CONSULTANT REPORT

PIER
Public Interest Energy Research
CALIFORNIA ENERGY COMMISSION

Buildings End-Use
Energy Efficiency

METHOD FOR DETERMINING MEASUREMENT ACCURACY AND DATA STORAGE FREQUENCY FOR IMPROVED BUILDING ENERGY EFFICIENCY

Gray Davis, *Governor*

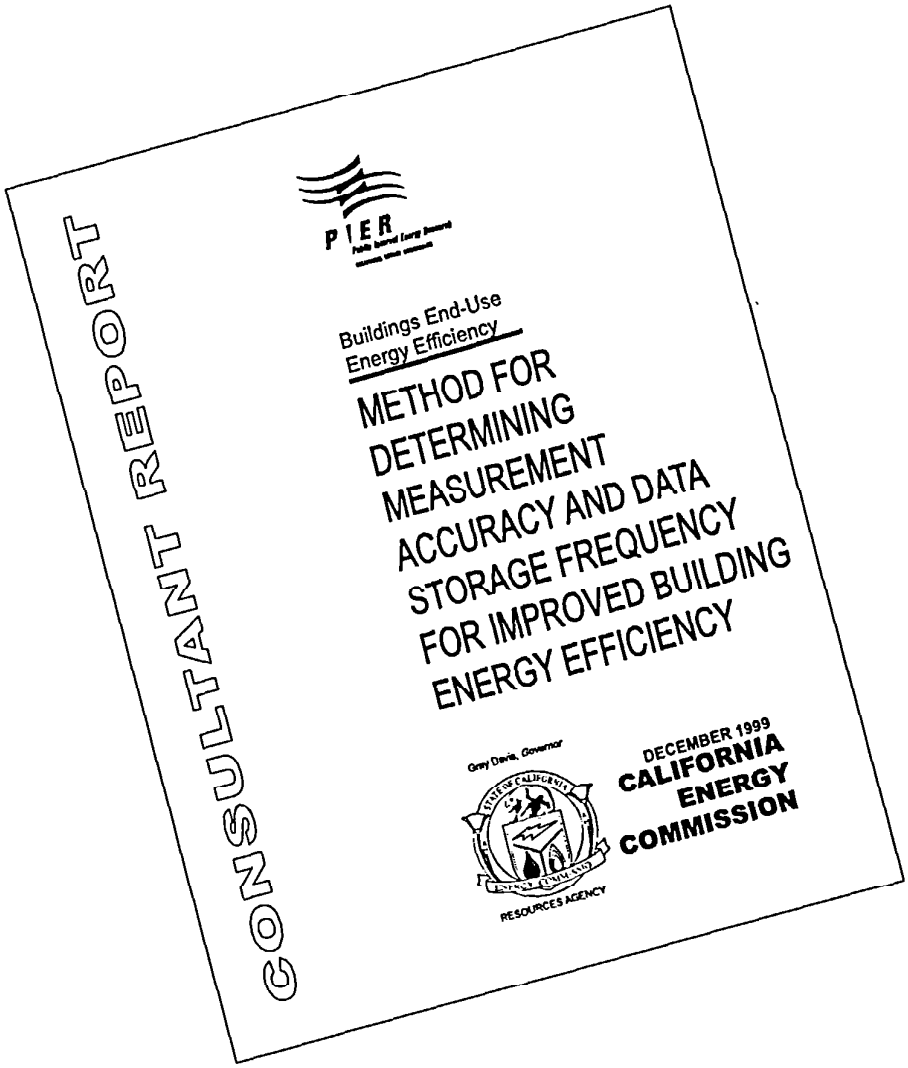
STATE OF CALIFORNIA
ENERGY COMMISSION

RESOURCES AGENCY

DECEMBER 1999

CALIFORNIA
ENERGY
COMMISSION

P600-00-025



CALIFORNIA ENERGY COMMISSION

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Contract No. 500-97-010
Project No. 03

Contract Amount: $250,000

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Acknowledgements

Great appreciation goes to those who helped with the development of this project. Rich Fromberg was the lead investigator for PG&E, and prepared most of this report. Steve Blanc identified the need for this work, initiated the project, and served as the project manager for PG&E. Greg Starnes assisted with the initial planning and literature search. Ron Kammerud provided guidance on project direction. Frank Mayhew helped with the control, operation, and diagnostics aspects of the analyses and with the bin energy analysis. Eric Kolderup developed and ran the DOE-2 models for the economic and sensitivity analyses. Manny D'Albora and John Blessent helped with the literature search, parameter lists, uncertainty analyses, and many other aspects of the project.

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Preface

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program, managed by the California Energy Commission (Commission), annually awards up to $62 million through the Year 2001 to conduct the most promising public interest energy research by partnering with Research, Development, and Demonstration (RD&D) organizations, including individuals, businesses, utilities, and public or private research institutions.

PIER funding efforts are focused on the following six RD&D program areas:

- Buildings End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy
- Environmentally-Preferred Advanced Generation
- Energy-Related Environmental Research
- Strategic Energy Research.

In 1998, the Commission awarded approximately $17 million to 39 separate transition RD&D projects covering the five PIER subject areas. These projects were selected to preserve the benefits of the most promising ongoing public interest RD&D efforts conducted by investor-owned utilities prior to the onset of electricity restructuring.

What follows is the final report for the Method for Determining Measurement Accuracy and Data Storage Frequency for Improved Building Energy Efficiency project, one of nine projects conducted by Pacific Gas and Electric Company. This project contributes to the Buildings End-Use Energy Efficiency program.

For more information on the PIER Program, please visit the Commission's Web site at: http://www.energy.ca.gov/research/index.html or contact the Commission's Publications Unit at 916-654-5200.

Executive Summary

Many standards and papers specify accuracy for various data acquisition functions performed with heating, ventilation, and air-conditioning (HVAC) and energy management and control system (EMCS) equipment, but they typically do not provide the basis for the specifications. Specifications are usually based on what sensor instrumentation is available, what is typical, or what is expected. A method was needed that provided a rationale for specifications of measurement accuracy and data storage frequency. The rationale should be based on the benefits of improved accuracy or faster data storage frequency and the costs of those improvements. In this project, Pacific Gas and Electric (PG&E) provides a method for determining those specifications and to test that method on HVAC systems and functions.

Objectives

- Develop a method to determine the measurement accuracy and data storage frequency needed for various data acquisition functions in commercial HVAC systems.
- Apply the method to determine specifications for project HVAC systems equipment measurement accuracy and data storage frequency, using criteria based on energy system operating needs and economics (efficiency improvement benefits versus diagnostic costs).
- Demonstrate the technique by modeling an example building under two different weather profiles (focusing on air-handling and chilled water temperature equipment), recommend measurement accuracies and storage frequencies, and show the potential energy savings benefits of improved measurement accuracy and better diagnostic techniques.
- Repeat the analysis on several other building types and sizes using a different energy simulation model, to expand the evaluation of the method and provide examples of recommended measurement accuracies and data storage frequencies and potential energy savings for buildings with different annual energy uses.

Outcomes

- PG&E developed a method for determining the accuracy and data storage frequency required for various data acquisition functions in commercial HVAC systems. The process by which this method was developed is as important as the method itself and the results of its application. In particular, the compilation of engineering and economic sensitivity information is a new way to analyze the data requirements from buildings. The details of this process can be found in Section 3.0.
- PG&E used criteria based on energy system operating needs and economics (efficiency improvement benefits versus diagnostic costs) to recommend air handler equipment measurement accuracy and data storage frequency for several example buildings.
- PG&E first demonstrated the technique by modeling one example building under two different weather profiles (focusing on the air-handling equipment and chilled water temperature), to show the potential energy savings if more accurate equipment and better diagnostic techniques were used. Table 1 and Table 2 show the recommended accuracy and data storage frequency for individual measurements and recommended commissioning activities. Table 3 lists the recommended accuracy and data storage frequency for

measurements used for system diagnostics. These results are based on diagnostic plots using actual site data and apply to all sites.

- PG&E extended the analysis to several other building types and sizes using a different energy simulation model, to provide a range of recommended measurement accuracies and data storage frequencies and potential energy savings for buildings with different annual energy uses. Table 4 and Table 5 respectively show measurement accuracy recommendations, and potential energy cost savings from improving accuracy of operation and control and commissioning functions for all eight sites.

Conclusions

- Based on a limited number of examples, the method (given in Section 3.5.1.1) appears to give consistent results.
- Recommended HVAC equipment measurement accuracy and data storage frequency determined by the method would provide significant potential savings for the buildings that were examined.
- As the size of a particular building type increases, improved accuracy will provide larger benefits. A warmer climate, where chiller use is higher, also offers greater benefits from improved accuracy. A medium-sized hospital with a constant volume air-handling system that operates 24 hours per day, has significantly greater potential for savings than the medium-sized office building, but also different accuracy requirements.
- The results of this project might be interpolated for use on other building sizes and types, but further research is needed to develop ways to generalize the recommendations. This would help determine how much can be invested in improving measurement accuracy. By improving measurement accuracy for air-handling equipment at the example buildings, PG&E estimated a reduction of their total energy bills of between two and twelve percent. Although there is great potential for energy savings, the benefit will vary depending on the buildings' current operating and maintenance practices, the total HVAC energy use, and how well operators incorporate the recommended practices. Recommended measurement accuracies and data storage frequencies could provide potential energy savings for all eight example buildings, ranging from $1,756 to $184,520 per year.

Economic Benefits to California

In California, operators of office and hospital buildings could save 2 to 12 percent on total energy costs if they 1) used more accurate instrumentation, 2) improved data storage rates, 3) performed more diagnostics, and 4) incorporated some commissioning for their HVAC systems. Since the total commercial building electrical energy cost (for buildings over 50,000-square-feet) is about $2.77 billion / year[1] (see page 31), the total potential savings could be $194 million / year (see page 31). Although there is great potential for energy savings, the benefit will vary depending on the buildings' current operating and maintenance practices, the total HVAC energy use, and how well operators incorporate the recommended practices.

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[1] Derived from PG&E, *Commercial Building Survey*, September 1997, p. 4; and from CALIFORNIA ENERGY COMMISSION, *1998 Baseline Energy Outlook*, August 1998, Energy Information and Analysis Division, p. 16.

In addition to the economic benefits, this method offers other advantages: a total potential energy savings of 1,940 Gigawatt hours (GWh) per year; no significant increase in labor to incorporate the method; reduction in CO_2, SO_2, and NO_x emissions; and improvement in the market value of buildings due to their improved energy efficiency.

Recommendations

Building operators and engineers can either use the results of this project to roughly estimate their own requirements or apply the method to their specific situations. If the building operator were to approximate the building's total annual energy use, the level of accuracy and data storage frequency, as well as the types of commissioning functions that would be economic, can be interpolated as a first approximation. A site-specific analysis can be performed using the method outlined in this report for more accurate results.

As a result of this analysis, plots were recommended for air handling system diagnostics. This set of plot descriptions and examples would be useful to plant operators who need to know how to set up their systems to perform basic plant diagnostics (Appendix III, pp. III-B-51 to III-B-64).

- As a follow-on to this research project, it would be useful to prepare a guideline or tool to help building operators determine the accuracy and data storage frequency needed to run their buildings at efficient levels.
- The main focus of the project was air handling system measurements, although the results include chilled water temperature specifications. Similar analyses could be performed for the measurements used around the chilled water plant. For other energy end-use systems, such as compressed air systems and pumps, if the potential for energy-use reduction was deemed to be significant, the method can be applied as well.

Abstract

The project objective was to develop a method for determining the measurement accuracy and data storage frequency needed for various data acquisition functions in commercial heating, ventilation, and air-conditioning (HVAC) systems. Recommendations for measurement accuracy were made, based on a cost/benefit analysis. Higher accuracy was justified when the potential energy savings from improved measurements were greater than the cost of more accurate sensor instrumentation. Determination of data storage frequencies is based on (1) the ability to produce data that can be used to detect such system dynamics as control instabilities and scheduling problems and (2) the number of readings needed to minimize the uncertainty of performance test results. The method was verified by determining the accuracies and data storage frequencies needed for key measurements used for control, operation, diagnostics, and commissioning of air-handling equipment. Accuracies and data storage frequencies were developed for a hospital and small, medium, and large office buildings for San Francisco and Fresno weather profiles.

1.0 Introduction

1.1 Background: Need for Building Energy Efficiency Analysis Method

Building energy management and control systems (EMCS) and heating, ventilation, and air conditioning (HVAC) systems can benefit from improved accuracy and data storage rates for data and from improved ways to use diagnostic data. With proper maintenance of measurement accuracy and data storage rates, energy efficiency and system troubleshooting can be improved.

In this project, Pacific Gas and Electric (PG&E) provided a method to develop a rationale for specifications of accuracy and data storage frequency. The benefits of improved accuracy or faster data storage frequency are compared to the costs of those improvements. This project focused on providing a method to determine those specifications, and testing of that method on specific HVAC systems and functions.

1.2 Objectives

- Develop a method to determine measurement accuracy and data storage frequency needed for various data acquisition functions in commercial HVAC systems. PG&E based this method on:
  - Use of economics to compare the benefits (in terms of reducing energy use) to the costs of improving accuracy or performing a commissioning activity.
  - Enabling the use of data to perform system diagnostics.
- Apply the method to determine specifications for project HVAC systems equipment measurement accuracy and data storage frequency, using criteria based on energy system operating needs and economics (efficiency improvement benefits versus diagnostic costs), including:
  - Cost of more accurate instrumentation
  - Cost of maintaining accuracy with regular calibrations
  - Potential improvement in building energy efficiency
  - Ability to enhance system diagnostics
  - Ability to maintain comfortable conditions and minimize the effort to solve problems
  - Capability to detect control instabilities and equipment malfunctions
  - Ability to measure improvements made to equipment (for M&V).
- Demonstrate the technique on an example building under two different weather profiles (focusing on the air-handling equipment and chilled water temperature), to show the potential energy savings if more accurate equipment and better diagnostic techniques were used.
- Repeat the analysis on several other building types and sizes using a different energy simulation model, to provide a range of recommended measurement accuracies and data storage frequencies and potential energy savings for buildings with different annual energy uses.

1.3 Purpose and Organization of this Report

The purpose of this report is to make the method and results available to those pursuing similar studies. Building operators and engineers can use the results of this project to estimate their own requirements or apply the method to their specific situations. The report is organized into the following sections: Introduction and Objectives; Technical Approach; Results and Outcomes, Conclusions; Potential Energy Savings and Recommendations. Six Appendices follow the report:

Appendix I, Task 3 – Literature Search

Appendix II, Task 4 – Site Survey and Prioritization of Equipment and Evaluations for Method Development

Appendix III, Task 5 – Draft method for Determining the Accuracy and Data Storage Frequency for Sensors Used in Air-Handling Systems for Operation, Control, and Diagnostics

Appendix IV, Task 6 – Method for Determining the Accuracy and Data Storage Frequency for Sensors Applied to Commissioning of Air-Handling Systems

Appendix V, Detailed Description of Fan Retrofit Measurement and Verification Study from Task 6

Appendix VI, Task 7 – Verification of Results--Application of Results to Small, Medium, and Large Office Buildings, and a Medium-Sized Hospital for Fresno and San Francisco Climates

2.0 Technical Approach

PG&E's technical approach encompassed the following eight significant tasks:

Task 1

PG&E defined the project Work Statement, including task deliverables, schedules and budgets.

Task 2

PG&E compiled and submitted quarterly project Progress Reports to the Commission.

Task 3

PG&E searched the literature for previous work on determining accuracy and data storage frequency. Many papers suggested data accuracy and data storage rates, but they typically did not provide a rationale for their recommendations. The interim report for Task 3 is in Appendix I.

Task 4

PG&E surveyed nine building operators to determine how they use their EMCSs and what their instrumentation capabilities and greatest needs were. Most operators wanted better control of, and information from, their zone terminal units; easier diagnosis of problems; and ways to reduce labor costs while maintaining comfort and responding to complaints. Based on the survey, PG&E decided to focus its initial efforts (for Task 5) on the operation, control, and diagnostics of air-handling equipment. The interim report for Task 4 is in Appendix II.

Task 5

PG&E developed a draft method and applied it to determine the accuracies and data storage frequencies needed for operation, control, and diagnostics of air-handling equipment. Table 1 and Table 3 summarize the results. If the accuracies and data storage frequencies given in the tables are used in the example 50,000-square-foot building in Alameda or Sacramento, $852 or $459 per year (respectively) in energy costs could potentially be saved. The interim report for Task 5 is in Appendix III.

Task 6

PG&E applied the method to the commissioning, and the measurement and verification (M&V), of air-handling equipment. Commissioning is defined as a process to achieve, verify and document that building systems meet design intent and operational needs. M&V is a process by which a system's energy savings are quantified and documented. Section 3.6 provides complete definitions for these terms.

Commissioning functions of project Task 6 included initial and periodic performance testing, diagnostic checks of new or existing equipment, and M&V. PG&E considered eight scenarios related to commissioning, and their economic viability in terms of potential energy savings. Appendix IV contains the results of Task 6, which are also summarized in Table 2. Appendix V describes the fan retrofit M&V study example. In the example 50,000-square-foot building, none of the eight commissioning tasks was determined to be economic, because the building's small size makes it more difficult to justify such investments.

Task 7

PG&E tested the method from Tasks 5 and 6 by extending the economic and sensitivity analyses to other building sizes and types. The results of this task are in Appendix VI and are summarized in Table 4 and Table 5, which respectively show measurement accuracy recommendations, and potential energy cost savings for the HVAC system operation and control, and commissioning functions for all eight sites.

PG&E used a more comprehensive simulation program (DOE-2) to model a 50,000, 250,000, and 1,000,000-square-foot office building and a 250,000-square-foot hospital in San Francisco and Fresno climate zones. If all recommended accuracies, data storage frequencies, and commissioning tasks are incorporated, total potential energy savings would range from two to twelve percent of the buildings' total energy costs (or between $1,756 per year and $184,520 per year).

Task 8

PG&E prepared this report, which constitutes the project Final Report.

3.0 Results and Outcomes

This section discusses the steps that were taken to complete the project objectives. Detailed results are also provided.

3.1 Work Statement Definition (Task 1)

PG&E defined the project Work Statement. Areas of the original scope of work that required clarification or slight modification were identified. Updated budgets and due dates for all task deliverables were also included.

3.2 Quarterly Progress Reports (Task 2)

PG&E compiled and submitted quarterly project Progress Reports to the Commission to track the status of the project.

3.3 Literature Search (Task 3)

A literature search was performed at the start of this project to look for information on how HVAC measurement accuracy and data storage frequency are determined. Appendix I contains the interim report—summaries of about 90 papers, standards, books, and handbooks on the operation, control, diagnostics, and commissioning of HVAC equipment. A number of sources specify accuracy and data storage frequency, but they typically do not provide a detailed rationale for the recommendations. The recommendations are usually based on the instrumentation that the users had or could afford, the capabilities of the EMCS or monitoring system, or what is typical in the industry. PG&E concluded that a method to determine measurement accuracy and data storage frequency was needed.

3.4 Site Survey (Task 4)

Nine sites were surveyed to determine how they use their EMCSs, their instrumentation capabilities, and their greatest needs related to use of their EMCS data. The interim report is in Appendix II. The survey results led PG&E to focus its Task 5 development efforts on air-handling equipment and on evaluation of their operation, control, and diagnostics. Our key findings were:

- Maintaining comfort and responding to complaints are a higher priority than energy savings.
- The EMCS is most valuable in helping to diagnose problems and in monitoring zones to look for problem areas.
- The ability to use the EMCS to keep labor costs down is very important.
- Operators want better information (i.e., direct digital control [DDC]) from the terminal boxes to help diagnose problems more easily.
- Operators want more control of their air handlers and terminal boxes.
- Operators want more user-friendly front ends and easier access to historical data for producing trends.

- Only 20 percent of the sites track some type of performance factor. About 80 percent track building energy use.
- Only 30 percent of the sites perform routine instrument calibrations, although the others wish they had the manpower to do so.
- Operators want more zone temperatures and terminal units for better control, and more power measurements to track equipment energy use.

PG&E chose to focus on air-handling equipment for this project for the following reasons:

- Terminal units cause the majority of operator problems.
- Many building operators are gradually replacing their pneumatic terminal boxes with DDC units and new sensors.
- Improved comfort as well as energy and labor savings would result from better control and monitoring of terminal units.
- Air handlers use a similar amount of energy as chillers, they control the load on the chillers, and they affect optimization of the building energy use.
- Many more sensors are used for air-handling operation than for chiller plant operation.

3.5 Method to Determine Accuracy and Data Storage Frequency (Task 5)

3.5.1 Method to Determine Accuracy and Data Storage Frequency

The method to determine measurement accuracy and data storage frequency was developed from common economic analysis techniques, where the benefits of an improvement are compared to the costs. (The method described here is outlined in Section 3.5.1.1Remove this Error Message !!!**Error! Reference source not found.**). The benefits are determined from analysis of the sensitivity of the building's energy use to an improvement in measurement accuracy. Standard uncertainty analysis techniques are used in the sensitivity analysis, in the combining of instrument inaccuracies into overall uncertainties, and in the M&V case study (part of Task 6). Building operators are most receptive when the benefits of accuracy and data storage frequency are put in economic terms.

The method involves first determining the measurements, factors, algorithms, or plots required for the types of evaluations to be performed with the equipment. PG&E primarily used ASHRAE standards and handbooks, engineering judgment, and some papers from our literature search. The diagnostic plots were developed with a controls consultant. Plots were chosen that would be easy to interpret and could be produced by most EMCSs. The plots can be used to diagnose most of the problems expected from air-handling systems.

Next, PG&E collected site data to produce sample plots and calculate performance factors. For parameters that affect energy efficiency, PG&E performed a sensitivity analysis to determine their effect on building energy use. For Tasks 5 and 6, PG&E used a bin energy analysis model of a 50,000-square-foot office building in Alameda and Sacramento to calculate how much the building energy use changes with small changes in the input parameters. In Task 7, PG&E verified the results and expanded the analysis to other buildings in similar climate zones (San Francisco and Fresno) using DOE-2 model simulations. Sensitivity analysis results, combined with assumed accuracy improvements, provide the information necessary to determine the

economic benefit of accurate measurements. The economic benefit of a measurement's accuracy is compared to the cost of installing and maintaining accurate instrumentation, to determine the level of instrument accuracy required to produce net savings.

The diagnostic plots or test averages help determine accuracy and data storage frequency from a different perspective. Using the diagnostic plots requires that the data be accurate enough to display instabilities, system response, proper operation, and comparisons between curves. For testing, measurements need to be accurate enough and include enough points to provide an adequate level of confidence in the final results.

Finally, the results of the accuracies and data storage frequencies from the economic analyses and diagnostic plots or tests are combined to determine the final recommendations.

3.5.1.1 The Method

The following is a brief outline of the method. The detailed description and application of this draft method can be found in Appendix III.

Initial step for determining accuracy and data storage frequency:

- Define the objective of the test or measurement activity.
- List measurements, performance factors, and algorithms needed to perform tasks to be accomplished.
- Determine what plots, if any, would be useful for evaluations.
- Develop plots and algorithms and calculate performance factors with actual site data.

Engineering and economic sensitivity analysis:

- Determine the sensitivity of factors and algorithms to their input measurements (engineering sensitivity).
- For each piece of equipment, develop a rough economic evaluation of the effect of varying parameters or measurements on energy use (economic sensitivity).

Accuracy and frequency based on analysis of energy use:

- Prioritize the measurements and factors in terms of their effect on building energy use.
- Considering the cost of instrumentation and calibration, determine the economic level of accuracy for each measurement and parameter.
- If test averages are calculated, determine the number of data points needed to keep the uncertainty at the desired level.

Accuracy and frequency based on use of plots of data:

- Describe how each plot can be used to perform the intended evaluation.
- Determine the potential benefits of using the plots.
- Determine the measurement accuracy and/or data storage frequency needed to use the plots for the intended evaluations.

3.5.2 Method Applied to Air-Handling Equipment Used in Operation, Control, and Diagnostics

The first application of the method was to determine the accuracy and data storage frequency requirements of measurements used for the operation, control, and diagnostics of air-handling equipment. Appendix III contains the interim report on this initial application.

PG&E listed the measurements, performance factors, and diagnostic plots that apply to air-handling equipment. PG&E found actual site data, calculated the performance factors, and created the plots. PG&E eliminated the performance factors and plots that were least useful or most difficult to use (mainly due to complexity, noise, unpredictability, or large uncertainties). For example, performance factors for fan efficiency and coil effectiveness were too sensitive to their measurement inputs (see Appendix III, pp. III-A-43 to III-A-50). While acceptable accuracy for performance factors may be attainable for commissioning purposes, maintenance of acceptable accuracy for operation, control, and diagnostics would be difficult.

An example building was modeled for our economic analysis, using a bin energy analysis model (described in Appendix III, pp. III-C-67 to III-C-68). The building was a 50,000-square-foot office space. Two weather profiles were used, one from Alameda Naval Base (which is similar to downtown San Francisco) and the other from McClellan Air Force Base near Sacramento. The annual fan and chiller energy use was calculated for a base case. The parameters that affect fan and chiller energy use were then varied around their base case values to determine the sensitivity of the energy use to measurement accuracy. Plots of added energy use versus the change in these parameters are in Appendix III (p. III-19). The potential for energy savings with improved accuracy of the measurements is compared to the cost of achieving better accuracy, which includes the cost of the more accurate instrumentation and the cost of annual calibrations.

From the diagnostic plots, PG&E determined the measurement accuracies needed to be able to detect operational or control problems so that building efficiency could be maintained. PG&E also determined data storage frequency so that instabilities could be detected and proper scheduling could be verified. Our rule of thumb is that at least five data points are needed to reproduce one cycle so that control problems can be detected (see Appendix III, p. III-27 for more explanation). Descriptions of the plots and how to use them, as well as example plots using actual site data, are in Appendix III (pp. III-B-51 to III-B-66).

3.6 Method Applied to Commissioning and M&V of Air-Handling Equipment (Task 6)

3.6.1 Method Applied to Air-Handling Equipment Used for Commissioning

To verify the method's general usefulness, PG&E applied it to measurements used for commissioning of air-handling equipment.

The American Society of Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE) defines commissioning in specific terms as "the process of ensuring that all equipment, systems, and controls have been correctly installed; are operated as specified; are tested, adjusted and balanced; etc." Other organizations define commissioning more broadly. Portland Energy Conservation's definition is "a process for achieving, verifying and documenting that the performance of a building and its various systems meet design intent and the owners and

occupants operational needs. The process ideally extends through all phases of a project, from concept to occupancy and operation."

Building commissioning and retrofit commissioning are generally thought of as total quality management processes rather than sets of specific tasks that can be packaged as tools. Nevertheless, there exist opportunities to delineate and further develop building system-specific techniques that a commissioning agent could use during particular phases of the commissioning process.

Commissioning activities included in this Task include initial and periodic performance tests, diagnostic checks, and M&V functions.

Appendix IV contains 12 examples of commissioning activities. The method was applied to each example separately to determine whether it was economic to perform and to determine the acceptable accuracy and, if applicable, data storage frequency. The steps are as follows:

- Define the commissioning activity to be performed.
- Determine the measurements and factors (and their equations) needed for commissioning each piece of equipment.
- Determine the acceptable benefit/cost ratio.
- Estimate the performance improvement likely to result from the activity. An amount of performance degradation needs to be assumed.
- Calculate the potential energy cost savings from that improvement. For the examples, PG&E simplified the economic analysis by assuming 0.10 $ per kWh. A more rigorous analysis would use time-of-use rates, capacity charges, etc.
- Estimate the cost for the instrumentation, testing, and/or annual calibration and maintenance needed to make the improvement. The level of accuracy should be good enough to provide or measure most of the improvement. To obtain annual costs, lump-sum costs were spread over a 3 to 5-year period, depending on the example.
- Calculate the benefit/cost ratio and compare it to the acceptable B/C ratio. If it is less than the acceptable ratio, the activity is not economical. If it is higher, the activity should be performed.
- If the activity is a performance test, determine the test or data storage frequency that would enable the acceptable level of accuracy.

The data storage frequency (or number of data points) can be determined for those tests that result in averaged data, as follows. If we can estimate the standard deviation of the data points, and we want the precision index (the portion of the uncertainty that indicates random errors) to add less than 10 percent to the overall uncertainty, we can determine the required number of data points from the plots in Appendix IV (pp. IV-16 and IV-19). Much of the analysis in this section is based on the same example building used in Task 5. Table 2 summarizes the results.

3.6.2 M&V Example Study

Measurement and verification (M&V) is a process by which a project's energy savings are quantified and documented. M&V can be viewed from a technical perspective, in which a system's energy performance before and after the installation of equipment is measured, the

energy savings resulting from the installation is quantified, and the equipment's continuing energy savings performance is verified. M&V is also an important part of energy savings performance contracts, in which it helps define and control risk. A project's risk is associated with many factors, such as the uncertainty of a project's savings, the cost of M&V in comparison with the energy cost savings and the equipment's long-term energy performance and maintenance requirements.

As part of Task 6, PG&E also considered the accuracy and data storage frequency requirements for an example M&V project. The results are summarized in Appendix IV (pp. IV-21 to IV-28) and are explained in detail in Appendix V. For the M&V example study, a fan with variable inlet vanes was replaced by an adjustable speed drive system. Pre- and post-retrofit performance test data (flow vs. power) as well as monitored site performance data (fan power) are used to determine the energy savings produced by the retrofit.

PG&E varied several test parameters to determine their effect on the energy savings and calculated uncertainty. Following are the parameters and their values (*bold type* indicates the baseline value):

- Number of test points for pre and post-retrofit performance curves: ***21***, 11, 5
- Data storage interval (minutes): **15**, 30, 60
- Uncertainties in power(%) / flow(%): **1/3**, 3 / 5, 5 / 10, 10 / 20
- Number of weeks in monitoring period: ***52***, 12 (winter), 12 (spring), 12 (summer), 12 (fall), 4 (winter), 4 (spring), 4 (summer), 4 (fall), 2 (winter), 2 (spring), 2 (summer), 2 (fall). The periods were chosen from the middle of each season.
- Use different instruments for pre- and post-retrofit testing: *no change (same instruments used for pre- and post-retrofit)*, different power instruments, different flow instruments, and different power and flow instruments. Power uncertainty is 1% and flow uncertainty is 3%.
- Power uncertainty (%) - same instrument for pre- and post-retrofit tests: *1*, 3, 5, 10
- Flow uncertainty (%) - same instrument for pre- and post-retrofit tests: *3*, 5, 10, 20

3.7 Verification of Project Results (Task 7)

For Task 7, a large number of DOE-2 building simulations were run to verify the results of Tasks 5 and 6 and to extend them to other building types and sizes. The analyses were repeated for a small, medium, and large office building and a medium hospital in typical San Francisco and Fresno weather profiles. Appendix VI describes the DOE-2 model and the building assumptions, and provides the results of the DOE-2 simulations in tabular and chart formats (Figures 1 through 8 and Charts 1 through 32 in Appendix VI). Chiller, fan, and total building (including chiller and fan use) annual kWh results are provided. The Total Cost is based on the total building annual kWh plus the boiler gas fuel cost. Electric costs are based on PG&E's commercial time-of-use rate schedule E19. Appendix VI also includes a table for each site (Tables 1 through 8) that shows how PG&E determined the measurement accuracies and commissioning functions that are economic, as well as the maximum potential for energy savings. Table 4 and Table 5 in this final report summarize the recommendations for instrument accuracy, data storage frequency, and commissioning functions that come from the tables in Appendix VI.

3.8 Final Report (Task 8)

PG&E prepared this report, which constitutes the project Final Report. PG&E met its project objectives, as established by the following outcomes.

Table 1. Recommended Accuracies and Data Storage Frequencies from Bin Analysis -Task 5 - Operation and Control (Sacramento and Alameda Small Office Buildings – 50,000 sf)

Equipment and Plot Parameters	Accuracy (ºF, %, or in. H_2O)	Data Storage Frequency (minutes)	Potential Net $/year Savings With Improved Accuracy
Terminal Units			
Zone Temperature	2	2	-
Reheat Valve Position	N/A	2	-
Discharge Temperature	2	1	-
Economizer/Mixed Air Damper			
Mixed and Outside Air Temperature	1	5	-
Return Air Temperature	2	1	-
Cooling Coil			
Supply Air Temperature	0.5	2	$171 to 378/yr
Fans			
Supply Duct Static Pressure	0.2	1	$144 to 237/yr
Filter			
Differential Pressure	0.2	N/A	$144 to 237/yr
Total Chiller and Fan Energy Use			$ 137,037
Total Chiller and Fan Energy Cost			$ 13,704
Total Potential Savings ($/year)			$459 to 852/yr

N/A – Measurement accuracy is not applicable to Reheat Valve Position because this is a calculated value.

Table 2. Summary of Example Economic Analysis for Commissioning of Air-Handling Equipment - Bin Analysis – Task 6

Alameda Small Office Building – 50,000 square feet								
Commissioning Activity, Improvement, or Sensor Installation	Assumed Deviation without Sensor orImprovement	Assumed Deviation with Sensor or Improvement	Potential Savings due to Improvement ($/year)	Assumed Cost of Improvement	Benefit to Cost Ratio[1]	Acceptable B/C Ratio[2]	Is Activity Ecomical?[3]	Net Potential Savings If Task Is Performed ($/yr)[4]
Terminal Unit Min Air Flow Calibration at Zero	High by 10% of full flow	5%	$2	$20/year	0.10	5	No	-
Terminal Unit Min Air Flow Install New Sensor	High by 20% of full flow	5%	$5	$500/5 year	0.05	5	No	-
Monitor DP across Coil	High by 0.1 in H_2O	0.05 in H_2O	$129	$200/year	0.65	2	No	-
Measure Minimum Outside Air Flow	MinOAF is 25% of full flow	Target MinOAF is 15% ± 3% of full flow	$7	$2,000/3 years	0.01	2	No	-
Detect Leaking Reheat Valves	A typical leak might raise SAT by 5ºF	2ºF	$240	$300/3 years	2.40	5	No	-
Test Coil Performance	Effectiveness low by 10%, SAT high by 3ºF	Effectiveness not degraded - relevant for 8% of operating hours	$160	$3,750/3 years	0.13	2	No	-
Test Fan Performance	Fan efficiency low by 10%	Fan efficiency low by 0%	$905	$3,850/3 years	0.71	2	No	-
Total Potential Annual Savings from Commissioning Projects[5]								$0

See following page for second example building, 50,000 sf

Sacramento Small Office Building – 50,000 square feet								
Commissioning Activity, Improvement, or Sensor Installation	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings due to Improvement ($/year)	Assumed Cost of Improvement	Benefit to Cost Ratio[1]	Acceptable B/C Ratio[2]	Is Task Ecomical?[3]	Net Potential Savings If Task Is Performed ($/yr)[4]
Terminal Unit Min Air Flow Calibration at Zero	High by 10% of full flow	5%	$5	$20/year	0.25	5	No	-
Terminal Unit Min Air Flow Install New Sensor	High by 20% of full flow	5%	$16	$500/5 year	0.16	5	No	-
Monitor DP across Coil	High by 0.1 in H_2O	0.05 in H_2O	$100	$200/year	0.50	2	No	-
Measure Minimum Outside Air Flow	MinOAF is 25% of full flow	Target MinOAF is 15% $\pm$ 3% of full flow	$194	$2,000/3 years	0.29	2	No	-
Detect Leaking Reheat Valves	A typical leak might raise SAT by 5ºF	2ºF	$345	$300/3 years	3.50	5	No	-
Test Coil Performance	Effectiveness low by 10%, SAT high by 3ºF	Effectiveness not degraded - relevant for 8% of operating hours	$80	$3,7500/3 years	0.06	2	No	-
Test Fan Performance	Fan efficiency low by 10%	Fan efficiency low by 0%	$1,038	$3,850/3 years	0.81	2	No	-
Total Potential Annual Savings from Commissioning Projects[5]								$0

[1] The B/C ratio for the lower table is calculated by: Potential Savings due to Improvement (assumed cost of improvement/3 years). The Cost of Improvement is annualized over 3 years.
[2] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is acceptable. Where there are many sensors (such as zone sensors), it includes the percentage of zones that might need improvement.
[3] The Commissioning Activity is recommended if the B/C ratio is greater than the Acceptable B/C ratio.
[4] The Net Potential Savings is calculated by: Annual Energy Savings - Annual Cost. The lump sum costs are spread over a 3-year period (i.e., they are divided by 3).
[5] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset of them.

Table 3. Accuracy and Data Storage Frequency Results Using Diagnostic Plots - Applies to all Sites

Sensor	Recommended Sensor Accuracy	Recommended Data Storage Frequency (from Diagnostic Plots)
Zone Cooling CFM	10%	1
Zone Heating CFM	10%	1
Mixed Air Temperature	1ºF	1
Cooling Loop Output Signal	N/A	2
Maximum Zone Damper Position	N/A	1
Low and High Zone Temperatures[1]	1	5

Note – These results are described in Task 5 – Analysis Using Diagnostic Plots (Appendix III, page 25). They depend on the system response, not the energy use of the site, and apply to all sites. It should not be inferred that these measurements are economic at any particular site, unless a cost-benefit analysis is performed.

CFM - cubic feet per minute

N/A – These are calculated values, so sensor accuracy is not applicable.

[1] Used for scheduling and advanced control, these sensors could save several $100/yr if they are used to optimize start and stop times of the HVAC equipment.

