Final Report on Retrospective Testing and Application of an Automated Building Commissioning Analysis Tool (ABCAT)

Submitted to:
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Executive Summary

More than $18 billion of energy is wasted annually in the U.S. commercial building sector. Commissioning services have proven successful in reducing building energy consumption, but the optimal energy performance obtained by commissioning may subsequently degrade. Therefore, it is very helpful to have tools that can help maintain the optimal building energy performance. An Automated Building Commissioning Analysis Tool (ABCAT) that combines a calibrated simulation operated in conjunction with diagnostic techniques is such a simple and cost efficient tool, which can continuously monitor whole building energy consumption after commissioning, warn operation personnel when an HVAC system problem has increased energy consumption, and assist them in identifying the possible cause(s) of the problem.

This report presents the results of six retrospective and nine live test case implementations of ABCAT on a total of fifteen buildings located in the United States and Europe. For each building, the energy simulation model used was calibrated to the building energy consumption data in a baseline period. Then, the model was used to predict the optimal cooling and heating consumption in the following days. A cumulative energy difference plot is the primary fault detection metric used in ABCAT; this plot continuously computes and plots the algebraic sum of the daily differences between the measured and simulated consumption. A fault detection standard is developed and defined in the report. In total, ABCAT detected 23 faults in ten of the fifteen buildings using the fault detection standard developed and other means. This report also outlines a methodology for identifying the cause(s) of the faults identified. Where applicable, the reasons for the detected faults are discussed in the report. The causes of some of the detected faults are verified with historical documentation, and the remaining diagnoses remain unconfirmed due to data quality issues, incomplete information on maintenance performed in the buildings and time constraints.

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1. Introduction

Commissioning services have proven to be successful in saving building energy consumption. The Energy Systems Laboratory at Texas A&M University has tracked results of their Continuous Commissioning® (CC®) process that evolved out of their work with the TexasLoanSTAR program. The average energy savings have 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 use (Mills et al. 2005).

The persistence of savings obtained in commissioning is a significant topic of concern. Claridge et al. (2004) presented 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. The major increases were not identified until two years had passed, and hundreds of thousands of dollars in excess energy costs had already occurred. Obviously there is 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. The Automated Building Commissioning Analysis Tool (ABCAT) will be such a tool for maintaining the optimal energy performance in a building.

An advanced prototype of ABCAT which can detect significantly increased energy use at the whole building level has been developed and tested in buildings. The fault detection and diagnostics approach are applied to whole building energy consumption data. First, a building energy simulation model is established and calibrated based on building performance in the baseline period chosen from a post commissioning time period when the building's operation is considered to be optimal. Then, subsequent heating and cooling consumption are simulated by the model and both the simulated and measured consumption are passed to the data analysis routine that generates building performance plots, compares and performs calculations on the simulated and measured consumption data, applies fault detection methods, and reports diagnostic and energy consumption statistics. Finally, the user of the tool evaluates the data presented and determines whether or not there is a fault that requires action. If a fault is identified, the user or other experts can use the diagnostic information provided by ABCAT to help identify and correct the fault, and follow up observations should observe a return to expected performance (Curtin et al. 2007).

It is believed by the authors that the types of faults that are most likely to avoid detection in buildings today 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. Therefore, one of the primary energy consumption metrics established in ABCAT is the cumulative energy difference plot, which takes the daily difference between the measured and simulated consumption of the previous day, and adds it to the cumulative difference from previous days. Providing this in cost form, which is simply the energy difference multiplied by a user specified cost per unit energy for the utility plotted, is expected to encourage users to take action when faults are detected, by speaking in the universal language of dollars and cents. These plots have been shown to be successful in identifying three significant consumption deviations in the four live test building implementations (Curtin et al. 2007). A cumulative energy difference plot can visually present the building's energy consumption performance, but is not sufficient to distinctively diagnose the faults.

In order to further test the capabilities of ABCAT, an initial multiple building retrospective test was performed. This initial group of five buildings on the Texas A&M University campus 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, and documentation of some control system set point changes during the period analyzed. This initial retrospective testing was covered in greater detail in a previous report and is only presented in a summary fashion in this report.

In this report, one additional retrospective building test and nine live test cases are presented in detail. Four of the live test cases are summarized in this report and not presented in complete detail since they were part of very early testing of the ABCAT tool and not the current work. The information presented for the remaining six buildings includes general building information, calibrated simulation results and any faults detected from the implementation of ABCAT as well as a discussion of the possible reasons for the faults detected.

To easily and quantitatively detect a fault, a simple fault detection standard is set in the report that identifies a fault if the deviation between measured and simulated consumption is greater than one standard deviation in the baseline period and persists for at least 30 days. A "days exceeding threshold" plot is drawn based on this standard. Every point in the plot represents the number of days in the next 30 days (including the day on which the point is plotted) where consumption has been at least one standard deviation above or below expected consumption. For example, a point at 10 means there are 10 days of the next 30 days when the measured consumption is more than one standard deviation above the simulated consumption, and a point at -10 means there are 10 days of the next 30 days when the deviation is more than one standard deviation below the simulated consumption. Thus a fault period appears as one or more points at ±30 on the plot. Where applicable, the influence of the fault on energy cost is shown on the cumulative cost difference plot. Where utilized, the assumed cooling and heating energy costs are $10/MMBtu and $15/MMBtu respectively in this report.

A method for identifying the cause of a detected fault is also presented and implemented. Where implementation was successful, a detailed description of the process and results is included. A combination of data quality issues, incomplete maintenance logs from the buildings throughout the period of the analysis, and time constraints limited the verification of the faults detected and the diagnostic results.

2. Previous Testing

2.1 Live Test Cases

The ABCAT was initially implemented in four live building situations, with various levels of automation and file manipulation built into the data collection process for each building based on its unique conditions regarding data availability and format. The testing of the ABCAT in the four buildings provided a live learning scenario that helped to influence continued developments, and a summary of these test cases is provided in Table 2.1 followed by relevant figures referenced in the table.

Table 2.1 Test Buildings, Results and Findings from Live ABCAT Implementation

Building Description	Location	Test Period	Results and Findings
82,000 ft^2 university dining facility	College Station, Texas	Mar 2005 – July 2007	• Detected excess cooling energy fault related to excessive latent cooling from low discharge air temperature on 2 of 3 Outside Air Handling Units – Summer 2006 shown in Figure 2.1.
482,000 ft^2 computing services facility	Austin, Texas	May 2005 – July 2007	• Detected significant decrease in measured cooling energy due to meter calibration – Oct 2005 (Figure 2.2). • A second fault, significant excess cooling energy was detected in Nov 2006 (Figure 2.3). • Also demonstration of successful short-term adaptation of simulation to multiple baseline changes.
180,000 ft^2 office building	Albany, New York	Jan 2007 – July 2007	• Successful monitoring of heating energy savings following implementation of EBCx measures (Figure 2.4). • Training and support for two ABCAT testers.
190,000 ft^2 high-rise office building	Omaha, Nebraska	Feb 2007 – July 2007	• Confirmation of optimal heating and cooling energy through continued tracking. • Identification of HW metering failure (Figure 2.5).

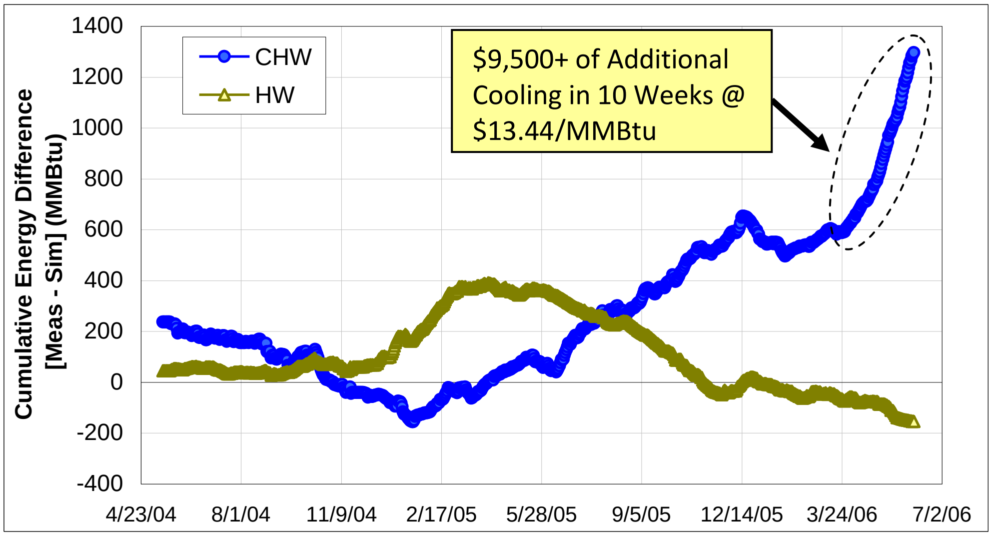


Figure 2.1 Sbisa Dining Hall Cumulative Energy Difference Meas – Sim (MMBtu) with Simulation Calibrated to Period of 5/01/2004 to 06/27/2006

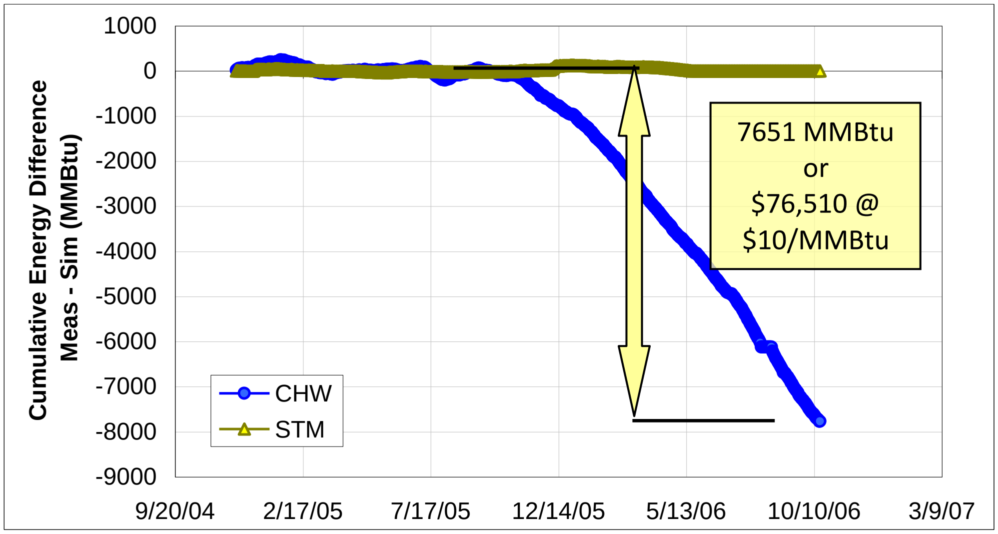


Figure 2.2 Computing Services Facility ABCAT Cumulative Energy Difference Meas – Sim (MMBtu) with Simulation Calibrated to Period of 12/01/2004 to 10/27/2005

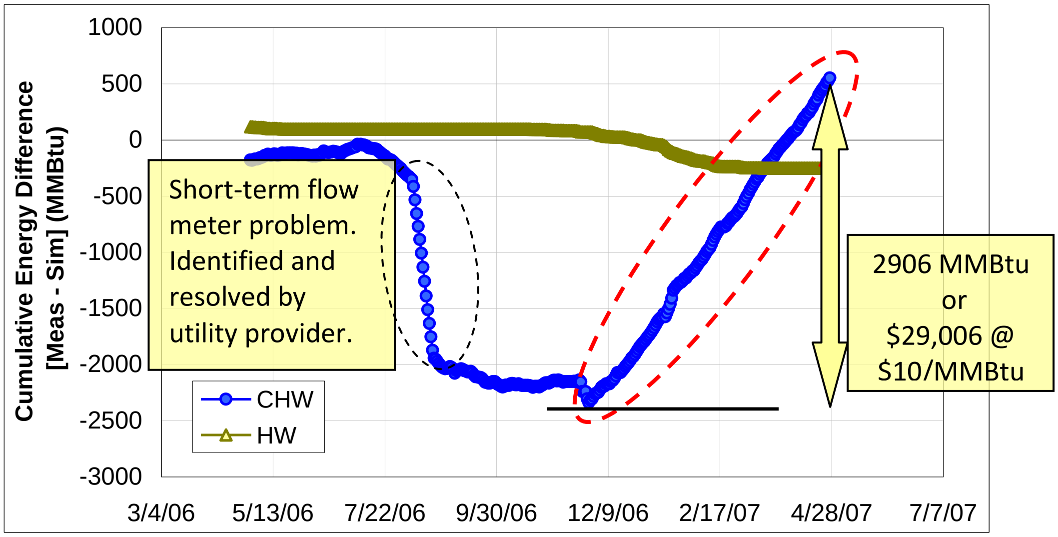


Figure 2.3 Computing Services Facility Cumulative Energy Difference for period starting 04/29/2006 for 1 year after simulation recalibrated to period of 10/27/2005 – 5/19/2006

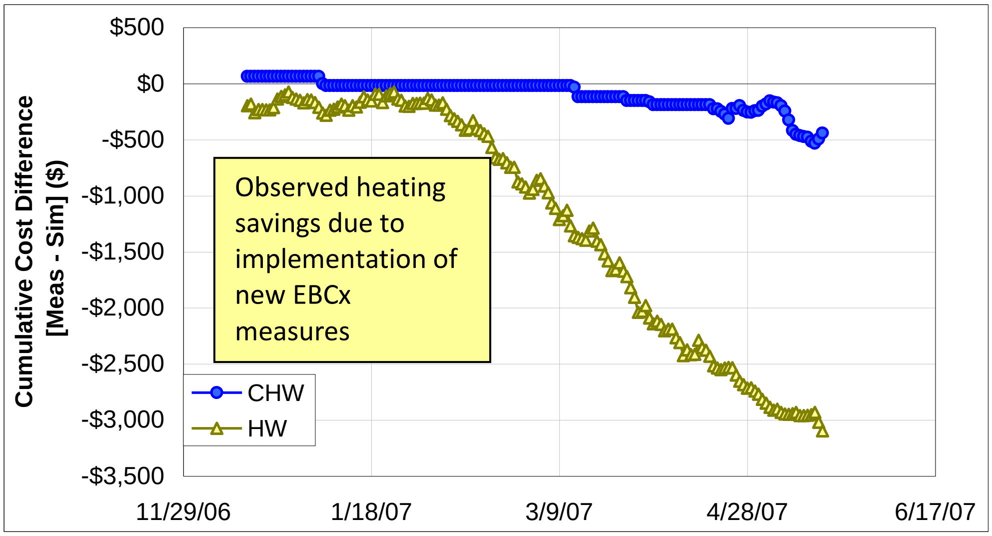


Figure 2.4 DASNY Cumulative Cost Difference ($15/MMBtu Heating, $10/MMBtu Cooling)

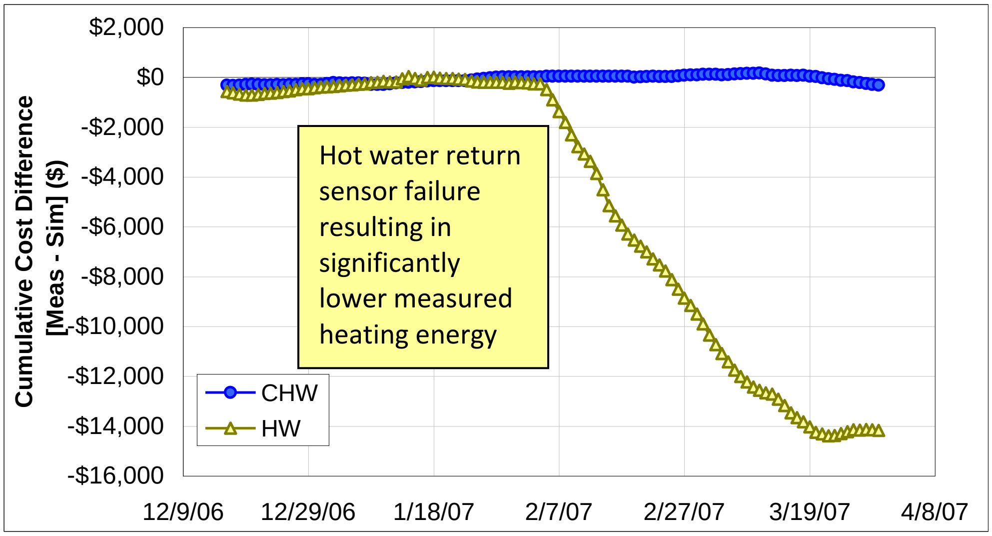


Figure 2.5 OPPD Energy Plaza Cumulative Cost Difference ($15/MMBtu Heating, $10/MMBtu Cooling)

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

- Whole building analysis can provide valuable diagnostic information
- Accumulated deviations from optimal performance provide a good indicator of significant faults that persist, and cost information
- The value of ABCAT does not appear to lay in daily short-term observations, but rather observations on the order of weeks to months.
- The advantage of using a first principles simulation model can be seen with occasional recalibration requirements due to changes in building operations

2.2 Retrospective Test Cases

In order to further test the capabilities of ABCAT, a multiple building retrospective test is performed. 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, and documentation of some control system set point changes during the period analyzed. It was expected that an analysis with ABCAT of a span of more than 15 building years, would provide some immediate feedback into the fault detection and diagnostic capability of the tool.

