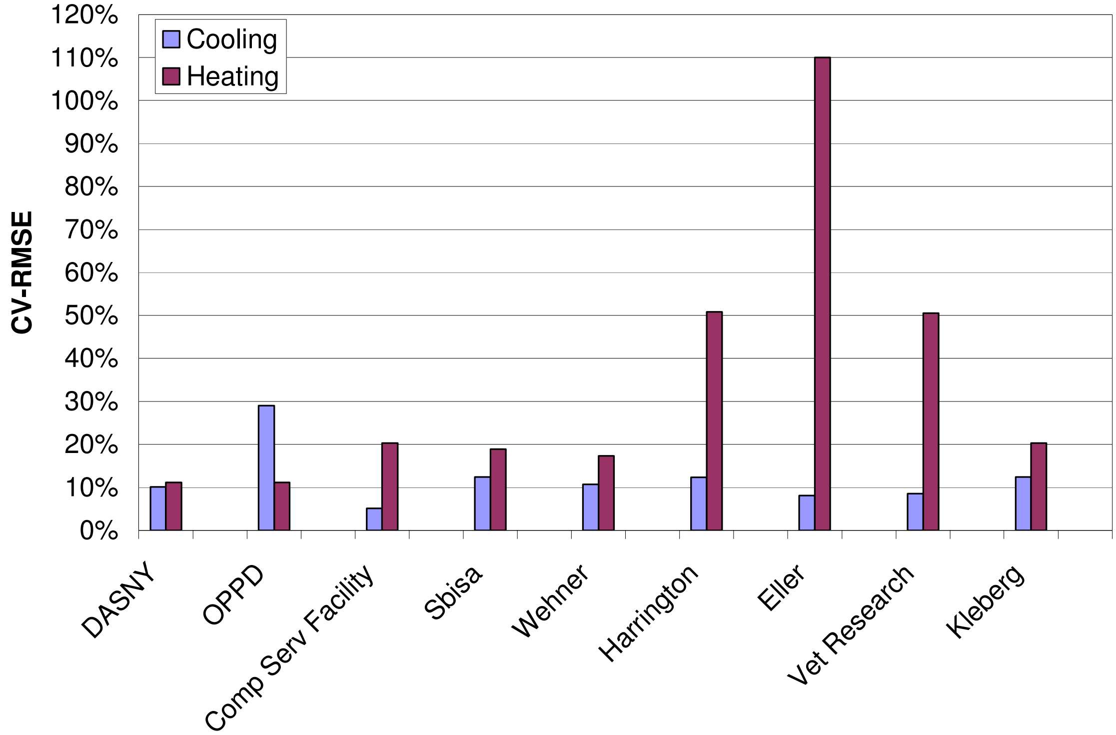

Figure 73. CV-RMSE of the Nine ABCAT Calibrated Simulations

Table 31 lists the calibrated simulation statistics again for the nine buildings, but for weekdays only. The SEAP model in these cases had a lower CV-RMSE in 12 of the 18 cases.

Table 31. Comparative Results of the ABCAT's SEAP Calibrated Simulation Model with a 4P-CP Model in each of the Nine Buildings for Weekdays Only

Bldg	Model	Utility	RMSE	MBE	Max	Avg	CV-RMSE
DASNY	4P-CP	CHW	5.21				20.92%
		HW	3.44				14.88%
	SEAP	CHW	2.27	0.01	37.00	25.19	9.02%
		HW	2.08	0.00	39.80	23.08	9.00%
OPPD	4P-CP	CHW	2.33				30.93%
		HW	1.97				8.96%
	SEAP	CHW	2.49	0.00	32.75	9.21	27.03%
		HW	2.29	0.00	45.78	21.99	10.44%

Table 31. Continued

Bldg	Model	Utility	RMSE	MBE	Max	Avg	CV-RMSE
Comp Serv Facility	4P-CP	CHW	12.30				5.47%
		STM	2.00				21.91%
	SEAP	CHW	9.56	-1.49	340.64	225.04	4.25%
		STM	2.08	-0.02	40.94	9.15	22.73%
Sbisa	4P-CP	CHW	7.87				14.73%
		HW	3.62				21.27%
	SEAP	CHW	7.73	-0.99	90.48	53.41	14.48%
		HW	4.81	-2.33	38.40	17.01	28.31%
Wehner	4P-CP	CHW	4.47				16.04%
		HW	5.47				26.32%
	SEAP	CHW	3.07	0.00	48.07	28.44	10.79%
		HW	3.87	0.00	47.94	21.23	18.21%
Harrington Tower	4P-CP	CHW	3.33				14.55%
		HW	3.38				67.12%
	SEAP	CHW	2.49	0.00	40.70	23.29	10.69%
		HW	2.79	0.00	42.01	5.11	54.69%
Eller O&M	4P-CP	CHW	10.35				16.38%
		HW	3.39				113.13%
	SEAP	CHW	4.74	0.00	94.09	63.76	7.44%
		HW	3.49	0.00	35.79	3.00	116.42%
Vet Research	4P-CP	CHW	7.42				11.97%
		HW	2.79				51.54%
	SEAP	CHW	4.78	0.00	137.04	62.93	7.60%
		HW	2.99	0.00	21.25	5.47	54.59%
Kleberg	4P-CP	CHW	9.57				11.79%
		HW	5.51				52.35%
	SEAP	CHW	9.91	0.00	166.30	82.94	11.95%
		HW	3.77	0.00	30.89	20.79	18.16%

Data Frequency Analyzed: Daily

APPENDIX G

ABCAT VBA CODE

The pdf file accompanies this thesis as a file available for downloading.

VITA

NAME Jonathan M. Curtin

ADDRESS 6161 Savoy Dr. Suite 700 Houston, TX 77063

EMAIL jmcurtin76@yahoo.com

EDUCATION

M.S. 2007	Mechanical Engineering, Texas A&M University, College Station, TX
B.S. 2000	Mechanical Engineering, Binghamton University, Binghamton, NY

EXPERIENCE

2007-	Wylie Consulting Engineers, Houston, TX
2004-2007	Research Assistant, Energy Systems Laboratory, College Station, TX
2002-2004	Endicott Interconnect Technologies, Endicott, NY
1999-2002	IBM Corp., Endicott, NY