Table 4. Summary of Recommended Sensor Accuracies for All DOE-2 Example Sites – Task 7

Air Handler Operation and Control - Sensors	Fresno Small Office	Fresno Medium Office	Fresno Large Office	Fresno Medium Hospital	S.F. Small Office	S.F. Medium Office	S.F. Large Office	S.F. Medium Hospital	Recommended Data Storage Frequency (from Diagnostic Plots)
Supply Air Temperature	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	2 min
Single Zone Temp (1000 sf)	2ºF	2ºF	2ºF	0.5 ºF	2ºF	2ºF	2ºF	0.5 ºF	2 min
Duct Static Pressure	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	1 min
Filter Differential Pressure	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	0.2 in. H_2O	Every 3 months
Mixed and Outside Air Temperature	1ºF	1ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	5 min
Return Air Temperature	2ºF	2ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	1 min
Chilled Water Temperature	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	0.5ºF	2 min
Commissioning Activity, Improvement, or Sensor Installation									
Calibrate Zone Min Air Flow at Zero									Zero Annually
Install New Zone Air Flow Sensor									Zero Annually
Monitor Coil Differential Pressure			0.05 in. H_2O	0.05 in. H_2O			0.05 in. H_2O	0.05 in. H_2O	Every 3 months
Install an Outside Air Flow Sensor		5%	5%				5%		Every 5 minutes
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks									Every month when no reheat
Test Coil Performance			5%						Test every few years
Test Fan Efficiency			5%	5%				5%	Initial test only

Table 5. Summary of Maximum Potential Savings for All DOE-2 Example Sites - Task 7

Air Handler Operation and Control - Sensors	Fresno Small Office	Fresno Medium Office	Fresno Large Office	Fresno Medium Hospital	S.F. Small Office	S.F. Medium Office	S.F. Large Office	S.F. Medium Hospital
Supply Air Temperature	$297	$1,740	$8,992	$48,459	$164	$1,097	$3,624	$27,666
Single Zone Temperature (1000 sf)	-	-	-	$49,641	-	-	-	$30,744
Duct Static Pressure	$513	$3,243	$15,387	$26,944	$282	$2,130	$10,938	$21,113
Filter Differential Pressure	$513	$3,243	$15,387	$26,944	$282	$2,130	$10,938	$21,113
Mixed and Outside Air Temperature	-	$175	-	$2,050	$544	$2,736	$16,474	$651
Return Air Temperature	-	$175	-	$2,050	$544	$2,736	$16,474	$651
Chilled Water Temperature	$434	$2,660	$10,243	$8,048	$104	$783	$6,956	$3,698
Commissioning Task, Improvement, or Sensor Installation								
Calibrate Zone Min Air Flow at Zero	-	-	-	-	-	-	-	-
Install New Zone Air Flow Sensor	-	-	-	-	-	-	$1,397	-
Monitor Coil Differential Pressure	-	-	$2,180	$3,945	-	-	$1,397	$2,655
Install an Outside Air Flow Sensor	-	$2,548	$15,501	-	-	-	$6,591	-
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	-	-	-	-	-	-	-	-
Test Coil Performance	-	-	$11,973	-	-	-	-	-
Test Fan Performance	-	-	$6,315	$16,441	-	-	-	$10,981
Total Potential Annual Savings	$1,756	$13,433	$86,327	$184,520	$1,919	$11,612	$73,031	$119,272
Total Building Energy Use (MWh/yr)	752	3,546	14,820	11,207	620	2,941	11,829	8,785
Total Building Energy Cost (k$/yr)	$94k	$439k	$1,872k	$1,597k	$77k	$364k	$1,497k	$1,215k
% Savings vs. Total Energy Cost	1.9%	3.1%	4.6%	11.6%	2.5%	3.2%	4.9%	9.8%

Note: The Total Potential Annual Savings include all improvements listed. In reality, most sites would require only a subset of them.

These are maximum potential savings. They are not adjusted for risk or the probability of occurrence.

3.9 Summary of Outcomes

- PG&E developed a method for determining the accuracy and data storage frequency required for various data acquisition functions in commercial HVAC systems. The process by which this method was developed is as important as the method itself and the results of its application. In particular, the compilation of engineering and economic sensitivity information is a new way to analyze the data requirements from buildings. The details of this process can be found in Section 3.0.
- PG&E used criteria based on energy system operating needs and economics (efficiency improvement benefits versus diagnostic costs) to recommend air handler equipment measurement accuracy and data storage frequency for several example buildings.
- PG&E first demonstrated the technique by modeling one example building under two different weather profiles (focusing on the air-handling equipment and chilled water temperature), to show the potential energy savings if more accurate equipment and better diagnostic techniques were used. Table 1 and Table 2 show the recommended accuracy and data storage frequency for individual measurements and recommended commissioning activities. Table 3 lists the recommended accuracy and data storage frequency for measurements used for diagnostics. These results are based on diagnostic plots using actual site data and apply to all sites.
- PG&E extended the analysis to several other building types and sizes using a different energy simulation model, to provide a range of recommended measurement accuracies and data storage frequencies and potential energy savings for buildings with different annual energy uses. Table 4 and Table 5 respectively show measurement accuracy recommendations, and potential energy cost savings from improving accuracy of operation and control and commissioning functions for all eight sites.

4.0 Conclusions

- Based on limited test results, the method appears to provide consistent results.
- Recommended HVAC equipment measurement accuracy and data storage frequency determined by the method could provide significant potential savings for the buildings that were examined.
- In Tasks 5 and 6, PG&E used its method to determine cost-effective accuracy, data storage frequency, and potential energy cost savings for a 50,000-square-foot office building in Alameda and Sacramento. For this step PG&E used a simplified model based on a bin energy analysis method. Table 1 and Table 3 provide the results. The recommended accuracies are 0.5°F for supply air temperature, 2°F for zone and discharge temperatures, 1°F for mixed and outside air temperatures, 2°F for return air temperature, 10 percent for zone air flows, and 0.2inH_2O for duct static pressure and filter differential pressure. For these small buildings, no commissioning tasks were determined to be economical, because the building's small size makes it difficult to justify such improvements. Total potential savings are $852/yr and $459/yr for the Alameda and Sacramento sites, respectively.

  Also in Task 5 (Appendix III, page III-27), PG&E used actual site data from several buildings to determine the recommended data storage frequencies (Table 1 and Table 3). All data storage frequencies should be one or two minutes, except for outside air temperature, which can be 5 minutes. Data should be stored for between 24 and 48 hours to be used for system diagnostics. In Table 1 and Table 3, since frequencies are based on how the plots should be used for diagnostics and on system response characteristics (not building size), these recommendations apply equally to all of our example buildings.

- In Task 6, the most significant M&V conclusions for the fan retrofit study were the following:
  - the same instrumentation should be used for pre- and post-retrofit testing;
  - power uncertainty should be kept at three percent or better;
  - flow uncertainty has little effect on the test uncertainty as long as there is no drift;
  - ten or more test points should be used to develop each pre- and post-retrofit fan performance curve.

  More detailed conclusions can be found in Appendix V.

- In Task 7, PG&E also used the method to determine cost effective accuracy, data storage frequency, and potential energy cost savings for a small (50,000-square-foot), medium (250,000-square-foot), and large (1,000,000-square-foot) office building and medium (250,000-square-foot) hospital in San Francisco and Fresno. For this step PG&E used a comprehensive hourly simulation model called DOE-2. The results of this task are in Tables 1 through 8 of Appendix VI and are summarized in Tables 4 and 5. For all eight sites the recommended accuracies are the same as for Task 5, except for 0.5°F return and outside air temperatures called for by the San Francisco sites and the Fresno large office and hospital

sites, and 0.5°F zone temperatures called for by the medium hospital sites. Chilled water temperatures should be 0.5°F accurate for all sites.

More of the commissioning tasks were considered economic as well. The large buildings with VAV (variable air volume) systems in Fresno could justify the most commissioning activities. The hospitals with CV (constant volume) systems and reheat had two commissioning activities that were shown to be economic. Recommendations for data storage frequency are the same as for the small office building in Alameda in Task 5. By improving measurement accuracy and applying cost effective commissioning tests, potential annual savings for the eight sites could range from $1,756/yr to $184,520/yr, or from two to twelve percent of their total energy bills.

As the size of a particular building type increases, improved accuracy will provide larger benefits. A warmer climate, where chiller use is higher, also offers greater benefits from improved accuracy. A medium-sized hospital with a constant volume air-handling system that operates 24 hours per day, has significantly greater potential for savings than the medium-sized office building, but also different accuracy requirements. This is because the reheat coils in a CV system waste a lot of energy, especially if their control is poor.

- The results of this project might be interpolated for use on other building sizes and types, but further research is needed to develop ways to generalize the recommendations. This would help determine how much can be invested in improving measurement accuracy. By improving measurement accuracy for air-handling equipment at the example buildings, PG&E estimated a reduction of their total energy bills of between two and twelve percent. Although there is great potential for energy savings, the benefit will vary depending on the buildings' current operating and maintenance practices, the total HVAC energy use, and how well operators incorporate the recommended practices.

5.0 Benefits to California

5.1 Potential Energy Savings for Example Buildings

The total potential energy savings for the small, medium, and large office buildings and medium hospital in San Francisco are $1,919, $11,612, $73,031, and $119,272 per year, respectively (Table 5). As a percent of total annual building energy cost, the potential savings are 2.5, 3.2, 4.9, and 9.8 percent, respectively. As energy use increases, a higher percentage of savings can usually be realized. More accurate instrumentation has a greater effect, and more commissioning projects can be justified on larger buildings.

The total potential energy savings for the small, medium, and large office buildings and medium hospital in Fresno are $1,756, $13,433, $86,327, and $184,520 per year, respectively (Table 5). As a percent of total annual building energy cost, the potential savings are 1.9, 3.1, 4.6, and 11.6 percent, respectively. As with the San Francisco example buildings, a higher percentage of savings can be found as the energy use increases.

5.2 Potential Benefits to California If Buildings Incorporate These Techniques

In California, operators of office and hospital buildings could save two to twelve percent on total energy costs, if they: 1) used more accurate instrumentation, 2) improved data storage rates, 3) performed more diagnostics, and 4) incorporated some commissioning for their HVAC systems. Of course, other building types and sizes would have different results. PG&E can roughly estimate the potential savings for all commercial buildings in California by assuming that similar improvements can be made at the other building types. Since the total commercial building electrical energy cost (for buildings over 50,000-square-feet) is about $2.77 billion / year[2], the total potential savings could be $194 million / year.[3] Although there is a huge potential benefit for energy savings, the benefit will vary depending on the buildings' current operating and maintenance practices, the total HVAC energy use, and how well they incorporate the recommended practices.

In addition to the potential economic benefits, there are a number of other potential benefits for commercial buildings in California, as summarized below:

- Total potential energy savings is 1,940 GWh / year[2].
- No significant increase in labor is required to incorporate the recommendations. As a result of better data and diagnostic techniques, maintenance and repair costs will improve.
- As a result of the reduced energy use, CO_2, SO_2, and NO_x will be reduced by 2.2 million, 11, and 2,300 klb per year (based on a gas-fired plant of 10,000 Btu / kWh heat rate producing 115, 0.0006, and 0.12 lb per year per MMBtu gas for CO_2, SO_2 and NO_x, respectively).

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[2] Derived from PG&E, *Commercial Building Survey*, September 1997, p. 4; and from CALIFORNIA ENERGY COMMISSION, *1998 Baseline Energy Outlook*, August 1998, Energy Information and Analysis Division, p. 16. Assumes a potential energy savings of 7%.

[3] Total potential savings = $2.77 billion / year * potential savings of 7% (average of 2 to 12% potential savings) = $194 million / year.

- Improved comfort levels with better control and operations will improve worker productivity, which is a significant benefit to commercial businesses.
- A more energy-efficient building has a higher market value. If the capitalization period for a building is 20 years and the building's energy cost is improved by $10,000/year, its value is increased by the present value of $10,000/year over 20 years, or about $100,000, if a capitalization rate of seven percent is assumed.

6.0 Recommendations for Future Efforts

Building operators and engineers can either use the results of this project to estimate their own requirements or apply the method outlined in this report to their specific situations. The level of accuracy and data storage frequency, as well as the types of commissioning functions that would be economic, can be roughly estimated by interpolating from Tables 4 and 5. Table 4 and Table 5 respectively show measurement accuracy recommendations, and potential energy cost savings for the air handler and chilled water temperature system operation and control and commissioning functions for all eight sites. (Appendix VI, Tables 1 through 10, includes more detail on individual examples). If the building operator were to approximate the building's total annual energy use, the level of accuracy and data storage frequency, as well as the types of commissioning functions that would be economic can be interpolated as a first approximation.

As a result of this analysis, plots were recommended for use on air handling system diagnostics. This set of plot descriptions and examples would be useful to plant operators who need to know how to set up their systems to perform basic plant diagnostics (Appendix III, pp. III-B-51 to III-B-64)

- As a follow-on to this research project, it would be useful to prepare a guideline or tool to help building operators determine the accuracy and data storage frequency needed to run their buildings at efficient levels.

- PG&E's main focus of the project was air-handling system measurements, although the results include chilled water temperature specifications. A similar analysis should be done for the measurements used around the chilled water plant. In addition, similar analyses could be performed for other energy end-use systems (e.g., compressed air systems and pumps) if the potential for energy-use reductions was felt to be significant.

APPENDIX I

TASK 3–LITERATURE SEARCH

APPENDIX II

TASK 4–SITE SURVEY AND PRIORITIZATION OF EQUIPMENT AND EVALUATIONS FOR METHOD DEVELOPMENT

APPENDIX III

TASK 5–DRAFT METHOD FOR DETERMINING THE ACCURACY AND DATA STORAGE FREQUENCY FOR SENSORS USED IN AIR-HANDLING SYSTEMS FOR OPERATION, CONTROL, AND DIAGNOSTICS

APPENDIX IV

TASK 6–METHOD FOR DETERMINING THE ACCURACY AND DATA STORAGE FREQUENCY FOR SENSORS APPLIED TO COMMISSIONING OF AIR-HANDLING SYSTEMS

APPENDIX V

DETAILED DESCRIPTION OF FAN RETROFIT MEASUREMENT AND VERIFICATION STUDY FROM TASK 6

APPENDIX VI

TASK 7–VERIFICATION OF RESULTS–APPLICATION OF RESULTS TO SMALL, MEDIUM, AND LARGE OFFICE BUILDINGS, AND A MEDIUM-SIZED HOSPITAL FOR FRESNO AND SAN FRANCISCO CLIMATES

Appendix I

Method for Determining Measurement Accuracy and Storage Frequency for Improved Building Energy Efficiency

Task 3—Literature Search

CEC Contract # 500-97-010

Project #3

November 1998

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Executive Summary

Building energy management and control systems (EMCS) are primarily designed to control energy-consuming equipment installed in commercial buildings. Many EMCS can also be set up to perform operational, diagnostic, maintenance planning, performance monitoring, performance testing, and commissioning functions. They often monitor most of the same data necessary to perform these functions.

This project was initiated to develop a method for the following:

1. Choose the measurements needed to accomplish the various data acquisition functions.
2. Determine the required accuracy and storage frequency of those measurements.

The method will be the basis for upgrading or designing building energy management systems (EMS) to perform these tasks.

The objective of Task 3 of this project was to search the literature to determine what has been published about EMCS. The literature was searched for information about measurement accuracy and collection rates required for operational, diagnostic, maintenance planning, performance monitoring, performance testing, and commissioning tasks.

Literature Search Results

- No papers provided a sound method for determining accuracy and data collection rates. Many papers describe data accuracy and data rates, but they do not provide a rationale for their recommendations, which are usually based on available or affordable instrumentation, the capabilities of the EMCS or monitoring system, or typical industry operations.
- A few papers describe methodologies and uncertainty analyses that are useful for this effort (ASHRAE Standards 150P, Heinemeier, Brandemuehl/ASHRAE 827). Other papers contain useful information about sensitivity analyses (Piette, Haberl, Burger, ASHRAE Application Building Operating Dynamics and Strategies, ASHRAE Guideline 14P, ASHRAE Standard 114 and 150P).
- A Lawrence Berkeley Laboratory (LBL) effort involved the design and installation of a diagnostic monitoring system at an office building in San Francisco (Piette Phases I and II). An extensive operations and maintenance (O&M) survey performed in Phase I concluded that currently used information tools limit a building manager's ability to assess O&M practices and give little feedback about system problems. The system was installed in May 1998 and is currently being tested and optimized. Current system instrumentation, measurement accuracies, and many useful real-time charts and diagnostic techniques are given, mostly related to the chilled water plant.

During Phase III, LBL will finalize and report on the energy savings and other benefits of the system and develop a preliminary specification to document the equipment, algorithms, and rules used in the system. LBL will determine the accuracy required for its diagnostics, and, where possible, will reduce system costs by using lower-quality sensors.

- A report by Brandemuehl describes chiller, fan, and pump testing guidelines (ASHRAE 827). The author recommends measurement accuracies and demonstrates performance and uncertainty analysis

calculations for testing of equipment. Brandemuehl's report will be useful when we consider measurement and verification of improved equipment.

- Other useful papers are those that describe how data trends were used to find problems and solutions, either during the commissioning process or during normal operation. Some papers list required measurement points for monitoring of specific equipment. Data collection rates appear to be based on the availability of storage and processing capability, rather than the requirements of the task being performed. Several papers provide useful discussion of instrumentation problems and recommendations for maintenance and calibration intervals. Most authors state that there are significant benefits to commissioning, monitoring, and maintenance.

Brief Summaries of Literature Search

Building Commissioning

- **Champagne** describes how direct digital controls (DDCs) should be used and fully tested, tuned, and calibrated during the commissioning process. Tuning requires trending of dynamic variables at 30-second to 2-minute intervals, and slower response variables every 10 to 60 minutes. Financial and energy-use data should be stored over the long term.
- **EPRI's** *HVAC Diagnostic and Commissioning System* includes a data acquisition system (DAS) and software that enables building systems testing. The report describes plots and their uses in performing building diagnostics.
- **EPRI's** *Office Complexes Guidebook* provides case studies of energy audits and diagnostics and troubleshooting.
- **PG&E's** *Chiller Monitoring Protocol* recommends instrumentation accuracies but provides no rationale.
- **Piette** (Phase I) has built a state-of-the-art Information Monitoring and Diagnostic System (IMDS) for use by building staff. The system was installed at one site. The IMDS stores 80 points once per minute and uses high-accuracy instrumentation (Table 4). Piette includes some discussion of the effect of inaccuracy on chiller sequencing and replacement and on humidity control and cooling tower performance. There is a general discussion of accuracy needs: Sensor inaccuracy can lead to false diagnosis and poor decisions. The price paid for a sensor depends on the economic consequence of a poor decision.
- **Piette** (Phase II) describes the installation of the IMDS at a bank in San Francisco (May 1998). Energy savings and usefulness to operators will be tracked to develop an automated diagnostic system with rules to help correct problems. With 56 sensors and 36 calculated points, the IMDS provides accuracy results and many good techniques and charts used for diagnostics, mostly for the chiller plant. In Phase III, Piette will investigate the reduction of instrumentation costs by reducing sensor quality, where possible, while maintaining the abilities of the system. The author plans to write a functional specification of the system and its algorithms.
- **Tseng** provides the monitoring points used to commission a government building and suggests installation of additional instrumentation, like CO_2 sensors, air flow sensors, and multiple measurement points. Tseng discusses problems that resulted from the commissioning. He stores 90 points for up to a year and 70 points for up to a week to develop a pattern of equipment performance.
- **Waterbury** describes software for evaluating the performance of commercial buildings. The report includes plots and calculations needed for analyzing heating, ventilation, and air-conditioning (HVAC) performance. Waterbury gives good examples of problems that were solved by using short-term data trends.

Building Energy-Use Modeling

- **Anstett** used a neural network to predict energy use in a building. Other papers discussed calibration of computer simulation models.

- **Curtiss and Kreider** discuss the use of neural networks to predict building energy use. With only 10 days of input data, errors were greater during holidays and for 3-day future forecasts.
- **EPRI's** *Desk Book* covers chiller performance, enables economic analyses, and gives case studies.
- **PowerDOE** could be used for sensitivity studies.
- **Stein** suggests using 7 to 12 months of whole-building hourly metered data to calibrate a model. The author explains how HVAC malfunctions can be discovered by comparing model results to actual building energy use.

Building Performance Monitoring

- **Brandemuehl** discusses optimization of control setpoints after commissioning. Outside air temperature is important in economizer performance. The author discusses the effect of interacting system components when one system is not operating properly. Logs 9 channels every 3 minutes, the remainder every 15 minutes.
- **Dodier, Curtiss, and Kreider,** *Small Scale, On-Line Diagnostics for an HVAC System,* describe the development of a real-time automated fault detection and diagnostic system at JCEM. It is a probabilistic system that identifies the costs of taking actions.
- **Dodier, Curtiss, and Kreider,** *Automated Whole-Building Energy Performance Diagnostician, Phase One,* discuss the development of the "Whole-Building Energy Performance Diagnostician" with DOE/PNL and Honeywell, which will use a probabilistic approach. The authors provide more detail than the previous reference on the various approaches.
- **Haberl, Claridge, and O'Neal** describe the data acquisition for the LoanSTAR program. Calibration accuracies are 2 to 10 times better than sensors. Inaccuracy of annual load profile prediction fell from 7 to 3% when the data set was increased from 1 to 5 months. The authors discuss uncertainty, O&M opportunities, and instrumentation problems. Weather stations require the most care (recalibration every 6 to 12 months).
- **Heinemeier** proposes general guidelines to determine if an EMCS can be used for building energy monitoring.
- **Joint Center for Energy Management (JCEM),** *Real-Time Energy Performance Monitoring, Volume I,* describes a building monitoring project in Canada that uses EMCS data to monitor and predict energy use and identify overconsumption. It requires consistent hourly data—it cannot use change of value (COV) data—and performs rigorous validations. Various prediction techniques and accuracy of simulation models are discussed. Errors are greater if the savings are small and if the input data are inaccurate. Uncalibrated models are 5 to 10% accurate for annual energy, and 10 to 15% for monthly energy predictions. Hourly prediction accuracy is unlikely. Data needed for performance calculations and redundancy for pump, fan, chiller, and so on are listed. Performance measures are described.
- **Katipamula** uses a neural network tool and periodic data to detect ventilation and economizer problems at the Pacific Northwest Laboratory (PNL) to demonstrate the use of automated diagnostics. The author describes the measurements necessary to monitor an air handler and the problems that were found as a result of the monitoring.

- **Meyers** presents examples of how data plots can be used to diagnose problems (economizers, fans, and outside air temperature sensors) and discusses how sensor accuracy needs to be based on the analysis to be performed.
- **Misuriello** discusses the benefits of field monitoring of buildings, several instruments that should be developed, and types of quality assurance checks.
- **So** describes how to put information on the Internet to centralize operations. His building automation system takes 10 seconds to update, so the system can be updated every 30 seconds on the Internet.
- **Subbarao, Hancock, and Nicoulin** performed long-term monitoring and short-term testing on an energy efficiency building. Hourly data was too infrequent to monitor fans used to cool the building and to monitor variations in solar radiation used for lighting.
- **Turner** gives accuracy specs for pressure sensors and flowmeters for EMCS, but no rationale.

Control Systems

- **Austin** uses data trends to analyze and fix HVAC operating, efficiency, and hardware problems. Good examples of trend analysis are provided.
- **Belur** uses 2- and 3-D graphs of hourly data over weekly periods to analyze building data.
- **Haines** prefers to calibrate resistance temperature detectors (RTDs) and thin-film relative humidity (RH) sensors every year, and thermisters and inWA pressure transducers every 4 to 6 months. If an EMCS is not in place, use a strip chart to trend data. Use a thin-film RH for 5% control, chilled mirror for 3% control. RTDs are accurate to 0.5°F and are cheaper over the long run.
- **Hartman** prefers limiting the per-channel cost of EMCS to $200—use thermistors for space temperature because it is stratified. A 5% accuracy on RH between 10 and 80% is good enough.
- **Krakow** tested a digital proportional integral control with short and long sampling intervals, and found that long sampling intervals do not detune the system, though they may produce adverse response phenomena if the process changes abruptly. The proportional coefficient can be changed to reduce this effect. Systems with thermal storage had similar responses with long or short sampling intervals.
- **Levine** discusses sampling rates and their effect on control and quantization error (see Chapter 16).
- **Nordeen** describes the fundamental characteristics of controls. The author suggests some ways of improving system design—by better matching equipment to load ranges, by better placement of vents, and by controlling differentials in some cases.

Data Acquisition Systems

- **Heinemeier** uses EMCS to monitor building energy use. The range of EMCS capabilities is described in terms of memory, time stamping, averaging, scan intervals, and storage intervals (15 and 60 minutes are most common). Several EMCS case studies are described. COV data is sometimes hard to convert to time-stamped data. Summarizes data storage problems. Suggests accuracy goals for energy calculations. Prism requires monthly data. Load signature analysis requires fractions of a second. Daily data detects long-term trends, and hourly data shows fluctuations. Slowly changing variables can be stored hourly. For more fluctuating parameters or better precision, store averages or

totals. For peaks, store maximums. Discusses system limitations. Also provided are graphs of LBL data, zone temperature calibration accuracies (p. 155), and allowable data storage rates (p. 160).

- **Mazzucchi** describes the measurement plan and equipment used to monitor the Federal building in San Francisco. One hundred sensors gather data at 15-minute intervals to determine baseline performance and energy savings after installation of a BACnet EMS. X-Y plots are used for data validation and other checks. Data plus 170 computed channels amount to 10 MB of storage per month.
- **Oak Ridge National Laboratory (ORNL)** describes field test systems; defines scan rate, scan interval, and throughput rate; and gives field setup accuracies of 3, 5, and 2% for heating, cooling, and water heating loads.
- **Sparks** compares nine data loggers for use in building control systems (BCS) monitoring and discusses some problem areas experienced when measuring building energy usage.

Energy Systems Maintenance

- **EPRI's** *Impact of Maintenance on Packaged Unitary Equipment* shows graphs for packaged unitary equipment temperatures vs. time and performance. Discusses effects of cycling and response time on ability to determine steady-state performance. Test instrument lists and accuracies are given. Scan rate increased from 15 to 2 minutes due to cycling. RH sensors respond in 2 minutes.
- **EPRI's** *Electric Chiller Handbook* discusses control strategies for chiller equipment operation.
- **Houghton** describes the economic and operating benefits of regular maintenance on rooftop air-conditioners. The author describes maintenance procedures and when they are justified, based on schedule, inspection, or measurements of differential pressure (DP) or differential temperature (DT).
- **Kennedy** states that good boiler maintenance can increase efficiency by 25%, and good HVAC maintenance can reduce energy consumption by 50%. Tables 14.2 to 14.7 list problems and solutions for boilers, HVAC, lighting and windows, hot-water systems, and air compressors. Table 14.14 lists boiler information to keep track of, and Table 14.18 and Section 14.7 list instruments useful for energy management. Kennedy recommends semiannual calibration of thermostats, annual calibration of controls and sensors, facility monitoring for 12 months before developing an energy management plan, and monthly checks for tracking the plan's effectiveness and for fine-tuning.

Instrumentation and Measurement

- **Brandemuehl, Krarti, and Phelan** describe the development of the chiller, fan, and pump testing guidelines (ASHRAE 827). The authors provide a literature review, instrumentation and required accuracies, modeling equations, uncertainty analysis, engineering principles, and test procedures. Several sets of site data are used to test the procedures. Factors affecting chiller, pump, and fan performances are discussed. The uncertainty in load distribution is likely to dominate all other factors but is ignored when comparing two alternatives. Recommend a minimum of 8 load points that cover 80% of expected loads, to minimize uncertainty in regression. The range of the loads tested is more important than the length of time monitoring. For chiller load, investment in accurate RTDs is more cost-effective than more accurate flowmeters. A 5% meter accuracy may be acceptable when calculating annual energy use (Figure 8-13). The primary loop chiller load may be more accurate than secondary loop measurements. Recommend instrument accuracies for testing. Detailed test data, with a large number of trend plots, are given in Appendix I.

- **Burger** discusses cooling tower sizing and O&M. A 1°F colder chilled water temperature (CWT) saves 2.5% of the energy required by a refrigerator compressor.
- **Fahlen, Andersson, and Ruud** evaluate the performance of humidity, CO_2, and gas sensors for use in HVAC. Humidity sensors last over 10 years, need calibration every 1 to 2 years, and half were 2 to 3% accurate.
- **Haberl, Claridge, and Harrje** review the design of experiments, different types of monitoring programs and their usefulness, types of parameters that could be measured, and methods of collecting data. Daily data is useful for operator feedback, hourly or faster data raises data set size issues. Calibrate often, use redundant sensors, and check data.
- **Hughes et al.** took data once per hour to analyze the performance of an earth-coupled heat pump.
- **Hurley** describes the different types of sensors used for temperature, humidity, and flow measurement in an EMS. The advantages and limitations of each are discussed. The author recommends calibration of all EMS instrumentation frequently and carefully. He has problems with most humidity sensors.
- **Hurley and Schooley** describe calibration techniques and discuss error determination.
- **JCEM,** *Testing Methods and Results for Natural Gas Engine-Driven Chiller*, used 0.1°F RTDs and 1% RPM sensors to run full- and part-load tests using 1-minute averages over 130 hours.
- **Misuriello** states that building energy use can be projected from just one week of data, though the optimum period for monitoring needs to be determined. Strip charts can help diagnose control problems, utility meters can provide annual energy consumption, and existing sensors can usually help determine economizer problems.
- **Smith** says that a sample rate 3 times the highest frequency is adequate to describe the entire signal. The conservative rule of sampling is 10 points per cycle.
- **Stebbins** recommends that flowmeters be kept clean. Vortex meters have no moving parts and are repeatable.

Real-Time Pricing

- **Daryanian, Norford, and Tabors** designed and tested a real-time pricing (RTP) system on several sites and predicted 20% savings over conventional time-of-use (TOU) pricing. Required measurements are heat or cold storage level, energy transfers into and out of storage and other parts of the system (sensor accuracy of 1°F minimum), plant electrical load, and indoor and outdoor temperatures. One month of data should be stored for forecasting requirements. It is difficult to measure cool storage capacity with ice.

ASHRAE Information

Handbooks—Applications

- **Energy Management** describes how to set up an energy management program.
- **Owning and Operating Costs** gives methods to estimate maintenance costs for economic analyses.
- **Testing, Adjusting, and Balancing** gives information on how to test specific equipment. The proper location and use of system instrumentation is vital to the accuracy of the system balance, and accuracy is essential to economical operation. Suggested tolerances for air flow balancing are given, and instrumentation and procedures are given for various tests.

- **O&M Management** shows how to calculate various O&M performance parameters.
- **Computer Applications** describes computer models and their calibration with measured data.
- **Building Energy Monitoring** provides general guidelines for developing monitoring protocols and describes types of projects. For building diagnostics, the storage rate should be 3 times faster than the time constant of the effect being monitored (several seconds to one hour), either intermittent or long term. The use of the data determines what data is needed and at what frequency. For integration of energy use over time, using models, the time step should be as long or longer than the response time of the building or system being evaluated. Scan rate should ensure that all significant effects are monitored. Perform uncertainty analysis. Table 9 recommends accuracy and scan rates for residential monitoring.
- **Building Operating Dynamics and Strategies** discusses control strategies for HVAC systems, local and supervisor levels, and global and local optimization. Gives sensitivities of power to various setpoint values (for example, if chilled water temperature is 3°F off, then power consumption is within 1% of its minimum value). Optimization and load prediction models are described. Information may be useful for sensitivity analyses.
- **Building Commissioning** general discussion of commissioning process.
- **Automatic Control** states that the requirements of accuracy, speed, and stability often conflict. An accurate sensor alone cannot maintain setpoints if the rest of the system (controller, actuator, etc.) does not perform adequately. Describes how HVAC components are controlled and operated. For digital controllers, a sampling interval of about one-half the time constant of the controlled process is usually adequate.

Handbooks—Fundamentals

- **Measurement and Instruments** describes and lists typical accuracies for various instruments.
- **Energy Estimating and Modeling Methods** discusses different methods used for estimating the energy use of building HVAC systems. The details could be useful for sensitivity analysis purposes.

Guidelines

- **14P, Measurement of Energy and Demand Savings (proposed),** states that greater accuracy comes at progressively greater expense. Gives an example of determining the uncertainty of calculating savings. Savings are significant if greater than the root mean square (RMS) error. Hourly data provides less error in energy savings (10%) compared to monthly data (20%) and gives energy-use patterns. Most systems are based on COV, and data must be converted to interval data or averaged before use. Graphs chiller heat rate error vs. flow and temperature differential error. For a chiller efficiency accuracy of 3%, flow should be 1% and temperature 0.05°F accurate. Discusses performance curve generation and chiller and fan instrumentation accuracies. Test instrumentation can provide O&M savings of 5 to 15% just by being left in place. Use redundant sensors and online checks. Strive for 10 times the scan rate of the period being measured. Lists types of data validation and discusses uncertainty. Recalibrate critical instruments every 6 to 12 months. Describes instrumentation and accuracies. Btu meters offer better than 3% accuracy, ultrasonic flowmeters are 5% devices. Appendix B describes the uncertainty of calculating energy savings.
- **GPC-13P, Guideline to Specifying DDC Systems (draft),** shows typical accuracy specs for an HVAC application in Table 1, but does not give the rationale. Provides examples of detailed

specifications for various measurements taken in an HVAC application and discusses factors that affect sensor accuracy.

Standards

- **114–1986, Energy Management Control Systems and Instrumentation,** provides guidelines for specifying instrumentation and verifying the accuracy. In DDC loops, a response time of 5 to 10 seconds should be adequate. Normal EMCS room temperature accuracy is ±2°F. Table 1 shows recommended accuracies for several types of usage. A typical error in energy calculation would be 7.5%. Check turbine meters every 6 months. Calibration accuracy should be at least twice the intended accuracy of the sensor.
- **111–1988, Practices for Measurement, Testing, Adjusting, and Balancing of Building HVAC&R Systems,** gives accuracies required for instruments used for air balancing. Gives fan, pump, and chiller equations.
- **150P, Method of Testing the Performance of Cool Storage Systems (draft),** states that the uncertainty analysis provides a simplified format for thermal discharge capacity. Requires the following accuracies: temperature (0.3°F), delta temperature (0.2°F), flow (5% over range), power (2%). Records averages of 20-second scans every 15 minutes. If the process is dynamic, the time series data may not show all of the precision error. Be careful about combining average flow and average dT in a dynamic process. Btu meters eliminate no-flow conditions. Uncertainty results for storage are discussed.

Literature Search Matrix

The following matrix of key words was used for the literature search. Each major category key word was combined with each subcategory key word, using a logical AND. This matrix focuses on published works that address building control systems that effectively manage energy use in commercial buildings. Specifically, how can existing commercial building control instrument systems best be used for energy management activities?

Results of the literature search are organized in the following categories: building commissioning, building energy-use modeling, building performance modeling, control systems, data acquisition systems, energy systems maintenance, instrumentation and measurement, real-time pricing, and ASHRAE information.

Major Category Key Words

Building Commissioning
Building Control Systems
Building Performance
Building Performance Monitoring
Commercial Building Codes and Standards
Commercial Building Operations
Commercial Buildings
Controls
Energy Analysis
Energy Management
Energy Management Systems
HVAC Control Systems
HVAC Controls
HVAC Systems
Measurement and Verification
Office Buildings
Uncertainty Analysis

Subcategory Key Words

Automation
Bandwidth
Calibration
Commissioning
Computerized Control Systems
Controls
Controls Monitoring
Data Acquisition
Data Collection
Data Leveraging
Data Quality
Data Requirements
Data Storage
Data Throughput
Data Visualization
DDC Control
Diagnostics
Energy Efficiency
Energy Management
Instrument Accuracy
Instrument Response Time
Instrument Time Constant
Instrumentation
Instruments
Load Control
Load Management
Measurement
Measurement & Verification
Measurement Systems
Monitoring
Optimization
Performance Based Codes
Performance Monitoring
Process Control
Process Evaluation
Quality Control
Regression Analysis
Reliability
Response Time
Sensor Accuracy
Sensor Service
Sensors
Sensors
Systems Analysis
Systems Response Time
Systems Time Constant
Thermal Performance
Time Constant
Time Series Analysis
Total Energy Systems
Uncertainty

Literature Sources Searched

ACEEE (ACEEE.org)
American Society of Mechanical Engineers (ASME)
ASHRAE Journal
ASHRAE Research projects
ASHRAE Transactions
California State University, San Luis Obispo
Colorado State University
EPRI HVAC Research Center, Madison, Wisconsin
EPRI Web (www.epriweb.com)
Heating, Piping and Air Conditioning (HPAC)
IEEE
Instrument Society of America (ISA)
International Energy Agency (Annex #25 and #34)
Massachusetts Institute of Technology
Purdue University
Texas A&M University
University of Colorado—Joint Center for Energy Management (JCEM)

Building Commissioning

Champagne, D.E. Application of DDC Systems in the Commissioning Process Should Be Considered in Every Building That Has DDC Controls

ASHRAE Journal, Vol. 35, No. 12, December 1993, p. 20.

Use direct digital controls (DDCs) during the commissioning process. The commissioning process includes:

1. Testing, verifying placement, and calibrating all sensors and actuators
2. Verifying and testing local control of installed equipment
3. Testing interactions between isolated components
4. Checking systemwide applications and interactions

Fine-tuning requires the ability to isolate variables and identify trends over time, to check for operational stability. Variables that change slowly over time (like room temperatures or relative humidities) can be sampled every 10 to 60 minutes. Dynamic trending can be sampled every 30 seconds to 2 minutes and can be displayed on dynamic plots. Command tracing is useful for commissioning. Long-term storage of financial and energy-use information is useful for optimizing control strategies to minimize energy use. Make sure that specifications address the commissioning process and that they include procedures and required documentation. Expert systems will be able to monitor performance, predict problem areas, and take corrective action. Processing at the sensor will enable expert systems to give warnings about malfunctions or the need for calibration.

Electric Power Research Institute (EPRI). HVAC Diagnostic and Commissioning System (HDCS)

EPRI Building Systems Analyzer: HVAC Program, Final Report CM-108359, July 1997, Palo Alto, California.

Enables the setup of the MicroDataLogger portable data acquisition system (DAS) to perform building commissioning testing. Recommends the measurement points for each system chosen. Provides the data in plots that can be used for system diagnostics. *Help menu describes all of the plots and discusses their use in diagnostics.*

Electric Power Research Institute. Office Complexes Guidebook—Innovative Electric Solutions

EPRI Report TR-109450, December 1997, Palo Alto, California.

Case studies of energy audits and energy-saving measures, diagnostics and troubleshooting, short-term monitoring with HVAC analyzer, new DDC, environmental, lighting, and HVAC (p. 191). About 50% of total energy and 33% of electricity in commercial buildings goes to heating and cooling (lighting is the largest electrical load). Provides packaged system costs, central air retrofit alternatives, and calculation of loads (p. 203).