The “Cumulative Energy (or Cost) Difference” plot can visually detect a fault and show how the fault influences energy cost. Because visual fault detection depends heavily on personal subjective experience, the “Days Exceeding Threshold” plot was developed and added into ABCAT to detect faults analytically. It is drawn based on the simple standard that identifies a fault if the deviation between the measured and simulated consumption is greater than one standard deviation in the baseline period and persists for at least 30 days. The reason for choosing 30 days as the fault definition is that the typical utility meter reading interval is one month. Every point in the plot represents the number of days in the next 30 days (including the day on which the point is plotted) where consumption has been at least one standard deviation above or below expected consumption. For example, a point at 10/-10 means there are 10 days of the next 30 days when the measured consumption is more than one standard deviation above/below the simulated consumption. Thus a fault period appears as one or more points at ±30 on the plot. Compared with the "Cumulative Energy (or Cost) Difference" plot, the "Days Exceeding Threshold" plot permits relatively precise identification of the time that a fault starts or ends and provides more objective fault detection metrics. In the retrospective cases, the "Days Exceeding Threshold" plot is used as the chief fault detection criterion.

Eighteen faults were detected in 15 building-years of consumption data with the "Days Exceeding Threshold" plot. One of the eight detected CHW faults and six of the ten detected HW faults are verified by the historical information. The remaining fault diagnoses remain unconfirmed due to data quality issues and incomplete information on maintenance performed in the buildings. A summary of these test cases is provided in Table 2.2 followed by relevant figures referenced in the table.

Table 2.2 Test Buildings, Results and Findings from Retrospective ABCAT Implementation

Building Description	Test Period	Results and Findings
192,000 ft^2 university teaching building	Jan 1997 – Dec 2000	• Detected two excess heating energy faults (HW Faults #1 and #2 in Figure 2.6) which might be related to scaling problems on the HW meter. • Detected one decrease in measured cooling energy (CHW Fault in Figure 2.6) which might be caused by an increase in the cold deck temperature.
165,000 ft^2 university teaching building	Nov 1996 – Dec 2000	• Detected significant decreases in measured heating energy (HW Faults #1 - 4, and #6 in Figure 2.7) due to a HW meter problem. • Detected one excess heating energy fault (HW Fault # 5 in Figure 2.7) due to the problems the Kleberg Center experienced after April 1999 as documented in Chen et al (2002). • Detected five excess cooling energy faults (CHW Faults #1-5 in Figure 2.7). CHW Faults # 1-3 and #5 can't be diagnosed because of data quality issues. The reasons for CHW Fault #4 were the same as for HW Fault #5.

Building Description	Test Period	Results and Findings
180,000 ft^2 university teaching building	Mar 1997 – Dec 2000	• Detected a significant decrease in measured heating energy (HW Fault #1 in Figure 2.8) which may be related to a HW meter problem. • Detected one excess heating energy fault (HW Fault #2 in Figure 2.8) which may be related to an increase in minimum airflow ratio and hot deck temperature. • The "Cumulative Cost Difference" plot (Figure 2.9) shows the CHW consumption deviation over four years. The maximum CHW consumption deviation over four years is approximately 1% of the cumulative consumption. This indicates that the simulation is capable of accurately predicting consumption if there are no significant changes in the building.
115,000 ft^2 university teaching building	Jan 1998 – Dec 2000	• Neither a CHW fault nor a HW fault was detected in the "Days Exceeding Threshold" plot (Figure 2.10).
131,000 ft^2 university teaching building	Aug 1996 – Dec 2000	• Detected two excess cooling energy faults (CHW Faults # 1 and #2 in Figure 2.11) which can't be diagnosed because of data quality issues.

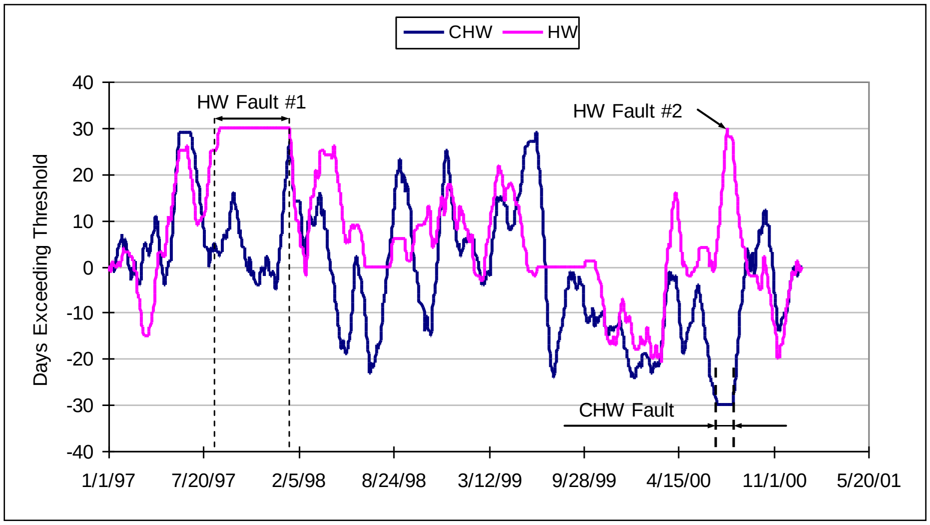


Figure 2.6 Days Exceeding Threshold in 30-Day Periods from 01/01/1997 to 12/31/2000 for the Wehner Building

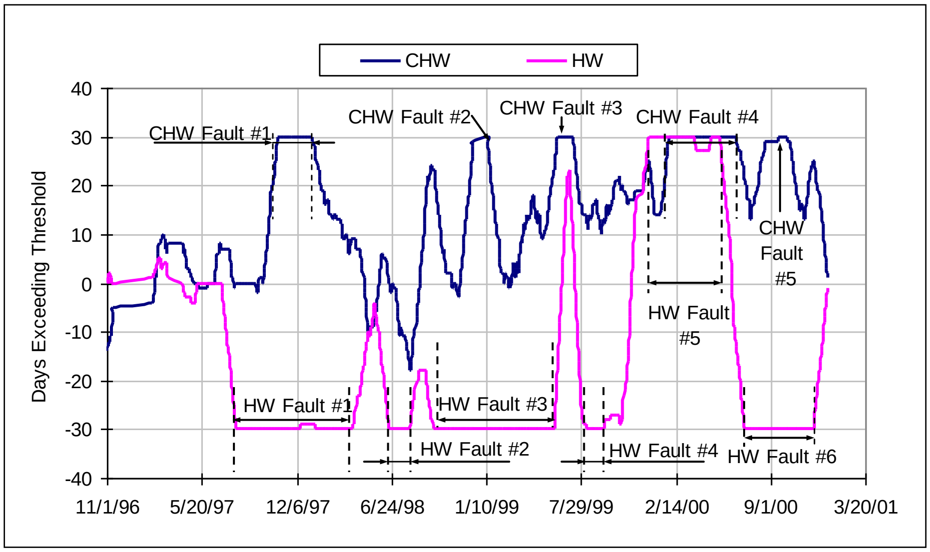


Figure 2.7 Days Exceeding Threshold in 30-Day Periods from 11/01/1996 to 12/31/2000 for the Kleberg Center

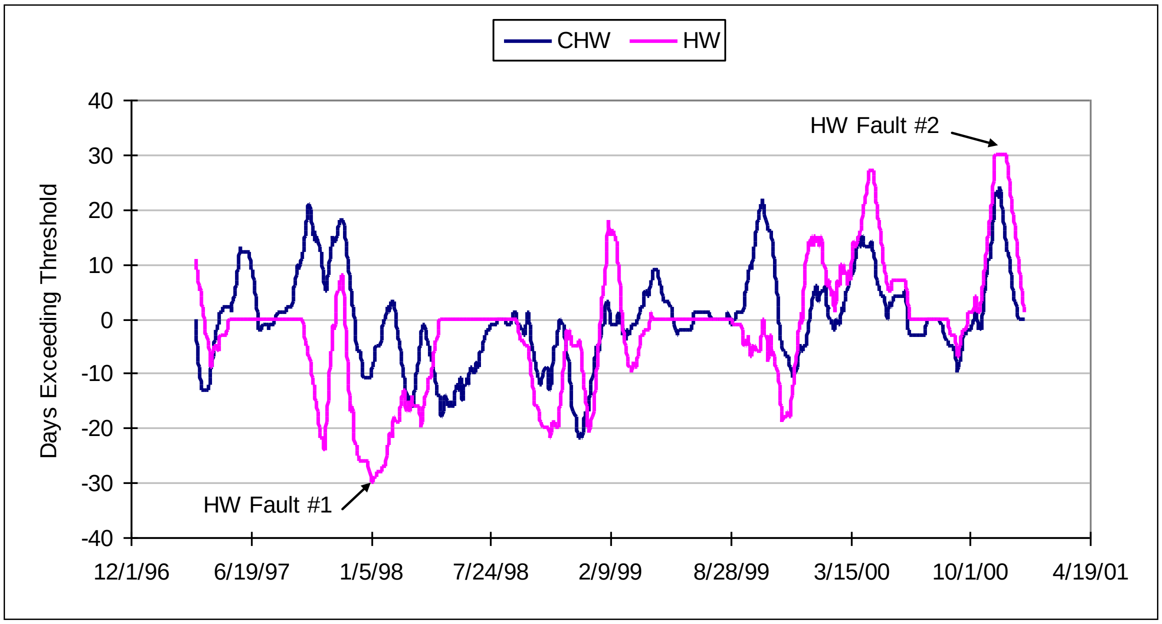


Figure 2.8 Days Exceeding Threshold in 30-Day Periods from 03/19/1997 to 12/31/2000 for the Eller O&M Building

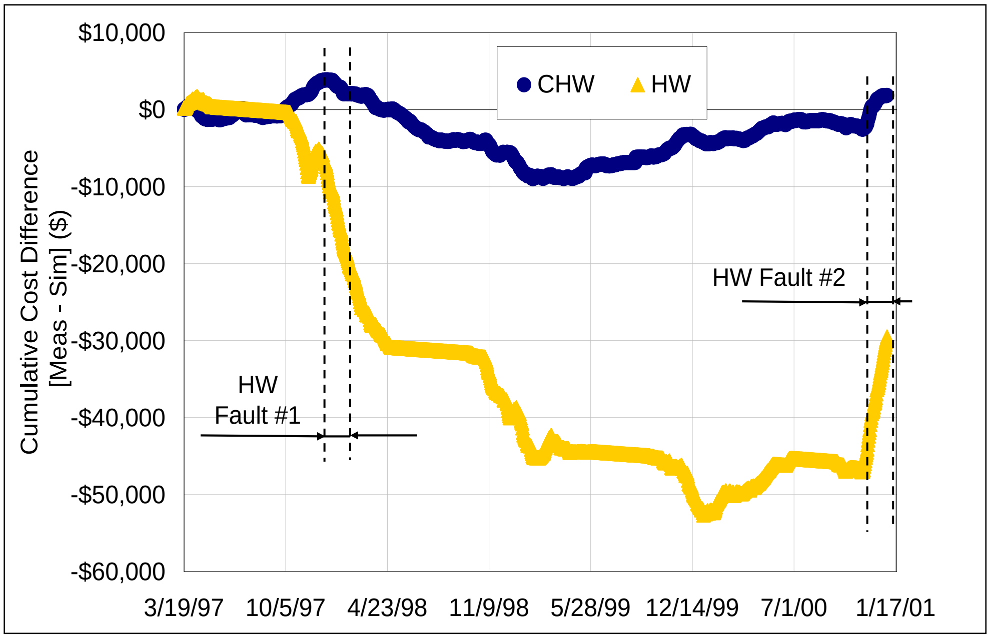


Figure 2.9 Cumulative Heating and Cooling Cost Differences for the Period of 03/19/1997 to 12/31/2000 for the Eller O&M Building (Assuming $10 and $15/MMBtu for CHW and HW respectively)

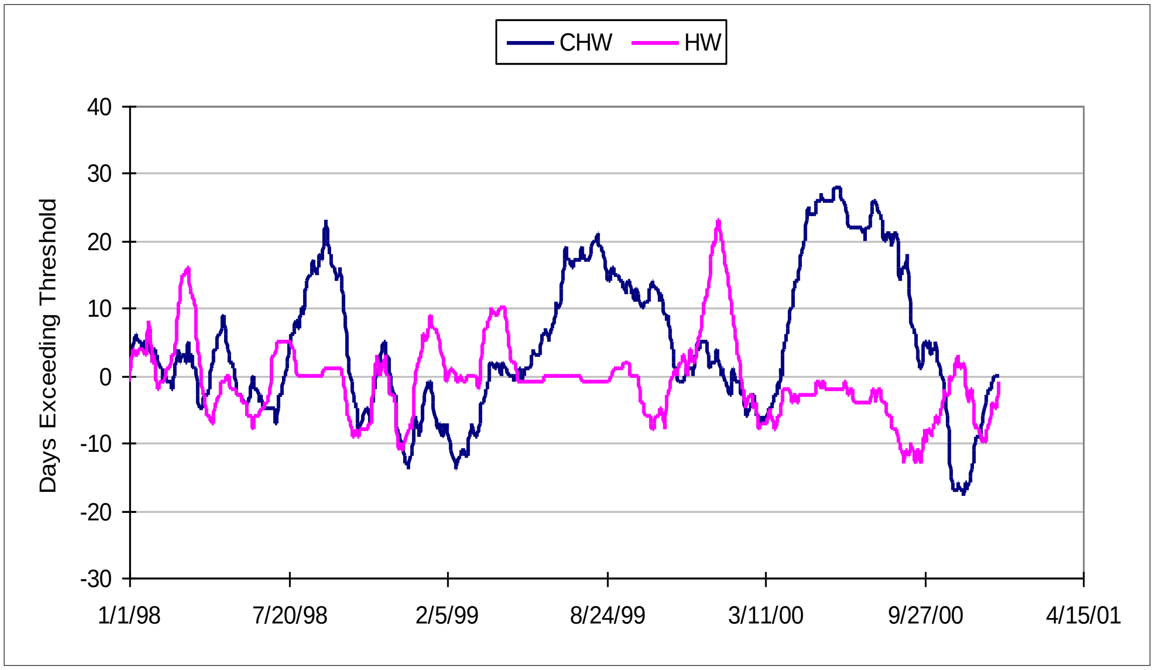


Figure 2.10 Days Exceeding Threshold in 30-Day Periods from 01/01/1998 to 12/31/2000 for the Veterinary Research Building

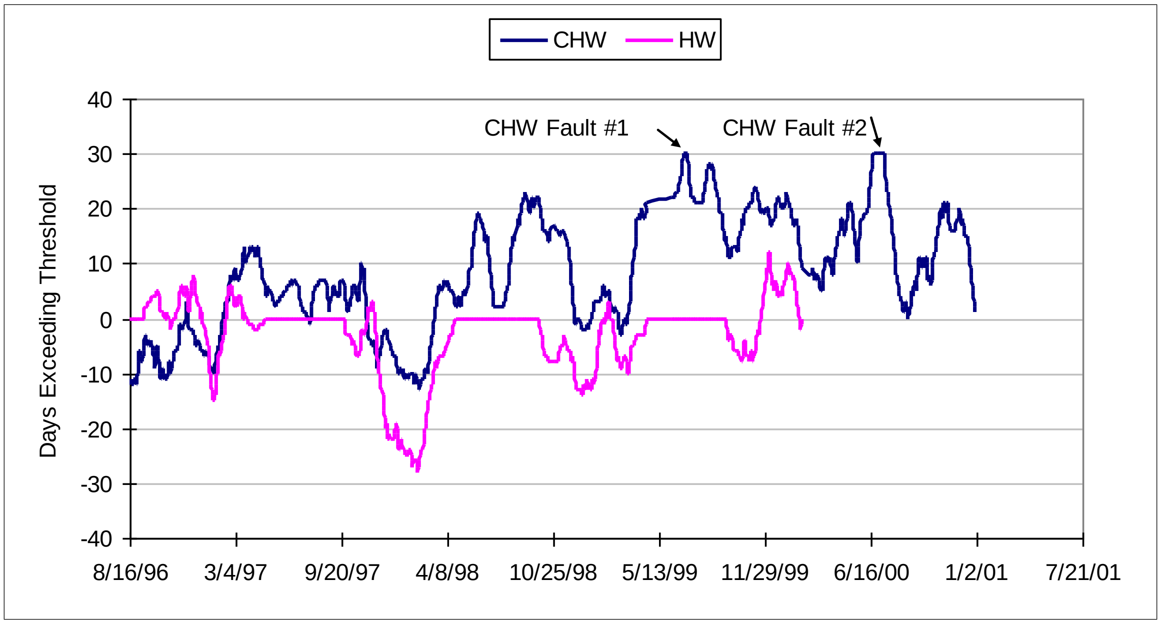


Figure 2.11 Days Exceeding Threshold in 30-Day Periods from 08/16/1996 to 12/31/2000 for Harrington Tower

The retrospective test cases provided an opportunity to test the simulation capabilities of ABCAT in five additional buildings of varying types and functions, and indicate ABCAT is a promising fault detection and diagnosis tool for post-commissioning use in buildings.