Pacific Gas and Electric Company. Chiller Monitoring Protocols

Report 9463.03, prepared by Energy Simulation Specialists, Inc., July 21, 1995.

Appendix D contains specifications for data loggers and instrumentation used to monitor flow, power, and temperature. Specifications include instrumentation accuracy; however, the rationale behind the specification is not discussed.

Piette, M. A., and Sebald, A. Diagnostics for Building Commissioning and Operation, Phase I

Environmental Energy Technologies Division, Lawrence Berkeley Laboratory, Report LBNL-40512, December 1997, Berkeley, California.

The goal is to design a building diagnostic system to improve operations and maintenance (O&M) capabilities and help implement cost-effective energy-saving investments for the energy management of building systems. A building diagnostic system, including sensors, computer, information processing, and data visualization, was designed. Automating the system will come in Phase II (building, deploying, and evaluating a system). Targeted toward sophisticated building operators and engineers. This permanent system with state-of-the-art sensors archives 80 points every minute in a top-down approach. Will explore how to automate the system for a broader class of users.

- Could save 15% or more of energy costs. System would cost $75K. (p. 5)
- Major types of O&M problems (from literature search and interviews). General problem is lack of information on energy performance of building systems. Limited diagnostic capabilities. Sensors not properly calibrated. Constraints include black box complexity, economics, energy cost (not a top priority), lack of knowledge of new technologies, poor initial design. (p. 10)
- State of diagnostic technologies. Concluded that top-down approach and human assistance in fault detection are most promising. Oriented to having the building technical staff as the main user (unlike previous approaches, i.e., Haberl Energy Systems Laboratory system is used by building researchers). Designed system is more accurate and reliable than current EMCS. (p. 14)
- *How good does sensing have to be? Good data leads to correct diagnoses of building problems and credible cost/benefit information. Incorrect dew point (by 2°F) can cause a 30% increase in pumping. Incorrect tons can alter chiller sequencing and reduce efficiency. Another example given of chiller replacement with a smaller unit.* (p. 19)
- *More accurate cooling tower cell outlet temperatures could detect poorly performing cells or imbalances.* Installed sensors are not good enough for this diagnostic monitor. Operators give up calibrating poor sensors and ignore them. Initially higher cost sensors have lower life-cycle costs. (p. 21)
- Focused the system on the whole building, cooling end use, and cooling towers and chillers. Lighting and ventilation are too complicated. (p. 25)
- *Description of diagnostic system. 3-D cooling load plot, energy-use intensity comparison, efficiency (kW/ton) vs. load (reasons for degradation), cooling tower performance (CWTemp vs. WBTemp by DeltaT (reasons for degradation).* (p. 27)
- System Specifications: Sensor accuracy shown in Table 4, points on pp. 37–39. (p. 35)

Some control companies said that operators do not exploit current EMCS, so why would they add a new system? New DDC systems are complicated and confusing. Decided not to partner with the controls industry.

Appendices for Piette and Sebald, Diagnostics for Building Commissioning and Operation, Phase 1, 1997

Appendix B, State of Diagnostic Systems and Related Technology

- Section 5.2, Sensing, discusses the state of sensors that could be used for diagnostics. It indicates that water-side sensors can be very accurate for a long period of time albeit quite expensive, whereas sensors on the air side are not as reliable due to fouling. Reference is made to Texas A&M University and Supersymmetry systems, which are accurate systems.
- Section 5.3, Data Communications, discusses the relatively inexpensive hardware that would be required for data logging, archiving, and diagnostics. EMCS typically have data logging systems that are inferior to the stated requirements.
- Section 5.4, Processing and Analyzing the Raw Data to Convert to Diagnoses, shows some installed systems and generic tools (e.g., neural nets, fuzzy logic, artificial intelligence) to illustrate the types of data processing. Table 2 includes data sampling frequencies: Texas A&M University (15 minutes), Supersymmetry (1 minute), and EMCS (15 minutes). Ten diagnostic plots can be used to analyze building and cooling system performance.

Appendix C, Report on Relevant Sensor Issues

This appendix includes a listing of the IMDS physical and calculated points, as well as the formulae for each calculated point and cost for physical points.

The approach used in this task poses two questions: (1) Can one get sufficiently accurate and robust sensors for areas of interest in this project? (2) How accurate should sensing be?

The answer to the second question is that it depends on the intelligence of the control architecture, especially its ability to diagnose and cope with sensor degradation/failure. It also depends on a cost/ benefit analysis. The project team attacked this problem on two fronts:

1. Conceptualizing why/where sensor errors get magnified when computing the measure of energy inefficiency.
2. Generating specific, quantitative *examples* that demonstrate cases in which inaccurate or nonexistent sensing has significant cost impact (cooling tower cell performance degradation with no outlet temps, chiller cooling load accuracy affects sequencing, humidity accuracy affects pumping load, chiller cooling load and performance accuracy affects retrofit decisions).

According to the report, all sensing capability, with the exception of relative humidity and comfort sensing, is available.

The appendix discusses two problems: sensor accuracy and longevity of its calibration. Sensor accuracy is affected by installation (e.g., dirt on air side) and maintenance. Purchasing high-quality sensors is more cost-effective over time because of sensor degradation (Figure 9). *Comment:* Consideration of initial accuracy as well as long-term performance of a sensor is important. They claim there is very little

problem with maintaining a good sensor on the water side of an HVAC system. The closed loop part of the water side is chemically treated.

The appendix discusses how sensor accuracy affects building efficiency, fault detection, and diagnosis. The crucial aspect here is how sensor accuracy can contribute to a false diagnosis. The section discusses how the intelligent systems can detect sensor degradation and inaccuracy and compensate for them.

The authors describe how sensor accuracy contributes to the total cost of detection, diagnosis, and decision making. The point is made that sensor accuracy is coupled with algorithms—techniques required to provide the information sufficient to make a decision—but that one must make a trade-off between the accuracy of the sensors and the algorithms/techniques. The ultimate goal is to make the whole process of generating the information necessary to make a decision understandable to the humans making the decision (see Figure 15)—"excellent sensing can dramatically enhance the accuracy of the diagnosis." Ultimately of utmost importance is the credibility of the diagnosis to the human making the decision to spend resources. *The price paid for a sensor should depend on the economic consequence of making an incorrect decision.*

Appendix E, Narrowing the Scope

The quality of sensing has a great deal to do with credibility and "understandability" of the results. "Understandability" refers to whether a human understands how a diagnosis was arrived at. Excellent sensing of all appropriate variables makes the decision straightforward (e.g., when V1 is greater than 2, the economizer is stuck open). "Credibility" refers to the degree to which one is willing to risk one's job to defend, for example, a proposal to spend money to retrofit a poorly functioning system. Excellent sensing also simplifies the computational and visualization tasks.

There is less risk to their project by installing the best sensors possible (called "excellent" sensors), and the benefits are greater than if inadequate sensors were installed. The risk is that the measurement system would have to be further engineered to see which sensors could be eliminated or replaced with less accurate sensors. Inadequate sensors are a risk in that the sensors could fail or provide erroneous readings.

Appendix F, The Knowledge Base System

This appendix contains many useful diagnostic plots and useful information about various plant components—fundamentals, diagnostic steps, failure modes, and so on. Identification of energy waste or building system malfunctions is based on comparing energy performance data from a single building (or building system) to performance benchmarks generated from a variety of sources, such as fundamental engineering principles, expert opinions, manufacturer's performance specifications, historical performance statistics, computer simulations, and shared data from similar buildings. The benchmark data and methods used to examine them are in a knowledge base system (KBS). The KBS should provide both the best conceptual framework for understanding each diagnosed system and the information on regimes in which the system is performing adequately or malfunctioning.

The KBS modules describe how a particular system (e.g., chiller) is supposed to work and how an expert would identify performance faults. The modules contain the following:

- Performance metrics to describe how the module's equipment is performing
- Graphical displays to evaluate performance and detect failures

- Quantitative benchmarks for typical and best available performance
- Definition of required measurements and sensors needed to support the module
- List of critical failure modes (Note: Failure can be a catastrophic failure or a failure to achieve proper performance)

Section 5 discusses the KBS in the above format for seven modules: whole-building energy, whole-building electricity, cooling system, chiller, cooling tower, sensor diagnostics, and cost/benefit analysis. Each module relies on the following basic relationship to analyze energy consumption:

$$\text{energy} = \text{efficiency} \times \text{power (load)} \times \text{time (schedule)}$$

The equation provides a framework for identifying and analyzing faults in each system. In some modules (cooling, chiller, and cooling tower), failure modes include efficiency degradation and problems with scheduling and load.

Section 5 contains listings of sensor accuracy and data sampling rates based on what the project team installed in the building, as well as references to required sampling rates, data accuracy, and data points. For example, the potential value of 1-minute data is referred to in 5.3.6: There are additional opportunities with 1-minute data. For example, one can identify start-up peaks for chillers and pumps.

Types of data are discussed in 5.4.2.4: Differential pressure measurements are useful in determining how the pump performs compared to the rated pump curve. The power meter is used to measure electricity use, determine the pumping schedule, and assess opportunities for efficiency improvements.

In 5.4.2.5 the relationship of data types is mentioned: Careful tracking helps to explain how the kW/ton ratio varies with other operational parameters, such as part loading, condenser water supply temperature, and chiller water supply temperature.

Implied in the discussion are the various general tasks such as operation, maintenance, performance monitoring, and cost-effective retrofits. Many graphics use kW/ton as a performance indicator. The before and after kW/ton is used to indicate the value of a maintenance activity such as cleaning chiller tubes (5.4.2.5.1).

Some implications of required accuracy are suspect. For example, in Step 4 of 5.5.1.5, it is suggested that "if the kW/ton is consistently more than 10% greater than the manufacturer's curve, check to ensure that the chiller is not fouled and that the refrigerant is properly charged." There is no explanation for the 10% figure. It may be just a rule of thumb. It is, however, suggesting a standard of performance and in doing so implies an accuracy requirement for the data. The data accuracy, for example, would need to be greater had the standard been 5%.

Some diagnostic graphs seem to imply a data accuracy: In Figure 50, a plot of condenser water supply temperature vs. wet bulb temperature, the condenser water temperature has a very small range of values. A 1°F uncertainty would likely make the data meaningless for performance analysis purposes.

Figures 23 and 24 are examples of data trend plots. These trends are highlighted by linear data regression, which depends on little or no uncertainty in the x-axis variable (outside air dry bulb temperature).

Piette, M. A., et al. Early Results and Field Test of an Information Monitoring and Diagnostic System for Commercial Buildings

Lawrence Berkeley Laboratory, Draft Phase 2 Project Report, August 12, 1998, Berkeley, California.

This report documents the early results of a project that developed and demonstrated an information system for continuously monitoring the performance of building energy systems. The system was designed to detect problems with the performance of the building energy systems and diagnose the source of the problems. Its purpose is to provide building owners and managers with reliable, understandable, and credible information about energy system performance. This information will support decisions to improve O&M practices in the building and to implement cost-effective retrofits for significant energy savings.

During Phase 1, the project team identified that building operators lack good information about major building energy systems. The project team therefore developed the Information Monitoring and Diagnostic System (IMDS) to meet this need.

During Phase 2, which started in May 1998, the system was installed in a San Francisco bank office building. The system consists of hardware (sensors, data acquisition, and communications equipment) and software. The data from the building is available locally to building operators and remotely to project researchers. The IMDS monitors the entire building energy consumption and the water side of the cooling system.

Phase 2 involves tracking energy savings and developing a diagnostic system with generalized rules to identify and correct problems with various building energy systems. The IMDS uses sophisticated monitoring and data visualization techniques to accomplish this task.

The goal for the remainder of this multi-year project is to determine whether this system can provide 15% energy-use savings.

This project has a strong focus on recruiting and working closely with building personnel who have a strong interest in the project's goal. The project team selected a building where state-of-the-art hardware and software would ensure the maximum possibility of success in accomplishing the project's goals.

Following are the major highlights of the report:

- Pilot site selection: A bank office building in San Francisco was selected as the pilot site. The property manager is an enthusiastic, technical innovator whose company is responsible for 5 million square feet of commercial property in California.
- IMDS description and accuracy: IMDS monitors 56 physical points related to whole-building electricity, cooling system, and weather. It has 36 calculated points. A discussion of equipment failure modes and diagnostic plots available through IMDS are presented. This section discusses sensor accuracy in detail; this issue will be examined further during Phase 3. The report also compares EMCS data and IMDS data: The differences are attributed, in part, to their respective locations.
- Building performance and findings from IMDS: IMDS initial use results are presented. Savings opportunities were not available in whole-building electricity use; however, O&M opportunities were evident from data visualization graphs (e.g., the chiller's operating for a short time without a load and cycling of the cooling tower fan).

- Automation of diagnostics: The current emphasis is on human's interpreting easy-to-understand graphics to detect faults. The project also includes researching automation of fault detection and identifying their source. Research indicates that enthusiasm for interpreting graphs wanes after a few months, so an automated process is needed to provide an alarm to which the operator can respond. This diagnostic system will initially be based just on predetermined failure modes, but eventually it will be able to interact with the operator to explain how it identifies a fault. They are exploring the possibility that the system could learn from its experience with little or no help from a human operator.
- Economic issues and related technologies: The current cost of the system is estimated at $1/square foot. The project goals are to bring this down to $0.30/ square foot by reducing the cost of system components as they become more generally used; and to investigate whether the number of sensors used and the required sensor accuracy can be reduced. It is expected that many of the measurement techniques, data archival systems, and analysis will be incorporated into EMCS technology over time. The relation of IMDS with other emerging technologies is also discussed.
- Conclusions and future plans: While implementing the IMDS in a commercial building, the project team is informing other property managers that the technology exists and is available for review. During Phase 3, the project team will develop a more detailed functional specification that documents the rules and algorithms to describe the most important faults detected with the diagnostic system. In addition, the team will continue to explore methods of automating the diagnostics.

Tseng, P. C., Stanton-Hoyle, D. R., and Wither, W. M. Commissioning through Digital Controls and an Advanced Monitoring System—A Project Perspective

ASHRAE Transactions 1994, Volume 100, Part 1. Presented at the 1994 Winter Meeting, New Orleans, Louisiana.

The use of DDC monitoring for commissioning and building turnover is essential. Owner oversight (preferably with a commissioning agent) and a well-planned monitoring protocol are required. Finding problems before turnover will avoid years of troubleshooting. Hidden problems, equipment defects, and design errors can be uncovered; and performance of equipment can be documented. This paper discusses use of a commissioning protocol on a multi-use government center in 1991 in Maryland, with state-of-the-art heating, ventilation, and air-conditioning (HVAC) and ice and heat storage systems. Diagrams of monitoring points shown for air handling, ice harvester, cooling tower, and metering points.

Many problems found and lessons learned:

- Combination of DDC and pneumatic controls (with no monitoring) was a problem.
- Install a full compliment of monitoring points—the incremental cost is small, and they pay for themselves during the first year of system shakedown.
- Install air flow sensors on both supply and return air ducts and all variable air volumes (VAVs) to perform air balances.
- Install CO_2 sensors.
- Install multiple thermistors to determine true zone temperatures. One temperature is not accurate enough.
- Do not use both variable speed drive (VSD) and vortex damper controls. Use on/off controls on return fans for adequate control.

- Software points should include building average temperatures, ice tank capacity, and peak demands.
- Perform cross-checking (ASHRAE 90.1-1989).
- Develop control sequences; do not rely on a design engineer.
- Look for meters that are not working and equipment that is the wrong size.
- Follow the Testing and Balancing (TAB) subcontractor. Make sure the sequence makes sense. Spot check.
- Use DDC on all VAV units.
- Ice tank bridging problems, refrigerant leaks, thermal storage undersized.

They trended 90 points for one year, using 22 MB storage to develop a pattern of equipment performance under varying operating conditions.

Waterbury, S. S., Frey, D. J., and Johnson, K. F. Commercial Building Performance Evaluation System for HVAC Diagnostics and Commissioning

ACEEE, 1994 Summer Study on Energy Efficiency in Buildings, Vol. 5: Commissioning, Operation, and Maintenance.

Paper describes the Commercial Building Performance Evaluation System (CBPES) software. This Windows program asks for HVAC system information, develops an instrumentation list, initializes battery-powered (wireless) data loggers, downloads data from the loggers, and provides the plots and calculations needed to analyze the HVAC system. About 40 hours of engineering time is required to set up the test, install the data loggers (data is collected for 2 weeks), collect them, and analyze the data. Typically ten 4-channel loggers are used.

Paper discusses three case studies:

1. Plots of zone temperature vs. time showed that one building was still heating at night when it was unoccupied.
2. Plots of static pressure vs. time showed that one building with VAV (static pressure should be constant with air flow) was not modulating its fans properly and was turning its third fan on and off, resulting in large variations in static pressure.
3. Plots of outside air fraction vs. outside temperature showed that one building providing a large variation of outside air below 40°F.

A great deal of insight can be achieved in a short period of monitoring.

Building Energy-Use Modeling

Anstett, M., and Kreider, J. F. Application of Neural Networking Models to Predict Energy Use

ASHRAE Transactions 1993, Volume 99, Part 1. Presented at the 1993 Winter Meeting in Chicago, Illinois.

Artificial neural networks (ANNs) were used to predict energy use at a student activities building at a Colorado university. Data from the BEACON system was used; the system consists of a spreadsheet program containing daily meter readings, weather, occupancy, and energy-use predictions (this program has led to energy conservation and maintenance measures). The ANN model is a pattern associator. The aim of the training process is to reduce error between predicted energy use and actual use. More than one year of data was used.

A single network produced the best result. Root-mean-square (RMS) errors of less than 0.1 were attained. Compared to the statistical prediction method (a variance of 0.3 for Feb 1990), the ANN variance was 0.7 (much better). The BEACON spreadsheet system has been augmented with neural network predictors for electricity, steam, water, and gas use. The ANN predictors can be as accurate as handcrafted predictors. ANNs degrade less than expert systems, but the training cost is expensive.

Bell, D., Kreider, J. F., and Curtiss, P. S. Energy Performance Model for Marriott Moscone Hotel — Tasks 3 and 4

Joint Center for Energy Management, JCEM/TR/96/5, February 11, 1996, University of Colorado, Boulder.

This report describes ongoing project work to develop a neural network model. The model will be used to predict electrical consumption for the Yerba Buena Ballroom and Conference Center at the Marriott Moscone Hotel. The report describes data problems, changes made to data, and various types of training sessions. Some key findings were that data sets used for neural net training must be carefully checked for correctness, and accurate and fast training of simple nets is possible with cleaned data sets. This report does not contain information relevant to this project, unless training of neural network models is used for collected data.

Curtiss, P. S., and Kreider, J. F. Performance of Neural Networks Used to Predict Future Building Loads Using Limited Inputs

Joint Center for Energy Management, JCEM/TR/96/11, 1996, University of Colorado, Boulder.

Two types of neural networks were trained to predict whole-building electricity consumption, cooling plant loads, and heating plant loads 1, 2, and 3 days in advance. In comparing the performance of a multiple input/single output network with a multiple input/three output network, it was found that the single-output network performed better (less error in prediction) than the three-output network.

The networks performed best at predicting whole-building electricity consumption and poorest at predicting building heating load. Errors increased as the network predicted further into the future because slight early errors tended to be amplified as the prediction time increased (i.e., day 3). Errors also tended to be large around holiday periods and is apparently related to the effect of the training period. Typically, the training did not represent the energy-use pattern for a weekday holiday such as Thanksgiving.

Likewise, the training period is too short. The 10-day training period for this study caused the predicted consumption patterns at the end of the Christmas season to be skewed.

Electric Power Research Institute. Desk Book—Commercial End-Use Technologies, V1.0 EPRI Software

EPRI Report AP-108045, December 1997, Palo Alto, California.

Describes chiller systems (Chapter 14), efficiency, and coefficient of performance (COP); shows COP vs. load; compares different systems, maintenance, and life-cycle costs; *optimization strategies* (Chapter 20); economic analysis example results; marketing statistics (Chapter 22); research on improved chillers (Chapter 30); 6 case studies. There is a fairly detailed analysis of the *chiller economic calculator* (a separate program).

Electric Power Research Institute. PowerDOE Quick Start Guide—Building Energy-Use Analysis Software

EPRI Report TR-105934, December 1996, Palo Alto, California.

Building energy-use software that might be useful for uncertainty analysis studies.

Kreider, J. F., and Curtiss, P. S. Energy Performance Model for Marriott Moscone Hotel—Final Report

Joint Center for Energy Management, JCEM/TR/95/9, February 28, 1995, University of Colorado, Boulder.

This report describes a neural network model developed for predicting electrical consumption for the Yerba Buena Ballroom and Conference Center at the Marriott Moscone Hotel. The network was trained with hourly occupancy data and metered electrical consumption between Sept 1992 and August 1993. The input data was reduced to occupancy numbers by zone, kitchen production information, and time of day. Electricity consumption was predicted with an accuracy of 15 to 25% for periods not included in the training data sets. The describes details of the neural network modeling, training, and testing. This report does not contain information relevant to this project, unless training of neural network models is used for collected data.

Manke, J., Hittle, D., and Hancock, C. E. Calibrating Building Energy Analysis Models Using Short-Term Test Data

Proceedings of the 1996 International Solar Energy Conference, March 31–April 3, 1996, pp. 369–78, San Antonio, Texas.

A test protocol was developed and used to test the energy demand of two buildings—a conference center in Colorado and a school in California—over a 3-day period. BLAST (Building Loads Analysis and System Thermodynamics) was used to model the energy demand. Four primary parameters were varied until the RMS difference between the test data and BLAST data was minimized. Total measured and predicted energy demands agreed within 0.6 to 1.8%.

Rabl, A. Parameter Estimation in Buildings: Methods for Dynamic Analysis of Measured Energy Use

Journal of Solar Energy Engineering, Vol. 110, p. 52, February 1988. Transactions of the ASME.

The paper describes forward and inverse models. Forward models are given a description of the building and solve for the energy use. Inverse models are given actual performance data and solve for the building's characteristics as a way to model the energy use. Inverse models have fewer parameters and are simpler: They include thermal networks, differential equations, ARMA (autoregressive moving average), and Fourier analysis. Calibration of computer models is not systematic, is labor-intensive, and is not suited for EMS. The paper mainly covers ARMA and uses it with data from an office building in Princeton, New Jersey. Estimated error is 15 to 20%. The ARMA model seemed to do as well as DOE 2.1. The results are worse than other investigations because of the building's complexity. Solar gain and air exchange present problems in the ARMA and differential equation models.

Rabl, A., and Rialhe, A. Energy Signature Models for Commercial Buildings: Test with Measured Data and Interpretation

Elsevier Science Publishing, Energy and Buildings, 1992, Vol. 19, pp. 143–54.

This paper investigates whether the application of the energy signature model PRISM can be improved by adding occupancy (occupied and unoccupied) as a variable. The hypothesis was tested with energy consumption data from 50 commercial buildings in France. The results show that inclusion of occupancy data can significantly improve energy signature models for commercial buildings. However, many of the buildings provided inconclusive data. The authors attributed these anomalies to poor data quality or uncertainty associated with energy consumption data.

Stein, J. Calibrated Simulation—An Improved Method for Analyzing Building Energy Use

Tech Update, TU-97-10, September 1997.

Calibration of simulation models to estimate energy savings is more reliable than statistical estimation techniques, does not require expensive end-use instrumentation, takes longer (7 months to 1 year of whole-building hourly metered data recommended), and is more precise than traditional building simulations. Calibrated simulation can be used to estimate or verify savings, allocate energy consumption to end uses, identify building malfunctions or "phantom" loads, and optimize HVAC control. The entire process can take 3 to 5 months. Can use DOE-2 (or PowerDOE), BLAST, etc. Only projects that affect the building's HVAC system usage are appropriate for calibrated simulation (others can be done more simply). Can use "typical-year" weather files for before and after runs. Building malfunctions can be discovered when actual energy use differs from modeled energy use (could be done in real time by an EMS).

Steps involved: (1) collecting whole-building hourly electric data, weather data, building data, and data on major electric load circuits if desired; (2) entering data into model and run; (3) comparing results to measured building load data; and (4) modifying the model until results compare well. Comparisons can be made with plots and statistical variance calculations.

Building Performance Monitoring

Brandemuehl, M., and Bradford, J. Implementation of On-Line Optimal Supervisory Control of Cooling Plants without Storage

Joint Center for Energy Management, JCEM/TR/98-3, January 1998, University of Colorado, Boulder.

1-1 Project goal was to optimize cooling system setpoints to minimize energy consumption for the entire cooling system, not just for individual components. List individual setpoints to be optimized.

1-2 In typical HVAC system, control systems not optimized to minimize system energy use. Control strategy—setpoints of the feedback loop prescribed by operator or by mapping to other system conditions. Lists typical setpoints for HVAC system components.

2-18 Basic mechanical system maintenance and commissioning important before optimizing control system. More savings can be realized from these actions than from control system optimization; in fact, should not try to optimize control system until these are done. Example: Improper calculation of outside air (software) and sensor out of calibration (hardware) caused outside air economizer to work improperly, overwhelm water-side economizer, and cause cooling plant to provide more cooling than necessary. This also demonstrates the interaction of HVAC system components; for example, changing chiller operation affects operation of chilled water pumps and supply air fans.

2-29 HVAC systems are very interactive. Cannot get one subsystem to operate efficiently without addressing all systems.

3.1 *Data Collection and Handling* (p. 3-30). Data is logged using history sheets defined in Staefa control system software. Each history sheet can log a maximum of 5 analog and 4 digital channels from building systems for later analysis. Collection occurs about every 3 minutes for each data point. History sheets are downloaded from a system node to a hard drive every 3 to 5 hours. Fifteen-minute data calculated from history sheets every 3 to 5 days. Generates csv file for each history sheet.

3.2 *Operation of System for Collection of a Rich Data Set* (p. 3-31). "A rich data set, with system operation over a wide range of controlled and uncontrolled variables, is required to adequately model the building HVAC system using historical data."

3.3 *Power Measurements.* Discusses several strategies to obtain electric power measurements due to physical configuration of the electrical system and cost of making measurements.

4 *Systemwide Models for Optimization.* Discusses models developed to optimize system energy consumption. One method (quadratic formulation) uses method similar to minimizing first derivative of a function. Others (global search and gradient search methods) search for a minimum by changing the values of a combination of variables that affect consumption.

5 *Component-based Model.* This appears to be similar to the systemwide model in that the processes used to determine the reset values for minimum energy consumption are the same. The component-based model is linked, simplified component models.

6 *Comparison of Optimal Control Methods.* Compares five control methods: (1) operation of system at constant design values, (2) resetting individual equipment setpoints without consideration of overall system energy use, (3) selection of reset laws based on raw historical data, (4) use of a systemwide quadratic model, and (5) use of a component-based model. Discusses the positive and

negative aspects of each. Component-based model seems most robust and is applicable to a variety of buildings.

7 *Implementation of Optimal Control Methods.* Discusses results of using the quadratic systemwide model and the component-based model on an actual building.

Dodier, R., Curtiss, P. S., and Kreider, J. F. Automated Whole-Building Energy Performance Diagnostician, Phase One

Joint Center for Energy Management, JCEM/TR/96/7, January 17, 1996, University of Colorado, Boulder.

This report discusses the "Whole-Building Energy Performance Diagnostician," a DOE/PNL project in collaboration with JCEM and Honeywell. The work discussed includes a literature search of the diagnostic and statistical literature, creation of a probabilistic approach, development and operation of a computer code to further assess the recommended approach, and assessment of work to be completed. This report contains much of the same information as Dodier, Curtiss, and Kreider (February 1996); however, it contains details on various approaches that were not discussed in the other report.

The report describes diagnosis by probabilistic inference by stating that the proposed system for diagnosing equipment faults is reduced to two basic steps:

1. For each possible equipment state S, estimate the probability of S given the observed data.
2. Of all the possible actions, take the action that has the least expected cost. The expectation is with respect to the state probabilities.

The report discusses various models to carry out this task. Some features could be useful in the final product.

The system is designed to tell an operator, based on probability, what state a specific piece of equipment is in—normal operation, some fault state, or an unknown state. In addition, it will be able to suggest the best course of action.

Sections 3, 4, and 5 discuss in great detail the probabilistic inference approach and its implementation. Section 6 discusses a demonstration of the basic system software, showing the output of the system and how it is interpreted. Section 7 states the progress to date.

Section 8 puts this work into a larger context by discussing the direction of future research. At the completion of this report, JCEM was ready to test the demonstration system (software) with real data acquired in its lab from a fan-powered mixing box. The system initially uses data only from a piece of equipment under normal operation to generate probabilities used in the model. Probability information for equipment operation under fault conditions will be obtained from expert knowledge initially programmed into the system.

The plan is to have the system adjust the probabilistic model as it assimilates data from actual equipment operation. It is assumed that this will correct errors in expert knowledge initially programmed into the system. The authors plan to research means of increasing the accuracy of the diagnosis by providing the system not only with raw data but also with preprocessed data. This data will be based on trends and spike features in the data. The accuracy of the diagnosis should also be improved by taking into account the relationship between successive equipment states.

Another research task was to develop techniques for handling missing data (especially from sensor failure) and developing a method for detecting sensor failure.

Dodier, R., Curtiss, P. S., and Kreider, J. F. Small Scale, On-Line Diagnostics for an HVAC System (RP 883), Progress Report 3

Joint Center for Energy Management, JCEM/TR/96/4, February 1996, University of Colorado, Boulder.

This report describes progress on the development of the Real-Time Diagnostic System (RTDS), an automated fault detection and diagnostic scheme for HVAC equipment. It describes the principles of its operation and the results of applying it to data acquired in JCEM's laboratory during the operation of a fan-powered mixing box.

The researchers are using this technique to diagnose equipment status, given some observed data from an HVAC system. They use an approach called "probabilistic inference." This technique is used to compute a degree of belief that the equipment has a certain status. It uses this degree of belief to determine the cost, in terms of risk or reward, of taking possible actions. This allows a decision maker to identify the best possible course of action.

Based on the discussion, all of the states of the equipment must be identified: the normal operating state, all failure states, and the unknown state. In addition, the probability of each state must be estimated, along with the probability of the state given specific observables (data).

The operating states of a fan-powered mixing box is used to illustrate the technique. Its state, which happened to be a failure state, was successfully predicted by this technique. The report details the calculations involved. Success with the approach was limited. The technique provided incorrect diagnosis when the data used to construct the model did not have a wide enough range (i.e., it did not include data encountered while running the system).

Future work on the diagnostic system will include modeling of temporal correlation and whole-building states. The temporal correlation enhancement relates a given state to previous states. There is a probability of making a transition from a previous state to a current state that is part of estimating the current state. ("Equipment states tend to persist through time, so there will be a strong correlation between successive states.") Whether that transition is made is based on a transition probability for equipment failure. That probability, P, is related to the sampling time, T, and the mean time between failure (MTBF) of equipment by:

$$P = 1 - \frac{T}{MTBF}$$

This technique was applied to a simple HVAC with a fairly small number of possible operating states. The authors had wanted to make diagnoses on larger systems, such as whole buildings. They discuss the problems with scaling the techniques up to those larger systems.

Gerold, J.S. OI Software Opens a Window to the World Wide Web

Control Engineering, February 1998, pp. 84–90.

Use of the Internet or Intranet for plant monitoring has several benefits: remote monitoring, access any device, ease of use (familiar tools), access to information anywhere and anytime, reduced costs (client/server architecture and Intranet/Internet wiring). “Thin” clients rely on servers to maintain the application and database. The Web is moving toward “push” technology, where client screens are automatically updated. Java would work on any platform, ActiveX takes advantage of existing software. Risky to be allowed to control equipment in large or hazardous applications. Intranets may dominate for this reason.

Haakenstad, L.K., and Tom, S.T. Using Native BACnet Systems in Open Protocol Installations.

ASHRAE Journal, March 1998, pp.57–64.

Use of an open protocol allows integration with different manufacturers’ building systems. It keeps options open for future expansion or replacement, operators need training in only one system, and it enables a facility-wide approach to energy usage. Of the several open protocols available, BACnet was chosen because it supports a wide range of communication network types and speeds, at all levels. It is object-oriented, so new features can be added.

Haberl, R., Claridge, T., and O’Neal, H. Measuring Energy-Saving Retrofits: Experiences from the Texas LoanSTAR Program

Texas A&M University, Energy Systems Lab, ORNL/Sub/93-SP090/1, February 1996, Office of Building Energy Research, DOE. Published by National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia.

This report documents how data was acquired and savings analyzed for the Texas LoanSTAR program. Four levels of instrumentation: (1) whole building, (2) limited submetering (electric and thermal), (3) more submetering (fans and motors), and (4) 20 or more submetered hourly data. Schematics on pp. 25–27. Keep costs within 3% of retrofit cost. Calibration lab set up at Texas A&M. Calibration accuracy is typically 2 to 10 times better than the sensors (Table 2.5). Humidity is problematic, especially in high-RH Texas. Paddlewheel insertion depth accuracy is critical. Energy consumption reports (p. 62) and plots (pp. 64–65). Short-term data errors fell from 7.3 to 3% for cooling and from 27.5 to 12.9% for heating when data sets went from 1 month to 5 months. An outdoor temperature close to the annual mean and a large temperature range during the period were critical. Uncertainty discussion on p. 77. O&M opportunities identified on p. 94. Instrumentation problems on p. 104. Maintenance problems on p. 108. Paddlewheel meters were removed for calibration and service every 12 to 18 months. Weather stations require the most care: calibration every 6 to 12 months, replace wind and RH sensors every 1 to 2 years.

Heinemeier, K., and Akbari, H. Proposed Guidelines for Using Energy Management and Control Systems for Performance Monitoring

ACEEE, 1992 Summer Study on Energy Efficiency in Buildings, Vol. 3, Commercial Performance: Analysis and Measurement, Lawrence Berkeley Laboratory: pp. 3.111–120.

EMCS are usually not designed with monitoring in mind, and the characteristics of EMCS are determined by a building’s control needs rather than by monitoring needs. However, EMCS generally contain nearly all of the equipment necessary for monitoring. This paper discusses guidelines for using

EMCS for building energy monitoring. Unfortunately, using an EMCS for this purpose may require the building engineer to solve a unique set of problems for the system to work effectively. Following is an outline of the proposed guidelines:

1. Determine if the EMCS has the necessary sensors to meet building monitoring objectives.
2. Determine if the sensors have the required accuracy to perform energy analyses that will meet building monitoring objectives.
3. Ensure that sensors are properly calibrated before beginning the monitoring program.
4. Ensure that the EMCS hardware and software can record the necessary historical data.
5. Ensure that instantaneous and average user-selected interval data is available for troubleshooting and analysis.
6. Ensure that the system has ample available data storage capacity to meet monitoring objectives.
7. Store historical data at specified times, not specified intervals; additionally if the system is restarted, it should begin collecting data at the correct time.
8. The user should be able to connect to the system remotely, using generic communications software.
9. The system should provide remote trending capabilities.
10. Ensure that historical data is easily accessible.
11. The time required to transmit data to a remote location should be as short as possible.
12. Ensure that remote data transmission errors are automatically detected and corrected.
13. Ensure that remote access to data does not interrupt other EMCS control or operations functions. Conversely, EMCS operator activities should not interfere with remote data collection.
14. Ensure that real-time and historical data are available in an easily processed format.

Joint Center for Energy Management. Determining the Time Constants and Thermal Characteristics of Stadium Bleacher Section

JCEM/TR/95/13, June 8, 1995, Dept. of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder.

Determined the time constant for modeling a stadium bleacher section that experiences extreme conditions and is an HVAC challenge. Used an instrumented test chamber with a small section of step and riser and a seat to perform the test. Heated by infrared (IR) lamps and measured with thermocouples (TCs). Used a stepup and stepdown in temperature for tests, then simulated different cooling mode patterns and solar, air temperature, and air flow rates, using the time constant results. The relevant results are surface temperatures.

Joint Center for Energy Management. Real-Time Energy Performance Monitoring, Volume I

JCEM/TR/91/5, March 27, 1991, University of Colorado, Boulder.

This Public Works Canada (PWC) project evaluated a method of monitoring building energy consumption: data were collected by standard EMCS using a PC-based computer program called an “energy management module” (EMM). The model has several functions: monitor energy consumption of individual buildings, predict expected energy consumption, identify over-consumption, and archive

important data. To perform these tasks reliably, the study concludes that the EMM must check for correct sensor readings frequently (hourly, daily, or weekly, depending on the size of the system) and use the data in robust statistical routines to predict expected energy use. *EMCS that archive data only on change of value, and not hourly, will not work for this application.* The use of one EMM for different buildings, with different EMCS, requires use of a standardized "Gateway" communication protocol that PWC is using.

The study also concludes that it is not practical to use hourly simulation programs for this real-time purpose at the time this study was performed (1990). Compared to statistical methods, the required expertise and effort to calibrate such a model makes it impractical. The study suggests that neural networks and the Building Coefficient of Performance concept are better possibilities.

The study states the need for continuous checking of data quality, using various methods:

- "Sum checks"—verify that individual electric submetered data add up to a separate total measurement (analogous to an energy balance check).
- Check for reasonableness against expected or previous values.
- Use range limits.
- Use rate of change of sensor readings.
- Do initial checking and calibration.
- Use good quality instrumentation.

The authors caution to be sure of a consistent time stamp for data from multiple sources. A reference clock time should be available and used for time stamp purposes, and clocks should be reset for various field data acquisition system (DAS) units that may have their own clock. Also, redundant measurements of critical parameters can be used to improve data quality and provide data checks. Another method is logical sensor checks (an event causes another event to happen, but the system does not indicate the event—indicates either a sensor problem or a control problem).

The types of data collected by the EMCS in this study include:

- temperatures (fluid loops, air distribution, liquid distribution, central plant
- liquid flows using annubars
- air flows
- duct pressures
- electric power

The processing of data for energy calculations takes place in a separate PC. This PC accesses the required data from the EMCS on an hourly basis for processing and archiving.

Various methods used for building energy analysis are discussed. Forward and inverse methods (e.g., *ASHRAE Fundamentals Handbook*, 1997, Chapter 30) are described. Standard regression techniques are described; however, they are described as either too simplistic or unreliable for complex commercial building applications. More robust statistical methods are recommended, such as Principal Component Analysis (PCA) and Singular Valued Decomposition (SVD). These techniques remove correlations between the predictor variables, which tend to make standard regression results unstable. Finally,

artificial intelligence methods are described: expert systems and ANNs. The expert systems can help interpret discrepancies between measured and predicted energy use (diagnostic function), but cannot by themselves do the predictions. ANNs learn from actual data and can be used for the energy prediction function. This method is recommended as a viable method for energy-use predictions.

The report discusses calibrated simulation models and their use for residential and commercial building energy analysis. Energy use is divided into three categories: appliances, lighting, and HVAC. HVAC is further broken down into envelope and internal loads. Residential loads are dominated by envelope loads, whereas commercial building loads are dominated by factors independent of the envelope (lighting and internal loads). Simulation methods include detailed hourly (DOE, BLAST, etc.), simplified hourly, and bin methods. Some general results of numerous validation studies are given: Simulated energy consumption is within ±20% of measured values; occupied buildings can be simulated with about the same level of accuracy as unoccupied buildings; cooling energy use is more difficult to predict than heating; simulated energy savings compared to actual energy savings is more inaccurate if the savings are small; and the largest discrepancies are due to verifiable errors in input data rather than model inaccuracy.

For commercial buildings, occupancy schedules significantly impact energy predictions. For uncalibrated models, these accuracy estimates can be broken down further: The limit for annual energy prediction appears to be about 5 to 10%; for monthly energy prediction, 15 to 20%. Calibration of the simulation models for commercial buildings is difficult and time-consuming. *Even with model calibration, it is concluded that 5 to 10% is the best to be expected for annual energy consumption predictions, and 10 to 15% for monthly predictions.* Accurate hourly or daily consumption using standard simulation programs is unlikely. Calibrated simulation models are therefore not practical for real-time (hourly) energy analysis for this program.

Basic and redundant data to be collected for various performance calculations are listed. Redundant data can be used for quality checks and to fill in when basic data is missing or bad. Following is a summary:

Chiller Performance

Basic data
- electrical input power
- chilled water flow
- chilled water inlet and outlet temperature
- condenser water flow
- condenser water inlet and outlet temperature
- cooling tower fan power

Redundant data
- compressor motor on time per hour
- chilled water pump on time and pressure rise
- redundant chilled water inlet/outlet temperature, or independent direct ΔT
- condenser pump on-time and pressure rise
- redundant condenser water inlet and outlet temperature, or independent direct ΔT
- cooling tower fan on-time per hour
- redundant flow sensors in chilled and condenser water loops

Fans

Basic data
- electrical input power
- total air flow
- supply, return, and mixed air conditions (temperature and humidity)
- fan pressure rise

- fan outlet temperature

Redundant data
- fan motor on-time per hour
- fan speed for variable speed drives
- independent measure of fan pressure rise
- redundant measure of air conditions (supply, return, mixed)
- coil inlet or distribution system air supply temperature (backup to fan outlet temperature)
- air handler damper angles (for diagnostics)

Pumps

Basic data
- electrical input power
- water flow
- water pressure rise

Redundant Data
- pump motor on-time per hour
- independent measurement of water pressure rise

A note is made that pump efficiency calculation is of relatively low priority until there is widespread use of VSDs; however, the data is also useful for diagnostic purposes.

Similarly, data requirements are listed for heat pumps, boilers, weather, lighting, and controls.

For lighting, the only measurement recommended is lighting power or light on-time, which can be used for diagnostics if lights are on when they should not be.

Control data sent with each hourly scan includes channel number, date and time, and possibly sensor status. For this study, the EMM clock is used as the standard, and other peripheral system clocks are reset hourly if they differ.

Data integrity and sensor checks are discussed. Sensor checks should include range checks and rate-of-change checks. Only measurements that should not change rapidly can be checked by the latter technique. Drift is difficult to detect, so redundant sensors and regular calibration of critical sensors is recommended. Consistency and reasonableness checks include conformance to first and second law of thermodynamics and logic tests (i.e., agreement between event sensors and power use by those systems). Other checks include comparing measured energy use with expected use (predicted).

Described performance measures start with whole-building measures. These are useful for long-term planning, budgeting, and trending. One such measure is the *Building Coefficient of Performance* (BCOP), defined as the total output divided by the total input, where output is the cooling or heating energy provided by the central plant and distributed by the secondary systems, and input is the utility energy consumed. It is an aggregated measure of total building performance (perhaps analogous to total plant heat rate for power generation facilities). The authors suggest that a daily value probably makes the most sense. Another measure is *Energy-Use Intensity (EUI),* defined as the annual energy consumption per unit floor area. This measure has a wide variation by building type. One possible recommended use is trending, while continuing to look for ways to modify the EUI to better account for these variations.

Performance measures for equipment or systems are important for finding and diagnosing problems. Whole-building performance measures do not allow this. Two methods are described for equipment or system performance evaluation: (1) *energy difference between actual and predicted* and (2) *specific*

equipment or subsystem efficiency. The energy difference measure is defined as a ratio of energy difference to the standard deviation of historical data for a given end use. This way, normal variations can be differentiated. The specific efficiency measures included pump efficiency, chiller COP, and fan efficiency. Differences from expected values or changes over time can be used to identify a problem.

Data archiving needs are discussed. For energy-use information, the authors recommend storing only the basic data and the calculated energy statistics (not the backup data). However, when diagnostic capabilities are included in the EMM, they recommend archiving all data. This will aid in future diagnostics.

The need for useful graphical interfaces to display important results to the operator is discussed.

The need for further work on ANNs to verify their performance on buildings and subsystems is discussed.

Three appendices give detailed case studies of the PCA statistical method (Appendix A), the SVD statistical method (Appendix B), and the ANN method (Appendix C) for electrical energy-use predictions in commercial buildings.

The report contains much information about building performance analysis and prediction. Useful measures are discussed, as well as the data required. Ranges of achievable accuracy for performance predictions are given. Mention is made of the need for data accuracy and methods to check and verify sensor reasonableness. However, *there is no specific information about sensor accuracy requirements or overall accuracy of measured performance indicators.* Hourly archiving of data and results is assumed, but frequency of data scanning is not discussed.

Numerous references are provided.

Katipamula, S., and Brambley, M. Improving Efficiency through Automated Diagnostics

Energy User News, Vol. 23, No. 4, Cahners Business Information, April 1998, p. 22.

This paper describes the benefits of combining building automation systems with a diagnostics software. The U.S. Department of Energy (DOE), in collaboration with industry, is developing a tool that automates detection and diagnosis of energy consumption problems. This tool will identify and diagnose problems with overall building energy usage and with the outdoor air/economizer.

Operational problems associated with degraded equipment, failed sensors, improper installation, poor maintenance, and improperly implemented controls plague most commercial buildings. The whole-building energy usage tool provides a mechanism to train neural networks to model and predict energy end uses of the whole building. The outside air/economizer diagnostician uses tools derived from engineering models to analyze and detect problems associated with air-handling performance.

Both tools use periodic data from the building's energy management system. This system was installed on seven air-handling units at the Pacific Northwest National Laboratory (PNNL). The outside air/economizer diagnostician has proven effective in identifying outdoor air ventilation and economizer operation problems.

These tools represent only two applications of automated diagnostics. Similar tools could be used to detect and diagnose problems with many other building HVAC components and systems (e.g., boilers, chillers, VAV boxes, heat exchangers, pumps, fans).

Katipamula, S., and Claridge, D. Importance of Monitoring Air Handler Performance

ACEEE, 1992 Summer Study on Energy Efficiency in Buildings, Vol. 3, Commercial Performance: Analysis and Measurement, Texas A&M: p. 3.164.

As part of the Texas LoanSTAR program, an air handler was monitored at an engineering center. The air handler is 20,000 cfm (including 2,000 cfm outside air), 40 hp (30 kW). Measurements included outdoor air, return air, mixed air, and cold duct temps and RH, air flow, fan power, filter DP, and hot duct temperature. Mixed air temperature vs. outdoor air temperature has a slope of 0.1°F per F, consistent with 10% outdoor air. Problems found:

1. The cold deck temperature showed a strong relationship to outdoor air temperature due to fouled coils—part of the coils were not providing cooling (effectively a bypass).
2. The outdoor air dampers were left open during a hard freeze, resulting in increased heating.
3. The hot deck temperatures were above 100°F, even during warm weather, because one of the two hot water pumps was always on; at low outdoor temperatures (below 40°F), the hot deck temperature was too low because the second pump did not kick on, indicating improper control.

Without monitoring, these problems would have been difficult to detect.

McGowan, J. J. Distributed DDC: Network, Architecture Questions Shape Trends

Energy User News, Vol. 17, No. 2, Cahners Business Information, February 1992, p. 22.

The latest technology in building automation is distributed DDC. DDC use with a network is called a local area network (LAN) building automation system (BAS). It can reduce energy and system costs and improve the quality of building operation. Distributed controllers are common with large HVAC equipment. Equipment-level controllers provide application-specific control sequences and integrate them with the island host and building-wide functions. Object-oriented programming is easier than computer language programming. With equipment-level control, a separate island host is needed for each manufacturer.

Meyers, S., Mills, S., Chen, A., and Demeta, L. Building Data Visualization for Diagnostics, Operator Feedback, and Performance Optimization

Third National Conference of Building Commissioning Proceedings, May 1–3, 1995, Milwaukee, Wisconsin.

This paper discusses the use of data visualization to recognize equipment failure and improper operation of equipment in buildings. It presents several detailed examples of how this was carried out for various lighting and HVAC system equipment in California buildings. These included malfunctioning fans, economizers, and faulty outside air temperature sensors.

The paper mentions development of custom data acquisition software, which interfaced with existing sensors and A/D converters of the UC Berkeley EMCS to collect and visualize data from the mechanical systems in 40 campus buildings.

It discusses sensor accuracy in general, saying that the variables that need to be measured and the necessary accuracy of the measurements depend on the analysis to be performed on the data. The required individual sensor can then be back-calculated to meet the targeted objectives.

Misuriello, H. Field Monitoring of Building Energy Performance

ACEEE, 1990 Summer Study on Energy Efficiency in Buildings, Vol. 10: Performance Measurement and Analysis, pp. 10.177–193.

This article documents the three major elements of field monitoring of buildings. Monitoring is conducted for either utility load research or to attain more specific information about building systems. Building energy efficiency topics include model development, ventilation, solar heating, efficiency standards, codes, behavioral aspects, weatherization, energy efficiency labeling and rating, and program evaluation. Many more monitoring protocols are needed, and Misuriello (1987) proposed a procedure for uniform development. Describes Mazzucchi (1987)—"A commercial building energy end-use monitoring protocol for utility load research"—and McDonald (1989)—"A protocol for monitoring energy efficiency improvements in commercial buildings." Packaged field data acquisition systems have come far in solving monitoring needs in a neat package.

Gaps: (1) need a way to measure gas end use without installing expensive new meters, (2) need a cheaper, better way to measure energy output from devices, (3) need a simple, low-cost, thermostat-setting monitor, and (4) need to consider short-term testing needs.

Quality assurance includes data verification, redundant measurements, installation tests, failure detection, calibration, range checks, relational checks, rate-of-change checks, and comparison to expected values.

Owens, G. R. Energy Management 2001—Predictions of What an Energy Management System Might Look Like in the Next Century

Heating/Piping/Air Conditioning, April 1992, p. 49.

This article predicts what the author thinks an EMS should look like by 2001. CPUs will be cheap enough to be installed in every component for control. Artificial intelligence will be used in EMS to predict the response of a building to optimize the operating strategy. Communication will be by traditional methods (twisted pair, coaxial, etc.) or by infrared or radio wave. A building's complete set of plans will be loaded into and used by the EMS for display screens. Video and audio of components will be available, and virtual reality could even be used to make the operator feel like he or she is at or inside the equipment.

So, A., Chan, W., and Tse, W. Building Automation on the Information Superhighway

ASHRAE Transactions 1998, Vol. 104, Pt. 2.

This article describes how to put information from a "smart" building automation system on a LAN and the Internet. The system can be used for monitoring, alarming, data and trend logging, control, energy auditing, and condition-based maintenance purposes. Five types of information: status (on/off), sensors (temperatures, flows, loads, pressures, and lighting), alarms, trends, and control. Not all equipment should be controlled remotely. Hardware required: ethernet card in one operator workstation, connection to a router, access to a gateway. A simulated air-handling unit can be accessed and controlled at *http://bcpc09.cityu.edu.hk/iba/*. Important to have a real-time video image to show the effect of control

actions. Status updated every 30 seconds. The BAS normally takes tens of seconds to update, so the Internet delay is negligible. Merits include ability of manufacturer to assess the equipment and centralize operations in a single office.

Subbarao, K., Hancock, C. E., and Nicoulin, V. Evaluation of the Energy Performance of a Building

Joint Center for Energy Management, JCEM/TR/93-32, March 1993, University of Colorado, Boulder.

This report describes the analysis of the electricity consumption of a small, two-story, low-energy office building near Portland, Oregon. The building was designed to minimize both lighting and cooling energy consumption. Lighting consumption is minimized using daylighting to cut back on artificial lighting; an outside air economizer and building and core flushing fans decrease chiller electricity consumption. The building is constructed with hollow-core floors and ceilings that allow cool outside air to maintain a cool building mass.

The analysis is based on data acquired from long-term monitoring and some short-term testing. It is not clear how many of the parameters were recorded on an independent data logger and how many came from the preexisting EMS. The authors make reference to three daylighting sensors and an outside air temperature sensor that are read by the data logger; and mention that various temperatures, solar radiation measurements, and supply air flow rates came from preexisting instrumentation. In addition, building floor plans show sensors for electric power, wind speed and direction, relative humidity, and water flow. Electric power was monitored on five circuits. The EMS controls the lighting, heating, and cooling systems.

There is no mention of the accuracy of the sensors used either by the EMS or those connected to the data logger. It appears that the data resolution for the analysis was one hour. In at least two instances, the authors refer to its effect on their analysis. In one case, they referred to the limitation of calculating the cooling COP for fans used to flush the building with cool air. They could not calculate a cooling COP (defined as the cooling accomplished by the fan divided by the heat energy it transferred out of the building) for hours when they knew the fan was not operating the entire hour. In another instance, they describe how archiving global horizontal solar radiation on an hourly basis is adequate for thermal analysis, but this time period is too long for lighting and daylighting because of potential variation of radiation throughout the hour.

Sensor issues were discussed in a number of places. For example, placement of sensors was an issue for the daylighting and thermal study. In the daylighting study, they discussed placing the daylight sensors so as to represent the amount of diffused light reaching the work surfaces in the building. Note that these sensors were read by the EMS which, using a control algorithm, controlled the on/off of banks of lights in the building. The authors refer to a combination of mathematical techniques and sensor placement to accomplish this goal. They also recommend using a combination of sensor readings as proxy to meet this need.

In the thermal study, the authors discussed problems related to sensor placement. For example, in describing the benefits of night flushing (using cooler air to lower the air temperature in the building), the authors gave significantly different results based on which sensor's data was used in the calculation. They also indicated that the flushing operation affected the data coming from the sensor.

The authors used a variety of analytic techniques to estimate the electricity consumption for lighting, heating, and cooling had the building not been designed with energy-saving devices. This provided them

with a baseline for estimating the savings from these energy-efficient design features and for determining whether and where additional savings might be found. The results of the study showed that the daylighting, heating, and cooling systems all had additional savings potential.

The data for these analytical techniques came, in part, from short-term tests. For example, a whole section of the report discusses the infiltration and ventilation characteristics of the building. These were determined from a number of short tests using tracer gas.

Turner, W. C., ed. Energy Management Handbook

Fairmont Press (distr. Prentice-Hall), 3rd ed., 1997, Lilburn, Georgia.

Table 5.4, Boiler Performance Troubleshooting, shows some operational problems that could be sensed with an EMCS and their possible causes. Section 12.B7.0, Devices, gives specifications for temperature sensors, pressure sensors, watthour transducers, and flowmeters for EMCS. Accuracy specs given for pressure sensors and flowmeters but not for temperature sensors. Table 14.14 (p. 400) shows information to be logged for boilers.

Control Systems

Austin, S. B. HVAC System Trend Analysis

ASHRAE Journal, February 1997, p. 44.

The author uses a DDC/EMS at Glaxo Wellcome in North Carolina to develop trends to analyze HVAC performance. Examples given of fan cycling every 16 minutes during night purging (put a deadband on the night purge criteria and minimum times on the on/off times of the units), economizer cycling (put a deadband on the enthalpy comparison of outside vs. return air), outside air temperature increased from 31 to 55°F at 12:30 a.m. (sensor was placed inside an air intake, which turned on at 12:30; replaced with 3 sensors placed properly), space doesn't need cooling without outside air intake (chilled water valve was leaking, thus still providing cooling even when not needed). Trend analysis can help solve operating problems, increase energy efficiency, locate defective hardware, identify out-of-calibration devices, improve comfort, and extend equipment life.

Belur, R., Kissock, K. and Haberl, J. Exploring an Enhanced Data Viewing Facility for Building Operators

ACEEE, 1992 Summer Study on Energy Efficiency in Buildings, Vol. 3: Commercial Performance: Analysis and Measurement, p. 3.33.

This paper illustrates how animation can improve the viewing of 2- or 3-D graphs of load vs. ambient temperature. Several weeks' worth of hourly data are shown on a graph, and the public domain software enables the operator to jump forward or backward in time (one week in this case). Animation might provide insight into how a building consumes energy, for calibrating simulation programs, and for viewing multiple interactions such as temperature, solar, wind, and humidity.

Bertini, D., and Brandemuehl, M. Testing and Evaluation of TESS Dynamic Performance

Joint Center for Energy Management, JCEM/TR/92/2, 1992, University of Colorado, Boulder.

This report describes the testing of the Teletimer Energy Saving Service (TESS), a programmable home automation system that can be used to control home HVAC equipment such as a heater, air-conditioner, or heat pump. The TESS consist of three components:

1. TESS Command Center: Transmits scheduling and weather information via pager.
2. HVAC controller: Performs digital PI control of the HVAC equipment based on room temperate and information it receives from the TESS Command Center.
3. SmartStat: Serves as a temperature sensor for the HVAC controller. It also provides a means of programming a setpoint temperature and viewing data.

The purpose of the testing was to evaluate the performance of the TESS HVAC controller against a temperature setpoint maintenance criterion (the controller should maintain the zone temperature within 1.5 degrees of the setpoint temperature) and temperature setpoint recovery criterion (the controller should return the control zone from the setback conditions no more than 20 minutes before or ahead of schedule). It appears that this control system would allow the homeowner to maintain the room air temperature within a very small range (3°F swing) while at home and be able to remotely schedule the

heater or air-conditioner to bring the room air temperature within this range from a setback condition at least 20 minutes before arriving home.

The report describes the experimental setup including data acquisition at JCEM's lab. Tests simulating an air-conditioner, a heater, and a heat pump operating under different part-load conditions were performed to capture the system's performance over three setback/recovery cycles. Each test lasted 24 hours.

Test results showed that the controller was able to maintain the space temperature within 1.5°F of the setpoint. The controller had the HVAC system recover the space temperature to the setpoint temperature between 0 and 40 minutes earlier than necessary. The authors recommend that the recovery could be delayed without affecting occupant comfort. Finally, the results indicate that the controller did not cycle the HVAC equipment more than other controllers and would not affect equipment life.

Curtiss, P. S., Kreider, J. F., and Brandemuehl, M. J. Adaptive Control of HVAC Processes Using Predictive Neural Networks

ASHRAE Transactions 1993, Vol 99, Part 1. Presented at the 1993 Winter Meeting, Chicago, Illinois.

This paper demonstrated that an ANN can control a water coil used to warm an air stream. Air flow and temperatures, as well as water flow and temperature can vary considerably and affect the coil time constant, or speed, during normal operation. Proportional integral derivative (PID) control is not adequate under some conditions. The ANN predicts how the process will behave over some finite number of steps into the future and "back propagate" to adjust the controller output so as to minimize the error between the desired setup and the predicted result. The best RMS error of the PID controller was 6.63. For F(future)ANN, the RMS was 6.90; for an I(integrated)ANN, the best RMS was 6.43. ANNs can be used for adaptive and predictive control of a building process. An AT-class machine was able to perform the ANN control in a 10-second scan rate. Both ANN controllers have the potential to outperform the standard PID algorithm.

Haines, R. W. Roger Haines on HVAC Controls

TAB Professional and Reference Books, 1991, Blue Ridge Summit, Pennsylvania.

Collection of articles published in *Heating/Piping/Air Conditioning* magazine.

- RTDs (thin film) should be calibrated every 12 months, thermisters every 4 to 6 months, strain gage pressure transducers (0 to 4 inWA), and diaphragm sensors every 4 to 6 months, RH thin or thick film sensors every year (use a chilled mirror to calibrate). If no EMCS, use a chart recorder to trend up to 7 days. (p. 16)
- For RH control to 5%, use a thin-film capacitance (or resistance) type whose accuracy is 3%. For 3% control, use a chilled-mirror sensor whose accuracy is 1°F (equal to or better than the solid-state sensor). (p. 130)
- Though thermistors are cheaper, they drift, and they require frequent calibration. For long-term cost and reliability, use RTDs. Absolute accuracy is 0.5°F and sensitivity is 0.1°F for all sensors. Thin-film drifts more than wire-wound. Thin- or thick-film RH sensors are 3% accurate and drift 1% per year. Chilled mirror is 3% accurate, but humidity can be controlled to 1%. Many clear and interesting articles on control of HVAC. (p. 158)

Hartman, Thomas B. Direct Digital Controls for HVAC Systems

McGraw Hill, 1993, New York.

Should limit per-channel cost to $200. Prefers thermistors because accuracy of space temperature is not that important due to stratification. Thin-film RH sensors cost $100 to $200 for 5% accuracy between 10 and 80% RH. Good enough. Silicon diaphragm pressure sensors are about $300 and can go down to 0.1 inch. Hot wire anemometers for air flow (24$ per point). Excellent reference for DDCs and advanced controls. Easy-to-understand explanations of control strategies.

Krakow, K. I. Sampling Interval Magnitude Relation to Digital PI Control System Performance

ASHRAE Transactions 1998, Vol. 104, Part 2.

This paper discusses the technical details of experimental and simulated response characteristics for a digital proportional integral (PI) controlled mixing valve for both first- and second-order PI control systems. The author investigates the difference between short and long sampling intervals and whether long sampling intervals can be used effectively.

For first-order systems (systems without thermal storage), long sampling intervals produced fewer deviations from target responses than did short sampling intervals. Long sampling intervals do not detune a system. However, long sampling intervals may produce adverse response phenomena if the process changes abruptly. Effects of this adverse response can be reduced or eliminated by changing the proportional coefficient rather than the magnitude of the sampling interval.

For second-order systems (systems with thermal storage), long and short sampling intervals yielded similar responses.

Levine, W., ed. The Control Handbook

CRC Press, 1996, Boca Raton, Florida.

Book on control theory and practices. Divided into fundamentals, advanced methods, and applications. Fundamentals include basics of control engineering, with subsections on digital controls and modeling of dynamical systems. Chapters on specification of control systems.

Chapter 16, Sample Rate Selection:

- Section 16.1, Introduction: Trade-off between cost (e.g., higher sampling rates require faster A/D conversion speed) and performance. Selection of sampling rate for digital control systems depend on factors including smoothness of time response, effects of disturbances and sensor noise, parameter variations and quantization.
- Section 16.2, Sampling Theorem: Discusses sampling and reconstruction. Sampling—process of deriving a discrete time sequence from a continuous time function; reconstruction is the reverse. Goal to obtain unique continuous time function from sampling.
- Section 16.5, Measurement Noise and Prefiltering: Discusses the filtering of high-frequency noise from input signal prior to A/D conversion to improve sampling of signal.
- Section 16.6 Effect of Sampling Rate on Quantization Error.

Nordeen, H. Fundamentals of Control from a Systems Perspective

Heating/Piping/Air Conditioning, August 1995, p. 33.

This paper describes how a basic HVAC loop is controlled (source/transport system/space). Controls function to provide comfort, manage energy use, and monitor conditions. Describes control loop performance parameters: stability, response time, overshoot, offset, settling time, and time lags. Controls are challenged by poor measurements, inadequate device turndown ratio, changes in system gain with operating point (e.g., steep fan curves, oversized valves), hysteresis (e.g., loose linkages), and interacting processes. Describes “time-proportioned on/off” control, and proportional control (with integral and differential terms). Cascade control uses more than one variable (secondary variables) to control a process. DDCs have reduced the cost of PID controls.

When designing a system, consider location of terminal units (place at building perimeter where heat gain takes place) and sizing (match to range of loads—turndown and efficiency are important). Some HVAC systems can control on differences—reduce hot water temperature difference when outside air temperature is higher or building load is less, reduce air differential pressure when air flow is reduced by VAV boxes (saves fan energy).

Data Acquisition Systems

Heinemeier, K.E., The Use of Energy Management and Control Systems to Monitor the Energy Performance of Commercial Buildings

Ph.D. Thesis, December 1994, LBL-36119, UC-1600, Dept of Architecture, UC Berkeley.

Investigates the use of EMCS, instead of dedicated data logging equipment, to monitor building energy use. Describes EMCS and data logging systems.

- Some EMCS store all points hourly for 24 hours (p. 26).
- System memory varied from 20 KB to 2 MB (EPRI 1992). Interfaces at the RCU, at the zone level instrument, or at a computer. Most EMCS can be programmed for energy monitoring (p. 29).
- Cites a dozen papers related to monitoring uses for EMCS. (p. 30). Data may not be coincident in time.
- Five methods for using the EMCS for monitoring. (p. 32).
- Good summaries of papers on monitoring and protocols (p. 41).
- Reasons for monitoring (p. 48).
- Factors to consider (p. 50).
- Analysis techniques (p. 53).
- Data collection intervals—15-minute and hourly are most common. For PRISM, monthly is fine (p. 62).
- Case studies (p. 64):
  - Levy: Data averages could be obtained as follows: 10 minutes of 1-minute averages, hour of 5 minutes, day of hourly, month of daily, or year of monthly. Capability of different intervals was useful.
  - Bullock's: Demand and dry bulb (DB) temperature averaged and stored every 15 minutes, downloaded every day for a year. Monthly kWh and peak demand stored for 3 years.
  - Prairie View and Lubbock A&M: 46 buildings. Trend of instantaneous data on demand only to disk or printer. Not easy to access or average.
  - SW Med Center Texas: Stored on COV, needed to be converted to hourly data, sometimes difficult (if data was stored less often than hourly - if COV is set too high), bad formats.
  - Texas Capitol: Flexible programming, can be stored at top of hour.
  - Texas A&M Engg. Bldg: Both EMCS and monitoring. Averaging limitations in the EMCS.
  - Compaq: Advanced EMCS stored data every half hour for up to a year. DDE in Windows OS allowed other programs to use data as well as over the network.
- Summary of data storage problems. Problems could be fixed in improved software, hardware not too bad. EMCS vary so much that it is not possible to design a monitor that would fit several. Monitors have to be designed for each. (p. 71)
- Table II-3 suggests accuracy goals for energy calculations. Actual goals depend on evaluation method. Accuracy calculation equation. Discussion of calibration. (pp. 25, 81)

- Data might be instantaneous, averages, totals, or maximums (p. 87). Monitors usually 15 minutes or hourly. Prism is monthly. Load signature analysis is fractions of a second. Daily can detect long term trends, hourly shows fluctuations. Slowly varying variables like outdoor air temperature can be taken hourly. For variables that change quickly or need more precision, collect averaged data. For peaks, collect maximum value data. Flow or energy may require totals. Some systems allow only one type of data collection, others more than one technique. If high-frequency data is collected, anything can be calculated. A watt transducer will need averaging; a watthour transducer with pulse needs a counter. Disk capacity needs to be considered. Some systems have a limit on number of samples per point for each trend or on number of points that can be trended. Time stamping at a specified time or on intervals. Hour before or after.
- *Graphs of data from test site at LBL* (p. 120).
- Calibration accuracy (p. 155).
- Data storage (p. 160).

Mazzucchi, R., Gillespie, K., and Lippman, R. Energy Data Acquisition and Validation for a Large Office Building

ACEEE, 1996 Summer Study on Energy Efficiency in Buildings, Vol. 3, Commercial Buildings: Technologies, Design, and Performance Analysis, p. 4.247.

Describes measurement plan and equipment, data processing, and validation used at the Federal Building in San Francisco to determine the energy savings from the installation of a BACnet EMS system. About 100 sensors were installed, and data is gathered at 15-minute intervals to determine baseline performance of the building. Data is collected via modem once per week. X-Y plots, such as cooling load vs. chiller kW, plug load vs. lighting load, and percent outside air vs. outdoor temperature, are plotted for data validation. Data statistics (minimum, maximum, and mean) are compared with archived statistics to detect large deviations or trends. Validation flags are set if data is OK, missing, outside of range, or fails a reasonableness check.

An insertion turbine meter failed because of water slugs; it was replaced with a vortex shedding meter. Five percent of records have validation flags (acceptable). With 170 computed channels, storage is 10 MB per month.

Oak Ridge National Laboratory. Field Data Acquisition for Building and Equipment Energy-Use Monitoring

Prepared for the Department of Energy, Proceedings of the National Workshop, October 16–18, 1985, Dallas, Texas.

General papers on how to set up field tests, descriptions of loggers and sensors, remote DAS, use of microcomputers.

- Scan rate (100 channels/sec), scan interval (5 minutes), and throughput rate (chan/sec rate through full computer process) are defined Integrating measurements reduces scan-to-scan variation, reducing error (p. 141).
- ORNL field setup had heating, cooling, and water heating load measurement uncertainties of 3.4, 5, and 1.7% (p. 175).
- No papers specifically addressing our topic.

Sparks, R., Haberl, J., et al. Testing Data Acquisition Systems for Use in Monitoring Building Energy Conservation Systems

Eighth Symposium on Improving Building Systems in Hot and Humid Climates, May 13–14, 1992, Dallas Texas, pp. 197–203. Sponsored by Energy Systems Laboratory, Department of Mechanical Engineering, Texas A&M University.

This paper discusses laboratory testing of nine data loggers for use in the Monitoring and Analysis Program of the Texas LoneSTAR program. These data loggers are used in parallel with building control systems to monitor energy savings from building energy conservation retrofits. The paper describes, in fair detail, how the tests were conducted and provides an overview of the results. Results include some of the problem areas that these data loggers experienced in measuring building energy usage. Results for specific data loggers were not provided.

Stroupe, R. Data Collection for Packaged HVAC Units

Slides from the PEC Workshop, Class Exercise: Packaged HVAC Diagnostics, May 6, 1998.

Five examples—air-side economizer performance, compressor cycling, evaporative precooling @ condenser, SEER rating, and CO_2 reset control—were examined for questions to answer about actual operation, required measurements, data logging intervals, duration of test, and interpretation of data.

Energy Systems Maintenance

Electric Power Research Institute. Electric Chiller Handbook

EPRI TR-105951-R1, February 1998, Palo Alto, California.

Refrigerant Management. Because CFC refrigerants are no longer being manufactured and because the EPA levies large fines for release of refrigerants, it is very important to keep refrigerant leaks to a minimum. Chapter 8, Chilled Water System Optimization, discusses chiller control strategies such as chiller sequencing and chilled water and condenser water reset. Also discusses operation of cooling tower and pumping system to minimize energy consumption (7.5.3).

Electric Power Research Institute. The Impact of Maintenance on Packaged Unitary Equipment

EPRI TR-107273, February 1997, Palo Alto, California.

- Graphs of supply, return, and condenser air temperatures for a packaged unit vs. time show effects of cycling (p. 4-1).
- *Difficulty in separating out steady-state performance while operating. Response time of instrumentation is also a factor. Compressor status point used to separate out data.*
- Instrument list and accuracies (p. 4-4). Scan rate increased from 15 to 2 minutes due to cycling. Longest interval that would allow discrimination of transient start-up and shutdown effects. RH sensors responded in 2 minutes. Maintenance procedures listed.
- *Performance vs. outdoor temperature* (p. 6-3).
- *Long-term performance plots* (p. 6-4).

Electric Power Research Institute. Commercial Building Energy Management Systems Handbook—Opportunities for Reducing Costs and Improving Comfort

EPRI TR-101638, RP-2830-10, June 1993, Palo Alto, California.

Concise description of energy management equipment and potential areas for improvement of each type. List of manufacturers.

Electric Power Research Institute. Assessment of Gas and Electric Cooling Equipment

EPRI TR-101142, August 1992, Palo Alto, California.

Installed costs, efficiencies, and uses for electric and gas cooling equipment.

Houghton, D. Operating and Maintaining Rooftop Air Conditioners

ASHRAE Journal, December 1997, p. 50.

Regular maintenance of rooftop air-conditioners costs little and can save hundreds of dollars per year (a 10 ton/35kW unit costs $2000/year to operate and $10,000 to replace). Air-side maintenance should be done first. When DP across filter is .5 to .75 inWa higher than new, replace (schedule every 1 to 6 months). Can reduce air flow (23%) and cut cooling capacity (7%). Dirty coil reduces airflow and degrades heat transfer, which cuts cooling capacity. Inspect annually and power wash. Check supply fans 2 to 3 times per year. Check belts once or twice per year. Specify premium fan motors (90% effective vs. 80% effective). Check outside air damper operation (clean, lube, test movement). Check economizer setpoint (can be 60 to 74°F). Check for cabinet leaks. Efficiency is sensitive to both over- and under-charged refrigerants. Superheat for most DX systems should be between 10 and 20°F (depends on ambient temperature—get manufacturer's curves). Megaohm and oil (acid or water) checks are made on the compressor motor. Clean condenser coil (could save $250/year). DeltaTemp across coil will verify effectiveness of cleaning. Rapid on/off cycling of condenser fan leads to poor control and rapid motor wear.

Kennedy Jr., W. J. Energy Systems Maintenance

Chapter 14 in Energy Management Handbook, W. C. Turner, ed., Fairmont Press (distr. Prentice-Hall), 3rd ed., 1997, Lilburn, Georgia.

Describes how to develop a maintenance plan for building systems. Four steps: determine present condition, list routine maintenance, develop a schedule, monitor to keep program in force. Any boiler not adjusted for 2 years can have its efficiency increased by 25%. It is not uncommon for a good HVAC maintenance policy to reduce energy consumption by 50%. Tables 14.2, 14.3, 14.5, 14.6, and 14.7 show problems and solutions for boilers, HVAC, lighting and windows, hot-water system, and air compressors. Recommends calibrating thermostats semiannually and controls and sensors annually. Table 14.14 lists boiler information to keep a log of. Some discussion of measurement instruments. Table 14.18 lists instruments for use in energy management, such as infrared photography, flow hood, light meter, stethoscope, flowmeters. Monitor each kind of energy used in a facility for 12 months prior to start of the energy management plan, then monthly to check effectiveness of plan and to fine-tune. Recent devices for energy efficiency are listed in section 14.7.

Instrumentation and Measurement

Brandemuehl, M., Krarti, M., and Phelan, J. Methodology Development to Measure In-Situ Chiller, Fan, and Pump Performance

Joint Center for Energy Management, JCEM/TR/96/3, March 22, 1996, Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder.

Volume I—Final Report for ASHRAE Research Project 827-RP

Describes the development and evaluation of in-situ testing guidelines for chillers, fans, and pumps to evaluate improvements in energy use. A relationship between power and load is developed for the equipment and system using a combination of direct measurements, statistical regression analysis, manufacturer's data, and engineering principles. Instrument placement and accuracy are based on accepted industry standards for stand-alone equipment testing. An uncertainty analysis is performed on the estimated annual energy consumption.

Test methods draw on existing ASME/ARI/AMCA test methods for the lab environment.

An evaluation of the annual energy consumption requires input of a load distribution. In most systems, the pump or fan power is primarily a function of fluid flow rate. Single point tests with and without manufacturer's curve and multi-point tests with imposed loads or short-term monitoring are described. Uncertainty includes instrumentation and systemic, regression, and load profile uncertainties. Each guideline specifies measurements, number of test points, accuracy of measurements, methods of artificial loading, and calculation equations and uncertainty analysis.

Methods to determine annual loads are not provided. Summaries of each guideline are provided.

For some chillers, chilled water supply and condenser water return temperatures are needed, along with the annual loads. Because of the number of variables affecting chiller performance and a limited number of test points and conditions, a model is used to characterize the chiller (p. I-10). Manufacturer's curves will not always agree with the simpler model. A temperature dependent model is also provided (p. I-11).

The uncertainty in load distribution is likely to dominate all other factors, but is often ignored when comparing two alternatives under the same load profiles. Its determination is not included here. Discussed calibration, measurement, and regression uncertainties, and how they can be reduced (such as by increasing the number of points or loads). For methods using manufacturer's curves, use 10% as the minimum prediction uncertainty, due to the difficulty of accurately estimating points from manufacturer's data. Discussion of measurement (including flow) uncertainty, regression uncertainty (uses standard least squares regression, but estimates the increased uncertainty due to random and systematic errors in both x and y variables). Discusses uncertainty analysis for both simple and temperature-dependent models. For annual energy calculation, the uncertainty is determined based on a weighting of each bin's uncertainty.

Three sites were used to validate the procedures. Instrument accuracies are provided, and uncertainties are calculated. *Recommends a minimum of 8 to 10 points to prevent the t statistic from dominating the annual uncertainty calculations.* Regression uncertainty is captured even if data points are reduced by averaging. For the pump results, the power was a major source of random uncertainty, either from the

instrumentation or the process. Results on p. I-26. Relation between power and flow is quadratic for variable speed pump. Single point tests are not applicable to variable speed pumping systems (p. I-32). Fan tests start on p. I-36 (5 minutes of 10-second data for each load). *Difference in uncertainty between 322 points and 14 instantaneous accurate points (at each damper setting) was small.* As for VSD pumps, the theoretical power relationships of the fan affinity laws do not always transfer to installed systems, and the manufacturer's curves cannot be used. For the secondary system pump, the linear and quadratic models differed greatly.