3. Recent Testing

3.1 Live Test Cases

The ABCAT tool was implemented in five live building situations in 2007-2009. Presented below are the building information, calibrated simulation results, and the findings of these test cases. Also included where applicable is the process by which the faults were determined to exist, and the investigative reasoning that led to the diagnosis in each case. Calibration signatures and characteristic signatures in the fault period are the primary tools used to diagnose faults in this section.

The calibration signature (Claridge et al. 2003) is a normalized plot of the difference between measured energy consumption values and the corresponding simulated values generated from the baseline calibrated simulation model as a function of outdoor air temperature. The calibration signature value for heating or cooling energy consumption is calculated as follows:

$$\textit{Calibration signature} = \frac{\textit{- Residual}}{\textit{Maximum measured energy}} \; x \; 100 \; \% \qquad (1)$$

where

$$\textit{Residual} = \textit{Simulated consumption with baseline model} - \textit{Measured consumption} \qquad (2)$$

In the fault period, some HVAC operation condition(s) must be different from the corresponding condition(s) in the baseline period. As a result, one or more of the simulation model input parameter values must be adjusted to reconcile the simulated consumption to the measured data.

The characteristic signatures can be calculated by simulating the building with an input parameter value in the baseline model, then changing that input parameter by a given amount and rerunning the simulation. The “residuals” between these two simulations are calculated, normalized, and plotted versus outdoor air temperature. The formula for calculating this characteristic calibration signature is as follows:

$$\text{Characteristic signature} = \frac{\text{Change in energy consumption}}{\text{Maximum energy consumption in baseline}} \times 100\ \% \qquad (3)$$

where the change in energy consumption is taken as the CHW or HW energy consumption value from the simulation with the changed input parameter minus the consumption from the simulation with the baseline value at the same temperature in the fault period. The denominator is the maximum CHW or HW consumption in the baseline period, respectively for a CHW or HW characteristic signature.

If we compare the characteristic signature with the calibration signature in the fault period, and the shapes match each other, then this is an indicator of which simulation input parameter must be changed in order to match the measured and simulated consumption in the fault period. Determining which input parameter must be adjusted provides a clue as to the cause of the fault in the building.

3.1.1 Bush Academic Building (College Station, TX)

3.1.1.1 Building Information

The Bush Academic Facility, pictured below in Figure 3.1, was constructed in 1997 and is located on the west campus of Texas A&M University in College Station, TX. It is home to the Political Science and Economics Departments, and consists primarily of offices and classrooms. The building has three floors for a total area of 133,326 ft^2. It is generally occupied on weekdays during the day, but also has some occupancy frequently at night and on weekends. Thermal energy is supplied to the building in the form of hot water and chilled water from the central utility plant. The HVAC system in the building is a dual duct VAV system. The commissioning work on this building was completed in May of 2007.

Department of Political Science, Texas A&M University

Figure 3.1 Bush Academic Building

3.1.1.2 Calibrated Simulation

Since the building controls apply different strategies during weekday and weekend periods, the measured data in the baseline period was sorted by weekday and weekend and calibrated in separate simulations. The ABCAT simulations were calibrated to the baseline consumption period of June 01, 2007-April 20, 2008, the results of which are presented in Figure 3.2 and Table 3.1.

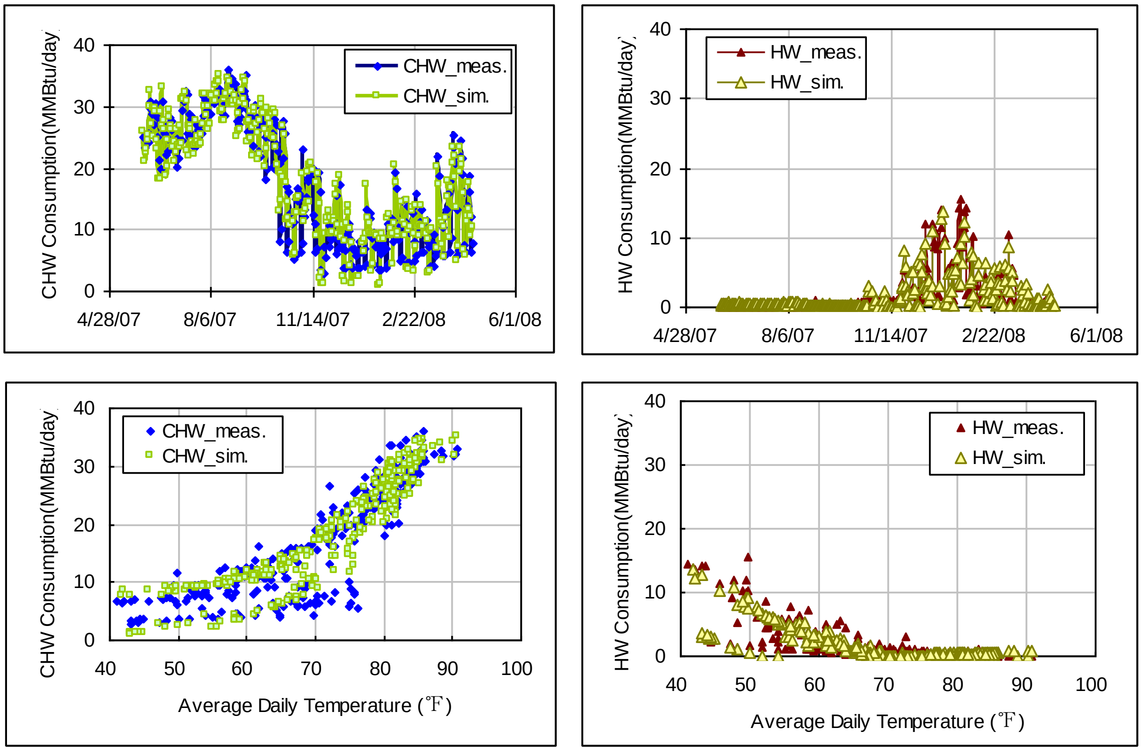


Figure 3.2 Measured and Simulated CHW and HW Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 06/01/2007 to 04/20/2008 for the Bush Academic Building

Table 3.1 Calibration Statistics for the Bush Academic Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	2.052	0.000	36.006	17.623	11.6%	MMBtu/day
HW:	0.978	0.000	15.502	1.758	55.8%	MMBtu/day

3.1.1.3 Discussion

Weekday - Bush Academic Chilled Water Energy Consumption Increase Fault Identified

Introduction

The weekday energy simulation model calibrated based on the measured CHW and HW consumption in the baseline period (weekdays in the period of June 01, 2007-April 20, 2008) was used to predict the subsequent CHW and HW consumption. During the weekday period of February 11, 2009 - July 30, 2009, an unexpected increase in CHW energy consumption was detected, at an additional cost to the campus of approximately $820/month (assuming $10/MMBtu for CHW). The fault was determined to be the result of a preheat valve leaking by on an outside air pre-treat unit in the building. Several figures from the ABCAT tool are presented below to explain how, through use of ABCAT, the conclusion was drawn that this fault existed. Also described is how the ABCAT tool, along with the addition of some adjuvant information, assisted the authors in narrowing down the likely cause(s) of the fault. Note that all of the plotted data are presented as daily averages of the weekdays.

Fault Detection

A significant increase in chilled water energy was detected with the Cumulative Energy Difference plot, Figure 3.3, in the weekday period of February 11, 2009 - July 30, 2009. The average daily CHW consumption increase during the period was 18.6% of the average daily baseline CHW and HW energy consumption (19.4MMBtu/day). Obviously, there was a chilled water consumption increase fault in this period.

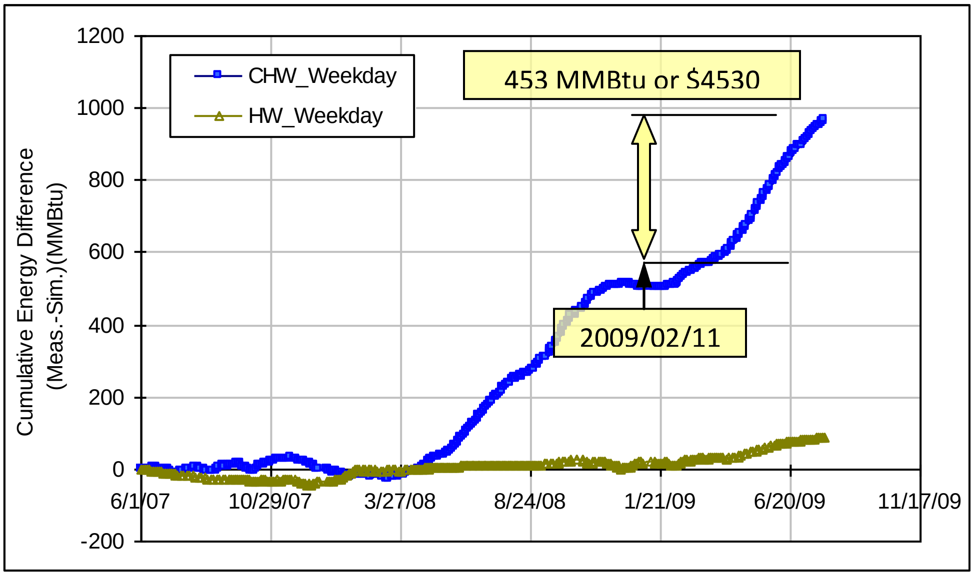
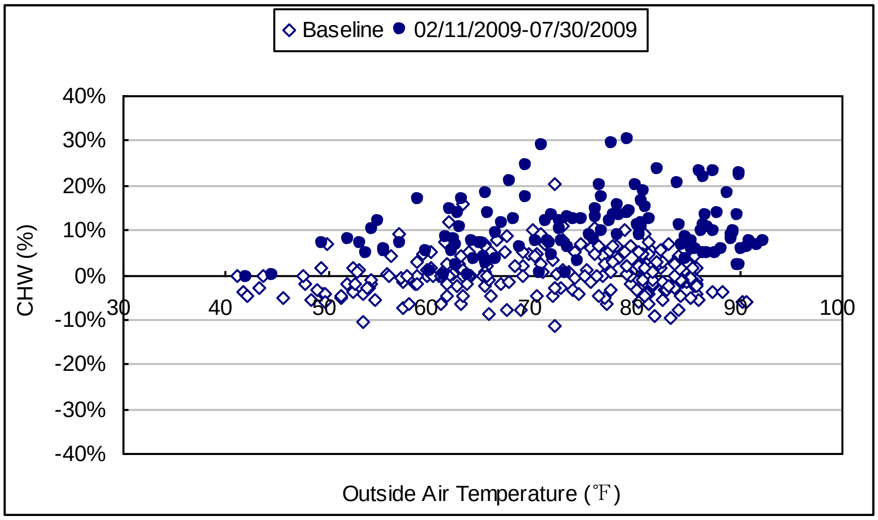


Figure 3.3 Cumulative CHW and HW Energy Differences for the Weekday Period of 06/01/2007 to 07/30/2009 for the Bush Academic Building

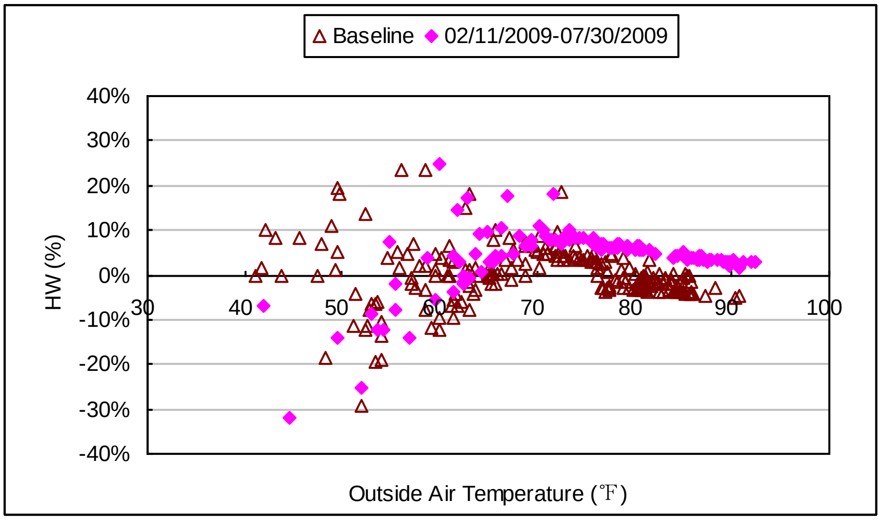
Fault Diagnosis

Figure 3.4 (a) indicates that the CHW calibration signature in the period of February 11, 2009 - July 30, 2009 is generally higher than the CHW calibration signature in the baseline period June 01, 2007-April 20, 2008 and the deviation over the high outside air temperature range is larger than the deviation over the low outside air temperature range. This suggests the measured CHW consumption is greater than the expected consumption in the fault period, and the discrepancy between measured and expected CHW consumption over the high outside air temperature range is larger than that over the low outside air temperature range.

Figure 3.4 (b) illustrates that the HW calibration signature in the period of February 11, 2009 - July 30, 2009 is greater than the HW calibration signature in the baseline period June 01, 2007-April 20, 2008 over the high outside air temperature range and basically coincides with the HW calibration signature in the baseline period over the low outside air temperature range. This means the measured HW consumption is greater than the expected consumption over the high outside air temperature range in the fault period, and stays in the normal fluctuating range over the low outside air temperature range.



(a) CHW Calibration Signature

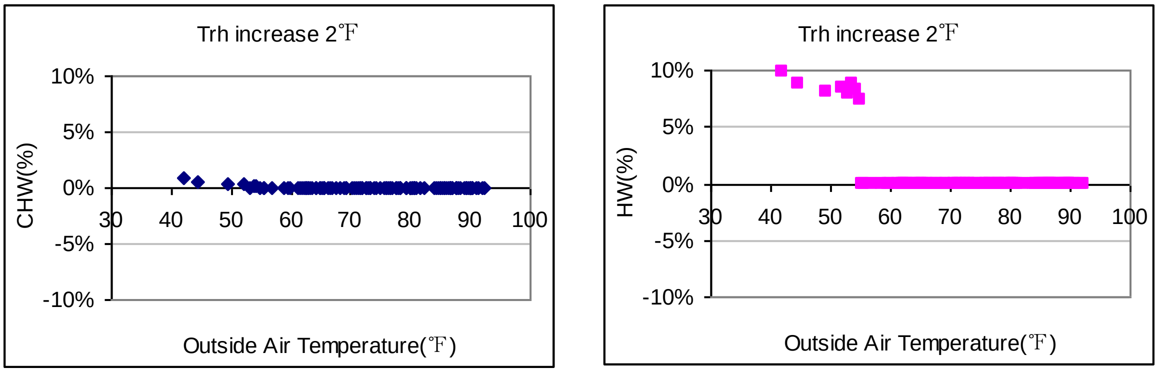


(b) HW Calibration Signature

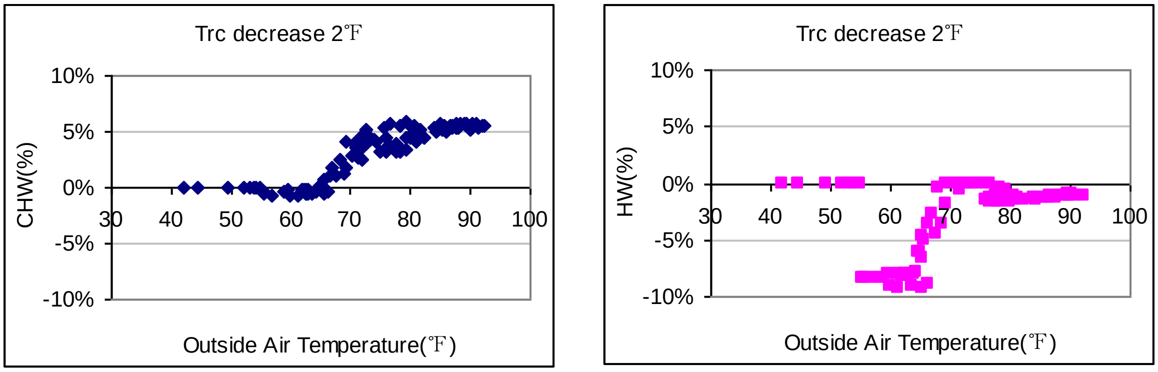
Figure 3.4 CHW and HW Calibration Signature Plotted as a Function of Outside Air Temperature for the Weekday Periods of 06/01/2007-04/20/2008(Baseline) and 02/11/2009 to 07/30/2009 (Fault period) for the Bush Academic Building

The characteristic signatures in the fault period were generated by running the simulation with the baseline simulation model input parameters, then altering key input parameters one by one and calculating the impact on CHW and HW energy consumption respectively. Figure 3.5 shows the change in CHW and HW energy use with the change of the key simulation input parameters with the magnitude of the change used to generate the characteristic signatures. Figure 3.5(h) and (j) indicate that either increasing air handing unit hot water valve leakage or increasing pre-treat unit hot water valve leakage would increase CHW and HW consumption over the high outside air temperature range with no change in HW consumption over the low outside air temperature range. These patterns are similar to the patterns shown in Figure 3.4 as described above – measured CHW and HW consumption are larger than the expected consumption over the high outside air temperature range and the differences between measured and simulated HW consumption are within the normal fluctuating range over the low outside air temperature range. Therefore, either more severe air handing unit hot water valve leakage or pre-treat unit hot water valve leakage appear to be the reason for the chilled water consumption increase fault in the weekday period of February 11, 2009 - July 30, 2009.

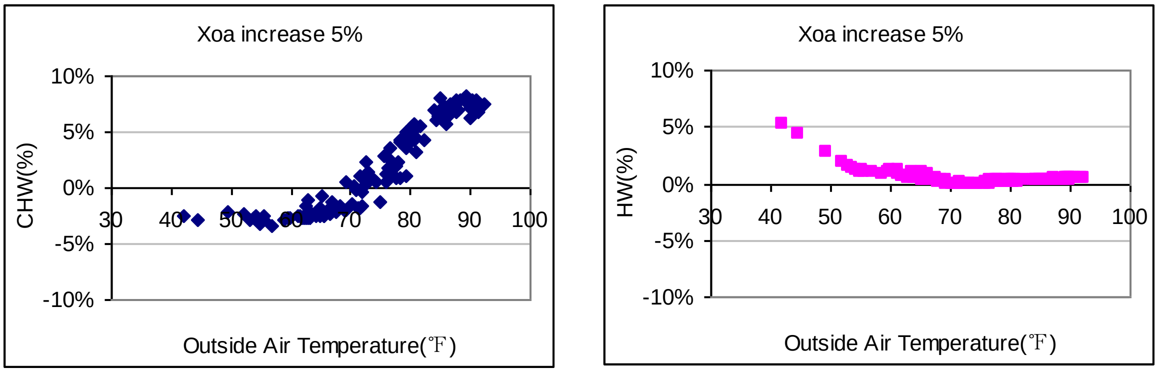
An inquiry was sent to the commissioning engineer asking if any air handing unit hot water valve leakage or pre-treat unit hot water valve leakage exists. The response was:
“We did notice a little bit of unnecessary HW flow, apparently due to a preheat valve leaking by on a pre-treat unit. …” This response effectively confirms the fault diagnosis result drawn above.



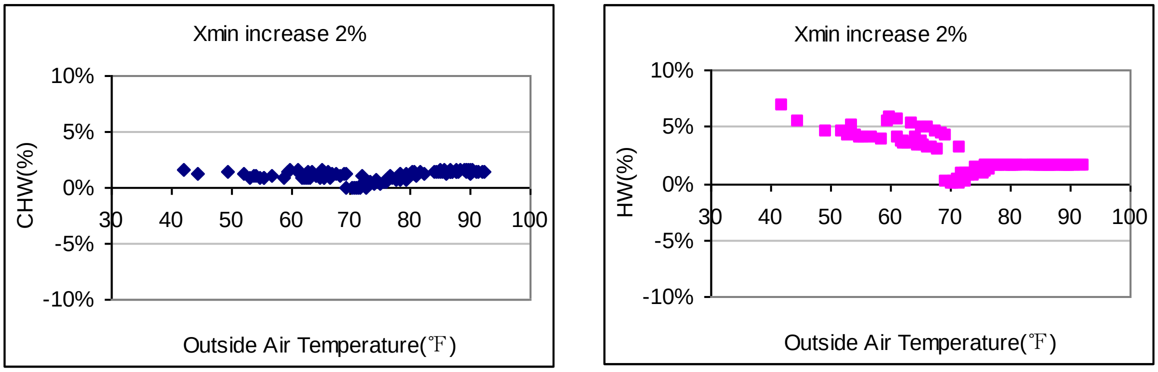
(a) Room Heating Temperature Setting Increase 2 °F



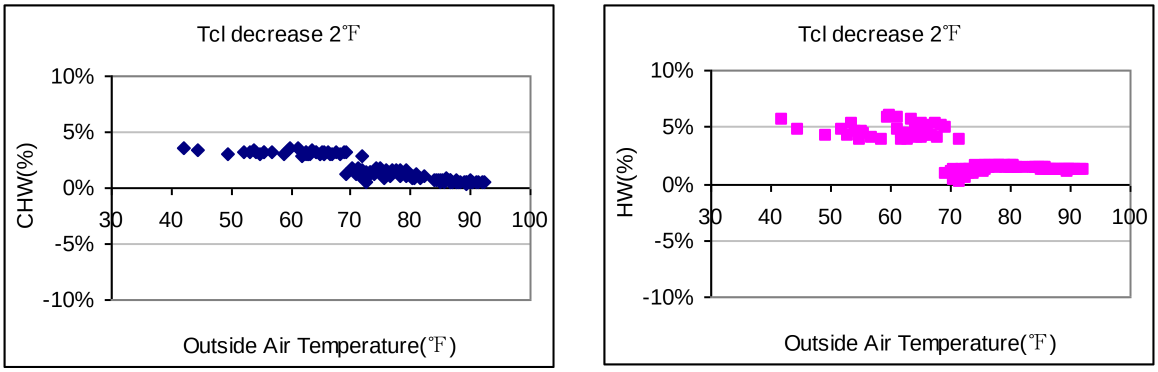
(b) Room Cooling Temperature Setting Decrease 2 °F



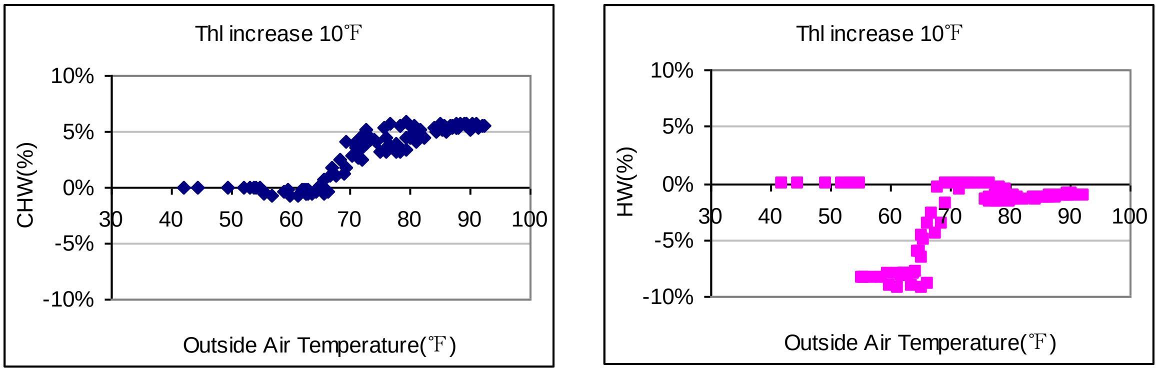
(c) Outside Airflow Ratio Increase 5%



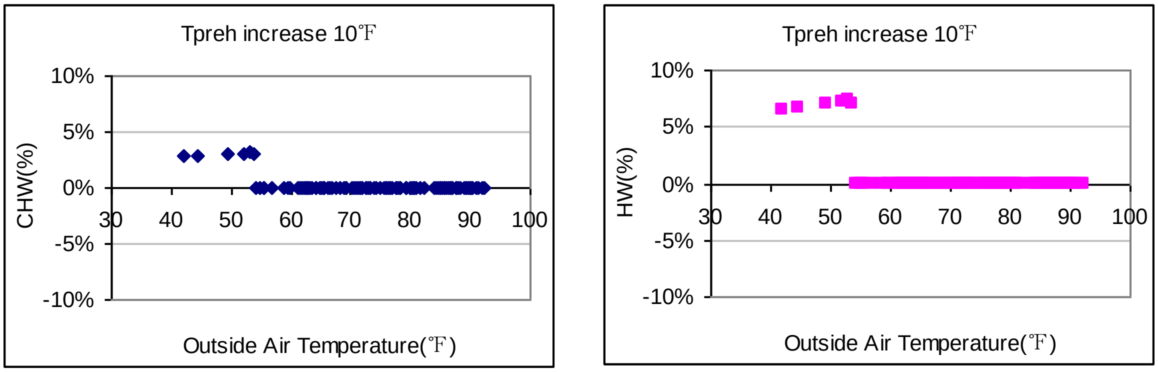
(d) Minimum Airflow Ratio Increase 2%



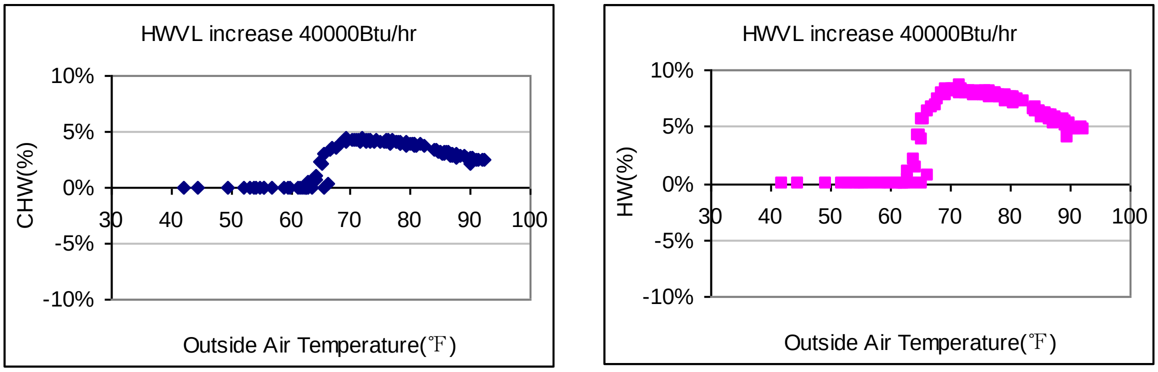
(e) Cold Deck Temperature Decrease 2ºF



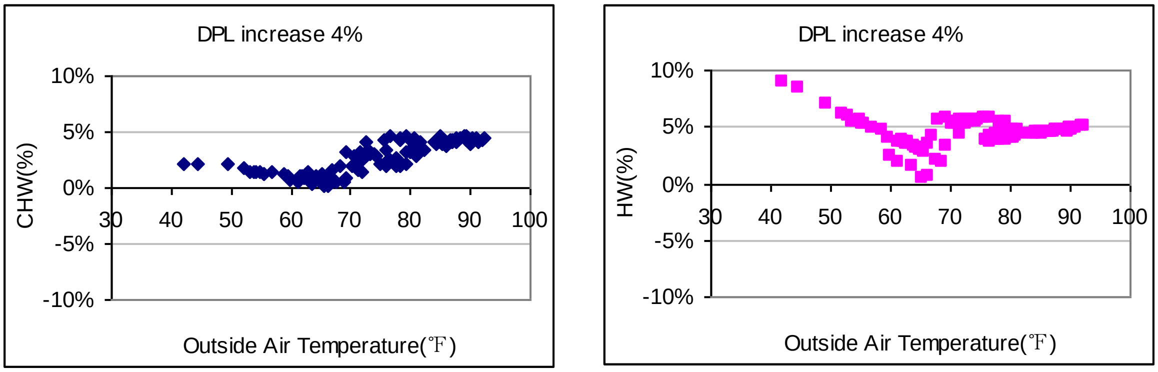
(f) Hot Deck Temperature Increase 10ºF



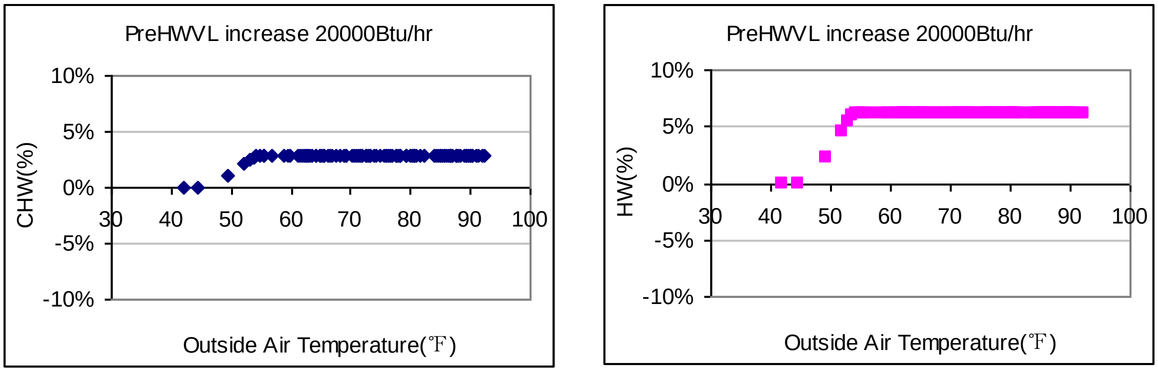
(g) Preheat Temperature Increase 10ºF



(h) Air Handing Unit Hot Water Valve Leakage Increase 40000Btu/hr



(i) Damper Leakage Increase 4%



(j) Pre-treat Unit Hot Water Valve Leakage Increase 20000Btu/hr

Figure 3.5 CHW and HW Characteristic Signatures Plotted as a Function of Outside Air Temperature for the Weekday Period of 02/11/2009 to 07/30/2009 for the Bush Academic Building

Weekend - Bush Academic Chilled Water Energy Decrease Consumption Fault Identified

Introduction

The weekend energy simulation model calibrated based on the measured CHW and HW consumption in the baseline period (weekends in the period of June 01, 2007-April 20, 2008) was used to predict the subsequent CHW and HW consumption. ABCAT detected two significant chilled water consumption decreases in the weekend periods of May 18, 2008 - October 05, 2008 and June 01, 2009 - July 30, 2009. The follow up investigation shows the situation was likely the result of a lower room cooling setpoint temperature or a lower outside airflow ratio. The following information and figures in this report will help explain how the fault was detected and how ABCAT, along with the addition of some adjuvant information, assisted the authors in narrowing down the likely cause(s) of the fault. Note that all of the plotted data are presented as daily averages of the weekends.

Fault Detection

Two significant decreases in chilled water energy use were detected with the Cumulative Energy Difference plot, Figure 3.6, in the weekend periods of May 18, 2008 - October 05, 2008 and June 01, 2009 - July 30, 2009. The average daily CHW consumption decreases during the two periods were -32.2% and -27.0% respectively of the average daily baseline CHW and HW energy consumption (19.4MMBtu/day). For a historical perspective, Figure 3.7 contrasts the CHW consumption in the weekend periods of May 18, 2008 - October 05, 2008 and June 01, 2009 - July 30, 2009 with that under similar conditions in the baseline period (June 01, 2007 - October 05, 2007). The consumption in those two periods is roughly one-third less. Apparently, chilled water energy decrease faults existed during these two weekend periods.