Chiller test results start on p. I-47 for both simple and temperature-dependent models. *The length of the monitoring period is less important than the range of characteristic loads included in the data set.* The temperature-dependent model results will be similar to the simple model if the water temperature ranges are small. The temperature-dependent model requires temperatures that are coincident with the load profile information, so it is more complicated. *Due to the cost of flowmeters, if the uncertainty in annual energy is too high, investment in more accurate temperature sensors may be the best option for improving the uncertainty (p. I-51). Figure 8-13 shows the effect of flow rate errors on the energy prediction error. A 5% error may still give acceptable results, depending on the accuracy of the other instruments. Calculating load from the chilled water loop (instead of the condenser loop) whose flow is variable, results in greater uncertainty at lower loads due to the flow's systematic uncertainty (p. I-65). This is a problem if the secondary loop has an inaccurate flowmeter.*

Volume II—Guidelines for In-Situ Performance Testing of Centrifugal Chillers

Similar to discussion in Volume I, except focused on chillers. Test procedures are more detailed. *Minimum required instrument calibration accuracies and precisions are given on p II-11.* (Power 1.0%, flow rate 2.0%, temperature 0.5.) The range of testing should cover 80% of the hours in the load profile, with a minimum of 8 testing levels. A minimum of 5°F (10°F preferred) range in chilled water supply and condenser return temperature is required. Equations and examples given.

Volume III—Guidelines for In-Situ Performance Testing of Centrifugal Fans

For a fan in an air distribution system, in most cases the power consumption is a function only of volumetric flow rate. Static pressure in a VAV system is usually maintained while the dampers modulate. Control strategies include constant volume (power remains constant) and variable volume without (use manufacturer's curves or multi-point testing) and with (use multi-point testing) fan control. *Minimum required instrument calibration accuracies and precisions are given on p. III-8.* (Power 1%, flow 2%, DP 2%, P 1%, RPM 1%, temperature 0.5%.) The range of testing should cover 80% of the hours in the load profile, with a minimum of 8 testing levels. Equations and examples given.

Volume IV—Guidelines for In-Situ Performance Testing of Centrifugal Pumps

For a pump in a fluid distribution system, in most cases the power consumption is a function only of flow rate. However, where the DP is reset to maintain at least one valve open, there could be different heads at similar flows. Building hydronic control strategies include constant speed and volume (uses bypass loops and power remains constant—single point test), constant speed and variable volume (no bypass valves—operating point moves along pump curve—single or multi-point testing), and variable speed and variable volume (no bypass valves, pump speeds changes to maintain static pressure—multi-point testing). *Minimum required instrument calibration accuracies and precisions are given on p. IV-9.* (Power 1%, flow 2%, DP 2%, P 1%, RPM 1%, temperature 0.5%.) The range of testing should cover 80% of the hours in the load profile, with a minimum of 8 testing levels. Equations and examples given.

Volume V—Literature Review for Methodology Development to Measure In-Situ Chiller, Fan, and Pump Performance

Summary descriptions of standards for temperature, pressure, air flow, liquid flow, power, thermal energy, and system (ASHRAE 111 gives accuracy requirements, but not calibration techniques or how to assess measured data). Equipment standards are described for chillers, fans, pumps, and motors. Most are applicable to laboratory situations and are designed for specific limited objectives, most commonly comparisons alternatives. Field testing objectives include general system evaluation, acceptance testing, proof-of-performance testing, operational analysis, and energy conservation evaluation. Many objectives are based on long-term performance or energy use, and in-situ testing entails many different configurations and control systems.

Literature on field testing and monitoring covers building monitoring protocols (ASHRAE Applications and other general papers), measurement and calculation techniques (ASHRAE Fundamentals, Heinemeier, and Hurley—varying load examples discussed in White [1993]), sensors, meters, and recording equipment (Baker and Hurley on flow; O'Neal discusses problems encountered with LoanSTAR; Feller on thermal meters), and accuracy of measurement (ASHRAE 114 provides typical accuracy requirements; Lock and Hibberd [3%COP requires 1% flow and 0.05°F temperature sensors]; Haberl recommends magnetic paddlewheel insertion meters).

Papers related to equipment testing include chillers (Anderson and Dieckert plot heat rate error vs. flow and temperature errors), fans (power = flowrate^n where n=2 to 2.5 for return fans and n=1.5 to 2 for supply fans), pumps, motors (Hoshide calculates efficiency from slip), VSD (pump vs. flow follows a square function rather than a cube function), and DSM evaluation/modeling (EPRI and ASHRAE toolkits for predicting energy consumption, other papers that look at short-term monitoring to estimate annual load profiles).

A bibliography is provided.

Appendix I: Summary of Field Site Monitoring Configurations and Instrumentation Calibration for ASHRAE RP-827, JCEM TR/96/3

The report details the monitoring configurations and instrument calibration for the various sites tested for validation of the chiller, fan, and pump testing guidelines. The Texas sites download hourly averages every week. About 2 dozen plots are shown for each one-week period. Calibrations are described and documented. Chiller, heat exchanger, fan, and pump manufacturer performance information is provided.

Burger, R. Wet Bulb Temperature: The Misunderstood Element

Heating, Piping, Air Conditioning, Vol. 65, No. 9, September 1993, p. 29(6).

Proper sizing, operation, and maintenance of cooling towers results in cooler water and lower energy use by chillers. Cold water temperature (CWT) is often overlooked when there are chiller problems. Cooling towers (CTs) are designed at the wet bulb temperature that is exceeded 2.5% of the time from June through September. CWT follows wet bulb temperature. *A 1°F colder CWT saves 2.5%* of the energy required by a refrigerator compressor by lowering the head pressures and temperatures. Nominal ratings on CTS are not necessarily design values. Buy a nominal tower 20% above what you need, for only 8 to 10% more. Rapidly pays back. Most older CTs can be upgraded.

Fahlen, P., Andersson, H., and Ruud, S. Demand Controlled Ventilating Systems: Sensor Tests

Dept. of Commerce, NTIS PB93127272, 1992, FF, Stockholm, Swedish NTRI, Report 1992:13.

Evaluates the performance of sensors used in the control of ventilation rates, in the lab, and in buildings (long term). Included are 9 humidity, 2 CO_2, and 5 mixed-gas sensors (VOC, CmHn, CO, etc). Capacitive RH sensors are well suited for control of humidity, CO_2 sensors are adequate, but calibration is time-consuming and mixed-gas sensors show mixed results. All sensors were sensitive to vibration, EM fields, and electric shocks. Most were insensitive to climatic tests. Describes RH sensors (p. 17), CO_2 (p. 19), mixed gas (p. 20). For humidity, service life is >10 years, calibrate every 1 to 2 years, 2 to 3% accuracy for less than half the sensors. Most had combined errors of <5%. Most proved stable over the long term. CO_2 sensors have errors within ±50ppm at 1000 ppm, which results in an adequate flow rate uncertainty of ±8%. Calibrate annually. Sensor specifications given. Many tests were done in a tobacco smoke environment.

Haberl, J. S., Claridge, D. E. and Harrje, D. T. The Design of Field Experiments and Demonstrations

Proceedings of the IEA Field Monitoring Workshop, April 2–5, 1990, Gothenburg, Sweden.

Paper discusses the general design of experiments used in commercial building.

- Who benefits from monitoring: utilities, energy analysts, manufacturers, energy consumers
- Types of monitoring programs: planning, end-use energy data for program evaluation, energy savings from retrofits, system efficiencies, building environment assessment, diagnosis of O&M problems
- Experimental parameters: fuel and thermal energy consumption, influencing parameters (weather, operational, occupancy, equipment settings)
- Types of experiments: on/off, before/after, simulated occupancy, compare to other similar buildings, run a model

Measurements can be made of whole-building data (hourly, daily or monthly). Submetering can be hardwired or it can analyze power signals or acoustics. On/off of subsystems can be detected. Utility billing data is cheap and very useful. Point-in-time data can be obtained by survey and one-time measurements. Time-sequenced data useful for determining how a building uses energy and if environmental conditions are being met (monthly, daily [good for operator feedback], hourly, or less [data set size issues]). Must be a systematic procedure for calibrating instruments and analyzing for errors. Precision must be better than what you want to measure. Calibrate often. Use redundant sensors and sum and range checks. Missing data can be thrown out, replaced, interpolated, or synthesized. Large bibliography.

Hughes, P. J., Hough, R. E., Hackner, R. J., and Clark, W. E. Results-Oriented Methodology for Monitoring HVAC Equipment in the Field

ASHRAE Transactions, Winter 1987, Vol. 93, Part 1, p. 1569, New York 87-18-1.

Describes the planning process for evaluating equipment performance and marketability via field testing through test marketing. Gather field data, develop and verify design and performance models, provide information to promote commercialization, transfer the information to the right audience. Organization described. Data list developed (an example for an earth-coupled heat pump is given). Installation, debugging, data collection, analysis, report. They take data once per hour.

Hurley, C. W. Measurement of Temperature, Humidity, and Fluid Flow

Oak Ridge National Laboratory, Field Data Acquisition for Building and Equipment Energy-Use Monitoring, October 1985, Dallas, Texas, pp. 43–58.

Describes the different types of sensors used for temperature, humidity, and flow measurement for energy management systems. Also discusses potential limitations and the advantages of each type. Calibrate all instruments in an EMS frequently and carefully.

Temperature

- Affected by other surface temperatures, stem losses.
- RTDs are most desirable for EMS due to linearity.
- With a positive coefficient, thermistors can be used for switching. Made linear with two or more oxides.
- Integrated circuit is sensitive to self-heating, limited applications.
- Thermocouples—type T for EMS, type J and K for higher temperatures. Fast response. Can be used in parallel for averaging, in series for differential.

Humidity

- Accuracy important, sometimes latent load can be 30% of total energy use.
- Psychrometer is simple, low cost, not used for monitoring.
- Ion exchange resin sensor is low cost, nonlinear, temperature-sensitive (for constant-temperature streams).
- Jason hygrometer is temperature-insensitive. Use below 85% RH. Sensitive to contamination.
- Thin film polymer or ceramic has a fast response, low to medium cost. Loses calibration at high RHs.
- Chilled mirror must be kept clean. Is expensive.
- Heated salt solution has an uncertainty of 2°C. Medium price.

Flow

- Deterioration of primary elements from abrasion, chemicals, or corrosion is major problem. Calibration of DP sensors is also important.
- Orifice, nozzle, venturi meters: Orifices are simple but with a high DP. Nozzles and venturis are more expensive but with lower pressure loss.
- Positive displacement and vortex shedding.
- Turbine requires clean water or a filter upstream, either pipe section or insertion (accuracy depends on velocity profile).
- Target: Drag force deflects a target.
- Multiple pitot-static and reverse-pitot tube assemblies: Only one DP needed for a cross-section. Calibrate in place.
- Ultrasonic: Transit time needs clean water, doppler needs reflective particles in water.

Hurley, C. W., and Schooley. J. F. Calibration of Temperature Measurement Systems Installed in Buildings

NTIS, National Engineering Lab, Jan 1984, NBS, Washington, D.C.

Describes techniques of calibrating EMCS sensors (in place, removed, remote) for glass thermometers, pressure, RTDs, thermistors, integrated circuit (IC) temperature sensors, TCs, etc. Page 58 discusses error determination.

Joint Center for Energy Management. Testing Methods and Results for Natural Gas Engine-Driven Chiller

JCEM/TR/91-6, September 23, 1991, Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder.

A 50-ton natural gas engine-driven chiller was tested in the JCEM lab to find its peak-load capacity and part-load performance. It achieved 70% of rated capacity, even after modifications. RTDs are 0.1°F and RPM is 1% accurate. Energy equations given on page 6. Test procedure and results are given in more detail. Used 1-minute averages of 10-second data. Full-load test was 53 minutes, and part-load data was taken from 130 hours. Chiller cycles dramatically to maintain part-load conditions; CWT could not be kept steady, so the part-load tests were not to code. Load curves on pages 21 and 29. After chiller modification with a new thermal expansion valve (TEV), there was little cycling.

Joint Center for Energy Management. Calibration Methods Used in the JCEM HVAC Laboratory

JCEM/TR/90-6, January 1990, University of Colorado, Boulder.

Calibration procedures for the following instrumentation are covered in this report:

- Air temperature measurement: point RTD, averaging RTD
- Air pressure measurement: duct static pressure, atmospheric pressure
- Volumetric air flow rate measurement: multi-pitot tube air flow station
- Air humidity measurement: Solid-state relative humidity sensor (3% calibration sensitivity)
- Water temperature measurement: RTD in thermowell
- Water flow rate measurement: venturis with pressure transducer
- Fan rotation speed measurement: tachometer
- Power measurement: Watt transducer

In-house calibration procedures discuss application of instrumentation, relating instrumentation output to engineering units, calibration standards, and calibration of standards.

Misuriello, H.P. Instrumentation Applications in Commercial Building Energy Audits

ACEEE, 1984 Summer Study on Energy Efficiency in Buildings, Vol. C: New and Existing Family Residences, pp. C205–17.

Describes measurement techniques to help an energy auditor find energy conservation opportunities. Techniques recommended are visual audits, strip charts, digital totalizers, storage devices, plant sensors, and readouts. Building energy use can be projected from short-term data. One work week and two weekends would give good confidence in data. (Optimum monitoring period needs to be determined.) Energy consumption is either weather- or nonweather-related. Strip charts can help diagnose control problems. Annual consumption can be determined from utility meters. Existing sensors can help determine economizer problems.

Smith, S. Digital Data Acquisition—Course Notes

Tustin Technical Institute, Inc., 1993, Santa Barbara, California.

Section 5, Sampling Theory. Shannon's Theorem: If we acquire more than two points per cycle of the highest frequency component in the signal, the entire signal can be reproduced exactly. Otherwise, it cannot be reproduced. The highest frequency is the one at which there is significant response as seen in the spectral domain plot. Control the bandwidth of the input signal by using a low-pass filter, so that it includes only the frequency range of interest. The conservative "conventional wisdom" rule of sampling is 10 points per cycle.

Stebbins, W. L. Energy Monitoring and Metering Systems—The "Two M" Metering Rule is Alive and Well

Energy User News, August 1996, p. 32.

To manage energy use, you must be able to meter it. Metering allows accurate charging to departments or production units, forecasting annual or monthly energy use, taking corrective action, measuring efficiencies, providing information to energy audit projects, identifying performance problems, and determining potential energy savings. Solid-state power meters can perform the tasks of 24 conventional meters for the price of three. RS-485 communication can monitor up to 70 values (minimum/maximum, time, alarms, temperature, etc.), can use a network to transfer data. Fluid flow is the second most important form of metering. Orifice plates, venturis and nozzles, turbine meters (must be kept clean), vortex meters (no moving parts, repeatable).

Turner, W. D., Haberl, J., et al. Calibration Facility for the LoanSTAR Program

Energy Systems Laboratory, Department of Mechanical Engineering, Texas A&M University. Solar Engineering, Vol. 2; ASME, 1992.

This paper describes the development and capabilities of a calibration facility for testing and calibrating sensors used in the Texas LoneSTAR program. The purpose of this facility was to:

- Perform NIST-traceable calibrations and verify the capability of selected sensors.
- Establish a troubleshooting facility where faulty field sensors can be brought in for diagnostics.
- Develop a field certification kit for in-situ sensor calibrations.

- Prequalify proposed hardware/sensor combinations prior to installation in the field.
- Develop field certification techniques, installation guidelines, and error analysis guidelines for the Texas LoneSTAR monitoring systems.

The paper gives a little detail on the capabilities of the calibration facility. No detail is given on how the goals are accomplished.

Real-Time Pricing

Daryanian, B., Norford, L. K., and Tabors, R. D. RTP-Based Energy Management Systems: Monitoring, Communication, and Control Requirements for Buildings under Real-Time Pricing

1992 ASHRAE Transactions, Winter Meeting in Anaheim, California, Vol. 98, Part 1. AN-92-15-3.

Paper describes a real-time-pricing (RTP) system that was designed and tested on several sites in the state of New York. Daily ahead and hourly ahead RTP prices were used, site and weather data were collected, thermal loads were predicted for 2 to 3 days, and an optimal schedule was determined using a linear programming technique (chiller performance was simplified). Difficult to measure cool storage with ice. Schedule was also modified to reflect hourly prices. Savings of about 20% over conventional time-of-use (TOU) system was predicted.

Minimum sensors required are heat or cooling storage level, energy transfer in/out of storage (flow and temperatures), electrical load of system, outdoor and indoor temperatures, energy transfers in other parts of the system (if sensors are accurate to 1°F). For forecasting, one month's data should be stored.

Kammerud, R., Blanc, S., and Kane, W. The Impact of Real-Time Pricing of Electricity on Energy Use, Energy Cost, and Operation of a Major Hotel

ACEEE, 1996 Summer Study on Energy Efficiency in Buildings, Vol. 4, Commercial Buildings: Technologies, Design, and Performance Analysis, pp. 4.201–4.210.

This paper describes the energy use of the San Francisco Marriott and potential savings from the RTP rate structure. The hotel has two 900-ton chillers and a 150-ton chiller with thermal energy storage (TES). Peak load is strongly correlated with daily total load. Load profile does not change much throughout the year. Climate signature on the building is weak. Describes the components of the RTP price and compares them to TOU prices for a year. Three types of electric "load management" strategies: load shifting, load sharing, and load shedding. Total costs to the hotel under RTP should be about 20% lower than under TOU.

During the worst RTP hours, the operators precool meeting rooms and then reduce cooling during the high-cost hours, cool the chilled water loop to 44°F (it is typically 55°F and they let it heat up to 65°F during the worst hours), and shut down chillers. There is a 350 kW reduction in load during the worst RTP days, and about 502 kW reduction in energy use. Due to the labor involved, these actions are taken only during the worst RTP days. Automation would help extend actions to more marginal days. A new control system and the new TES will help lower costs.

ASHRAE Information

Handbooks

ASHRAE Handbook, 1995 HVAC Applications, 1995 Edition

Chapter 32: Energy Management

Provides information about how to set up an energy management program. Includes organizational issues, financing, and the types of projects to implement. Does not discuss specific instrumentation accuracy or data collection issues.

Chapter 33: Owning and Operating Costs

Discusses owning and operating costs for building HVAC systems. There is no information related to instrumentation accuracy or data collection methods. The chapter does give some methods to estimate maintenance costs of HVAC systems, including relative adjustments for different types of equipment and the age of equipment. This information can be used for economic analysis of systems and alternatives. Techniques for economic analysis are given (payback, present value, etc.). There may be some useful information for prioritizing equipment to evaluate if maintenance is a selected type of evaluation.

Basic annual maintenance costs are estimated at about $0.33/square foot, and then adjusted for age and type of equipment.

Other potential references: ASHRAE Fundamentals Handbook, 1997, Chapter 30: Energy Estimating and Modeling Methods.

Chapter 34: Testing, Adjusting, and Balancing

Discusses requirements and procedures for testing and balancing environmental control systems in buildings. It is suggested that testing and balancing is a commissioning effort and should be repeated as systems are renovated or changed. *Information in this chapter may be useful if testing, adjusting, and balancing is chosen as one of the "types of evaluations" using data from the building EMS.* The information about testing specific types of equipment may also be useful.

A statement is made that "both air and water side balancing techniques must be done with sufficient accuracy to ensure that the system operates economically, with minimum energy, and with proper distribution." Another statement: "The proper location and use of system instrumentation is vital to the accuracy of the system balance."

Suggested tolerances for air flow balancing: ±10% for individual terminals and branches in noncritical applications and ±5% for main ducts.

Suggested duct air flow measurement technique: pitot tube traverse. Fan power input can be used as a guide to flow, but it is not an accurate quantitative value. Vane anemometers and flow hoods at discharge grilles are also used.

Instrumentation and procedures for *balancing air distribution systems* are given. For *hydronic systems,* sensitivity of heat transfer to flow and temperature changes are discussed. Also discussed are s*team distribution systems, cooling tower testing, field surveys for energy audits, and testing for sound and vibration.*

Chapter 35: Operation and Maintenance Management

Gives some general information about how to organize, evaluate, and document an O&M program. No specific information about data acquisition requirements. There may be some use in the information given about how to calculate various O&M "performance parameters" (e.g., capability, dependability, reliability).

Chapter 36: Computer Applications

Describes the use of computer programs for building HVAC applications. There is general information about how to select hardware and software and the trade-offs. Discusses use of computers for design (duct, piping, acoustics, equipment selection, etc.) and building energy analysis; the need for calibrating the models with measured data; and artificial intelligence systems (e.g., knowledge-based systems, neural networks, fuzzy logic), which can be used for design, control, and diagnosis. There are also brief descriptions of computer communications, data acquisition, and monitoring and control. No specifics are given for data accuracy or frequency.

Information in this chapter may be of some use if calibration of computer models is chosen as an important use of test data. References to artificial intelligence applications and monitoring and control may also be of value.

Chapter 37: Building Energy Monitoring

Provides general guidelines for developing building monitoring protocols. The chapter stresses that there is a wide range of building monitoring data, uses of that data, and analysis methods. Building performance data can range from individual end uses (lighting) or components (HVAC equipment, walls) to the entire building (total electrical meter readings). Time collection rates for data can range from seconds (controllers) to years.

Monitoring projects are defined as one of four types:

1. Whole-Building Energy Use: Measuring the total consumption for a building to get average energy use for building types. Typically small number of data points averaged or summed over a long time.
2. Energy End Use: Monitoring individual energy systems in particular buildings to get average energy use for specific end use types. Frequency of data collection may range from one time at one load to continuous measurements.
3. Specific Technology Assessment: Field performance testing of specific equipment, possibly to determine retrofit improvements. Typically requires detailed monitoring of critical parameters. Frequency and complexity depends on specific objectives and conditions.
4. Building Diagnostics: Measuring physical and operating parameters to solve problems, provide inputs to models, or isolate component effects. Usually one-time or short-term monitoring. Frequency varies from several seconds to about an hour, *but must be at least 3 times faster than the time*

constant of the effect being monitored. Sometimes requires intermittent or long-term continuous data collection.

Emphasis of this chapter is on how to design building energy monitoring projects. The design is described in nine steps:

1. Identify project goals, objectives, research questions.
2. Specify data products and project output.
3. Specify experimental design approach.
4. Specify data analysis procedures and algorithms: Discusses the issue of needing to specify how the data will be processed and used to specify the data needed and the frequency of data collection. For integration of energy use over time through the use of models, the time step should be as long or longer than the response time of the building or system being evaluated.
5. Specify field data monitoring points: Discusses scanning and recording intervals. Scan rate should be sufficient to ensure that all significant effects are monitored.
6. Specify building characteristics.
7. Resolve data product accuracies: Perform uncertainty analysis.
8. Specify verification and quality assurance procedures.
9. Specify recording and data exchange formats.

The section on *Protocols for Retrofit Performance Monitoring* includes a table (Table 9) that gives some recommendations for **accuracy and scan rate** for residential monitoring.

Chapter 38: Building Operating Dynamics and Strategies

Discusses control strategies using computerized control systems for HVAC systems in commercial buildings. It describes two basic levels of control: local loop control, which controls the hardware to a single setpoint; and the supervisor control level, which specifies the setpoints and other time-dependent modes of operation. Also described is global optimization (simultaneous optimization of the entire system and building) vs. local optimization (optimizing operation of a single component).

The chapter focuses on different control strategies and the effects on building HVAC system operation and performance. It describes control strategies for air handling systems and systems without storage, including the chillers, pumps, and cooling towers. Control strategies for thermal energy systems are also described. Although specific reference are not made to sensors and their data collection, references are made to sensitivities for system power consumption to various setpoint control values (supply air temperature, chilled water supply temperature, pump speed, etc.). An example for a chiller water loop: If the supply air temperature and chilled water supply temperature are within about 3°F of their optimum values, the power consumption is within about 1% of the minimum value. A few more degrees in the wrong direction can significantly increase power consumption. Example curves are given.

A global optimization method is described (Cumali). A building load prediction model is used to predict loads on a 5- to 15-minute period. The models are calibrated using actual building data. Optimal operation of the system is compared to other situations.

The chapter concludes with information about energy-use forecasting and its relationship to control optimization. The forecasting methods use current measured data combined with predictive models to estimate future cooling loads. Various types of data are needed depending on the sophistication of the technique and the systems being modeled. Forecasts for 1 to 24 hours are described.

Information in this chapter may be of use if building control optimization is one of the "types of evaluations" investigated. Some of the descriptions, graphs, equations and models may be of use in sensitivity analysis. The instrumentation used for control and its required accuracy and storage frequency is not addressed. However, depending on the sensitivities for such things as setpoint control, sequencing of chillers, or cooling tower cells, these instrumentation issues may be important.

Chapter 39: Building Commissioning

Briefly discusses the general commissioning process for buildings. It references ASHRAE Guideline 1 for procedures for HVAC systems. The chapter does not give any information about instrumentation requirements, accuracy, etc.

Chapter 42: Automatic Control

Discusses the design of automatic control systems for HVAC applications. It covers fundamentals, different types of control components, control loops, complete control systems, design considerations, and start-up and testing.

Time constant is defined as the time it takes for the output to reach 63.2% of its final value with a step change in the input. The dead time is the time between a change in the process input and when that change affects the output. Dead time can cause control problems and can be due to a *slow sensor,* a time lag in the signal from the controller, or the transportation time of the control agent (i.e., steam, air). *Control system performance is evaluated in terms of speed of response and stability.* A statement is made that the requirements of accuracy, speed, and stability often conflict.

Different types of control systems are discussed: pneumatic, electric (DDC), and self-powered. Sampling interval for DDC is briefly mentioned: It must be properly chosen so that it does not degrade performance.

Accuracy, repeatability, and response time issues are briefly mentioned under a section on sensors. But the point is made that an accurate sensor alone cannot maintain setpoints if the rest of the system (controller, actuator, etc.) does not perform adequately.

There is a lot of information about how different HVAC components are controlled and operated. This includes fans, heating coils, cooling coils, central air handling systems, and central plants. This information may be useful when evaluating specific components and different control and operating scenarios.

Under start-up and testing, discusses tuning of controllers. *For digital controllers, a sampling interval of about one-half the time constant of the controlled process is said to usually provide adequate control.*

In summary, there is no detailed information in this chapter about accuracy requirements—only general comments about its importance. A few details about sampling intervals and response times for digital

controllers are given. A lot of information about control and operation of different HVAC components is given. This information may be useful when evaluating specific components for control and operation.

ASHRAE Handbook, 1997 Fundamentals, 1997 Edition

Chapter 14: Measurement and Instruments

Discusses instrumentation used in the HVAC field for both laboratory and field applications. It has a short overview of uncertainty and more detailed sections on the various measurements and instruments used for those measurements (temperature, humidity, pressure, velocity, flow, electrical, speed, sound and vibration, lighting, thermal comfort, and others). It concludes with a short section on data acquisition. Tables list typical accuracies for the various parameters using various instruments. No details on determining accuracy and frequency requirements for specific end uses.

Information in this chapter may be useful when detail is needed about specific instrument types used for specific measurement purposes.

Chapter 30: Energy Estimating and Modeling Methods

Discusses methods for estimating energy use of HVAC systems in buildings as a guide for design, standards compliance, and economic optimization. This can allow comparison of different system and component options.

The chapter goes into details about analytical methods used to calculate space conditioning loads, resulting loads on the HVAC equipment, and the energy required by the equipment. Heat balance, weighting factor, and thermal network methods are described. A discussion of the secondary system components (ductwork, fans, pumps, heat exchangers, etc) is given, along with analysis methods (NTU-effectiveness methods for heat exchangers, etc.). The primary system components, the major energy-consuming equipment in the building (chillers, boilers, cooling towers, etc.), are described next. Methods of modeling these systems include regression models using manufacturer's data or first-principle models using complex engineering analysis. Discussions of boiler, vapor compression, and cooling tower models are given.

Overall system modeling describes the steps used to solve the equations developed above, as well as various modeling strategies. Most models use one-hour time steps. Again, these models only compare design alternatives.

The detailed models described earlier are complex and require significant computations. Simplified methods are also used, including the Degree-day Method, Bin Methods, and Correlation Methods. These methods and their uses are described. The Degree-day Method is the simplest, but assumes that HVAC equipment efficiencies and the building heat loss coefficient are constant. Bin Methods separate out the number of hours at different conditions so that variable efficiencies and load patterns can be factored in. Correlation Methods simply relate the energy use of a building or system to selected inputs through databases and statistical means to develop the correlations. The accuracy depends on the quality of the data in the database, and how representative a particular correlation is for the system under evaluation.

The difference between Inverse Modeling and Forward Modeling is described. Forward Modeling uses fundamental engineering principles, descriptions of building and HVAC components, etc., to model the system. Inverse Modeling uses empirical relationships between building and component response and

one or more driving forces. There are two basic types of Inverse Models: steady-state and dynamic. These typically involve regression techniques using experimental data. Neural Network Models, which "learn" by example, are briefly described. Inverse Model applications include evaluation of energy conservation programs, prescreening of buildings for energy auditing purposes; building energy management, optimal control, and in-situ characterization of HVAC systems. Models which use both forward and inverse techniques are called "hybrid models." DOE-2 or BLAST are examples where a forward model is calibrated using actual data.

The chapter ends with two summary tables that classify the various modeling methods and provide a decision diagram for selecting an appropriate technique.

This chapter does not provide specific information about instrumentation accuracies or data collection frequencies. However, there is a lot of information about the use of data for modeling purposes. This may be useful for sensitivity analysis purposes.

Guidelines

ASHRAE Proposed Guideline 14P: Measurement of Energy and Demand Savings, June 1997

- More accurate methods follow the law of diminishing returns, where further reductions in error come at progressively greater expense. (3.4)
- A project that expects 30% savings wants to estimate it within 10% with a 95% confidence. Fuel use uncertainty should be less than 1.5% ($0.5 \times 30\% \times 10\%$). (Table 5.1)
- Baseline conditions can use 12 months of utility bill data (energy and peak demands) and monthly average weather data. Savings are significant if greater than the RMSError. (6.1.2)
- Using hourly data to determine retrofit savings gives less error and gives energy-use patterns. At least 12 months required. EMS system data that is COV (change of value) must be converted to interval data. If demand savings are determined by the utility on a 15-minute (or other) basis, data should be recorded at the same frequency. Submetering reduces errors. (6.1.3.1.1)
- Energy savings should be accurate to 20% using monthly data, and 10% or so using hourly data. (6.1.5)
- List various standards that discuss instrumentation accuracy. ASHRAE 30-1978 Methods of Testing Liquid Chilling Packages graphs heat rate error vs. flow and temperature differential error. Hourly data of kW/ton given as examples. (6.2.1.1)
- Boiler efficiency heat loss vs. I/O. A 1% error in measurements gives 0.8% for I/O and 0.2% for heat loss. (6.2.1.1.13)
- ASHRAE Std 114-1986 provides typical values for accuracy required for different applications. Lock and Hibberd (1992) say for a chiller efficiency (kW/ton) of 3%, flow should be 1% and temperature 0.05°F accurate. (6.2.1.21)
- Spot measurements can be made if load varies by 1 to 5% (1 point) or up to 10% (several points). (6.2.4.1)
- Discussion of chiller performance curve modeling. (6.2.5.3)
- Fan test instrumentation accuracies/specifications. (6.2.7.2.1)

- Chiller instrumentation accuracies. (4.2.3 - page before Ref for 6.2) Accuracies of tests can be ±10 to 20%, leading to errors of 100 to 200% in savings. O&M savings as high as 5 to15% can be had just by keeping test equipment in place. (6.2.7.3.1)
- Use redundant sensors and online checks. (7.2)
- Strive for 10 times the scan rate of the period being measured. DAS capabilities described here. Most EMCS archive data on a COV basis with a time stamp. Most cannot do interval-based averaging. Averages are retrieved and calculated when requested. (7.3.1)
- Calibrate with NIST procedures—through the system. Focus recalibration on critical points. (7.5)
- Data validation techniques include duplicate measurements, energy or flow balances, check channels, time-step, range check, relational checks, graphical and statistical methods. (7.6)
- Uncertainty discussion. (7.7)
- Recalibrate critical instruments every 6 to 12 months. Post-test calibration for long-term tests. Spot or temporary instruments should be calibrated within past 6 months. (7.8)
- Power transducers account for power factor. Digital metering equipment is good for non-sinusoidal waveforms from uninterruptible power supplies (UPS) and VSDs and reactive loads (like fluorescent lights and motors) in calculating true RMS power and energy. Sensor type descriptions. RTDs 4 wire (0.01°F), 3 wire (0.25°F), 2 wire (0.5F), and 4 wire with current transmitter (0.1°F). Magnetic flowmeters 0.25 to 1% accuracy. (A1.1)
- Btu meters offer better than 3% accuracy. (A1.8)
- Calibration techniques. RH to 3%. Ultrasonic flowmeters (UFMs) are 5% devices good for rough checks. Inspect air flow arrays and calibrate sensors periodically. Field calibrate with traverses or with energy balances. (A2)
- Measurement standards listed. (A3)
- Costs of instruments given. Instrument errors start on p. 42 - power, gas, temperature, RH, flow, Btu, ventilation, pressure, etc. (A5)
- Uncertainty of calculating energy savings. (Annex B)

ASHRAE Guideline 1-1989, Guideline for Commissioning of HVAC Systems

Provides procedures and methods for documenting and verifying the performance of HVAC systems so that they operate in conformity with the design intent. End result is a fully functional, fine-tuned system. General guidelines discussed.

ASHRAE Guideline 4-1993, Preparation of Operating and Maintenance Documentation for Building Systems

Presents a comprehensive and systematic approach to the preparation of O&M documentation to support the development and management of O&M programs in buildings. Covers the format, content, delivery, and updating of documentation provided by the design and construction team. A test section should contain performance targets, testing protocols, and test results.

ASHRAE GPC-13P, Guideline to Specifying DDC Systems (Public Review Draft, April 1998)

Helps DDC system designers write a specification for a DDC system. It contains a number of references to sensor accuracy. However, it does not indicate the reasoning behind those accuracy specifications. It is stated (p. 35 - Reporting Accuracy) that the accuracy specifications are those typical for a comfort HVAC application and that the required accuracy may be higher for an industrial application. Table 1 (p. 35) shows these accuracy specifications. The guideline provides a full example of a specification. Following is a sample section of their spec:

> Space Static Pressure Sensors (p. 104)
>
> Outputs of 4–20 mA or 0 to 10 VDC and inputs of -60 to 60 Pa [-0.25 to 0.25 in. wc] are standard. The input range needs to be negative to read accurately to zero. The range should be selected to make maximum use of full span, while affording an accurate indication of all conditions. The Subcontractor will select the proper range to fulfil the performance criteria defined in the specification.
>
> Specification of output variations (e.g., less than 0.3% of full scale range for supply voltage variations of ±10%) is a requirement for accuracy based upon voltage changes. Include a definition of required accuracy such as combined hysteresis, repeatability, and non-linearity effects should not exceed ±1.0% of full scale range. Characteristics such as operating temperature range of 0°C to 60°C [32°F to 140°F] and 10 to 90% RH (non-condensing) need to be defined to include likely ambient conditions. An example of the effect on accuracy due to ambient conditions is ±1.0% of full scale range per 28°C [50°F] change in temperature.
>
> The over-pressure input protection should be included to protect the device from damage or inaccuracies due to application of excessive pressure. Zero and span should be field-adjustable. This allows for on-site recalibration for critical applications.

It also refers to sampling frequencies and intervals. Again, there is no discussion of the rationale behind those specifications.

Standards

ASHRAE Standard 114-1986, Energy Management Control Systems Instrumentation

Provides guidelines for specifying measurement and instrumentation requirements for EMCS and their HVAC systems and methods for verifying the accuracy.

- Shows how to calculate end-to-end accuracy. (p. 4)
- Accuracy is represented as the range into which 99% of all measurements will fall. (p. 5.2.1)
- In DDC loops, a system response time of 5 to 10 seconds should be adequate (measurement/calculation/command execution time). (p. 5.2.2)
- Normal EMCS room temperature accuracy is ±2°F. (p. 5.2.3)
- Types of control sequences listed. (p. 5.2.4)
- Energy-use logs must be done as accurately as possible. *Table 1 shows recommended end-to-end measurement accuracies for several types of usage.* A typical error in energy calculation is ±7.5%. (p. 5.2.5)

- Energy usage vs. sensor cost trade-off. (p. 6.2)
- Btu/ft^2/°day can be tracked for building performance. (p. 6.3)
- Periodic checking of some instruments (every 6 months) can detect lead connection problems and drift. Dew point sensors require frequent maintenance. Turbine meters should be inspected every 6 months. (p. 6.4)
- Calibration accuracy should be at least twice the intended accuracy of the sensor. (p. 7.1)

ASHRAE Standard 111-1988, Practices for Measurement, Testing, Adjusting, and Balancing of Building HVAC&R Systems

Provides procedures for making measurements for commissioning in the field. (5.3.2) Describes instruments used for air balancing. Accuracies should be as follows: tachometer (0.5%), clamp-on volt-ammeter (3%), clamp-on wattmeter (1.5%), vane anemometer (5% above 200 fpm, 10% below 200 fpm for uniform flow, 30% for nonuniform flow), hot-wire anemometer (10% above 100 fpm), pressure (1%), DP (2%), sling psychrometer (1F), RH (2 to 3% from 20% to 95%). Discusses air balancing. Fan and pump equations. (Section 12) Chiller testing equations.

ASHRAE Standard 150P, Method of Testing the Performance of Cool Storage Systems (Public Review Draft, November 1997)

Prescribes procedures for determining the cooling capacities and efficiencies of thermal storage systems.