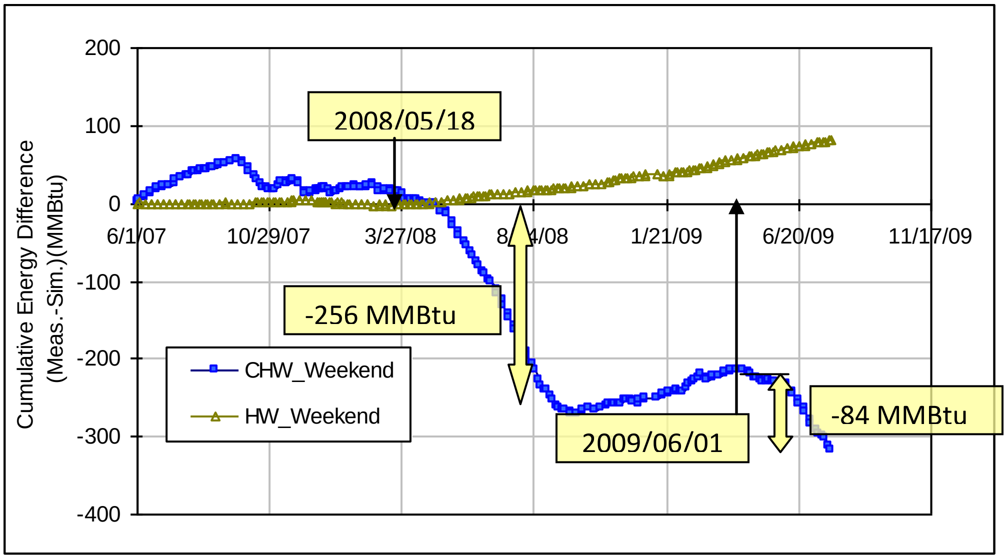


Figure 3.6 Cumulative CHW and HW Energy Differences for the Weekend Period of 06/01/2007 to 07/30/2009 for the Bush Academic Building

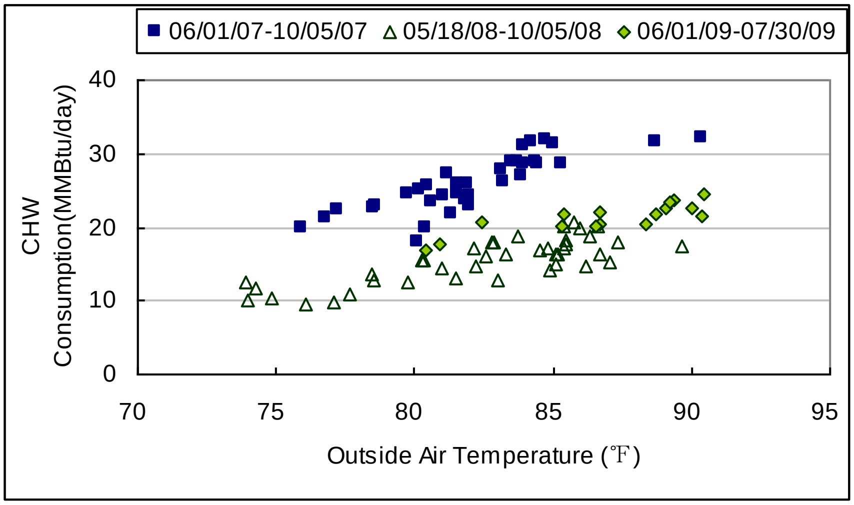
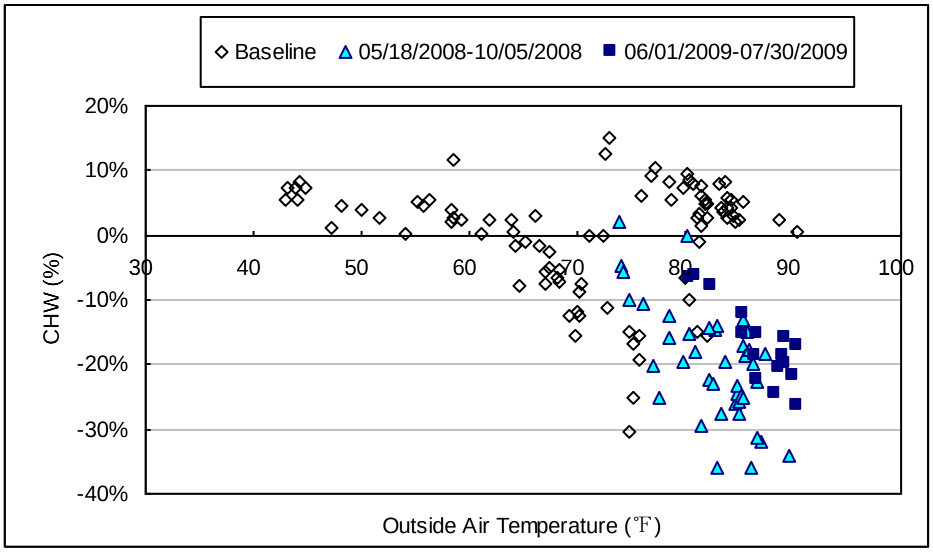


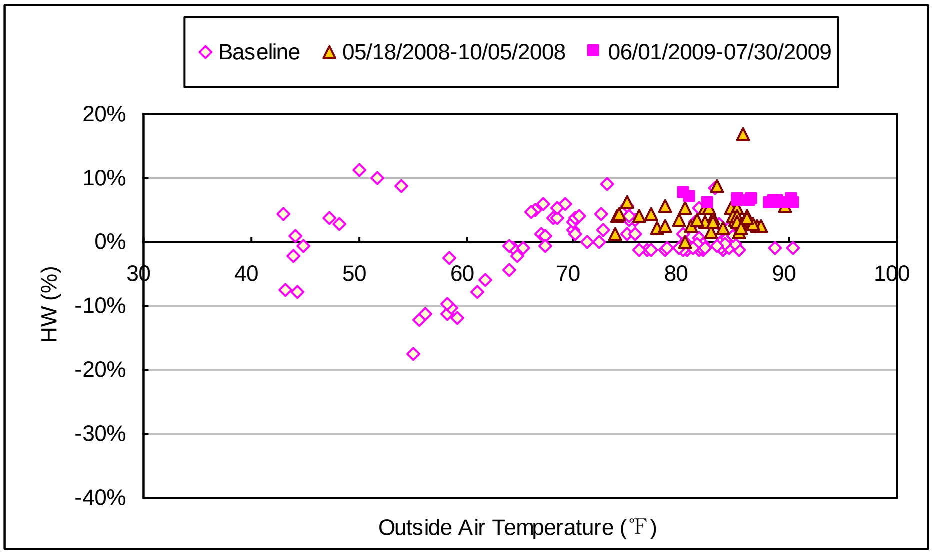
Figure 3.7 Measured CHW Consumption Plotted as a Function of Outside Air Temperature in the Weekend Periods of 06/01/2007 - 10/05/2007, 05/18/2008 - 10/05/2008 and 06/01/2009 - 07/30/2009

Fault Diagnosis

It is found that in Figure 3.8 the patterns of the CHW and HW calibration signatures in the two fault periods are very similar, which indicates the reason for decreased CHW consumption in the two periods might be the same. The CHW calibration signatures in the two fault periods are generally lower than those in the baseline period June 01, 2007 - April 20, 2008 over the similar outside air temperature range (70-90°F), and the deviation increases with the increase of outside air temperature. The HW calibration signatures in the two fault periods are roughly in agreement with those in the baseline period over the same outside air temperature range. That is to say, the measured CHW consumption in the two fault periods was less than the predicted consumption and the measured HW consumption remained roughly as expected.



(a) CHW Calibration Signature



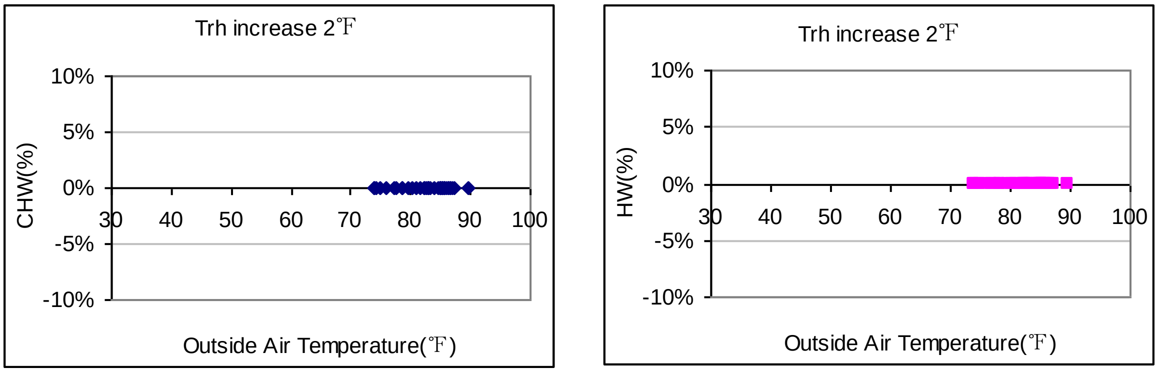
(b) HW Calibration Signature

Figure 3.8 CHW and HW Calibration Signatures Plotted as Functions of Outside Air Temperature for the Weekend Periods of 06/01/2007 to 04/20/2008 (Baseline), 05/18/2008 to 10/05/2008 and 06/01/2009 to 07/30/2009 for the Bush Academic Building

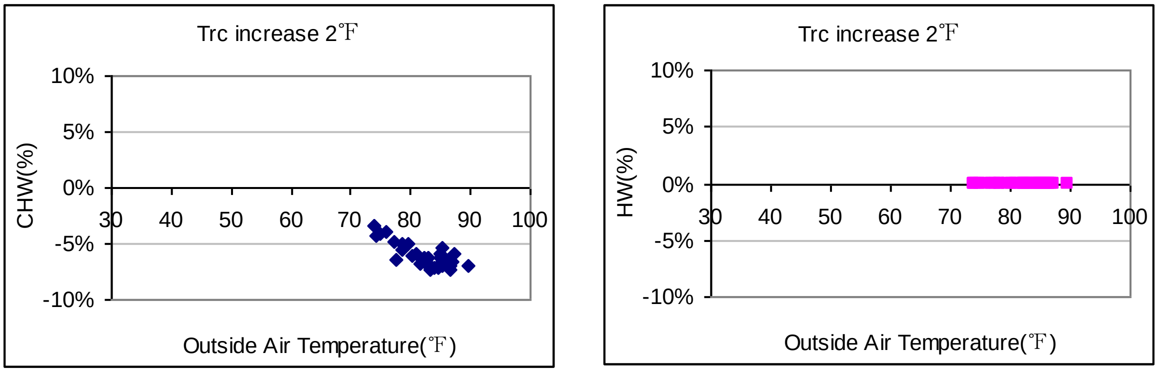
The characteristic signatures in the weekend period of May 18, 2008 - October 05, 2008 were generated by running the simulation with baseline simulation model input parameters, then altering key input parameters one by one and calculating the impact on CHW and HW energy consumption respectively. Figure 3.9 shows the characteristic signatures and the key simulation input parameters with the value changes used to generate the signatures. Only the patterns of Figure 3.9(b) and (c) are consistent with the calibration signature pattern in Figure 3.8 - the CHW consumption declines while the HW consumption remains constant. As a result, we can infer that either higher room cooling temperature setpoints or a decreased outside airflow ratio may be the cause of the chilled water decrease in the weekend period of May 18, 2008 - October 05, 2008.

Similar analysis was conducted for the weekend period of June 01, 2009 – July 30, 2009. The characteristic signatures are generated by using the same key simulation input parameters listed in Figure 3.9. They have the same shapes with the shapes shown in Figure 3.9. Therefore, the chilled water decrease in the weekend period of June 01, 2009 – July 30, 2009 may also be due to higher room cooling temperature setpoints or decreased outside airflow ratio.

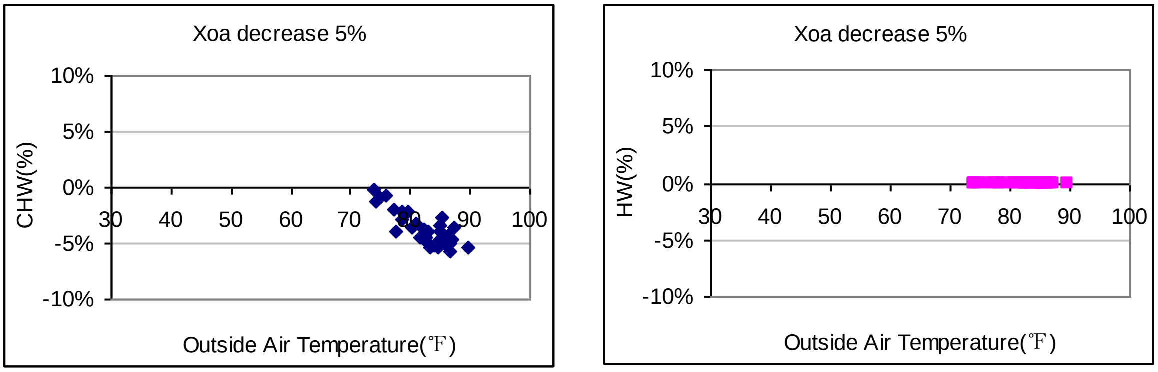
An inquiry was sent to the commissioning engineer asking for the current room cooling temperature setpoints and outside airflow ratio setting but no response was received.



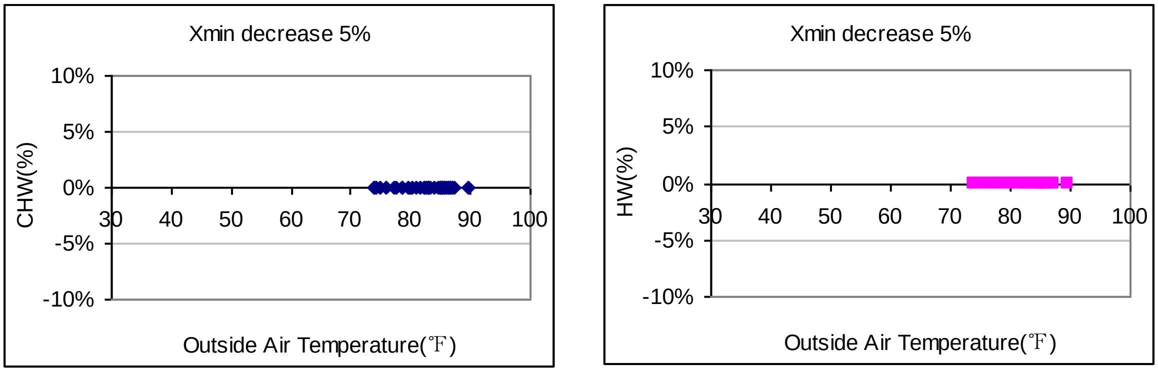
(a) Room Heating Temperature Setting Increase 2 °F



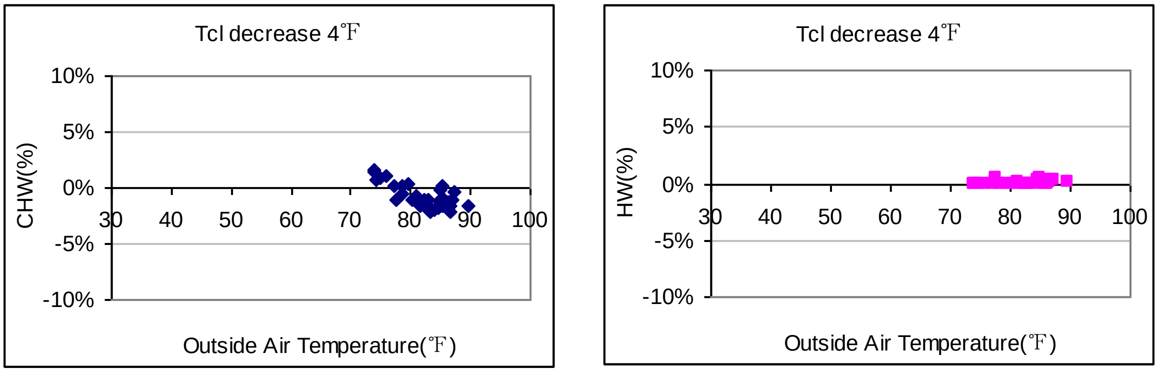
(b) Room Cooling Temperature Setting Increase 2 °F



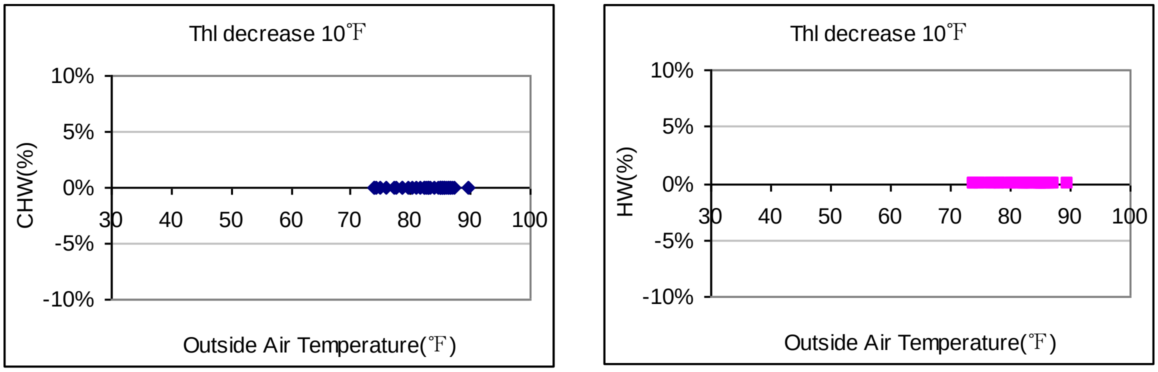
(c) Outside Airflow Ratio Decrease 5%



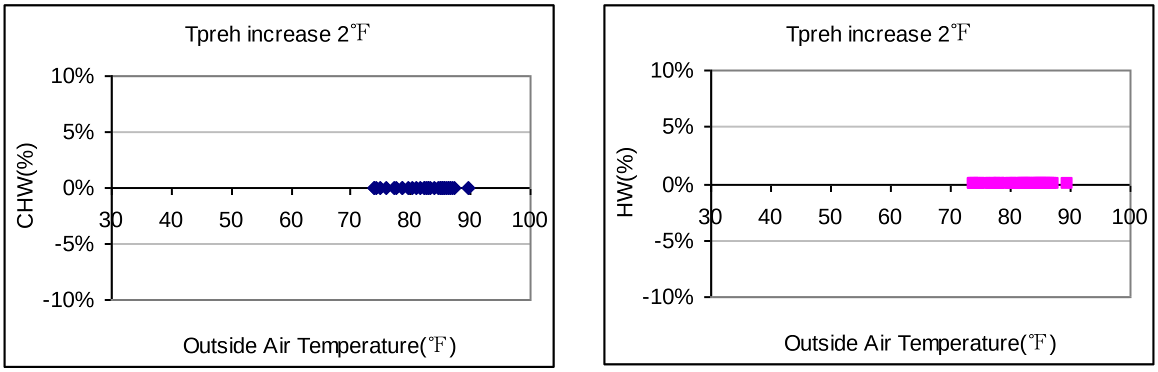
(d) Minimum Airflow Ratio Decrease 5%



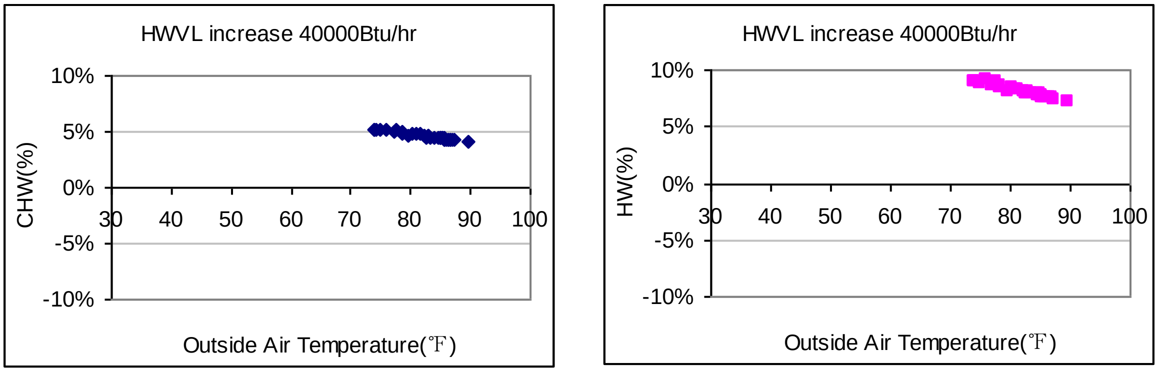
(e) Cold Deck Temperature Decrease 4ºF



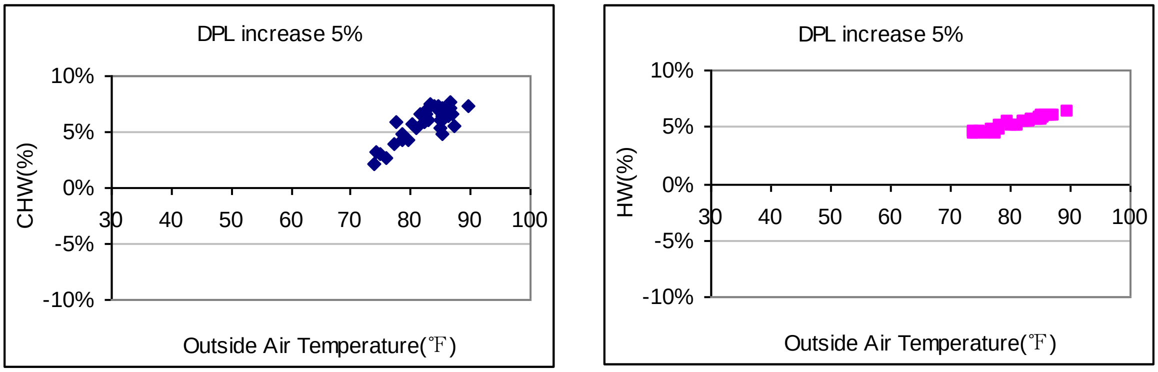
(f) Hot Deck Temperature Decrease 10ºF



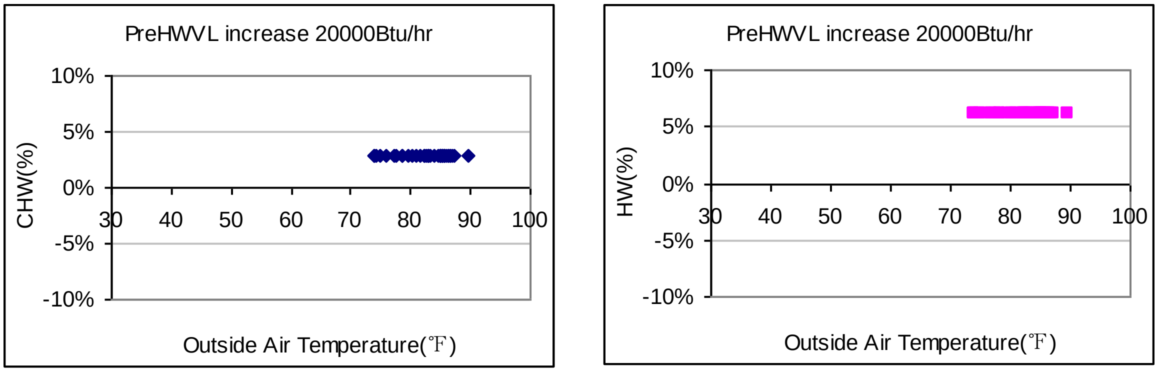
(g) Preheat Temperature Increase 2ºF



(h) Air Handing Unit Hot Water Valve Leakage Increase 40000Btu/hr



(i) Damper Leakage Increase 5%



(j) Pre-treat Unit Hot Water Valve Leakage Increase 20000Btu/hr

Figure 3.9 CHW and HW Characteristic Signatures Plotted as Functions of Outside Air Temperature for the Weekend Period of 05/18/2008 to 10/05/2008 for the Bush Academic Building

3.1.1.4 Conclusions

The monitoring of the Bush Academic Building with ABCAT resulted in the identification of a significant increase in chilled water energy consumption in the weekday period and two significant decreases in chilled water energy consumption in the weekend period. Through comparing the patterns of calibration signatures and various characteristic signatures in the fault periods, it is surmised that the CHW increase fault may be due to air handing unit hot water valve leakage or pre-treat unit hot water valve leakage, and the two CHW decrease faults may be caused by higher room cooling temperature setpoints or decreased outside airflow ratios. The commissioning engineer confirmed that there is a preheat valve leaking by on a pre-treat unit in the weekdays and did not respond about the room temperature setpoints and outside airflow ratio setting during the weekends.

3.1.2 Gibb Gilchrist Building (College Station, TX)

3.1.2.1 Building Information

The Gibb Gilchrist Building, pictured in Figure 3.10, was constructed in 1999 and is located on the west campus of Texas A&M University. It is one of the buildings used by the Texas Transportation Institute (TTI), and consists primarily of offices and conference rooms, with some transportation laboratories as well. The building has three floors for a total area of 67,143 square feet. It is generally occupied on weekdays from 8:00 AM to 5:00 PM, but also has some occupancy later in the evening and on weekends. Thermal energy is supplied to the building in the form of hot water and chilled water from the central utility plant. The HVAC system in the building is a single duct VAV system with terminal reheat. The commissioning work on this building was completed in October of 2007.

Figure 3.10 Gibb Gilchrist Building

3.1.2.2 Calibrated Simulation

Since the building controls apply different strategies during weekday and weekend periods, the measured data in the baseline period was sorted by weekday and weekend and calibrated in separate simulations. The ABCAT simulations were calibrated to the baseline consumption period of November 01, 2007- September 20, 2008, excluding February 23, 2008 – July 28, 2008 for both cooling and heating because of missing measured data. The results are presented in Figure 3.11 and Table 3.2.

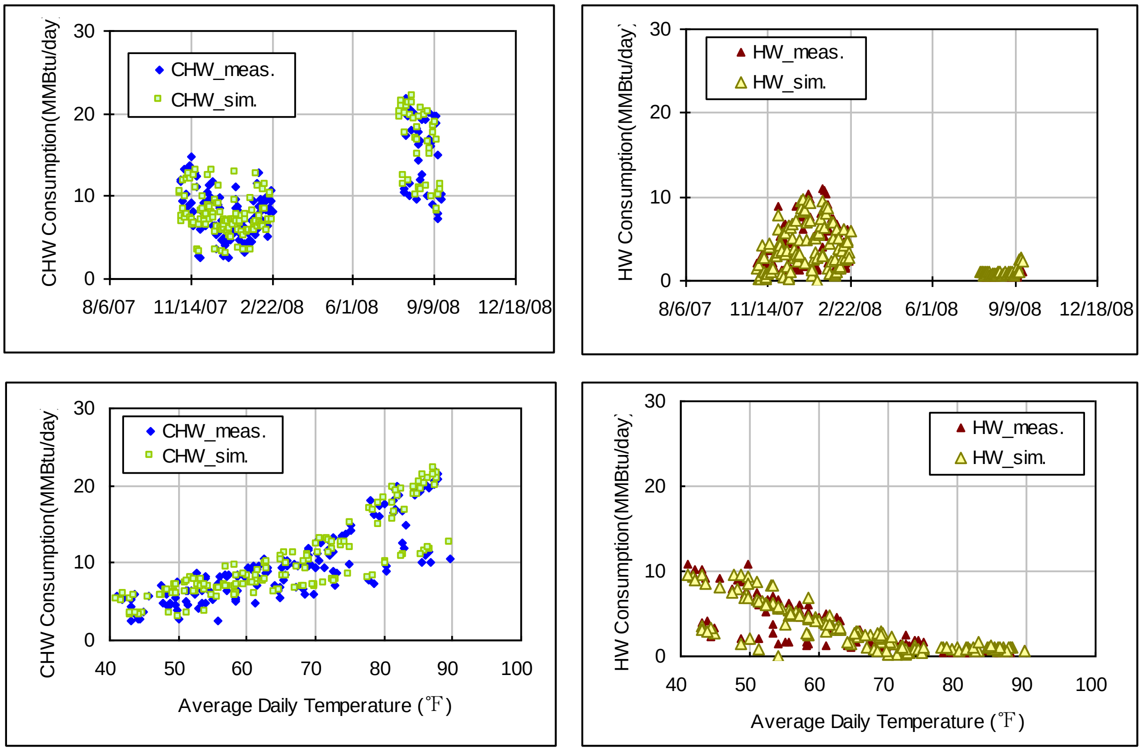


Figure 3.11 Measured and Simulated CHW and HW Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 11/01/2007 - 09/20/2008 for the Gibb Gilchrist Building

Table 3.2 Calibration Statistics for the Gibb Gilchrist Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	1.292	0.000	21.771	9.883	13.1%	MMBtu/day
HW:	0.888	0.000	10.917	3.157	28.2%	MMBtu/day

3.1.2.3 Discussion

Gibb Gilchrist Chilled Water Energy Increase Consumption Fault Identified

Introduction

Monitoring of the Gibb Gilchrist Building resulted in the identification of a huge increase in chilled water energy consumption in November, 2008. It was determined that the situation was the result of a chilled water flow meter abnormality. The following section will present the analysis of the building CHW and HW energy performance and describe the conditions that indicated a fault occurred during November 2008.

Fault Detection and Diagnosis

Figure 3.12 shows the cumulative energy difference between the measured and simulated consumption for the period of November 01, 2007- July 30, 2009. The dashed encircled area indicates the period of November 7, 2008 – November 28, 2008, where the cumulative CHW difference increases approximately 210 MMBtu/day on average. Figure 3.13 also indicates the measured CHW consumption was much higher than predicted throughout the entire range of operation. Investigation of the measured CHW flow and differential temperature data revealed that a chilled water flow meter abnormality was the culprit. Due to the fault's magnitude, it was quickly recognized, investigated and corrected by the utility provider, without any assistance from ABCAT. Although ABCAT did not play a role in this fault's identification or resolution, the fault was clearly identifiable in ABCAT as seen in Figure 3.12 and Figure 3.13.

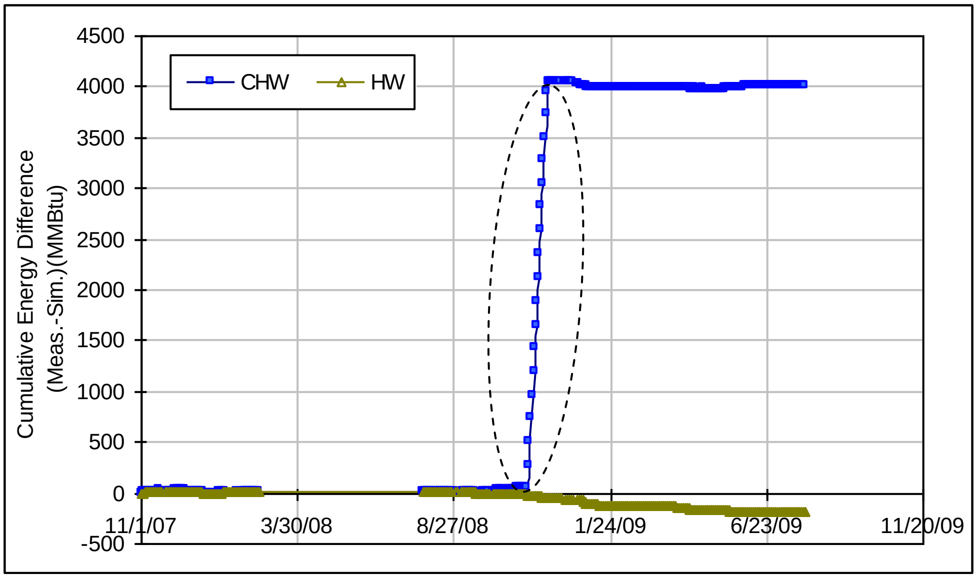


Figure 3.12 Cumulative CHW and HW Energy Differences for the Period of 11/01/2007 to 07/30/2009 for the Gibb Gilchrist Building

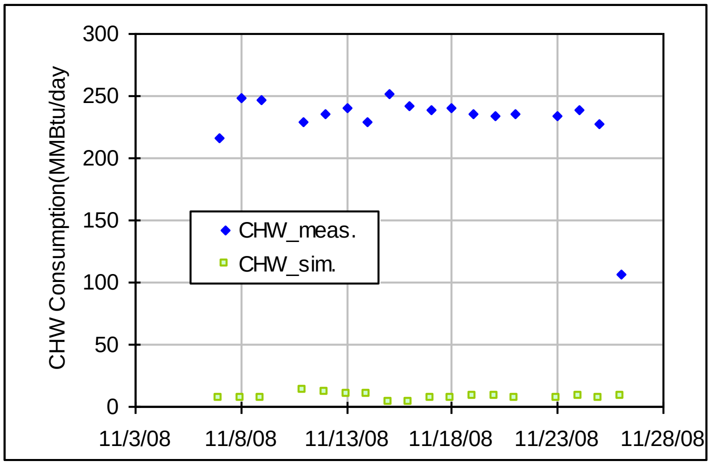


Figure 3.13 Measured and Simulated CHW Consumption Plotted as a Function of Time for the Period of 11/07/2008 - 11/28/2008 for the Gibb Gilchrist Building

3.1.2.4 Conclusions

The use of ABCAT detected a significant CHW energy consumption deviation from that expected in November, 2008 in the Gibb Gilchrist building. The follow up investigation indicates this huge CHW increase is the result of a CHW flow meter malfunction.