- Temperature accuracy of 0.3°F and DT of 0.2°F. Flow accuracy of 5% over entire flow range, calibrated within last year at 3 to 5 points. Electric accuracy better than 2% true RMS. (p. 6)
- Record data at least every 15 minutes. Averages shall consist of at least 45 measurements, with a minimum 20-second interval. Recording device accuracy of 0.25%. Describes field calibrations. (p. 9)
- *Appendix B provides a simplified format for uncertainty analysis* on total usable discharge capacity of a thermal system. Time series data—the average includes all precision error sources. For dynamic processes, precision error may not be identified unless DAS can determine it and record it. *High sample rate (>30 samples/period) and short averaging periods (<=15 minutes) can minimize this precision error. Do not include data (i.e., temperature) in an average used in a calculation with other data (i.e., flow) when the flow is zero.* Btu meters eliminate no-flow conditions. Equations for storage capacity and general and specific uncertainty given. For fixed flow and DT between 0 and 12°F, DT has the biggest impact. Flow has bigger impact when DT is between 12 and 30°F or when flows below 10:1 turndown ratio occur frequently.
- *To obtain a 22 ton U_{rss} uncertainty in 15-minute average storage discharge capacity and load cycle efficiency, uncertainties were 8% for flow, .5°F for the temperatures, and 0.02 #/gal for density.* The 11 hour U_{rss} was 4% or 92 tons out of 2200 tons. (p. B-6)
- Example TES schematics given in Annex C.

Appendix II

Method for Determining Measurement Accuracy and Storage Frequency for Improved Building Energy Efficiency

Task 4—Site Survey and Prioritization of Equipment and Evaluations for Method Development

CEC Contract #500-97-010

Project #3

December 1998

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Executive Summary

This interim report summarizes the results of Task 4 and part of Task 5 of the CEC project. The final product of this project is a method that can be used to determine the accuracy and storage frequency of building energy management and control system (EMCS) data necessary to perform a selected type of function or evaluation. The method will also outline the types of evaluations that can be performed on equipment based on available measurements.

A matrix was developed to show the systems/equipment and types of evaluations that could be used to demonstrate the method. Nine building sites were surveyed to determine how they use EMCS, their instrumentation capabilities, and their greatest needs. Based on the survey results, we decided to focus our initial development efforts on air-handling equipment (including air-side economizers, fans, and terminal units) and on evaluations related to their operation, control, and diagnostics.

During the next phase of this project (Task 5), the initial method will be developed.

Introduction

The objective of Task 4 and part of Task 5 was to prioritize building plant systems/equipment and the types of evaluations for the equipment using monitored data. This information will provide the direction for the remaining project tasks. (Appendix A contains the work statement descriptions for Tasks 4 and 5.) Prioritization was based on several criteria, including the relative energy use of the equipment, the sensitivity to data accuracy and storage frequency, and feedback from the end users of building energy management and control systems (EMCS).

To accomplish this goal, we surveyed building operators to determine how they currently use their EMCS, what else they would like to use them for, what their biggest needs are related to their building's energy systems, and their experience with sensor accuracy and its impact on their use of the EMCS.

Prior to conducting the surveys, we developed a matrix of the equipment and types of evaluations commonly monitored through building EMCS. Based on the surveys and the other criteria mentioned above, we prioritized which systems and evaluations were most important to the building operators and to California's commercial building energy-use market.

The final product of this project is a method that can be used to determine the accuracy and storage frequency of building EMCS data necessary to perform a selected type of function or evaluation. The method will also outline the types of evaluations that can be performed on equipment based on available measurements. Initially, the method will focus on the highest priority equipment and functions determined from Task 4. The following sections detail the steps taken to set these priorities.

Equipment and Evaluation Types

A matrix was constructed of the equipment and evaluations that could be considered for the development of the method for this project (see Table 1). The Systems/Equipment category includes the main energy users in commercial buildings, such as whole building, lighting, heating and cooling, and plug loads. The Levels of Evaluation category describes different ways that building energy data could be used. The Types of Evaluations category includes (1) operation and control, (2) commissioning, (3) diagnostics, (4) retrofits and design optimization, (5) verification of energy savings, and (6) energy accounting. Each evaluation category lists specific evaluations that could be performed, in approximate order of complexity, depending on available data.

For each piece of equipment or system, and for any type of evaluation, we can determine a list of measurements, instrument accuracy, and data storage frequency required to perform that evaluation to a desired degree of confidence. To develop a method for determining these results, we decided to focus on some selected systems and types of evaluation. This approach is recounted in the ensuing sections.

Table 1. Matrix of Equipment and Evaluation Types

CEC Building Control System Project Matrix

Types of Evaluations

Performance Monitoring & On-going Commissioning

Levels of Evaluation	Operation & Advanced Control	Initial Commissioning Verification & Performance Testing	Diagnostic Identification of Maintenance Problems	Auditing, Retrofit Identification, and Design Optimization - for Mgmt Decision Making	Measurement and Verification of Energy Savings	Whole Building Energy Accounting
	Is it on or off? What load level? Alarms Is maintenance required Logbooks Is it cycling too much? Sequencing Is schedule right? Forecast needs. In expected range? Response to RTP.	Control system verification Interface with other control systems. Verification of ancillary equipment function Performance indices Corrections to design pt. Determine baseline data. Other diagnostic data.	Performance indices Corrections to design pt. Other diagnostic data. Compare to baseline. Verification of ancillary equipment function	Performance indices Correct to design pt. Other diagnostic data. Compare to baseline. Verification of ancillary equipment function Data needed for equip mod and bldg simulation tools	Performance indices Correct to design pt. Other diagnostic data. Compare to adjusted baseline. Data for whole bldg analysis Data needed for equip models and bldg simulation tools	Whole bldg indices related to equipment Whole bldg data that affects equipment Data needed for equip models and bldg simulation tools Data needed to make adjustments to baseline

Systems/Equipment	Operation & Advanced Control				Initial Commissioning Verification & Performance Testing				Diagnostic Identification of Maintenance Problems				Auditing, Retrofit Identification, and Design Optimization - for Mgmt Decision Making				Measurement and Verification of Energy Savings				Whole Building Energy Accounting							
	Update Sec	Storage Min	Sensitivity %/%	Accuracy %	Update Sec	Storage Min	Sensitivity %/%	Accuracy %	Update Sec	Storage Min	Sensitivity %/%	Accuracy %	Update Sec	Storage Min	Sensitivity %/%	Accuracy %	Update Sec	Storage Min	Sensitivity %/%	Accuracy %	Update Sec	Storage Min	Sensitivity %/%	Accuracy %				
Whole Building																												
Plant	15	15	1	2	15	15	1	1	15	2	1	1	15	2	1	1	15	15	1	1	15	60	1	3	15	60	1	1
Lighting																												
Bldg Cooling/Heating Load																												
Chiller																												
Chilled Water Pump																												
Boiler																												
Ventilator																												
VAV Boxes																												
Economizer																												
Building Environment																												
Cooling Tower																												
Condensate Pump																												
CT Fans																												
Thermal Storage																												
Plug Loads																												
Air Compressor																												
Hot Water																												
Other?																												

Survey of Building Operators

A survey was developed for building engineers and operators to find out how they use their building energy systems and what their biggest needs are related to the equipment, EMCS, and instrumentation. (See Appendix B for the survey form.). We interviewed building engineers or operators at nine sites in PG&E's service area; each interview lasted about 2 hours. The intent of the interview was to:

- Collect building and equipment information
- Describe the EMCS and data storage capabilities
- Determine what the EMCS was used for and what more they want from their EMCS
- Find out what equipment has the biggest effect on plant operating costs and what equipment has the most problems
- Discuss their general instrument accuracy and improvements that they would like in their sensors

The results of all interviews are summarized in Appendix C. In general, we were impressed by the engineers/operators' level of knowledge, interest in getting the most out of their operating systems and equipment, and desire to keep costs down.

Our key findings are the following:

- Maintaining comfort and responding to complaints is a higher priority than energy savings.
- The EMCS is most valuable in helping to diagnose problems and in monitoring zones to look for problem areas.
- Using the EMCS to keep labor costs down is very important.
- Operators at older buildings want better information from terminal boxes to be able to diagnose problems more easily. They are slowly replacing their pneumatic terminal boxes with direct digital controls (DDCs).
- The more control of terminal boxes and air handlers, the better.
- Many sites want more user-friendly front ends and easier access to historical data for producing trends.
- Most sites do not track performance factors or building energy use.
- About half of the sites want as much automation as possible, and the other half trust operator intuition more (especially those with thermal storage).
- No sites used their EMCS for predictive maintenance.
- Most sites want more zone temperatures and terminal units for better control, and more electrical metering for better information on energy use.
- Most sites want more variable frequency drives (VFDs) on pumps and fans.
- Some engineers/operators regularly calibrate their sensors; most wish that they could afford the labor to do so.
- A common desire is for more accurate, reliable, and cheaper flow sensors (either water or air).

These findings will help us determine the equipment and evaluations that should be the focus of our initial project method.

Prioritization of Systems/Equipment for Research

In addition to the survey, we used several other criteria to help determine which plant equipment to focus on for our initial efforts in this project:

- Relative Energy Use (kWh/sf) from an extensive 1997 PG&E commercial building survey: The overall average energy use by equipment type per square foot of building space. Heating, cooling, and ventilating equipment energy use is divided by the area served by those systems. The other equipment energy use is divided by the total building area.
- Adaptability of Results: How well can the method be adapted to other equipment (i.e., how similar will the instrumentation, performance factors, and engineering methods be)?
- Data Availability: Will we be able to get actual site data for use in the development process?
- Importance of Data Accuracy and Storage Frequency: How important is the specification of data accuracy and storage frequency to the types of evaluations that can be performed on that equipment?
- Importance to Site Personnel: From the survey results, did site personnel name this equipment as a big energy user or a system with a lot of problems?
- Potential for Energy Savings: Based on the Relative Energy Use, what is the potential for savings compared to other systems?
- Potential for Labor Savings: Based on the site surveys, what is the potential for labor savings if we improve the monitoring of those systems?

Each system/equipment was given a rating from 1 to 3, with 3 indicating the highest importance for each criteria. The average ratings are shown in Table 2. Chillers and air handlers have the most relevance for this project and were cited by building operators to be the most important in terms of potential energy and labor savings. While lighting and boilers used more energy than chillers and air handlers, they were not as relevant to this project (lighting sensors were different from other equipment sensors; boilers do not use electrical energy) and did not have the potential for labor savings.

For Task 5, we chose to focus on air handlers and terminal units (over chillers) for the following reasons:

- Air-handling equipment and terminal units use a similar amount of energy as chillers, but have a greater potential for labor savings.
- They have a significant effect on overall plant energy use—they control when and how much the chiller is used.
- Many more sensors are being used to track air-handling equipment than chiller equipment.
- Many buildings are gradually replacing their pneumatic terminal boxes with DDC units and new sensors.
- In the older buildings, a majority of operator problems are with terminal boxes; the operators would be able to fix problems more quickly with better information from that equipment.
- Improved comfort and energy and labor savings would result from better control and monitoring of terminal units.

Table 2. Equipment Ranking

	Systems/Equipment								
Criteria	**Lighting**	**Chillers/ CTs**	**Boilers**	**Pumps**	**Air Handlers**	**Terminal Units**	**Thermal Storage**	**Plug Loads**	**Comp Air**
Relative Energy Use (kWh/sf)[1]	4.2	3.4	4.3	1.0	3.6	-	-	2.0	<1
Scale is from 1 to 3 for Criteria below									
Adaptability of Results	1	3	2	3	3	2	2	1	2
Data Availability	2	3	2	3	3	2	2	1	1
Importance of Data Accuracy and Storage frequency	2	3	3	2	2	2	2	1	1
Importance to Site Personnel	2	3	2	3	3	3	2	1	1
Potential for Energy Savings	3	3	3	1	3	3	1	2	2
Potential for Labor Savings	1	2	2	1	3	3	1	1	2
Average Rating[2]	1.8	2.8	2.3	2.2	2.8	2.5	1.7	1.2	1.5

[1]From Commercial Building Survey Report, Sept 1997, PG&E. Boiler usage calculated by 46 kBtu/sf ÷ 10.6 kBtu/kWh to get equivalent kWh usage.

[2]Average is based only on the criteria that have a scale rating of 1 to 3.

Prioritization of Types of Evaluation

From the survey results, we ranked the importance of the six types of evaluation to the engineer or operator. The ratings range from 1 to 3, with 3 indicating the most relevance to the building operator. See Table 3 for the ranking.

Table 3. Ranking of Evaluation Types

CEC Sensor Project Survey Results
Relevance of Evaluation Types
(Ratings show the degree to which the functions are relevant to the operators and engineers that were interviewed.)
(Scale from 1 to 3)

Site	Operation & Advanced Control	Initial Commissioning Verification & Performance Testing	Diagnostic Identification of Maintenance Problems	Auditing, Retrofit Identification, and Design Optimization for Mgmt Decision Making	Measurement and Verification of Energy Savings	Whole Building Energy Accounting
1	2	1	3	1	1	1
2	3	2	3	2	1	2
3	3	1	3	1	1	1
4	3	2	3	2	2	2
5	3	2	3	2	2	2
6	3	1	3	2	2	2
7	3	1	3	2	2	2
8	3	2	3	1	1	1
9	3	2	3	1	1	1
Average Ratings	2.9	1.6	3.0	1.6	1.4	1.6

From the averages, it is clear that operations, advanced control, and diagnostic identification of maintenance problems are most relevant to building engineers and operators. Therefore, we decided to focus our determination of required frequency and accuracy, as well as our initial method development, on these two types of evaluation.

Data Availability to Perform Equipment Evaluations

In the previous sections, the equipment and evaluations were chosen for initial development of the method in Task 5 of the project. We decided to focus on air-handling equipment, with evaluations related to operations, control, and diagnostics.

The following air-handler-related site data is available:

- Hong Kong Bank / LBL data: Temperature, pressure, and power data around one air handler—a scan every two minutes—5/98 to present.
- 450 Golden Gate: Temperature, power, and RH data around West, East, and Courtroom air handlers—15-minute averages—9/95 to 4/97. Also available are 2 weeks of commissioning data on all air handlers and most terminal units, 5 minute averages (from ESS Engineering in Tempe, Arizona).
- Marriott: 5-minute instantaneous data for air handlers.

A combination of data from the various sources will be needed to cover fans, economizers, coils, and terminal units.

Conclusions

Surveys were successfully performed at nine sites. We determined how engineers and operators use their EMCS and what their greatest needs are. The most significant key findings were:

- Maintaining comfort and responding to complaints is a higher priority than energy savings.
- The EMCS is most valuable in helping to diagnose problems and in monitoring zones to look for problem areas.
- Using the EMCS to keep labor costs down is very important.
- Operators at older buildings want better information from terminal boxes to be able to diagnose problems more easily (they are slowly replacing their pneumatic terminal boxes with DDC).
- The more control of terminal boxes and air handlers, the better.

We prioritized the systems and equipment based on their relative energy use, data availability, relevance of data accuracy and frequency, importance to site personnel, and potential for dollar savings. We chose to focus our initial development efforts on air-handling equipment (including air-side economizers, fans, coils, and terminal units) and on evaluations related to their operation, control, and diagnostics for the following reasons:

- Air-handling equipment and terminal units use (or affect) a similar amount of energy as chillers, but have a greater potential for labor savings.
- Many more sensors are being used to track air-handling equipment than chiller equipment.
- Many buildings are gradually replacing their pneumatic terminal boxes with DDC units and new sensors.
- In the older buildings, a majority of operator problems are with terminal boxes; the operators would be able to fix problems more quickly with better information from that equipment.
- Improved comfort and energy and labor savings would result from better control and monitoring of terminal units.

Based on the site surveys, the most relevant evaluations from the building operator's perspective are operations, control, and diagnostics. Site data for air handlers and terminal units are available at intervals of 2 to 5 minutes. This will help with the development and testing of the method.

Appendix A—CEC Work Statement Descriptions of Tasks 4 and 5

Task 4.0 Interviews and Surveys

Interview and survey controls vendors, building designers, and selected customers to determine state of building energy management technologies, standard energy management industry practices, awareness of potential energy usage improvements, types of data and results necessary for building owners/managers/operators to identify and improve building performance; and types of plants most commonly seen. Investigate the greatest needs for building owners/managers in the areas of control, performance monitoring, diagnostics, and commissioning in order to focus research on systems and applications that will have the greatest impact on the bottom line. Develop interview and survey typical installed instruments. Results from task 3 serve as basis for queries. Assemble interview and survey candidates from controls industries, designers and customers. Conduct instrument and typical systems surveys, analyze results, and use results to adjust interview questions. Conduct interviews, develop results, and summarize findings.

Deliverables: Interim report summarizing the findings of the interviews and surveys. The report will provide insights and conclusions as to the state of the art and state of the marketplace relating to data characterization, acquisition and analysis. The report will also assess the energy management what additional tools, if any, building owners/managers need to effectively manage energy usage. This will provide a baseline of vendor, building designer and customer knowledge in data acquisition and database design, as well as insights into the highest priority needs for characteristic data. Included will be: copies of the survey and interview instruments and lists, procedure for conducting surveys and interviews, and raw and analyzed survey and interview data.

Task 5.0 Analyze, Develop and Test Data Structures and Intervals for Various Systems; Provide Sensitivity Study of Data Sampling Impacts

Identify the gaps between data collection needs and the current state of technology and industry practice in building control systems, sensors and data acquisition. Based on information from Tasks 3 and 4, and the identified technology gaps, develop a method for building owners/managers to identify and prioritize systems with the greatest potential for improving building energy usage and reducing operating costs. Using this prioritization, choose a characteristic plant setup for test. Develop and carry out a plan to test and/or model the chosen plant, for the purposes of performing the necessary sensitivity analysis. Analyze the response times of various plant configurations and components to determine the best frequency of data acquisition (frequency vs. granularity) for the various plant components. Develop sensitivity studies of the plant processes to determine the optimal data acquisition frequency, accuracy requirements and importance of the data.

Deliverables: Interim report summarizing the evaluation of the gaps between current industry practices and building owner/manager/operator needs and a method that building owners/managers can use to identify and prioritize systems to achieve the greatest financial impact. Results are envisioned to include system response time results, data gathering interval results, sensitivity analysis, and any developed plant models.

Appendix B—Building Operator Survey Form

CEC project description

Help improve the usefulness of existing and future energy management systems. Create a workbook that outlines how to evaluate equipment, and recommends sensor accuracy and storage rates for each type of evaluation.

Survey objective

Gather information to determine the biggest needs that building operators have regarding the usefulness of their EMCS data, and to help prioritize the equipment and evaluations to be studied.

Site information

- Contact
- Location

Major equipment descriptions: equipment, when installed, fuel type, rating, description, schedule and operating mode, range of operation

- Chiller
- Cooling tower/fans
- Air handler
- Thermal storage
- Boiler
- Fan control (CV, VAV)
- Terminal unit (reheat, single duct, dual duct, etc.)
- Chilled water pumps
- Condensate pumps

Building information

- Building use, total square feet, floors, occupancy, weekly schedule

EMCS

- Model
- Data update rate
- Data storage capability (memory, time span, storage rate, averaging, change of value [COV], integration, time stamp)
- Trends
- Reports

- Flexibility to add measured and calculated channels and new trends or x-y plots
- If no EMCS, ability to get strip chart trends

Other survey questions

What is EMCS used for?

- Control
- Operations
- Performance verification
- Diagnostics
- Maintenance
- Performance trending
- Prediction
- Energy accounting

For each area, is the EMCS providing what you need? What more would you want in each area?

- Control
- Operations
- Performance verification
- Diagnostics
- Maintenance
- Performance trending
- Prediction
- Energy accounting

In general, what else do you wish you could use the EMCS for?

What equipment has the biggest effect on your plant's operating costs?

What equipment do you have the most problems with?

What would you like to monitor better? What instruments would you like to add or improve?

Operator info

- How long have you used the EMCS?
- What can you do with it? How much is automated, manual, over-ridden?
- How accurate is your data in general?
  - RTDs
  - Flows
  - Loads
- Are you satisfied with your data accuracy?
- Would it help to know what instrumentation to focus on (for calibration, additional sensors, repairs, replacements, etc.)?
- Can you download a point list with not too much trouble?

Wish list/major complaints

Appendix C—Survey Summary and Detailed Results

CEC Sensor Project Survey Summary

We surveyed nine sites. Detailed survey results are listed below. References to site names have been removed to maintain confidentiality.

The sites ranged from about 80,000 ft^2 to 2 million ft^2, with most of the sites over 1 million ft^2. Chiller capacity ranged from 195 to 5,000 tons total. At the larger sites, fan power totaled between 360 and 1000 hp, chilled water pumps totaled between 100 and 1100 hp, and condenser pump power totaled between 150 and 600 hp. Auxiliary power could represent a significant percentage (about 30%) of the chiller power plant requirements.

Most sites have either just upgraded their EMCS system or are in the process of an upgrade. Refresh rates range from 1 to 30 seconds. Data is stored every 15 minutes to one hour for periods ranging from 1 day to several years, though in some cases, not at all.

Many sites can trend chiller plant sensor readings and measurements at zones. No sites monitor chiller performance continuously, although some have enough information to calculate performance. A couple run chiller performance tests at regular intervals. A couple of sites track building energy use. Most operators rely on the EMCS primarily to check on zone or room temperatures and to diagnose problems with air handlers and terminal boxes. Most sites find it inconvenient to graph trends from historical data.

About half of the sites prefer to run their chillers automatically. Typically, the sites with thermal storage or more variability in weather prefer to trust operator intuition more than they trust the computer. Operators did not have a good knowledge of TOU power rates, although they often took pride in trying not to start too many chillers. Their biggest use of the EMCS was in tracking and diagnosing building problems and in responding to complaints. The more control of the air handlers and terminal boxes the better. None used the EMCS for predictive maintenance. Most follow planned maintenance schedules, although they check chiller approach temperature differences to detect fouled chiller tubes. Energy management is usually performed by someone other than the operations staff.

Most of the operators and engineers wanted improvements in the terminal boxes, in order to get better operating data and more remote control. In buildings that are fairly new (less than 10 years), the terminal boxes are pretty reliable. In the older buildings, they are gradually replacing the old boxes with new DDC units. Most want more zones for better control of area temperatures. Most wished for more power metering of individual plant components. Some wanted more automatic control of equipment, while others preferred to rely on operator intuition. Some want better information on TOU electric rates. They also want to be able to trend historical data more easily. Most would like more VFDs on pumps and fans.

Most believed that chillers and auxiliary equipment had the biggest effect on operating costs. A couple thought that lights were a significant component. Most problems were with the air-side of the system - with older terminal units and control of zone temperatures. Most wanted more control of VAV boxes and more information from them. Many also wanted more VFDs on their pumps or fans.

Some sites performed regular calibrations on their plant instrumentation, though most waited until instrumentation failed or until they received complaints before checking sensors. Many wished that they

could perform regular calibrations, but that would require too much labor. Most sites wanted more accurate, reliable, and cheaper flow sensors.

Half of the sites fix problems in response to complaints, while the other half are more pro-active, in that they try to detect problems before there are complaints. Most use the EMCS to scan their buildings for problems regularly. All would like to use the EMCS more to be able to monitor and diagnose problems at the zones and terminal boxes. Some want more automation for starting and stopping equipment, while others prefer to rely on operator intuition. If there is a storage system, operators can use weather predictions and control start/stops better. For all, comfort, along with the ability to easily fix problems, have priority over energy savings.

CEC Sensor Project Survey Results

Site information (font format is set to hidden to keep sites confidential):

- Contact and Interview Data:
- Location:

Building information

1. San Ramon - 80,000 sf, mostly one floor, weekdays 7 to 6pm, 150 people.
2. San Francisco highrise is 862,000 sf, 35 floors, 3500 people, weekdays
3. SF office building - 1.2 million sf, 22 stories, weekdays 6a to 5p.
4. SF hotel - 1.5 million sf, 80,000 sf meeting rooms, 1500 guest rooms, 5 story low rise, 40 story tower, 7x24 hours.
5. Central Valley college campus - 1.4 million sf, ~40 buildings, weekdays, summer school, highest loads at end of August and September.
6. San Ramon Business Park - 1.4 million sf, 14 buildings, 7 days/week. 90% of systems shut down at 18:00 and come back on at 06:00.
7. San Ramon large business center - 2 million sf, 10 buildings, 7000 people, 5 days/week.
8. San Ramon training facility - 177,000 sf, 6 or 7 buildings, mostly weekday hours.
9. San Ramon office complex - Site 6 has 5 buildings. Site 9 is similar. Older two story buildings have package units (56 - 20 year old units). Occupied 7am to 7pm Monday to Friday.

Equipment

1. One York 195 ton (1989). Marley Series 220 cooling tower with one 7.5 hp fan. Two supply fans (25 and 30 hp) and two return fans (15 and 7.5 hp). Boiler is 200 MBh. Chilled water pump is 7.5 hp and condenser pump is 10 hp.
2. Two 550 ton Carrier Centrifugal (1989), two 550 ton York absorption para-flow, one 550 ton York screw (2,750 tons total). Three Baltimore Air Coil 2500 ton cooling towers (CV). CV fans - supply (100 hp) and return (60 hp) plus 4 fans (two 60 and two 30 hp). Boiler (750 hp and 500 hp). Internal reheat CV boxes, perimeter heating coils, VAV in 215 Market. Chilled water pumps - three 350 hp and one 100 hp. Condenser pumps - eight 75 hp.

3. For chilled water two-1275 ton and one 850 ton centrifugal Carrier (.82kW/ton), for floors 17 to 20 two 65 ton, for floors 12 and 13 two 40 ton (3,610 tons total). Two towers, 3 one speed fans each. Chilled water pumps 40, 80, 80 hp. Condenser pumps 40, 50, 50 hp. Eight dual duct AHs from central plant (CV) and 13 single zone AHs. Three 22 MBtu boilers (70% eff). Dual duct VAV to mixing boxes.
4. Two 900 ton and one 150 ton (for storage) chillers (1,950 tons total). Cooling tower fans are 80 hp. Air handlers are 1000 hp total. 3000 ton-hour of ice storage. Two 350 hp boilers. 4-pipe fan coil units in rooms, VAV and CAV elsewhere. Chilled water pumps are 375 hp total. Condensate pumps are 150 hp total.
5. Trane chillers - 1250, 1250, and 1280 tons (0.8, 0.8, and 0.55 kW/ton, resp.) - 3,780 tons total. CTI 3750 ton tower with VFD. Various air handlers. Thermal storage is 1,350,704 gallons of water, 20kton-hr. Two 30,000 lb/hr boilers. VAV boxes are reheat. Chilled water pumps - 25 hp primary and three 30 hp secondary (VFD). Condensate pumps are two 75 hp VFD.
6. Carrier chillers - three 1200 ton and one 1400 ton (15 years old) - 5,000 tons total. Water side economizer for free cooling. One 3 fan and one 1 fan cooling tower (4-75 hp two speed fans). One air handler for each half of each building. One boiler for each building. Typically VAV with reheat (not many reheat terminal units in interiors). Three buildings have CV systems. One (sometimes two) 75 hp chilled water pumps (building pumps usually not needed). Four 100 hp condenser pumps.
7. Three 500 hp Frick screw compressors to make ice at night (2 kW/ton). One 500 ton York and one 1000 ton Carrier (VSD) (both centrifugal) for baseload daytime use. 1800 tons of evaporative chiller capacity is rarely used - just for occasional peaking. Separate from central plant - 1200 ton York reciprocating air condensers (1.3 kW/ton) used for baseload (?). (about 5,000 tons total). Ice storage of 12,000 ton-hrs can supply 1800 tons of cooling. Lake with spray nozzles used for cooling (no treatment allowed because it is used for irrigation). Air handlers include 12 - 50 hp VFD fans and 24 - 30 hp fans (1 out of 4 of which are VFD lead fans) for supply. An equal number of 10 to 15 hp exhaust fans. Three boilers for reheat and perimeter heat. Two riser ducts per building, VAV boxes on floors, baseboard heat on perimeter, reheat in centers. Chilled water pumped by 7 - 60 hp pumps. Condenser pumps include 3 - 60 hp, 1 - 100 hp, and 1 - 40 hp. Lighting control of 75*75 ft zones - adding motion detectors.
8. Two 120 ton Carlyle-Carrier reciprocating compressors (rated 60 tons each when making ice) and one new 110 ton unit for chilling, as a booster to the ice cooling. Two evaporative condensers with a total of four 7.5 hp fans and a 1.5 hp spray pump. One or two air handlers per building. Thermal ice storage of 4400 ton-hr (two ice harvester units) recently expanded (1.1 kW/ton). VAV boxes in all buildings. Reheat only in Building E. Chilled water pumps of 30 and 15 hp - VFD. One 10 hp ice water spray pump. Ice produced only in summer.
9. At Site 6 (5 newer buildings) - about 100 tons per building - 15 to 30 ton reciprocating compressors (0.5 kW/ton). DX cooling, hot water heating, pressure dependant VAVs, CV on heating side. One 150 hp vane axial air handler and economizer per building. No chilled water pumps. Evaporative condenser fans are about 25 hp. Pneumatic controls on interior and perimeter terminal units. Primary controls are digital.

EMCS information—model and data storage

1. No EMCS. York microprocessor on chiller. Parameter on cooling tower. Campbell 21x data logger collects corrosion related parameters, chiller temperatures, makeup/BD flows, steam pressure, and ambient temp. Stores instantaneous hourly data for 6 weeks, which is then downloaded by modem.

2. Honeywell XBS, XL500, XL+. Can set up trends if needed, but not normally trending data from the highrise. Upgrading system for automatic controls and better trending within a year. The recently remodeled building can trend all 50 zones, on DDC - equipment is already automatic.
3. BacNet - Allerton Beta Site. Sweeps every 20 sec. Storage rate depends on point. Up to one month of data stored. 1910 devices with up to 10 points each are monitored. Easy to add trends and screens.
4. Inet - easy to set up screens, data backup is easy. Storage rates vary. Some points are every 5 minutes.
5. Barber-Colman Network 8000 - on OS2 - Will soon replace with Windows NT version. Refresh rate is 10 sec. 15 min averages and peak power storable for over 1 year. 200MB set aside for data storage, 1GB Jaz drives set up for backup.
6. Siemens System 600 - two years old. Refresh rate is 2 sec. Data storage rate and time span depends on point. Can use COV or time steps.
7. Johnson Control 8540 just converted to Metasys (more automatic control than the Johnson). Refresh rate about 30 sec. Stores 30 minute averages for several years on selected points (see below).
8. Andover AC8 and Andover Infinity System. Update rate once per minute. Stores data for 24 hours, 30 minute intervals. No long term storage.
9. Landis/Stafa System 600 - Siemens - Insight Windows system. Refresh rate about one to two seconds. Can store on COV or time interval. Only stores data when needed because it can bog down system. Trimax control is a time clock that is programmable for night setback, warm-up, and cooldown.

EMCS trending and reporting

1. Monthly downloads and reports produced.
2. Highrise is not trended; will be after upgrade. The 2nd (remodeled) building - all 50 DDC zones can be trended. Maintains an activity log. Monthly log of Btu/sf since 1994. Manual chiller performance tests performed twice per year.
3. Can trend any of 5000 points for a month. Zones are monitored on each floor by reviewing summary screens by floor (air flows, supply air temps, space temps).
4. They use system to trend performance.
5. Trend power usage (buildings, parking lights, plant, etc.), sensors on all major equipment, some building cooling loads, problem areas, and important zones. Computer printed logs every shift and manual logs every two hours. Can use data in Excel. Can change math functions and programming. Daily peak and total energy are provided by EMCS.
6. Stores kW and kWh - trended twice per day for each building and overall plant. They do not trend everything. Can add points to trend if they need to focus on them. Trend graphs can only be shown for a recent snapshot. They cannot be graphed for previous days. They can be stored on disk in column form, and replotted in Excel (inconvenient). Report on compressor and building energy use once per week.
7. Trending of chiller plant (chilled water supply and return, condenser supply and return, temps and flows), outside air temp and relative humidity (used to control economizers), lake temp, air supply and return temps, and valve positions on Metasys terminal boxes. Out of 1200 zones, 100 have

Metasys boxes. History graphs for past 24 hours only. Column format for data further back. Easy to add trends and screens. Data backed up on ZIP disks - different formats for various program versions.

8. Trends air handlers and ice harvester. Does not trend terminal units. Could store data longer than 24 hours, but no front end to display historical data. A little tricky to add trends. No performance calculations. Power is used to see if pumping is on or off.
9. Only set up for trending when there is a problem. No storage of data normally. No measurement of kW and no performance calculations.

EMCS control, operations, and maintenance functions

1. Monitor corrosion and makeup/blowdown rates to maintain proper chemistry levels. Uses a combination of local controls and timers to control system. Chiller maintains 44°F water, and cuts out below 53°F outside air temp. VAVs controlled by zone temps. VFD fans controlled by 2 supply and 2 return duct pressures. Manually increase hot water temp in the winter. Timers are installed to control fans, but the fans run continually.
2. The recently remodeled building has equipment operation fully automated. Each VAV box provides CFM and valve and position damper positions. The chiller plant will be automated in a year (staging of chillers is currently manual). Uses a Job Tracking program for scheduled maintenance - no predictive maintenance. EMCS resets chilled water temperature based on outside air temp, controls heating water supply, and supply air temp. Upgrade will stage chillers based on demand and optimal start (done manually now). Considers demand reduction - lead chiller in summer is gas absorption. TOU rates do not show up on bill.
3. Can adjust VAV box settings on floors 3, 4, and 5. Alarms are too numerous to check. Uses floor summary screens to detect problems. Trends help solve problems. Air handlers are scheduled by EMCS. Boilers and chillers not yet automated. Several floors' chillers can be started automatically. Lighting on floors 3 to 5 can be controlled automatically. EMCS reduced need for 2 to 3 hot/cold guys. Not enough people to handle alarms. Actions are based mainly on complaints.
4. 75% of equipment is controlled by EMCS. Boilers are not controlled by EMCS. Ice is charged full each night, even if it is not fully melted every day. Uses PG&E's schedule program to change setpoints of chilled water temp, based on 24 hour ahead TOU rates. Operator intuition is used to control building temperature swings.
5. They set a ceiling on kW demand. Using cold water storage, chiller demand is traded off for more air handler demand during the day. There is an inter-relationship between fan energy, chilled water temp, and chiller demand. Demand is limited such that only #3 and either #1 or #2 chillers are used to charge tank at night. Control storage tank inlet to 39 to 40°F, and campus loop DeltaT to 20 to 24°F. Chillers are controlled and sequenced automatically, boilers are just monitored. Cooling tower is fully automated. Operators start and stop building fans based on building use schedules. Operations controls all air handlers. In new buildings, fans are on VFD and DDC, and every zone box is controllable. In older buildings, only two zones are controlled in each. Temperatures indicate if air handlers are working properly. They have about 50 air handler screens. Operators pay close attention to approach temperature differences on chillers, to maintain tube cleanliness. Cooling is getting more difficult due to increase in PCs. Comfort is 1st priority, saving money is 2nd. Operators look at weather predictions to determine how much to charge cold water tank (better than computer forecasts).

6. Their Chiller Advisory could start and stop chillers automatically. They prefer to let the operator control the chillers. They can predict weather better, such as approaching clouds, and avoid sudden start/stops. All zone temps can be controlled and room temps checked in three buildings. Other buildings have zone temps that are averaged that control each half of the building. One person is assigned to every 2 to 3 buildings for maintenance and temperature control. They try to catch problems before complaints. An alarm summary is given to each shift. They react to all alarms. No predictive maintenance. Chiller deltaT and deltaP checked manually. Try to account for TOU. Take pride in not starting a chiller. Know when to pre-cool. Outside consultant performs energy management with energy reports and surveys.
7. EMCS used to control supply fans. Chillers are sequenced manually. Used for troubleshooting and to change setpoints on all zones. On Metasys boxes, can see flow, temps, and damper and valve positions. Can trend, diagnose, and fix many problems. Most maintenance is scheduled, based on availability of chillers. Approach temperature difference should not exceed 3 to 6°F. Could add to EMCS - currently a manual check. EMCS used to pre-cool buildings, based on previous day's temperature. Not used to float building temperatures to reduce demand charges, because they need to keep equipment cool.
8. Could use EMCS to optimize start-ups based on return air temperature and weather, but they need more sensors. Charge until 12 noon on weekdays and 24 hours on weekends to reduce peak demand. Ice harvester cannot keep up after a few summer weeks. Just added a new chiller, which runs a lot. EMCS used to track main equipment, pumps, VFD rates, kW's. Can schedule and change set point temperatures with Infinity system controllers remotely - DDC. No energy accounting. The AC8 system is not DDC and not as easy to program. Data from air handlers include temperatures, damper position, flow (on/off), and static pressure.
9. Uses EMCS for start/stop, uses historical data for optimization of start (up to 4 hours early). Can change average building setpoint temperatures. Reads return and outside air temps, damper position, set points, static pressure, fan speed, and chilled water temp at air handlers/economizers. To keep from too many start/stops, false loading is placed on condenser water using return air during cold days. Maintenance performed at regular intervals. No energy accounting. Use EMCS for monitoring and alarms every day. Can call in to check monitors and alarms. Can have automatic hot water or chilled water resets. Can easily change setpoints.

What improvements do operators and engineers want?

1. More zones for better control of individual room temperatures. Look into shutting fans off at night or on weekends. Less complex equipment and more uniformity for easier troubleshooting. Chiller printout log doesn't work - needs to fix to help troubleshooting.
2. Automated control of equipment on highrise (planned). Better flow measurement on each chiller (currently an annubar DP or the DP across the evaporator) and condenser flow. Better space temperature monitoring to reduce chiller start/stops. Convert from pneumatic to electronic heating valves. VFDs on pumps. New high-rise EMCS will supply better air supply control (reset, scheduling, better valve and damper control) and better chiller sequencing.
3. Want a history of individual equipment problems available on screen. Add automatic control and monitoring of chillers, boilers, and cooling towers to EMCS. Add electric metering to each major piece of equipment. Sound card to EMCS to provide different sounds for different alarms or problems.

4. Automate chillers. Switch from charge to melt automatically. Shift boiler setpoint based on load and on outside air temperature. Enable better response to complaints. Ability to turn off room air when not occupied. Operations needs to focus on economizers more. Existing cooling towers sometimes cannot handle both chillers. May need to add an extra heat exchanger somewhere (i.e. domestic hot water). Add VFD to fans.
5. Convert older building terminal units to VAV and DDC for more complete automation and more mixing box control. Converted remote air coils from 4 row to 8 row, better sized for 20°F differential. Upgrade #2 chiller to 1500 ton. Wants a Windows NT upgrade. Needs to get a breakdown of TOU rates (not currently being supplied by electric provider).
6. Wants DDC on all zones for central control - easier and safer. Wants to be able to trend historical data easily. Reduce pump sizes. Improve fan and pump motor efficiencies by going to VFD.
7. Want more Metasys terminal boxes and more automation of the chiller plant. Need cooling towers - lake doesn't cool adequately and lack of water treatment adds to tube plugging and fouling. Would like more VFDs - adding to chilled water pumps. Could add approach temperature alarms and kW/ton calculations. Could look at load shedding, such as for lighting - need to consider negative affects on workers.
8. Need more sensors to use optimization startup program. Store information long-term to be able to bill tenants if they use buildings off-hours. Would like monthly statistics and graphs. VAV boxes are pretty reliable - they are less than 10 years old. Wants to replace single VFD controller for two condenser water pumps with two VFD controllers. VFDs on air handlers and economizers are working well. Uses EMCS to check alarms Monday through Thursday. Does walk around on Fridays.
9. Wants more control - DDC to terminal units - is it cost effective? DDC will give better accuracy (0.5°F) compared to pneumatic (3°F). Wants more sensors per zone for tighter zone control. Wants more information before sending people out. Wants better air balances. VFDs on Site 6 fans won't save much energy. Heating fans are already variable vane. All new buildings will have VFDs. Water-side economizers may help save energy.

What equipment has the biggest effect on the plant's operating cost?

1. Boiler gas use. Fans running all night.
2. HVAC is only 25% of bill. Lighting is 40% of bill.
3. Do not know.
4. Chiller. Compact flourescents are being used, but there are no occupancy sensors. Motor efficiencies could be increased. Room air should be turned off if not occupied.
5. Scheduling of chillers (need to know demand charges).
6. Chillers and pump and fan motor efficiencies could be improved.
7. Compressors and chillers, Frick units, then fans.
8. Labor to overhaul ice harvestors every two years is high. Labor is biggest expense.
9. Lighting may have largest potential for improvement. Chillers are already very efficient, although they are a large energy user. Air-side economizers help with efficiency.

What equipment has the most problems?

1. Boiler maintenance (different maintenance companies set things differently). Chiller has hammering in condensate makeup sump. Temperatures can vary significantly within zones - balancing difficulties. Fan VFDs couldn't handle poor power quality - changed to Emerson which work fine.
2. Air-side damper problems. Sometimes short on air. VFDs needed on oversized pumps.
3. Ten VAV terminal unit problems to every air handler control/scheduling problem.
4. No nagging problems. New planned maintenance system is helping out.
5. Need more terminal unit mixing box control and information.
6. Old reliance drives on pumps and old VAV boxes that are gradually being replaced.
7. Condenser water fouling problems and older VAV boxes.
8. Metal roofing has problems around skylights. Problems with video surveillance system.
9. Terminal units don't have a lot of problems. Package units are the most maintenance intensive.

How accurate is your instrumentation and what problems do you have with sensors?

1. Corrosion monitor temperatures are checked every 6 months. Doesn't know if York calibrates the chiller's temperature probes during routine maintenance. Conductivity meters checked every 3 to 4 months.
2. Calibrate probes only if there is a problem. Annubar flows are not trusted - poor location. Turbine meters are okay in remodeled building. For chiller testing, need 0.1°F accuracy on temperatures and 1% on flows. Not as much accuracy needed for trending. If 10°F chiller DeltaT is 0.5°F accurate, that's good enough. Checked once per year.
3. Thermistors have been reliable. Uses an IR sensor to check temps when there is a complaint. Pitot tubes that we used for air flow can get plugged.
4. Will begin to check RTDs annually. Pressures biannually. Chilled water and condenser flows are accurate (turbine meters). Magnahelix pressure gages on filters could be used to determine when to replace them (currently on Predictive Maintenance). Satisfied with accuracy and reliability.
5. Calibrate equipment RTDs annually. Calibrate building RTDs if there is a problem. 12 foot averaging RTD sensors at heat exchangers fail often (least reliable). Would like to see magnetic flow meters come down in price. Turbine meters gum up. Target meters are reliable, but air/water slugs can bend them or throw off their calibrations.
6. Satisfied with accuracy. Use paddle wheel insertion meters to trend flows. They calibrate chiller plant instrumentation quarterly to 0.5°F, duct static pressures and temperatures (to 2°F) annually. Return air flow is 10% less than supply flow.
7. Some RTDs are calibrated in the field. RTDs are replaced when they fail - complaints lead to detection of failures. Most system sensors are stable. Room temperatures tend to fail and drift more. Flows are measured with turbine meters. Condenser flow meters foul.
8. Wants to upgrade AC8 system to Infinity. Wants a better front-end with better trend capabilities and more user-friendly. Sensors fail sometimes. Flow meters drift sometimes. Have backup flow meters so that they can be replaced. Can compare flow to kW.

9. Needs more sensors for zone control. DDC would give 0.5°F accuracy, compared to pneumatic controls that give 3°F accuracy. RTDs are usually 1 to 1.5°F accurate, though they are sometimes way out. Need a regular calibration program. Currently checked based on complaints. No flow measurements. Would like an outside air damper assembly that measures air flow, to optimize indoor air quality. Present method of % outside air volume is not that accurate. Chiller loads are not measured - just % load.

General remarks

1. Mostly a trial and error process to try to satisfy complaints. Doesn't want to change things too much - afraid of throwing things off.
2. Looking forward to automating highrise. Could use better flow meters. New control system will meet needs, if it is not too complicated.
3. Wants more automation. Floor summaries are most useful. Alarms are too numerous to respond to. Most actions are in response to complaints.
4. Operator intuition is good regarding temperature swings. Use of PG&E's schedule program to set chilled water temperatures is very useful. To respond to complaints, the more automation, the better. Wants to automate chillers and boilers. Wants to make more use of weather forecasting and historical operating data.
5. Comfort 1st, savings 2nd. Operator intuition is better than computer artificial intelligence at this time. They use weather forecasts to set storage and allow temperature swings. Needs to know demand charges to understand costs of scheduling better. Computers not good with the unexpected. Operators are there anyway, and their intuition is good for scheduling.
6. Operators can predict weather and control start/stops better than a computer. Monitor is used to catch problems before clients do, for proactive control.
7. Would like more DDC terminal boxes and better control of fouling problems. Most important priority is keeping equipment cool and workers comfortable.
8. Satisfied with data accuracy. Needs more sensors for optimization program, but they're expensive. Labor is biggest expense. VAV boxes are reliable. Needs a better front-end for longer term data trending and more user-friendly screens for setting control points.
9. It would help to know what instrumentation to focus on. Would like more control over air and water balances, improvements not always made.

Appendix III

Method for Determining Measurement Accuracy and Storage Frequency for Improved Building Energy Efficiency

Task 5—Draft Method for Determining the Accuracy and Data Storage Frequency for Sensors Used in Air-Handling Systems for Operation, Control, and Diagnostics

CEC Contract #500-97-010

Project #3

June 1999

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Executive Summary

Building energy management and control systems (EMCS) are primarily designed to control energy-consuming equipment installed in commercial buildings. Many EMCS can also be set up to perform operational, diagnostic, maintenance planning, performance monitoring, performance testing, and commissioning functions. They often monitor most of the same data necessary to perform these functions.

This project was initiated to develop a method for the following:

1. Choose the measurements needed to accomplish the various data acquisition functions.
2. Determine the required accuracy and storage frequency of those measurements.

The method will be the basis for upgrading or designing building energy management systems (EMS) to perform these tasks.

This Task 5 interim report summarizes the first application of the draft method to determine the sensor accuracy and storage frequency for the operation, control, and diagnostics of air-handling system equipment:

1. Initial step for determining accuracy and storage frequency
   - List measurements and performance factors needed for tasks to be accomplished (in this case, operation, control, and diagnostics of air-handling equipment).
   - Determine plots useful for evaluations.
   - Gather site data, develop plots, and calculate performance factors with real site data.
2. Accuracy and frequency based on energy benefits
   - Determine sensitivity of factors to their input measurements.
   - For each piece of equipment, develop a rough economic evaluation of the effect of varying parameters or measurements on energy use.
   - Prioritize the measurements and factors in terms of their effect on building energy use.
   - Considering the cost of instrumentation and calibration, determine the economic level of accuracy for each measurement.
3. Accuracy and frequency based on plots of data
   - Describe how the plots can be used for the evaluations (in this case, operation, control, and diagnostics of air-handling equipment).
   - Determine the potential benefits of using the plots.
   - Determine the measurement accuracy and storage frequency needed to use the plots for the evaluation.
4. Based on the economic analyses and diagnostic plots, determine recommended accuracies and storage frequencies for each measurement.

Table ES-1 summarizes the recommended accuracies and storage frequencies for our example building (a 50,000 sf office building).

Table ES-1. Recommended Accuracies and Storage Frequencies

Equipment/Plot/Parameters	Accuracy	Storage Frequency (min)	Comments
Terminal Units			
Zone Temperature	2.0°F	2	5-min storage frequency is OK. Calibrate only if cost is less than $30 to $50.
Zone Cooling CFM	10%	1	Store running averages if possible. Zero flows when fans are off. Not economic in our examples.
Reheat Valve Position	N/A	2	5-min storage frequency if space is an issue.
Discharge Temperature	2°F	1	Not economic in our examples.
Zone Heating CFM	10%	1	Zero when fans are off. Not economic in our example building.
Economizer/Mixed Air Damper			
Mixed Air Temperature	1°F	1	
Outside Air Temperature	1°F	5	
Return Air Temperature	2°F	1	
Cooling Coil			
Supply Air Temperature	0.5°F	2	
Cooling Loop Output Signal	N/A	2	
Fans			
Supply Duct Static Pressure	0.2 inH_2O	1	Real-time plots of 1- to 10-sec data desired. Storage of fast data not recommended.
Maximum Zone Damper Position	N/A	1	
Low and High Zone Temps	1°F	5	
Filter			
Differential Pressure	0.2 inH_2O	N/A	Can be checked manually once a month, or more often if filters plug up at a faster rate.

CFM = cubic feet per minute, N/A = not applicable.

For those measurements where we recommend higher accuracies (either 0.5°F or 0.2inH_2O), the energy savings will more than cover the cost of the better sensors and annual calibrations.

For the purpose of the economic analysis, we used a 50,000-square-foot office building with 100 hp of fan power and a 0.85kW/ton chiller in Alameda and Sacramento, California, type weather climates. The recommended accuracies and storage frequencies are the same for both sites. For other buildings, the energy benefits could be scaled up or down and the accuracy and storage frequency results reevaluated, depending on their typical energy use.

During the next project phase, Task 6, the method will be retested to determine the accuracy and storage frequency needed for the commissioning of air-handling equipment. Commissioning will include performance testing, performance monitoring, and measurement and verification.

Introduction

Background

Building energy management and control systems (EMCS) are primarily designed to control energy-consuming equipment installed in commercial buildings. Many EMCS can also be set up to perform operational, diagnostic, maintenance planning, performance monitoring, performance testing, and commissioning functions. They often monitor most of the same data necessary to perform these functions.

This project was initiated to develop a method for the following:

1. Choose the measurements needed to accomplish these functions.
2. Determine the required accuracy and storage frequency of those measurements.

The method will be the basis for upgrading or designing building energy management systems (EMS) to perform these tasks.

Objective

The objective of Task 5 was to develop a draft method to determine the recommended instrument accuracy and storage frequency for air-handling equipment. We focused on functions and evaluations related to the operation, control, and diagnostics of air-handling equipment, including fans, economizers, coils, and terminal units.

In this report, we describe measurement accuracy and building heating, ventilation, and air-conditioning (HVAC) response; and outline the method used to determine accuracy and storage frequency. We then apply the method to the operation, control, and diagnostic functions of air-handling equipment—determining the measurements, factors, and plots required; collecting site data to produce sample plots; and performing economic and sensitivity analyses to determine the effects of accurate data on building energy use.

Considering the cost of installing and maintaining accurate instrumentation, we use the economic and sensitivity analyses to determine the economic level of instrument accuracy. Using site data for the diagnostic plots, we estimate the storage frequencies needed to reproduce cycling and instabilities so that control problems can be diagnosed.

For the next project phase, Task 6, the method will be applied to commissioning functions related to air-handling equipment, including performance testing, performance monitoring, and measurement and verification. This will be a test of the method’s general applicability.

Discussion

Measurement Accuracy

For the purpose of this project, accuracy is defined as the overall accuracy of the measurement, which is a composite of the following sources of error:

1. Sensor
2. Lead wire resistance and noise
3. A/D converter
4. Number of bits (or resolution) of A/D converter
5. Accuracy of manufacturer's calibration
6. Accuracy of field calibration and calibration standard
7. Drift rate of sensor
8. Installation (effects such as stratification, turbulence, heat radiation or conduction, location, orientation, sizing, smoothness of holes, integrity of pressure tubing, and proper grounding)
9. Time response of the sensor
10. Rate of change of the state of the process

A detailed discussion of instrument accuracy can be found in Annex A of ASHRAE's proposed guideline 14P, Measurement of Energy and Demand Savings (ASHRAE June 1997). The guideline covers different types of measurements, their calibration, and applicable standards. ASME Performance Test Code (PTC) 19.1 (ASME 1998) describes procedures used to determine uncertainties of measurements and subsequent test results.

Manufacturers typically provide sensor accuracies that include hysteresis, repeatability, and as-received. Their accuracy sometimes includes drift, but they usually do not provide either the time period or the rate of drift. They sometimes provide the accuracy in terms of percent of either full scale or reading value, although it is unclear where that applies throughout the instrument's range. The most useful specification would be a percent of reading value over a given range, what exactly the accuracy includes, and an indication of how the accuracy might change over time.

A through-system calibration technique is the best way to calibrate an instrument. After the sensor is connected, it is subjected to a known state (temperature or pressure), and the EMCS reading is then adjusted to match that state. It is preferable to calibrate a sensor at more than one point. A good rule of thumb is that the calibration device should be four times as accurate as the sensor being calibrated.

This project states recommended accuracy in terms of the overall uncertainty across its operating range. To ensure that a measurement meets the criteria, the instrumentation, installation, calibration, and process dynamics need to be accounted for. A measurement's accuracy includes a bias component (the combination of a measurement's fixed or offset errors) and a precision component (the uncertainty based on random errors).

The overall accuracy of a measurement can be significantly greater than the sensor's accuracy. For example, the accuracy of a mixed air temperature measurement with one probe can be the combination of the following uncertainties (all values are ±):

- Sensor (0.25°F)
- Number of bits (or resolution) of A/D converter (0.02°F - 12 bit)
- Accuracy of field calibration and calibration standard (0.1°F)
- Drift rate of sensor (0.5°F/yr)
- Installation, assuming 2°F of stratification across the duct (1°F)
- Rate of change of the state of the process (assume temperature cycling of 2°F peak-to-peak, causing a precision uncertainty of 0.5°F)

The root sum square of the uncertainties is 1.25°F, which is much larger the 0.25°F uncertainty of the sensor alone. The accuracies for all factors should be considered when determining the overall accuracy of a measurement.

In our example, the 12-bit A/D converter contributed little to the measurement uncertainty. If the number of bits is less than 12, the effect would be greater. Table 1 shows the percent of (full scale) resolution for various levels of digital conversion (a positive range was assumed).

Table 1. Percent of Full-Scale Resolution for Digital Conversion

Number of Bits	Resolution (% of full scale)
8	0.4
10	0.1
12	0.02
14	0.006
16	0.001
18	0.0004
20	0.0001

System Response

The accuracy and storage frequency recommended for the measurements depend on the response characteristics of the building's HVAC system. It also depends on the ability to diagnose operational problems and evaluate various performance factors that affect building energy use.

A system's response characteristics depend on several time delays inherent in all systems, as well as on the way a control system is tuned. Time delays may make it appear that a control system isn't functioning when a change is made to a setpoint; only a few systems have time constants so small that they are negligible. Four basic time lags contribute to overall system response:

1. **Capacity time delay** exists where there is a large mass to be heated or cooled, such as a large room. A relatively long delay occurs between a change in the controlled device and the time the sensor senses a change. The delay is governed by the size of the zone and the air change rate. A temperature

sensor in the chilled water line near the chiller would have a very short capacity time delay and could make the loop difficult to tune because it is so fast.

2. **Transfer delays** are the delays inherent in the sensors. Once the control action takes place, a time delay occurs due to the mass of the sensor and the mass surrounding the sensor (such as its thermowell or the wall it is mounted on). A lower mass sensor, such as a resistance temperature detector (RTD), has a lower time delay than a higher mass sensor, such as a bi-metal sensor.
3. **Dead time** is caused by the sensor's location in a room. If a room sensor is not in a moving stream of air (for example, in a room with a radiator), the temperature change can take a long time to reach the sensor. A sensor located in a fast-moving air stream has less dead time. Dead time can be up to an hour in poor locations.
4. **Equipment response time** depends on the size of the equipment. Oversized equipment changes the room temperature much faster than undersized equipment. Once a valve is opened, there is a time delay for the hot water to reach the coil. A longer time delay would occur if the boiler has to be started to heat up that water, which explains why hot and cold water typically circulate continuously.

A system's overall response characteristic is a combination of the response times of the sensor, the equipment, the size of the HVAC system, the capacity of the building or zone, and the location of the sensor in the zone. EMCS measurements used in our diagnostic plots show the response characteristics of the sites. Our use of actual data to determine the required accuracy and storage frequency for our example already accounts for the response characteristics of the control system. Other systems, which may have longer or shorter overall response characteristics, may need to use different accuracy and storage frequency specifications for their EMCS. The plots must use data taken fast enough to show the cycling.

Draft Method

The draft method for determining sensor accuracy and storage frequency involves determining the measurements, factors, or plots required for the types of evaluations to be done with the equipment; collecting site data to produce sample plots and to perform a sensitivity analysis of the factors to their input measurements; performing an economic analysis to determine the effect of the factors and measurements on building energy use; and using economic and sensitivity analyses to determine the level of instrument accuracy required to produce energy savings that will cover the cost of installing and maintaining accurate instrumentation.

Following is an outline of the proposed method:

1. Initial step for determining accuracy and storage frequency
   - List measurements and performance factors needed for tasks to be accomplished (in this case, operation, control, and diagnostics of air-handling equipment).
   - Determine plots useful for evaluations.
   - Gather site data, develop plots, and calculate performance factors with real site data.
2. Accuracy and frequency based on energy benefits
   - Determine sensitivity of factors to their input measurements.
   - For each piece of equipment, develop a rough economic evaluation of the effect of varying parameters or measurements on energy use.
   - Prioritize the measurements and factors in terms of their effect on building energy use.
   - Considering the cost of instrumentation and calibration, determine the economic level of accuracy for each measurement.
3. Accuracy and frequency based on plots of data
   - Describe how the plots can be used for the evaluations (in this case, operation, control, and diagnostics of air-handling equipment).
   - Determine the potential benefits of using the plots.
   - Determine the measurement accuracy and storage frequency needed to use the plots for the evaluation.
4. Based on the economic analyses and diagnostic plots, determine recommended accuracies and storage frequencies for each measurement.

Diagnostic plots help determine accuracy and storage frequency from a different perspective. Here we account for the system response shown by the site data and the way the measurements are used to operate the air-handling system and to diagnose problems.

The results of the accuracies and storage frequencies from the economic analyses and diagnostic plots are then combined, to determine the final recommendations.

Application of Method to the Operation, Control, and Diagnostics of Air-Handling Systems

This section applies the proposed method to determine the accuracy and storage frequency requirements of measurements used for the operation, control, and diagnostics of air-handling equipment. For our economic analysis, we used a 50,000-square-foot office building with 100 hp of fan power and a 0.85kW/ton chiller in Alameda and Sacramento, California type weather climates. This method could be applied to other building types and locations, or our results could be adjusted to reflect other building sizes and types. In any case, the results provide a rough idea of the accuracy and storage requirements for a typical building energy management system in a small commercial building.

Setup

Measurements, Parameters, and Performance Factors

Table 2 lists air-handling measurements that can be available through an EMCS. Not all sites have all measurements, but we assume they are available for the purposes of this example. The measurement list includes parameters that would be useful for the operation, control, and diagnostics of air-handling equipment.

Table 2. Measurements and Parameters for Air-Handling Equipment

Category	Measurement
Weather	Outside Air Temperature Outside Air RH
Return Air	Return Air RH (not commonly measured in California) Return Air Temperature Return Fan Status (on/off, kW, or speed) Return Fan DP Return Fan Air Flow
Supply Air	Supply Air Temperature Supply Air RH (not commonly measured in California) Supply Fan (on/off, kW, or speed) Supply Fan DP Supply Fan Air Flow Supply Fan Discharge Pressure Filter DP
Cooling Coil	Cooling Coil Airside Inlet Temperature Supply Air Temperature Chilled Water Inlet and Outlet Temperatures Chilled Water Flow

Table 2. Measurements and Parameters for Air-Handling Equipment

Category	Measurement
Duct or Zone	Duct Static Pressure Duct or Cooling Coil Exit RH (not commonly measured in California) Space Static Pressure Zone Temperature Zone Temperature Setpoint VAV (hot or cold) Damper Positions (calculated, not measured) Air Flow at VAV boxes Zone Occupancy
Economizer	Mixed Air Temperature(s) Return Air Temperature Outside Air Temperature Outside Air Flow (not common) Exhaust, Recirc, Outside Air Damper Positions Minimum Outdoor Air % Target CO_2 Sensors (not common)
Typical Setpoints	Cold Deck Temperature or Supply Air Temperature Setpoint Duct Static Pressure Setpoint Zone Temperature Setpoint Low Limit on Mixed Air Temperature Low Limit on Supply Fan Discharge Temperature

DP = differential pressure, RH = relative humidity, VAV = variable air volume

For this project, we also developed a list of performance factors that might be used for air handlers. See Appendix A (page III-A-43) for the factors that were considered. We chose not to use coil effectiveness, fan efficiency, outdoor air fraction, and filter factors for the following reasons:

- It was more straightforward and easier to use the measurements directly, rather than the factors.
- It was confusing to use measurement differences or ratios.
- Many performance factors were affected by too many variables to be reliable indicators of performance (i.e., they varied too much with operating conditions).

Diagnostic Plots

There are many ways to view EMCS data, such as those described in the Electric Power Research Institute's (EPRI) HVAC Diagnostic and Commissioning System (HDCS) program (EPRI/AEC July 1997). We decided to focus on plots that show data as a function of time, since the time of day is usually necessary to understand the operation of a building's HVAC system. When we looked at x-y plots of the data (where measured data are plotted on both axes), we usually needed to look at the data plotted vs. time in order to understand any problems. (X-y plots are of greater value when the test conditions can be better controlled, so that there is less variation in the data.) We also tried to focus on just the few plots that would be essential for diagnostics to help building engineers and operators focus their time and effort.

Following are the plots that we suggest would be most useful to help building engineers and operators diagnose problems and make decisions. We use them in our analysis. More detailed descriptions and discussion are provided in Appendix B (page III-B-51).

Terminal Unit Operation and Zone Control

1. Zone Temperature vs. Time
2. Zone Temperature and Zone CFM vs. Time
3. Zone Temperature, Zone CFM, and Reheat Valve Position vs. Time (for exterior zones with reheat)
4. Zone Temperature, Zone Discharge Temperature, Zone CFM, and Reheat Valve Position vs. Time (for exterior zones with reheat)
5. Zone Temperature, Zone Cooling CFM, and Zone Heating CFM vs. Time (for exterior zones with a double duct VAV system)

Economizer/Mixed Air Damper Operation

- Mixed Air Temperature, Expected Mixed Air Temperature, Outside Air Temperature, and Return Air Temperature (optional) vs. Time

Cooling Coils

- Supply Air Temperature, Mixed Air Temperature, and Cooling Loop Output Signal vs. Time

Fans

1. Supply Duct Static Pressure vs. Time
2. Supply Duct Static Pressure and Maximum Zone Damper Position vs. Time
3. Supply Fan Status (such as fan on/off, DP, power, or current) and Low and High Zone Temperature vs. Time

Site Data

The plots are intended to cover the instrumentation available at a wide range of sites. We used several sources to find data to create the plots, and we tried to find data stored at relatively short intervals (1 to 5 minutes) so that we would be able to see any significant responses of the systems. The following three sites were used as sources for the data in this report:

- EPRI/AEC Project #2: Sample data from a large VAV system with zone reheat, provided with EPRI's HDCS program (EPRI and AEC July 1997). Instantaneous data stored every 2 minutes.
- Government Building: Commissioning data taken from a large office building in San Francisco, provided by Martin Applebaum of ESS Engineering, Inc, Tempe, Arizona (Mazzucchi, Gillespie, and Lippman 1996). Data is averaged and stored every 5 minutes.
- SF Hotel: Data from a large hotel in San Francisco, provided by Srinivas Katipamula of Pacific Northwest National Laboratory, Richland, Washington (Kammerud, Blanc, and Kane 1996). Instantaneous data stored every 5 minutes.

Analysis Using Energy Benefits

Sensitivity of Factors to Their Input Measurements

The performance factors considered for this example are in Appendix A, along with the reasons we chose not to use them for operations and diagnostics. In summary, it was less confusing to use the direct measurements rather than combining them into differences or ratios. For factors such as fan efficiency or coil effectiveness, the factors were very sensitive to their input measurements' uncertainties and to the

equipment's operating conditions. Since some factors varied significantly with operating conditions, it was difficult to determine what the target values should be, to be able to detect equipment degradation.

Effect of Deviations of Input Measurements and Factors on Building Energy Use

This section describes how building energy use is affected by measurements in the air-handling system. Building energy use was determined by a bin energy analysis method, using bin weather data. This method is described in Appendix C (page III-C-67). For measurements that affect the operation of the building's HVAC system, the building's chiller and fan annual energy use was determined.

The following measurements were varied:

- Zone temperature
- Supply air temperature
- Fan efficiency
- Filter DP
- Duct static pressure
- Outdoor air temperature
- Return air temperature
- Zone discharge temperature (to show the effect of a reheat valve leak)

The measurements were varied above and below their nominal setpoints (or baselines) to see how the annual energy use varied. Figures 1 and 2 and the parameters they are based on (Table 3) show the sensitivity of the example building's energy use with changes in measurements. The measurements shown in Table 3 are the actual system conditions. A sensor would need to drift in the opposite direction to result in that condition. For example, if the zone temperature sensor (Table 3–3D) drifted up (or read too high) by 1°F, the actual zone temperature condition would be controlled to a 1°F lower temperature, or 71.0°F (if the zone setpoint were 72°F).

The analysis was performed for a 50,000-square-foot building with a VAV air-handling system. Fan-rated air volume flow is 50,000 CFM and chiller efficiency is 0.85 kW/ton. The bin weather file is from the Alameda Naval Base. The climate is similar to downtown San Francisco. The analysis was repeated using McClellan Air Force Base bin weather data, which is near Sacramento and represents the high temperatures of the Central Valley (see Appendix D page III-D-69 for McClellan results). Most of the results are similar, so the following discussion focuses mostly on Alameda.

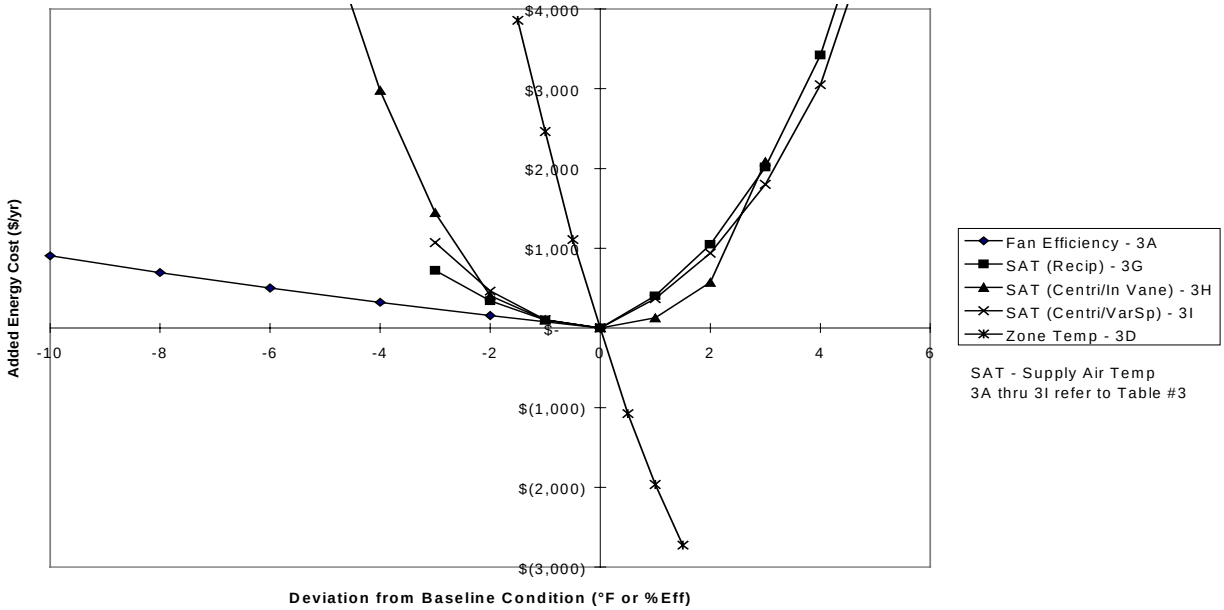


Figure 1. Added energy cost due to off-design conditions (Alameda 50,000sf office building)

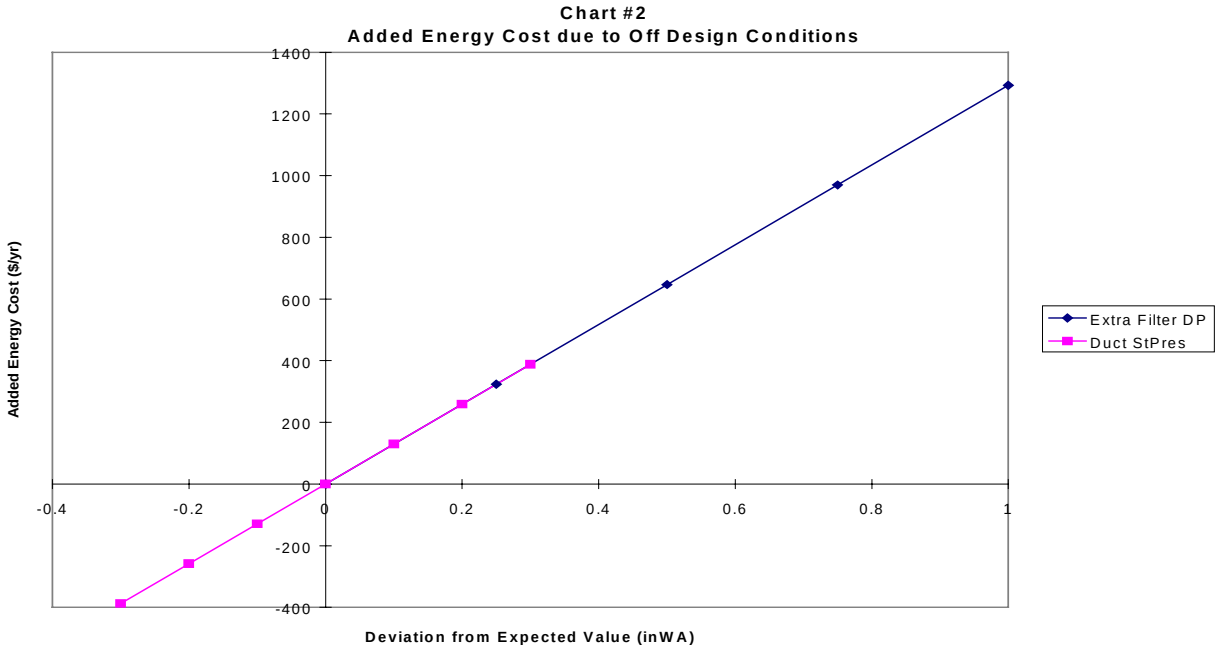


Figure 2. Added energy cost due to off-design pressures (Alameda 50,000sf office building)

Table 3. Fan and Chiller Energy Use vs. Air-Handling System Parameters

Fan and Chiller Energy Use vs. Several Air Handler System Parameters

Alameda Naval Air Station Weather File **$/kWh Cost = 0.10**

3A - Fan Efficiency

Fan Average Efficiency (%)	Fan Energy (kWh)	Fan Demand (kW)	Added Energy Cost ($/yr)
Baseline	45,246	39.6	-
Baseline - 2%	46,806	41.0	$ 156
Baseline - 4%	48,478	42.4	$ 323
Baseline - 6%	50,274	44.0	$ 503
Baseline - 8%	52,207	45.7	$ 696
Baseline - 10%	54,295	47.5	$ 905

3B - Clogged Filter

Differential Pressure (in H2O)	Fan Energy (kWh)	Fan Demand (kW)	Added Energy Cost ($/yr)
Baseline	45,246	39.6	-
Baseline+0.25" w.c.	48,478	42.4	$ 323
Baseline+0.5" w.c.	51,710	45.3	$ 646
Baseline+0.75" w.c.	54,942	48.1	$ 970
Baseline+1.0" w.c.	58,174	50.9	$ 1,293

3C - Outdoor or Return Air Temp Sensor Accuracy

Shift in Economizer Change Point Temperature (°F)	Chiller Energy (kWh)	Chiller Demand (kW)	Added Energy Cost ($/yr)
= RAT+2	71,500	103	$ 37
= RAT+1	71,249	103	$ 12
= RAT (Baseline)	71,134	103	-
= RAT-1	71,293	103	$ 16
= RAT-2	71,560	103	$ 43

RAT = Return Air Temperature

3D - Effect of Zone Temperature on Energy Use

Zone Temperature	Total Energy Use of Fan and Chiller (kWh/yr)	Energy Use Gas-Therms	Added Energy Cost ($/yr)
70.5	175,718	37.2	$ 3,859
71.0	161,738	42.6	$ 2,464
71.5	148,157	47.9	$ 1,109
72.0	137,037	53.2	-
72.5	126,270	58.5	$ (1,074)
73.0	117,341	63.8	$ (1,963)
73.5	109,711	69.1	$ (2,723)
74.0	102,300	74.4	$ (3,461)

3E - Effect of Leaking Reheat Valve on Energy Use

Zone Supply Temperature	Total Energy Use of Fan and Chiller (kWh/yr)	Total Energy Use Gas Therms	Added Energy Cost ($/yr)
65	144,475	346.8	$ 920
60	139,176	96.0	$ 240
55	137,037	53.2	-

3F - Duct Static Pressure Sensor

Static Pressure (in H2O)	Fan Energy Use (kWh)	Fan Demand (kW)	Added Energy Cost ($/yr)
Baseline + 0.3	49,125	39.6	$ 388
Baseline + 0.2	47,832	39.6	$ 259
Baseline + 0.1	46,539	39.6	$ 129
Baseline + 0.0	45,246	39.6	-
Baseline - 0.1	43,953	39.6	$ (129)
Baseline - 0.2	42,660	39.6	$ (259)
Baseline - 0.3	41,367	39.6	$ (388)

3G - Reciprocating Chiller - Variable Speed

Supply Air Temperature (°F)	Total Energy Use of Fan and Chiller (kWh)	Total Demand (kW)	Added Energy Cost ($/yr)
50	133,768	141.7	$ 722
51	129,960	144.4	$ 341
52	127,556	147.8	$ 101
53*	126,550	152.0	-
54	130,594	157.4	$ 404
55	137,037	164.4	$ 1,049
56	146,720	173.5	$ 2,017
57	160,774	189.0	$ 3,422
58	181,874	213.1	$ 5,532

3H - Centrifugal Chiller- Inlet Vanes

Supply Air Temperature (°F)	Total Energy Use of Fan and Chiller (kWh)	Total Demand (kW)	Added Energy Cost ($/yr)
50	220,493	141.7	$ 5,020
51	200,084	144.4	$ 2,979
52	184,763	147.8	$ 1,447
53	174,326	152.0	$ 403
54	171,293	157.4	$ 100
55*	170,297	164.4	-
56	171,564	173.5	$ 127
57	176,014	189.0	$ 572
58	191,141	213.1	$ 2,084

3I - Centrifugal Chiller- Variable Speed

Supply Air Temperature (°F)	Total Energy Use of Fan and Chiller (kWh)	Total Demand (kW)	Added Energy Cost ($/yr)
50	125,301	141.7	$ 1,072
51	119,215	144.4	$ 463
52	115,618	147.8	$ 103
53*	114,584	152.0	-
54	118,260	157.4	$ 368
55	123,975	164.4	$ 939
56	132,597	173.5	$ 1,801
57	145,099	189.0	$ 3,052
58	165,543	213.1	$ 5,096

*This temperature is used for the baseline, because it has the minimum energy use in this case.

Assumptions

VAV System
Fan Rated CFM = 50,000
Fan & Drive Efficiency = 60%
Fan Motor Horsepower= 100
Chiller kW/ton = 0.85
VSD Fan Min = 50%

Building
Perimeter Wall Area = 18,000
R-Value of Perimeter 1.5
Floor Area = 50,000
Watts/SqFt Lights = 1.5
Zone Ft2 = 800

W/SqFt Plug Load = 2.3
Nb of Occupants = 300
Internal Load BTUH = 743,001
ASHRAE 0.1% Design °FDB = 88
$0.60 per therm

Total annual building energy costs (air handler and chiller) were very sensitive to the average zone temperature in the building (Figure 1 and Table 3–3D). If the zone temperature measurement is high by 1°F, not only might the occupants feel discomfort (the building would be kept 1°F cooler), but this particular building would spend an additional $2,500 per year on energy—a lower building temperature should lead to a higher cooling load because of greater heat gain from the outside air. In addition, extra fan energy is required to keep the building cool. For the same cooling load, if the difference between the supply air and the zone temperatures (about 15°F) is reduced by 1°F, the fans must supply a greater air flow to maintain the same cooling capacity. If there are many zone temperature sensors, the overall inaccuracy will be smaller, but it is important to make sure that there is no prevalent bias associated with all the sensors.