3.1.3 Coke Building (College Station, TX)

3.1.3.1 Building Information

The Coke Building, pictured in Figure 3.14, is located on the main campus of Texas A&M University. It is home to the College of Liberal Arts, and consists primarily of offices and conference rooms. The building has three floors for a total area of 24,446 square feet. It is generally occupied from 6:00 AM to 10:00 PM. Thermal energy is supplied to the building in the form of hot water and chilled water from the central utility plant. The HVAC systems in the building include three singe-duct VAV air handling units with electric reheat and one multi-zone air handling unit. The HVAC systems only operate during the occupied periods and are off during the remainder of time. The commissioning work on this building was completed in October of 2008.

Figure 3.14 Coke Building

3.1.3.2 Calibrated Simulation

Since the building controls apply different strategies during weekday and weekend periods, the measured data in the baseline period were sorted by weekday and weekend and calibrated in separate simulations. The ABCAT simulations were calibrated to the baseline consumption period of January 19, 2009- July 30, 2009. The results are presented in Figure 3.15 and Table 3.3.

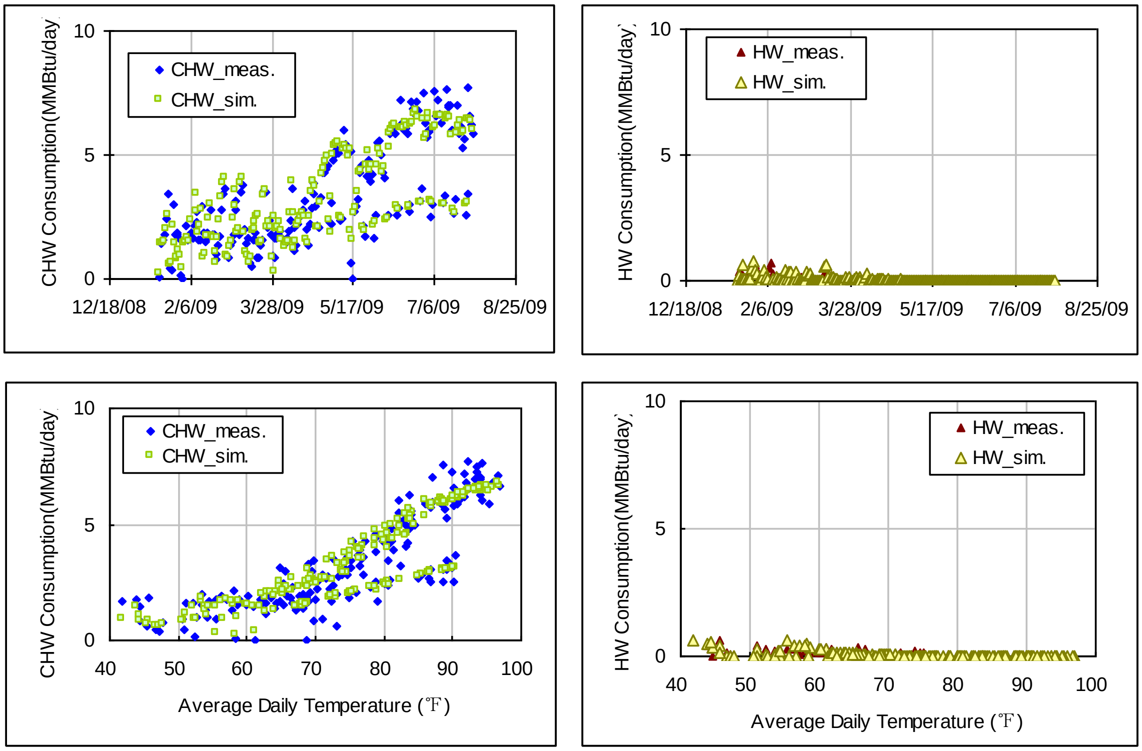


Figure 3.15 Measured and Simulated CHW and HW Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 11/01/2007 - 09/20/2008 for the Coke Building

Table 3.3 Calibration Statistics for the Coke Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	0.481	0.000	7.707	3.323	14.5%	MMBtu/day
HW:	0.077	0.000	0.728	0.063	121.8%	MMBtu/day

3.1.3.3 Discussion

Because the latest measured data available is from July 30, 2009, we could not complete the detailed fault detection and diagnostics analysis of the Coke building for this report as we did for the other two buildings. The building will continue to be monitored by ABCAT and further analysis will be undertaken in future.

3.1.3.4 Conclusion

Since the commissioning was completed at the end 2008, only the calibrated simulation model was completed for the Coke Building. The measured and simulated CHW and HW consumption match well in the calibrated baseline period. ABCAT will continue to monitor the energy performance of the building.

3.1.4 Vertigo Building (Eindhoven, The Netherlands)

3.1.4.1 Building Information

The Vertigo Building (Figure 3.16) is located on the campus of the Eindhoven University of Technology (TU/e) in Eindhoven, The Netherlands and is the home of the Department of

Architecture, Building and Planning. The 280,000 ft^2 (26,000 m^2) building has 12 floors with two floors below ground level, a three floor large footprint low rise section, and a seven floor smaller footprint high rise portion. The top four floors have a large central atrium with a glass roof and are primarily office space. The lower floors consist of classrooms, laboratories and some additional office space. The building was built in the 1960's and underwent a large retrofit in 2002. The controls were adjusted in 2006 to the current state of operation.

The HVAC system of the building consists of a heat pump and two natural gas boilers. The ventilation is provided by four constant volume air handling units located in the basement, each of which have a chilled water coil, a hot water coil, and a heat recovery wheel. In the top four floors, which share the atrium, additional ventilation is provided by an automated natural ventilation system using roof and façade shutters. Further space heating and cooling is provided by a combination of a four-pipe climate ceiling system in the office spaces, radiators along the exterior walls and ten fan coil units in select spaces with large internal heat gains.

Figure 3.16 Vertigo Building

3.1.4.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 01/01/2007 – 12/31/2007, the results of which are presented in Figure 3.17 and Table 3.4.

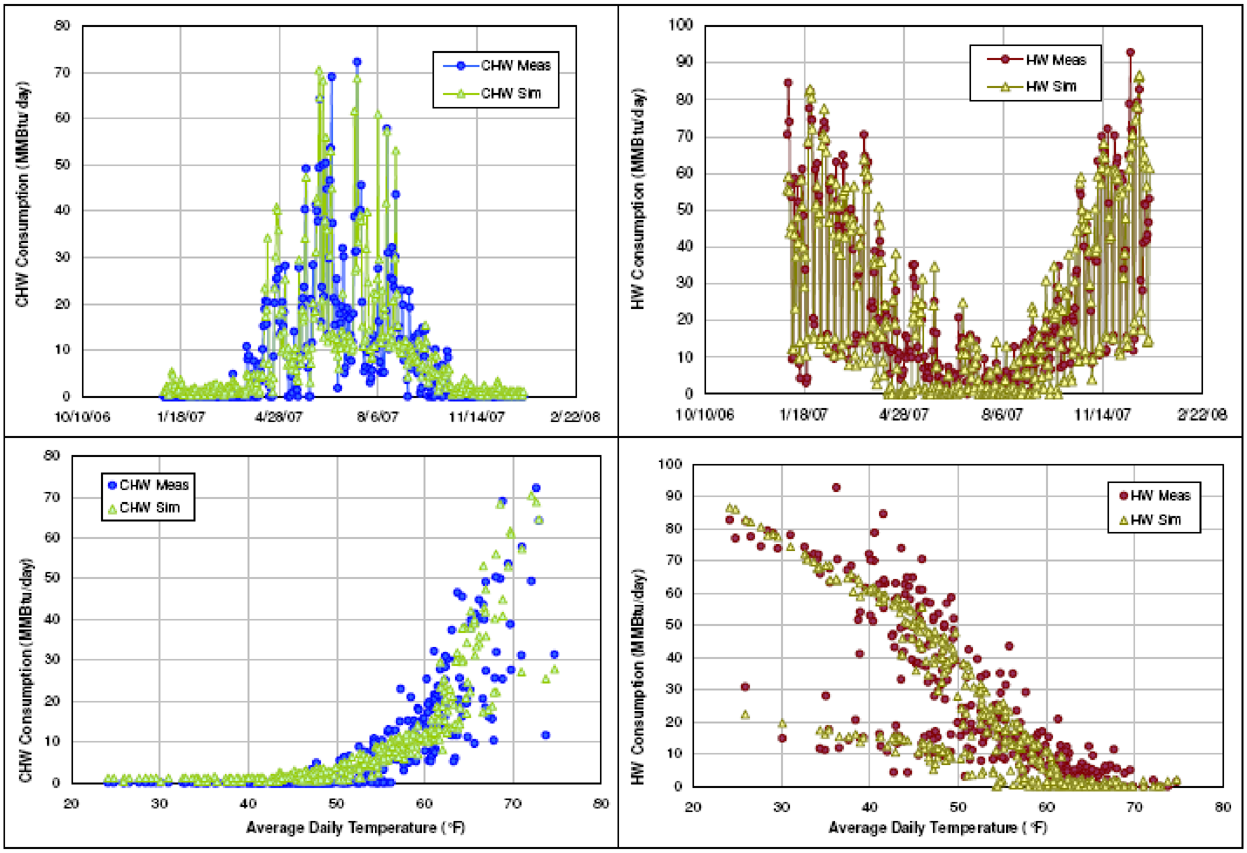


Figure 3.17 Measured and Simulated Cooling and Heating Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 01/01/2007 to 12/31/2007 for the Vertigo Building

Table 3.4 Calibration Statistics for the Vertigo Building

	RMSE	MBE	Max	Average	CV-RMSE	
CHW:	6.193	0.828	72.200	8.734	24.5%	MMBtu/day
HW:	7.602	-2.179	92.846	25.257	30.1%	MMBtu/day

3.1.4.3 Discussion

Measured data from 2008 and well over half of 2009 were used with ABCAT to diagnose any potential faults in the Vertigo building during that time period. A fault involving increased weekend heating consumption was noticed first on the weekend of 06/28/2008. The increase is more sustained and pronounced from 09/06/2008 through 09/23/2009 as detailed in the time series energy consumption graph shown in Figure 3.18. The heating consumption during the period from 06/28/2008 till 09/23/2009 is shown versus daily average ambient temperature in Figure 3.19. In the second figure, the difference in the trend of the weekend heating consumption over the fault period can be seen clearly.

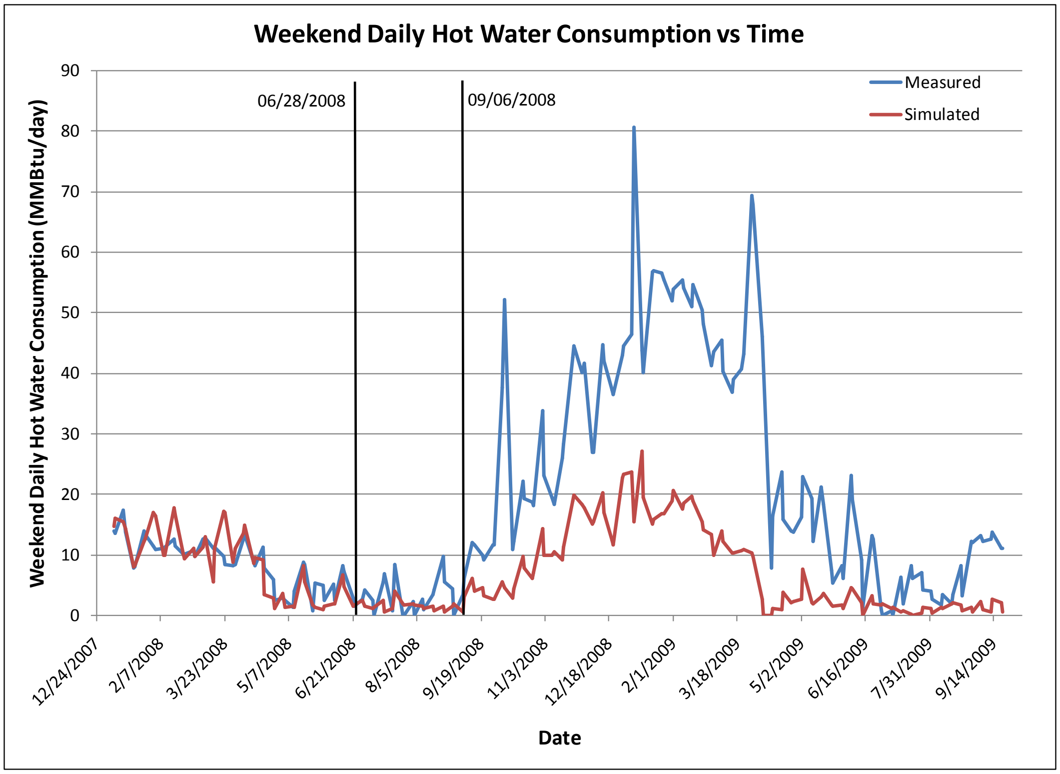


Figure 3.18 Weekend daily hot water consumption versus time from 01/01/2008 – 09/23/2009 with dates of increased consumption marked

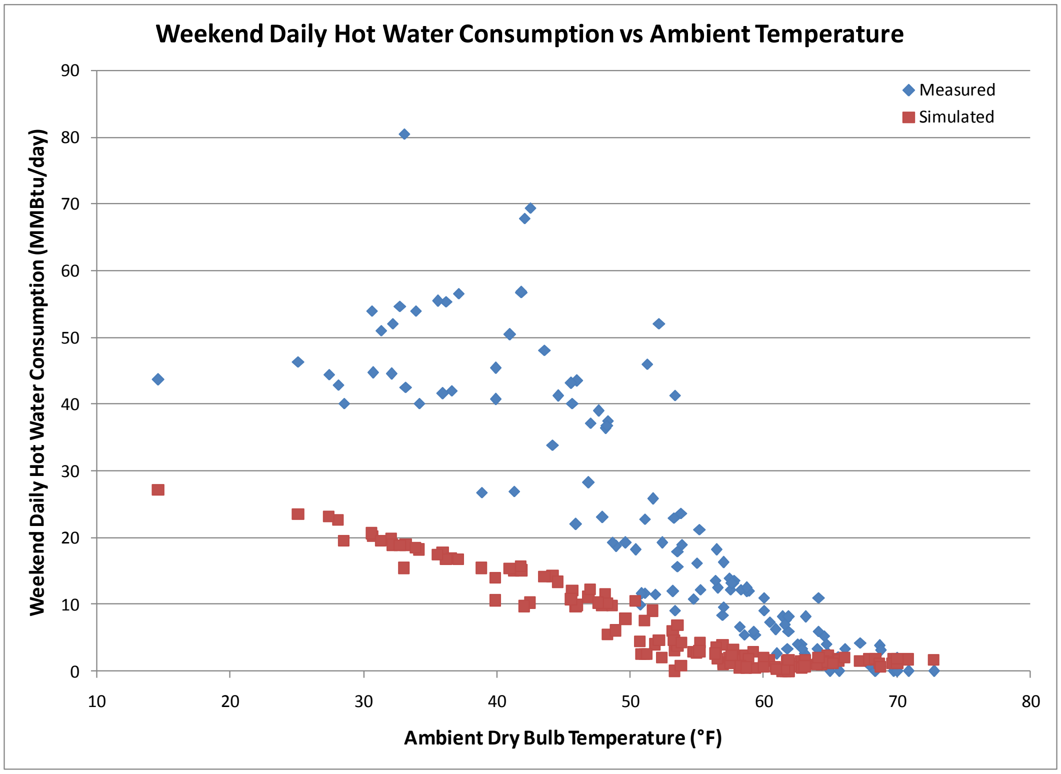


Figure 3.19 Weekend daily hot water consumption versus daily average ambient temperature from 06/28/2008 – 09/23/2009

After the potential fault was identified, the starting point for our diagnosis was to determine if any changes were made to the control sequence near this time. The building operator identified changes that were made to address comfort complaints from occupants at some point during 2008 or 2009 but was not certain of the exact date. The most common comfort issue was the space temperature on Monday mornings. The changes included raising the space temperature set point 1°C during occupied and unoccupied hours and implementing a varying start time algorithm for the radiators which is based on the heating needs during the previous days. The first change, believed to have been implemented in early 2009, would result in an increase in measured heating consumption across the board. A review of the 2009 ABCAT results does show that measured heating consumption was consistently greater than the simulated consumption during weekends and weekdays. The second change, believed to have been implemented in late 2008, was seeking to eliminate early morning comfort complaints by allowing the radiators to start early in order to have the space temperature at the desired level when occupants arrive. Given that there is no limit to when the early start time may occur, it is possible that this control change may account for the increased measured weekend heating consumption.

For further fault diagnosis, changes were made to the ABCAT simulation to see what input changes would produce similar changes in simulated consumption over the periods in question. The increased room temperature set point did increase simulated heating consumption at all temperatures but the increase was not large enough on weekends to account for the change in measured weekend consumption. Next, the outside airflow was increased by 15% but the resulting change in simulated consumption was not enough to account for the change in measured consumption either. Finally, the operating hours of the system were increased for weekends and weekdays and the resulting simulated consumption pattern is closer to the measured consumption pattern than the original calibrated simulation. This result was expected given the description of the control changes provided by the building operator discussed above.

3.1.4.4 Conclusions

The use of ABCAT detected one weekend heating consumption change that is believed to be the result of a control change which was made to address occupant comfort issues. The experience of using ABCAT on a building with system types, such as some in the Vertigo building, not currently included in the simulation options is encouraging. Despite this limitation, a heating consumption fault was still identified.

3.1.5 Neues Regionshaus Hannover Building (Hannover, Germany)

3.1.5.1 Building Information

The Neues Regionshaus Hannover, the New House of the Region of Hannover, (Figure 3.20) is located in Hannover, Germany and is an addition to the existing campus of the regional government. The 90,860 ft^2 (8,440 m^2) building has 6 floors which house offices for 300 employees and conference facilities. The building was completed in 2007 and is a part of the EnOB (Forschung fur Energieoptimiertes Bauen), or research for energy-optimized construction, research program sponsored by the German Federal Ministry of Economics and Technology (BMWi).

The building and its HVAC system were designed to meet very specific energy efficiency standards. Cooling is provided by an array of 12 borehole heat exchangers with an onsite chiller for backup use only. Heating is provided by a connection to the existing district heating system. Ventilation is provided for the conference rooms and restrooms by variable air volume air-handlers which have heat and moisture recovery capabilities. Operable windows allow for natural ventilation in the office spaces. The borehole heat exchangers are also used to preheat the outdoor air for the conference room in the winter. This practice reduces the heating load as well as increases the cooling potential of the borehole heat exchangers in the summer by further cooling the earth in the winter. The rooms are heated by radiators and are cooled using a concrete core activation system.

Figure 3.20 Neues Regionshaus Hannover Building

3.1.5.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of 12/03/2007 – 03/09/2008, the results of which are presented in Figure 3.21 and Table 3.5.

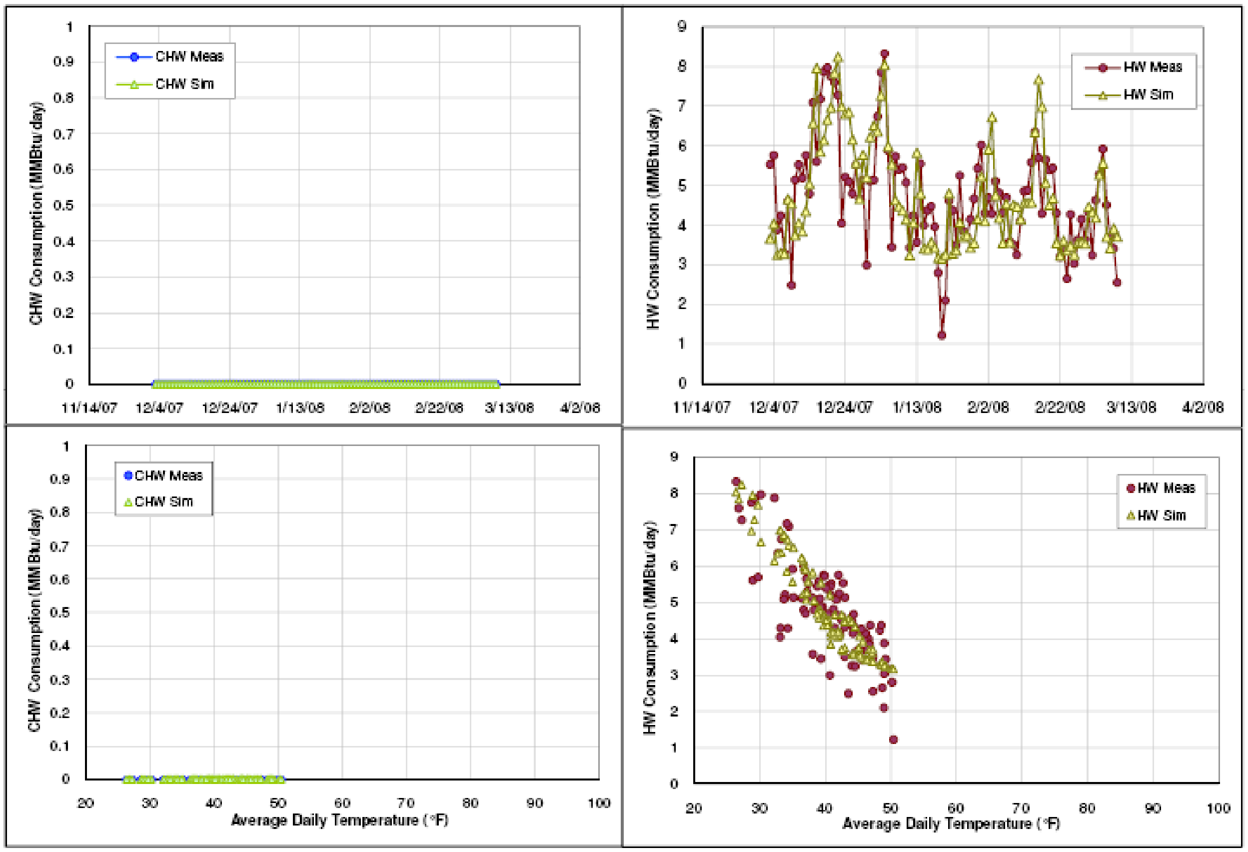


Figure 3.21 Measured and Simulated Cooling and Heating Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 12/03/2007 to 03/09/2008 for the Neues Regionshaus Hannover Building

Table 3.5 Calibration Statistics for the Neues Regionshaus Hannover Building

	RMSE	MBE	Max	Average	CV-RMSE	
CHW:	**0.000**	**0.000**	**0.000**	**0.000**	**0.0%**	**MMBtu/day**
HW:	**0.811**	**0.000**	**8.240**	**4.755**	**17.1%**	**MMBtu/day**

3.1.5.3 Discussion

One item of note is the lack of measured cooling in the data provided. Considering that the data available was from the winter season only, the lack of cooling in this building is not out of the question considering the climatic conditions. However, the lack of measured cooling in the period used for calibration and the inputs used to calibrate to the available data suggest that under different conditions, the simulated cooling will need further calibration.

The building was completed in March of 2007 and the period of data available began in December of 2007. This amount of data was only enough to calibrate the simulation within ABCAT. Unfortunately, efforts to continue the implementation of ABCAT at the Regionshaus building beyond the calibrated simulation were delayed. Additional consumption data will not be available until January 2010 after the writing of this report. As a result, no faults were identified at the Regionshaus building.

3.1.5.4 Conclusions

Even though ABCAT was not used beyond the initial stages at the Regionshaus building, the experience of setting up the simulation for the system was beneficial. The experience indicates that further development of ABCAT may be necessary for implementation of the tool in some high efficiency buildings utilizing system types, such as those found in the Regionshaus building, not currently included in the simulation options.

3.2 Retrospective Test Case

3.2.1 Koldus Building (College Station, TX)

3.2.1.1 Building Information

The Koldus Building, pictured in Figure 3.22**Error! Reference source not found.**, is located on the main campus of Texas A&M University. It is home to the Texas A&M Athletic Department, and consists primarily of offices. The building has two stories and a basement for a total area of 111,022 square feet. It is generally occupied weekdays from 8:00 AM to 5:00 PM. Thermal energy is supplied to the building in the form of hot water and chilled water from the central utility plant. The HVAC system in the building is a single-duct VAV system with economizer. The commissioning work on this building was completed in early 1997.

Figure 3.22 Koldus Building

3.2.1.2 Calibrated Simulation

The ABCAT simulation was calibrated to the baseline consumption period of April 16, 1997 – December 30, 1997 excluding July 01, 1997- August 31, 1997 for heating. It was found that the simulated CHW and HW consumption could not match the measured CHW and HW consumption simultaneously unless a constant value was added to either simulated CHW or HW consumption (13MMBtu/day for CHW or -11MMBtu/day for HW). The calibration results are presented in Figure 3.23 and Table 3.6. In the calibrated simulation model, the measured and simulated CHW energy use agree with each other and the measured HW energy use is on average 11MMBtu/day less than the predicted consumption. The reason for the failed calibration is explained in the next section.

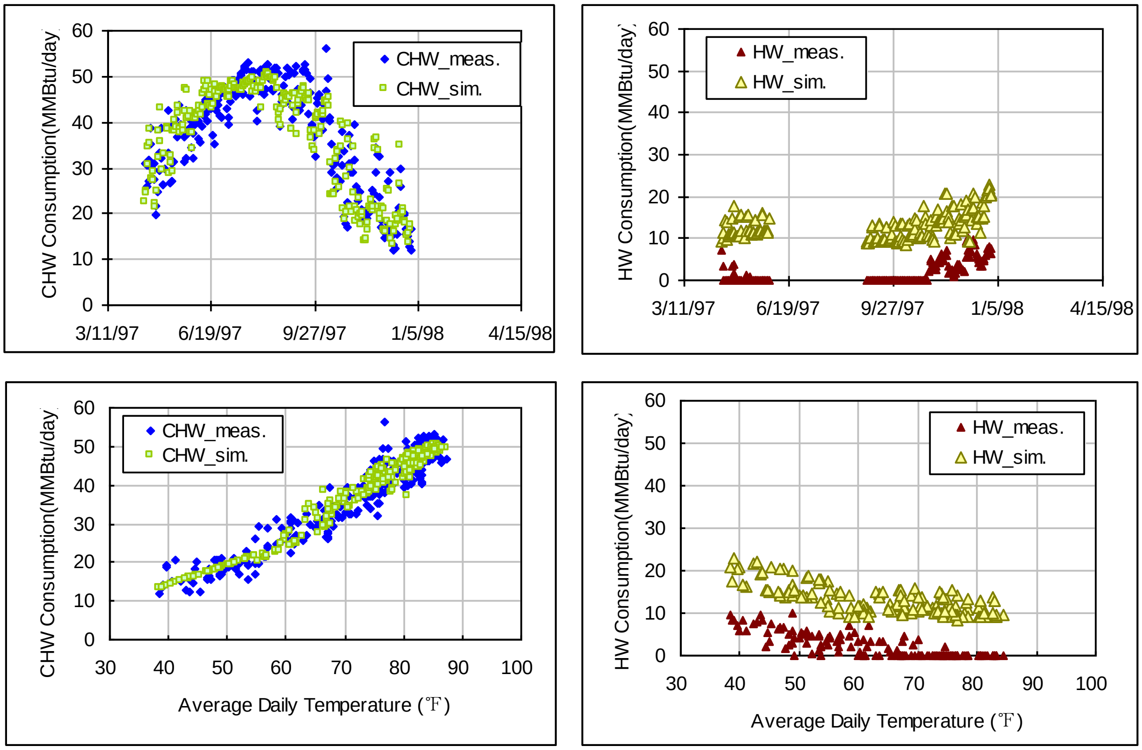


Figure 3.23 Measured and Simulated CHW and HW Consumption Plotted as Functions of Time and Outside Air Temperature for the Calibration Period of 04/16/1997 - 12/30/1997 for the Koldus Building

Table 3.6 Calibration Statistics for the Koldus Building

	RMSE	MBE	Max	Average	CV-RSME	
CHW:	3.526	0.000	56.127	36.511	9.7%	MMBtu/day
HW:	2.545	-11.022	9.972	1.966	129.5%	MMBtu/day

3.2.1.3 Discussion

Koldus Hot Water Meter Problem Identified

Introduction

The calibrated simulation model was used to predict the CHW and HW consumption in the periods of January 1, 1998 – December 30, 2001 and July 22, 2006-July 31, 2008. No simulation was run between the two periods because of the missing measured data. The following section will present the analysis of the building CHW and HW energy performance and explain the reasons why the calibration results are unsatisfactory.

Fault Detection and Diagnosis

Figure 3.24 shows that the cumulative HW energy difference keeps declining until the end of 2001 and is roughly flat after mid 2006.The cumulative CHW energy difference fluctuates around zero in the period of April, 1997 – December, 2001 and increases progressively after mid 2006. It is clear that some system operation change or meter change occurred sometime in 2002-2006. The following feedback was received from the commissioning engineer: “The Energy Office of Texas A&M University began replacing the old metering system on campus with a new metering system in 2005, and Koldus was one of the first groups of buildings. But it was not specifically done because they realized there was a HW meter problem. It was just part of a campus upgrade." Further investigation points out that the old metering system utilized paddle wheel meters, whose wheel is always made of plastic. A common problem with the plastic wheel is that it is very likely to melt when it encounters high temperature water. As a result, the meter may sometimes have no readings due to the melted wheel. The new flow meter is an electromagnetic meter, and is more accurate than the older paddle wheel meter. According to the investigation results, we believe that the old malfunctioning HW meter in Koldus is the main reason for the unsuccessful calibration in the baseline period.

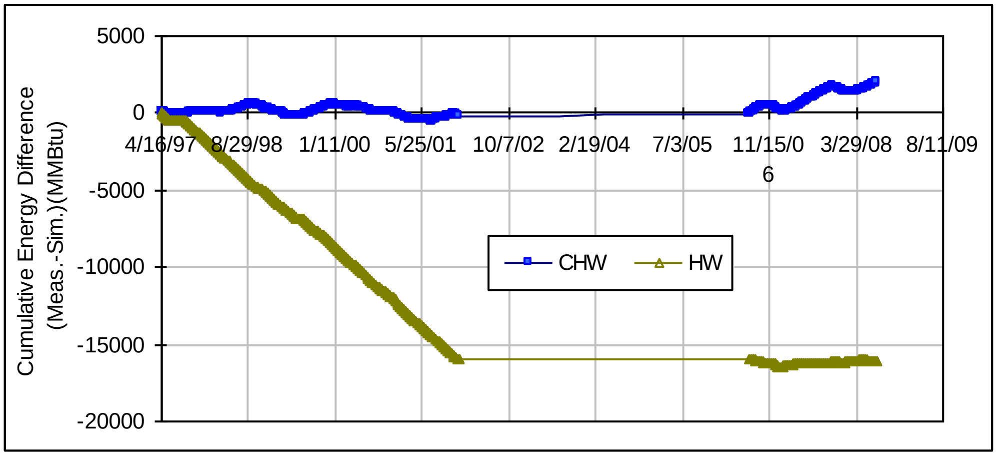


Figure 3.24 Cumulative CHW and HW Energy Differences for the Period of 04/16/1997 to 07/31/2008 for the Koldus Building

3.2.1.4 Conclusions

The calibrated simulation can't reconcile the simulated CHW and HW consumption with the measured data in the mean time. The supporting evidence in this report indicates that the failed calibrated simulation is linked to the HW meter problem during that time.

4. Summary

ABCAT has been implemented in 15 buildings with varying degrees of success. Where complete data, information, and time was available, ABCAT was able to diagnose a total of 23 faults in ten of the fifteen buildings. Of the 6 buildings detailed in this report, a total of 5 faults were identified in three of the six buildings. In the remaining buildings, a variety of reasons prevented complete application of the ABCAT tool including incomplete information and timing issues.

The implementation of both a fault detection method and a fault diagnostic method were shown to be successful when complete information is available. The detection method is fairly simple and clearly indicates when a fault has occurred in most cases. Currently the diagnostic method requires a fair amount of expertise and may be difficult for inexperienced users.

The application of ABCAT in the two European buildings demonstrated the robustness and the weaknesses of the tool in its current form. The experience indicates that under some circumstances, ABCAT can adequately simulate system types other the specific types currently included in the tool and in some circumstances the tool may require further development for successful implementation.

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