Supply air temperature accuracy also has a significant effect on HVAC performance (Figure 1 and Table 3–3G to 3I). If it is off by about 2°F, it could cost the building owners between $300 and $1,000 a year, depending on the type of chiller and the direction of the deviation. If this sensor reads low and the supply air temperature is controlled high, the fans must provide more air to cool the building. If it reads high and the supply air temperature is controlled low, fan energy is saved but chiller energy increases. The optimal supply air temperature for the variable speed chillers was 53°F; for the inlet vane chiller it was 55°F. (Using the McClellan Air Force Base weather file, the optimal supply air temperatures ranged from about 50 to 53°F. An ASHRAE Research Project performed by Brandemuehl (TRP-823, in progress) used more sophisticated models to show that the optimal supply air temperature in most buildings is 52°F.)

For our example building, maintenance or an upgrade of fan efficiency (Figure 2 and Table 3–3A) can also save up to $900 per year (for a 10% efficiency change). This does not include the cost of fixing or upgrading the fan, which would need to be considered in the economic analysis.

Filter differential pressure should be checked periodically to ensure that it does not increase too much. Figure 2 (and Table 3–3B) shows that an extra 1.0 inH_2O pressure drop across the filter can cost an extra $1,300 per year in additional fan power. Keeping filters clean is a relatively simple task.

Likewise, the duct static pressure sensor (Figure 2 and Table 3–3F) should be kept accurate—if it drifts low by 0.3 inH_2O, the actual duct static pressure would increase by 0.3 inH_2O. This would cost our example building $388 per year in extra fan energy costs. If it drifts high, the building's air flow requirements may not be met. Since the duct static pressure directly controls the fan output, it should be kept accurate to maintain adequate ventilation while allowing the fans to modulate enough to minimize fan energy use.

We also looked at the effect on building energy use of the outdoor air and return air sensor readings (Table 3–3C). If these readings are off, the economizer change point shifts. The change point is the switch from using 100% outside air (when the outside air temperature is lower than the return air temperature) to using minimum outside air (when the outside air temperature is greater than the return air temperature) to reduce cooling costs.

This change point is shown at 75°F on Figure 3. The chart illustrates a typical economizer's operation as a function of outside air temperature and the corresponding heating or cooling use. The accuracy of the change point is not so critical since the number of hours per year that are affected (where the outside air temperature is close to the return air temperature) is not so great (on the order of 100 hours per year). If the change point shifts in either direction by 2°F, the extra energy cost per year is about $40. Therefore, the accuracy of the outdoor air and the return air temperature sensors is not of great concern in our example.

Storage frequency is not a factor because these benefits are based on real-time control accuracy. The data does not need to be stored or averaged over time to attain these benefits.

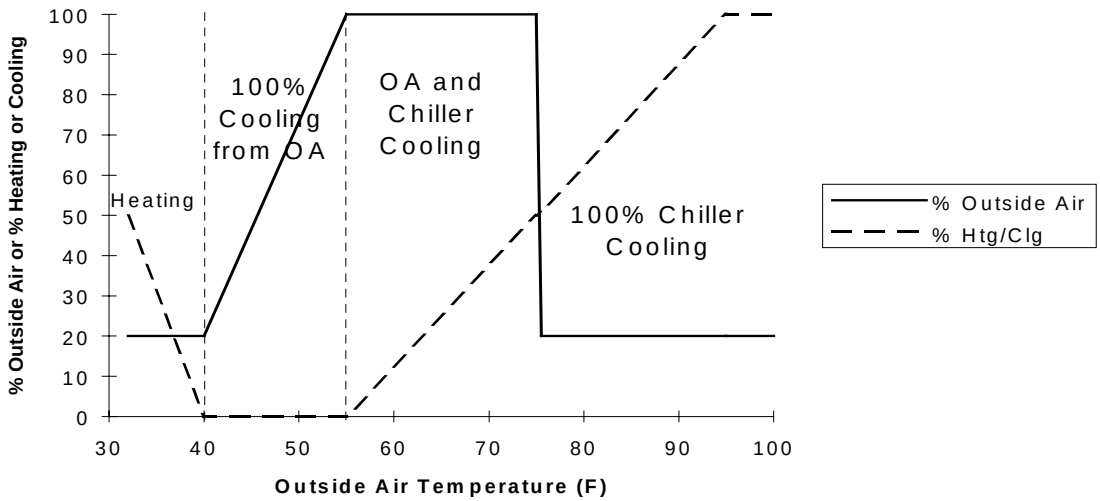


Figure 3. Air-side economizer operation

Prioritization of Measurements and Factors

Based in part on the economic analysis, we can prioritize the importance of the various air-handling measurements in terms of their effect on building energy use:

Most Important

- Supply Air Temperature: Affects fan and chiller power.
- Zone Temperatures: Any overall bias in one direction or the other affects either comfort or building energy use.
- Duct Static Pressure: Directly controls fan power.
- Filter Differential Pressure: Determines when filters need to be maintained.

Average Importance

- Outside Air Temperature: Used to control the *upper and lower* economizer change points and to calculate mixed air fraction, although this ratio's usefulness is not clear. Value for diagnostic plots is discussed below.
- Return Air Temperature: Used to control the *upper* economizer change point and to calculate mixed air fraction, although this ratio's usefulness is not clear. Value for diagnostic plots is discussed below.
- Mixed Air Temperature: Does not directly control fan or chiller, although it does indicate proper economizer operation. Used to calculate mixed air fraction, although this ratio's value is not clear. Importance regarding diagnostic plots is discussed below.

- Fan Efficiency: Lower efficiency fans or a degradation in fan efficiency could increase building energy use.
- Fan Air Flow: Used to determine fan efficiency. Could be used to determine minimum outside air flow, which is important in maintaining building air quality.
- Fan Static Pressure: Used to determine fan efficiency.
- Fan Power: Used to determine fan efficiency and to verify fan scheduling and modulation.
- Fan Status: Importance regarding diagnostic plots is discussed below.
- Terminal Unit Air Flow: Importance regarding diagnostic plots will be discussed below.
- Outside Air Flow: Important in maintaining required ventilation levels. Not typically available.
- Economizer Damper Position: Not typically measured.

Least Importance

- Relative Humidities: Not commonly measured in California.
- Space Static Pressure: Accuracy is not critical. Positive pressure should be maintained to minimize unconditioned air infiltration. Excessive positive or negative pressure increases load on the HVAC system.
- Zone Occupancy: High accuracy is not important. Occ/Unocc status is useful if VAV boxes are controlled based on occupancy. Occupancy is also useful for optimizing lighting controls.

Instrument Accuracy Chosen to Minimize Building Energy Use

This section focuses on the more important measurements listed in the previous section. Figures 1 and 2 and Table 3 are used to estimate the appropriate levels of measurement accuracy, based on the building energy analyses. The figures show the affect of changing the accuracy of pressure, supply air temperature, and zone temperature measurements. We first made assumptions of how much accuracy improvement we can expect, and then estimate the cost of the more accurate sensors and the cost to calibrate the sensors annually. (Note: These costs will vary based on the actual site requirements. Sites different from our example must also adjust the results in Table 3 to reflect their actual fan and chiller energy use.)

Our assumptions are that we need to improve temperature measurement accuracy from 2.0 to 0.5°F and pressure measurement accuracy from 0.5 to 0.2 inH_2O. This will cost about $100 per year to calibrate and maintain the higher accuracy instrumentation. In addition, it would cost $100 to purchase a more accurate sensor. This cost can be spread over 2 years ($50 per year). If the energy savings from improved accuracy is greater than the cost of improved accuracy ($150 per year), it is worth the extra effort to improve measurement accuracy. For zone temperatures, we assumed that it would cost $20 per year to calibrate each sensor.

Table 4 steps through the benefit/cost analysis, which helps decide whether or not to improve measurement accuracies at the Alameda and Sacramento example sites. The additional energy costs for the worse accuracy and improved accuracy cases are shown for six measurements. The difference is the annual energy savings that can be expected from improving the accuracy of the measurements. The annual energy savings is divided by the assumed cost of making the improvements to calculate a benefit/cost ratio for each sensor type. The B/C ratio is compared to the acceptable B/C ratio, which is

based on the chance that savings will not occur, as well as the margin of economic uncertainty that is acceptable.

For supply, return, and outside air temperatures, we chose an acceptable B/C ratio of 1.0, since savings would occur with sensor drift in either direction (around an optimum setpoint). For the 50 zone temperatures, drift would be more random, with some zones compensating for drift in other zones. We set the acceptable B/C ratio to 5 in this case, to reflect the fact that not all zone temperatures will drift in the same direction by a significant amount. Another way to look at it is, if all sensors are improved, only one out of five sensors will provide the benefit shown in the table. The pressure sensors were given acceptable B/C ratios of 2.0, because if they drift in one direction costs will increase, but if they drift in the other direction energy costs will decrease. There is a 50% chance that the drift will be in the direction where benefits will occur. The acceptable B/C ratios will be different for other situations. These were based on our personal assumptions and acceptance of risk.

Table 4. Sensor Accuracies and Other Improvements based on Energy Benefits

Alameda Small Office Building - 50,000 sf - Bin Analysis Approach

Air Handler Operation and Control - Sensors	No. of Sensors	Added Annual Energy Cost with Baseline Accuracy (2°F or 0.5 inH_2O)	Energy Cost with Improved Accuracy (0.5°F or 0.2 inH_2O)	Annual Energy Savings from Improved Accuracy	Assumed Annualized Cost of Improvement	Benefit to Cost Ratio	Acceptable B/C Ratio[1]	Recommended Sensor Accuracy[2]	Maximum Potential Net Savings if Sensors are Improved[3]
		($/yr)	($/yr)	($/yr)	($/yr)				($/yr)
Supply Air Temperature	1	$628	$100	$528	$150	3.5	1	0.5°F	$378
Zone Temps (one per 1000 sf)	50	$5,145	$1,109	$4,036	$1,000	4.0	5	2°F	-
Duct Static Pressure	1	$646	$259	$387	$150	2.6	2	0.2 inH_2O	$237
Filter Differential Pressure	1	$646	$259	$387	$150	2.6	2	0.2 inH_2O	$237
Outside Air Temperature[4]	1	$40	$7	$33	$150	0.2	1	1°F	-
Return Air Temperature	1	$40	$7	$33	$150	0.2	1	2°F	-
Total Potential Annual Savings[5]									$852

McClelan/Sacramento Small Office Building - 50,000 sf - Bin Analysis Approach

Air Handler Operation and Control - Sensors	No. of Sensors	Added Annual Energy Cost with Baseline Accuracy (2°F or 0.5 inH_2O)	Energy Cost with Improved Accuracy (0.5°F or 0.2 inH_2O)	Annual Energy Savings from Improved Accuracy	Assumed Annualized Cost of Improvement	Benefit to Cost Ratio	Acceptable B/C Ratio[1]	Recommended Sensor Accuracy[2]	Maximum Potential Net Savings if Sensors are Improved[3]
		($/yr)	($/yr)	($/yr)	($/yr)				($/yr)
Supply Air Temperature	1	$406	$85	$321	$150	2.1	1	0.5°F	$171
Zone Temps (one per 1000 sf)	50	$6,352	$1,382	$4,970	$1,000	4.9	5	2°F	-
Duct Static Pressure	1	$490	$196	$294	$150	2.0	2	0.2 inH_2O	$144
Filter Differential Pressure	1	$490	$196	$294	$150	2.0	2	0.2 inH_2O	$144
Outside Air Temperature[4]	1	$41	$3	$38	$150	0.3	1	1°F	-
Return Air Temperature	1	$41	$3	$38	$150	0.3	1	2°F	-
Total Potential Annual Savings[5]									$459

[1] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is acceptable. Where there a many sensors (such as zone sensors), it includes the percentage of zones that might need improvement.

[2] The Improved Accuracy or Proposed Improvement is recommended if the B/C ratio is greater than the Acceptable B/C Ratio.

[3] The Maximum Potential Net Savings is calculated by: (Annual Energy Savings - Annual Cost). The lump sum costs are spread over a 3-year period (I.e. they are divided by 3).

[4] Outside air temperature should be 1°F accurate, in order to use the diagnostic plots shown in Task 5. Depending on the energy analysis results, the OAT accuracy is set to 1°F or better.

[5] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset of them.

Based on the results shown in Table 4, it would pay to install and maintain more accurate sensors for the supply air temperature, duct static pressure, and filter differential pressure. Potential net savings at Alameda are $852/yr, and savings at Sacramento are $459/yr.

Analysis Using Diagnostic Plots

In the previous section, the annual cost of energy was calculated for different operating points of several air-handling system parameters (filter DP, zone temperature, supply air setpoint, etc.), giving the change in annual energy use with deviations from the various parameter baselines. The results indicated the measurement accuracies needed to operate the system at more cost-effective levels. Because this approach focused on real-time control of the system, we did not recommend storage frequencies.

This section takes a different approach to determine storage frequencies and accuracies. Here we look at diagnostic techniques that can be used to find control or operating problems. Problems can be diagnosed in different ways—using real-time data, short-term trends, or long-term monitoring. In the previous section, we used real-time data to maintain proper operating levels. Here we use short-term (i.e., daily) trends as a way to find most of the control and operating problems that might occur. Most EMCS have the capability or are already set up to trend data for 24-hour periods. Most operators surveyed used 24-hour trends (as well as real-time traces) to find problems. While long-term monitoring would help determine equipment degradation and keep track of energy-use patterns (which is useful for developing better operating strategies), most of the benefit would come from using short-term trends to solve noticeable control or operating problems.

The actual diagnostic process does not have to be done via plots. It can be done automatically with computers, visually with plots, transferred into a spreadsheet, or by another technique using the data from storage. Diagnostics entails (1) gathering the data, (2) preparing the data in a useful format (such as plots), (3) using diagnostic rules to detect and solve problems, and (4) deciding how to fix the problem. Even though we use plots to determine the accuracy and data storage frequency needed to detect and diagnose problems, the results are useful for the other diagnostic techniques as well.

Appendix B (page III-B-51) describes the diagnostic plots that we believe would be most useful to plant operating personnel. Plots are provided for zone temperature control and terminal units, economizers, cooling coils, and duct pressure or fan control. For each plot, we give a description, a sample plot using real data, a discussion of what the plot should look like, and an analysis of the sample plot.

In this section, the diagnostic plots are used to decide what measurement accuracies and storage frequencies are needed to perform effective diagnostics. After first discussing the potential economic benefits of diagnostics, we then use the example plots to determine the measurement accuracies that would provide ample benefits and the ability to detect problems. Finally, the instabilities or cycling found in the sample data, as well as the need to check scheduling, helps us determine the storage frequency required to detect problems.

Potential Economic Benefits of Diagnostic Plots

Terminal Unit Operation and Zone Control

1. Zone Temperature vs. Time

Maintenance of occupant comfort provides a more productive environment; benefits vary depending on the type of activity performed in the space. People often work more slowly if the space is too warm or leave the space if it is too cold. The cost to the occupant could be significantly higher than energy costs. The energy cost analysis indicated that more than $2,000 per year would be incurred for each 1°F that the average zone temperature varies from its target (for the 50,000-square-foot example building).

Another benefit of this plot is in adjusting the timing of building warm-up/cooldown. For the example building, the total annual energy cost (chiller plus fan) is about $12,000. If the building reaches or maintains operating temperature one hour earlier every day, for example, the building is maintaining space conditions an extra 10% of the time, which translates into approximately $1,200 per year in energy costs.

2. Zone Temperature and Zone CFM vs. Time (for interior zones)

This plot helps solve zone temperature control problems; the benefits are similar to those described in #1. Its use can help save time finding solutions to problems, which would result in labor savings to the facility.

3. Zone Temperature, Zone CFM, and Reheat Valve Position vs. Time (for exterior zones with reheat)

This plot helps solve terminal box problems. The benefits include those described in #1 and #4. Use of this plot saves time and labor while solving problems. Energy savings may also come from being able to lower hot water temperature to reduce heat losses.

4. Zone Temperature, Zone Discharge Temperature, Zone CFM, and Reheat Valve Position vs. Time (for exterior zones with reheat)

This plot can help determine if the reheat valve is working properly. If the valve is leaking, or open when it should be closed, the zone discharge temperature is also high. According to the energy cost analysis for our example building, if one valve is leaking and the discharge temperature is high by 10°F, an extra $900 per year will be spent on energy.

5. Zone Temperature, Zone Cooling CFM, and Zone Heating CFM vs. Time (for exterior zones with double duct VAV systems)

   The potential benefits of this plot are similar to #4, even though the parameters are different. If the heating flow is not controlled properly, extra heating and cooling energy costs are the result. In the example building, if 100 CFM of heating air leaked continuously into a single zone during building hours, and raised the discharge temperature by about 10°F, an extra $900 per year will be spent on energy.

Economizer/Mixed Air Damper Operation

- Mixed Air Temperature, Expected Mixed Air Temperature, Outside Air Temperature, and Return Air Temperature (Optional) vs. Time.

  The economic analysis for the example building shows that if the economizer's changeover point (where the outside air temperature equals the return air temperature) is shifted a degree or two, the effect on operating cost is not significant because the amount of time that the problem occurs is small. On the other hand, a continuous problem like the one in the economizer plot (page III-B-60), where the mixed air temperature is high by about 2 degrees all morning, would lead to more significant energy costs. Chiller power would increase by about 15% during the morning only. Assuming a total annual chiller energy cost of $6,500, the extra energy cost of the economizer's poor performance would be about 7.5% times $6,500, or about $500 per year.

Cooling Coils

- Supply Air Temperature, Mixed Air Temperature, and Cooling Loop Output Signal vs. Time.

In addition to verifying that the cooling coil controls are working properly, this plot can check that the supply air temperature is maintained at its optimum level. As shown in the example economic analysis, if the supply air temperature is off by 2°F, the extra energy cost would range from $300 to $1,000 per year (depending on the direction of the error and the type of chiller).

Fans

1. Supply Duct Static Pressure vs. Time

This plot verifies that the duct static pressure is maintained at the proper level. As demonstrated in the example economic analysis, if the pressure is high by 0.3 inH_2O, energy costs would increase by $300 per year. It also verifies the operating schedule of the fans. If the fans start one hour earlier each day, this could cost an extra $600 per year in fan energy costs.

2. Supply Duct Static Pressure and Maximum Zone Damper Position vs. Time

This plot enables advanced control of the fans by adjusting duct static pressure to minimize pressure drop through the terminal units. As in the previous plot's example, several hundreds of dollars in energy costs can be saved each year if the duct static pressure can be modulated by several 0.1 inH_2O.

3. Supply Fan Status[1], Low Zone Temperature, and High Zone Temperature vs. Time

   This plot helps verify that the morning warm-up/cooldown schedule is optimal, so that all zones reach a comfortable temperature level before the building is occupied. If one hour can be shaved off the morning operating period all year, about $600 can be saved in annual energy costs at our example building. This strategy also minimizes the number of complaints by ensuring that all zones are at the right temperature at the right time.

Accuracies and Storage Frequencies Needed for Diagnostic Plots

In this section, we determine the accuracy and storage frequency requirements for the measurements used in the plots, based on how the plots will be used to look for potential energy savings and to diagnose control and stability problems. We assumed the following:

1. It costs about $100 per year to calibrate and maintain each instrument so that temperature measurement accuracy improves from 2.0 to 0.5°F or pressure measurement accuracy improves from 0.5 to 0.2 inH_2O.
2. It costs $100 to purchase a more accurate sensor, and this cost can be spread over 2 years ($50 per year). The total cost of maintaining better accuracy is $150 per year. If the benefit of the better accuracy is greater than $150 per year (by an acceptable margin), then the extra maintenance to attain that accuracy is recommended.

Storage frequencies are recommended to ensure that the plots (or data) are detailed enough to perform diagnostics. The data should be stored for at least 24 hours (or if possible, 48 hours, so that a contiguous occupied period of data can always be viewed). For better resolution, data should be plotted only for the period during which the HVAC system is operating.

All recommendations of storage frequency are based on use of instantaneous data for the plots (except for air flows). Most measurements (such as temperature) will not experience enough noise or cycle enough during a short period of time to justify using averaged data. If a reading has significant electronic

[1]Supply fan status may be indicated using fan differential pressure, duct static pressure presence, fan power, or fan current.

noise, the noise should be eliminated. We recommend averaging only for air flow readings, where turbulence may affect the reading's stability (and hence, its accuracy) enough to warrant some type of damping. Some EMCS could be slowed by averaging too many data points, or they may not have enough room for the additional channels used for averaging.

The recommended storage frequencies are based on being able to see the details and changes in the diagnostic plots in Appendix B. According to Shannon's Theorem, if we acquire *more than* 2 points per cycle of the highest frequency component in the signal, the entire signal can be reproduced exactly. Otherwise, it cannot be reproduced (Smith 1993). The highest frequencies of interest are those that represent potential HVAC control instabilities. The cycling that we want to capture is not regular and may even occur sporadically. To capture every event, we recommend storing at least 5 points per (shortest) cycle, to be conservative.

Since the use of these plots for diagnostics is more "qualitative," our estimates of accuracy and storage frequency are also more "qualitative." Our accuracies are based on, for example, what can be detected in terms of personal comfort, what indicates instabilities, or what provides enough benefit to reduce building energy costs. To determine storage frequency, we take the shortest cycle that shows potential instabilities and divide the period by about five to get the storage rate.

Terminal Unit Operation and Zone Control

1. Zone Temperature vs. Time

   – **Accuracy Requirement:** Zone temperature is not a critical function since comfort is relative to several factors in addition to dry bulb temperature. ASHRAE Standard 55-1992 describes the comfort zones and relevant factors for most people (ASHRAE 1992). It is usually sufficient to control dry bulb to within ±2°F of a target (generally about 72°F) to maintain comfort. The zone temperature setpoint can be adjusted if there are complaints, so accuracy is not critical. However, on the terminal unit plots in Appendix B, a resolution of ±0.5°F is recommended to detect zone temperature instabilities of ±1°F.

   – **Storage Frequency:** To verify that comfort is being maintained, we recommend a storage frequency of 15 minutes. Zone temperatures change slowly due to their sensor's time constants and the capacity delay of the space. To observe control stability, storage at least every 5 minutes is recommended; every 2 minutes is preferred, if possible. Terminal Unit Plot #3 (Appendix B) uses a 5-minute rate, and Plot #1 (Appendix B) uses a 2-minute rate. Both plots show adequate detail to detect instabilities. A 5-minute storage rate is sufficient to verify the timing of the early morning warm-up/cooldown cycle. For our example building, if the start time is adjusted to within 15 minutes of the optimum start time, the annual energy savings would be within about $300 of optimum, which is acceptable.

2. Zone Temperature and Zone CFM vs. Time (for interior zones)

   – **Accuracy Requirement:** This plot adds Zone CFM to Plot #1 (Appendix B), so that proper terminal unit operation can be verified. The same Zone Temperature recommendations apply. The accuracy of the flow measurement is not as important as the relationship of the flow to the zone temperature (the flow should increase as the zone temperature increases and vice versa). Typical flow device accuracy of ±10% is good enough to be able to see the relationship.

     The CFM measurement is controlled based on how the zone temperature compares to the zone's setpoint. Even if the CFM measurement is inaccurate, the temperature setpoint can be changed to

adjust for comfort (i.e., the CFM is self-compensating). However, if the minimum CFM is inaccurate (i.e., actual flow is higher than the reading), the terminal unit will use excess energy when it is controlled to its minimum flow position. In this case, we do not recommend regular calibrations, but we do recommend that they be zeroed when the zero flow reading shifts by more than 2% of full scale. It is very important to make sure the actual duct flow is zero before adjusting the calibration and that there are no mechanical or naturally induced drafts. The box should also have enough straight duct leading to it so that there is less potential for error.

- **Storage Frequency:** The recommended storage rates for flow are more frequent than those for temperature, since flow has a much shorter response time compared to zone temperature. Terminal Unit Plot #2 (Appendix B) shows cycles occurring about once every 5 minutes. To adequately reproduce this cycling, we recommend a storage rate of 1 minute. Storage of average flows are preferable to instantaneous flows to dampen noise in the flow measurement due to turbulence in the actual air flow.

3. Zone Temperature, Zone CFM, and Reheat Valve position vs. Time (for exterior zones with reheat)

   - **Accuracy Requirement:** This plot adds the control signal for Reheat Valve Position. This is not a measurement of the actual valve position, nor is it a good indication of the actual flow, since valves and coils do not necessarily have linear relationships. It is the signal to the valve that controls the valve opening. There is no accuracy requirement because it is a calculated value. The Zone Temperature and CFM recommended accuracies remain the same.

   - **Storage Frequency:** Terminal Unit Plot #3 (Appendix B) uses data from a different site than Plots #1 and #2. Notice that the Cold Air Flow CFM cycles about once every 12 minutes. Even though a storage rate of once every 2 minutes would be adequate in this case, once a minute is recommended in general.

     The storage rate of the Reheat Valve Position (or other control signal) should be similar to that for the Zone Temperature, since its value is calculated based on the Zone Temperature. We recommend a rate of once every 5 minutes (2 minutes if storage space is not an issue).

4. Zone Temperature, Zone Discharge Temperature, Zone CFM, and Reheat Valve position vs. Time (for exterior zones with reheat)

   - **Accuracy Requirement:** In Terminal Unit Plot #4 (Appendix B), we add a curve for zone discharge temperature. In this case, we are looking for signs of poor control or reheat valve leakage, which would be seen as a rise in air temperature of several degrees. From the economic analyses, we know that a leak that causes a 5°F rise in discharge temperature at a terminal unit results in an extra energy cost of $240 per year. To detect this level of leakage, the accuracy of the discharge temperature should be about 2°F.

   - **Storage Frequency:** The zone discharge temperature will have a much faster response time than the zone temperature measurements because it is subject to the air velocity in the duct; the duct temperature will change faster than the room temperature because is has a smaller thermal heat capacity time delay. To detect changes or instabilities in the terminal unit, data should be stored at the same rate as the Zone CFM, one scan per minute.

5. Zone Temperature, Zone Cooling CFM, and Zone Heating CFM vs. Time (for exterior zones with double duct VAV systems)

   - **Accuracy Requirement:** The added parameter in this plot is the Zone Heating CFM. Its accuracy and storage frequency should be the same as for Zone Cooling CFM. The accuracy of

the flow measurement is not critical. The plot should enable us to see the relationship of the flow to the zone temperature. Typical flow device accuracy of ±10% is good enough to be able to see the relationship. The accuracy is not critical because the CFM control is self-compensating. The CFM measurement should read zero when the fans are off to be able to verify that the heat flow is zero when no heat is required. We do not recommend calibrating the flow meters on an annual basis, but we do recommend that they be zeroed when the zero flow reading shifts by more than 2% of full scale (make sure the flow is actually zero before zeroing).

- **Storage Frequency:** The Heating CFM should be stored as often as the other air flows to detect potential instabilities and cycles as short as 5 minutes. The recommended storage rate is once a minute. Storage of average flows would be preferable to instantaneous flows to dampen noise in the flow measurement that might be due to turbulence in the actual air flow.

Economizer/Mixed Air Damper Operation

- 1. Mixed Air Temperature, Expected Mixed Air Temperature, Outside Air Temperature, and Return Air Temperature (Optional) vs. Time
  - **Accuracy Requirement:** This plot is used to make sure that the economizer controls the actual mixed air temperature such that it tracks the expected mixed air temperature (based on the rules given page III-B-59). Based on the rough economic analysis using our example building above, where a continuous 2°F shift in mixed air temperature adds $500 per year to the annual energy cost, we recommend that the mixed air and outside air temperatures be measured to 1°F accuracy, in order to use the economizer plot for diagnostics. The return air and outside air temperatures require less accuracy (about 2°F) to control the crossover point, which was shown to have little effect on the annual energy use.

    The accuracy of the mixed air temperature control also affects fan energy directly when the chiller is off (i.e., when the outside air temperature is below the supply air temperature setpoint). (Note: The supply air temperature control affects fan energy when the chiller is on.) The plot would be used to ensure that the mixed air is controlled to the supply air temperature setpoint. For this case as well, the mixed air temperature should have an accuracy of 1°F. Because of stratification between the return air and outside air, this may be difficult to achieve unless there is an array of temperature sensors. In any case, the average mixed air temperature should have an accuracy of 1°F.
  - **Storage Frequency:** The mixed air and return air temperature sensors have a fairly rapid response time because they are placed in a high-velocity air stream. They are used to check the stability of the economizer and require fairly rapid storage rates. The economizer plot (Appendix B) shows cycling about once every 5 minutes; therefore, we recommend storing mixed and return air temperatures once every minute.
  - Outside air temperature may change only a few degrees per hour, as seen in the economizer plot. Since it changes very slowly, we recommend a storage rate of once every 5 minutes to detect changes down to about 0.5°F.

Cooling Coils

- Supply Air Temperature, Mixed Air Temperature, and Cooling Loop Output Signal vs. Time
  - **Accuracy Requirement:** Based on our economic analysis, the supply air temperature should be kept within 0.5°F of the optimum setpoint, in order to save $300 to $1,000 per year. The economizer plot showed that mixed air should be accurate to ±1.0°F. The cooling loop output

signal is a calculated value based on the supply air temperature, so it does not require an accuracy specification.

- **Storage Frequency:** This plot helps us check for stability and response characteristics. The supply air temperature and Chilled Water Valve % cycle every 8 minutes. We recommend a storage rate of at least once per 2 minutes for both parameters in this example.

Fans

1. Supply Duct Static Pressure vs. Time
   - **Accuracy Requirement:** Based on the economic analysis, where a deviation of 0.3 inH_2O adds about $300 to our example building's annual energy cost, we recommend that duct static pressure be accurate to 0.2 inH_2O, so that the savings (about $300 per year) are still greater than the calibration plus sensor costs (about $150 per year). More importantly, the sensor should be selected with a maximum range close to the control point. A sensor with a wide range will not control as closely as one that is selected near the expected control range. For a supply duct static pressure of 0.6 inH_2O, the maximum range should be 0–1.0 inH_2O.
   - **Storage Frequency:** In Fan Plot #1 (Appendix B), cycles occur about once every 6 minutes. To reproduce the cycles and verify supply duct static pressure stability, we recommend a storage frequency of once a minute. To observe control stability over shorter time periods, a sample rate of 1 second would be helpful; however, sampling times up to 10 seconds can be used. The 1– or 10–second data need not be stored; it can be plotted in real time.

2. Supply Duct Static Pressure and Maximum Zone Damper Position vs. Time
   - **Accuracy Requirement:** The duct static pressure measurement recommendations are the same as above. This plot adds Maximum Zone Damper Position, which is calculated. No accuracy recommendations are needed.
   - **Storage Frequency:** The Maximum Zone Damper Position should be stored at the same rate as the Supply Duct Static Pressure—if there is a control problem with pressure cycling, we can tell if it is due to the damper signal cycling. We recommend storing the Damper Position once a minute.

3. Supply Fan Status[2], Low Zone Temperature, and High Zone Temperature vs. Time
   - **Accuracy Requirement:** This plot is used to check the efficacy of the morning warm-up/cooldown program. We want to make sure that the worst-case zone temperature is 70°F for warm-up and 74°F for cooldown within 15 minutes of occupancy. An accuracy of 1°F is sufficient to ensure that the building temperature is close to the comfort range of 72 ±2°F.
   - **Storage Frequency:** Since we need to know if the space is conditioned within 15 minutes of occupancy, the storage frequency should be at least every 5 minutes.

Summary of Accuracy and Storage Frequencies Needed for Diagnostic Plots

This section summarizes the recommended accuracies and storage frequencies, based on using diagnostic plots to reduce energy use and improve system stability and comfort.

Terminal Units

[2]Supply fan status may be indicated using fan differential pressure, duct static pressure presence, fan power, or fan current.

- Zone Temperature: 0.5°F resolution is needed to detect zone instabilities. An accuracy of 2.0°F for zone temperature accuracy is adequate, since comfort levels are maintained by shifting setpoints anyway. Storage frequency every 5 minutes to verify morning warm-up/cooldown cycle and stability. Every 2 minutes would be preferred to verify stability.
- Zone CFM: 10% accuracy to verify proper relationship to zone temperature. Zero flows periodically to ensure minimum flow position accuracy. Store averages every minute to reproduce 5-minute cycles. Note: For our 50,000 sf example office building, it was not shown to be economical to install or calibrate the zone CFM sensors.
- Reheat Valve Position: This is calculated and does not require an accuracy specification. Store at the same frequency as the zone temperature, once every 5 minutes (or every 2 minutes if storage space is not an issue).
- Zone Discharge Temperature: A 2°F accuracy would enable detection of a 5°F temperature rise, to detect a reheat valve leak costing $240 per year. Store data at the same rate as the zone CFM (i.e. once per minute). Note: It was not shown to be economical to install these sensors in our example buildings.
- Zone Heating CFM: Use the same accuracy as Zone CFM, or 10%. Zero periodically. Store data once per minute.

Economizer/Mixed Air Damper

- Mixed Air Temperature: 1°F accuracy would enable detection of continuous 2°F deviations, which can cost our example building $500 per year. Store every minute to detect 5-minute cycles of the economizer.
- Outside Air Temperature: 1°F accuracy is adequate to be able to check economizer control within 2°F , which can cost our example building $500 per year. Store once every 5 minutes since OAT changes slowly.
- Return Air Temperature: 2°F accuracy is adequate since RAT has little effect on annual energy use. Store every minute to detect 5-minute cycles of the economizer.

Cooling Coil

- Supply Air Temperature: Maintain a 0.5°F accuracy to save $300 to $1,000 per year. Store every 2 minutes to reproduce 8-minute cycles.
- Cooling Loop Output Signal: No accuracy specification needed for this calculated value. Store every 2 minutes to reproduce 8-minute cycles.

Fans

- Supply Duct Static Pressure: Maintain a 0.2 inH_2O accuracy to save about $300 per year. Store data once per minute to reproduce 6-minute cycles. Real-time plot of 1– or 10–second data (not stored) should be available.
- Filter DP: Maintain a 0.2 inH_2O accuracy to save about $300 per year. Check the filter DP every month, more or less often based on experience.
- Maximum Zone Damper Position: No accuracy specification is needed for this calculated value. Store at the same rate as the Supply Duct Static Pressure (once per minute).
- Low and High Zone Temperatures: To ensure that the building is close to the zone setpoint temperature before occupancy, an accuracy of 1°F is adequate. To check the warm-up/cooldown schedule, store once every 5 minutes.

Recommended Measurement Accuracies and Storage Frequencies

This section combines the measurement accuracies and storage frequencies from the economic analyses and diagnostic plots to give the recommended values for operation, control, and diagnostics of air-handling equipment. See Table 5.

The calibration frequency to maintain the equipment depends on the stability of the sensor. Anything that requires accuracy of 0.5°F or 0.2inH_2O or better probably requires an annual calibration. For some sensors, we have demonstrated that the assumed cost of better sensors and annual calibration is covered by the annual energy savings associated with better control.

Table 5. Recommended Accuracies and Storage Frequencies (applies to Alameda and Sacramento Sites)

Equipment/Plot/Parameters	Accuracy	Storage Frequency (min)	Comments
Terminal Units			
Zone Temperature	2.0°F	2	5-min storage frequency is OK.
Zone Cooling CFM	10%	1	Store running averages if possible. Zero flows when fans are off.
Reheat Valve Position	N/A	2	5-min storage frequency if space is an issue.
Discharge Temperature	2°F	1	Not economic for our example sites.
Zone Heating CFM	10%	1	Zero when fans are off.
Economizer/Mixed Air Damper			
Mixed Air Temperature	1°F	1	
Outside Air Temperature	1°F	5	
Return Air Temperature	2°F	1	
Cooling Coil			
Supply Air Temperature	0.5°F	2	
Cooling Loop Output Signal	N/A	2	
Fans			
Supply Duct Static Pressure	0.2 inH_2O	1	Real-time plots of 1- to 10-sec data desired. Storage of fast data not recommended.
Maximum Zone Damper Position	N/A	1	
Low and High Zone Temps	1°F	5	
Filter			
Differential Pressure	0.2 inH_2O	N/A	Can be checked manually once every month or so, or more often if filters plug up at a faster rate.

CFM = cubic feet per minute, N/A = not applicable.

Focus for Task 6—Applying and Testing the Method on Air-Handler Commissioning

During Task 5, we developed a method to determine sensor accuracy and storage frequency for measurements related to air-handling equipment needed for operation, control, and diagnostics. The objective for Task 6 is to test the method (and refine it, if necessary) on another type of system (such as chillers) and/or type of evaluation (such as performance testing). For Task 6, we will focus on air-handler commissioning functions, including initial and periodic performance testing and measurement and verification (M&V) testing.

We chose to continue with air handlers for the following reasons:

1. Our results will affect many more sensors in the air-handling system than for any other system.
2. Air handlers use as much or more energy than any other system.
3. The air-handling system controls the load on the chiller plant. By optimizing building energy consumption with the air handler, the chiller plant works at more optimal conditions.
4. Compared to chillers and cooling towers, not much sensor accuracy work is being done on air handlers.
5. Our work will nearly complete the application of our method for air handlers (having covered most types of evaluations).
6. Storage frequency and accuracy requirements will be different for commissioning efforts compared to operation/control/diagnostic efforts.

We expect the accuracy and storage frequency results for commissioning to be different from those for operation, control, and diagnostics. Commissioning requires accurate performance testing and long-term monitoring, whereas for Task 5 we focused on real-time control and diagnostics using 24-hour data. We found that the coil effectiveness and fan efficiency could not be used for operation, control, and diagnostics because of large variations in operating conditions and sensor instability. For Task 6, we will use these factors for initial and periodic performance testing; and we will need to specify the required length, storage frequency, and stability of any test period. Long-term energy use monitoring will also require different accuracies and storage frequencies.

One would expect the accuracy requirements to be stricter to test performance for warranty purposes. Storage frequency might be lower because tests will be performed under steady-state conditions, or they might be higher to collect a specified number of data points in a short time to keep the uncertainty low. It will be valuable to see the differences between the two approaches with the same equipment.

Suggested General Method Revised for Task 6

We have revised the Task 5 method that determines accuracy and storage frequency for air-handling equipment related to operation, control, and diagnostics. For Task 6, we will study the same equipment, but change our focus to commissioning functions, including initial and periodic performance testing and M&V. Task 6 will verify that the method developed in Task 5 works for a different example.

The proposed method for Task 6 is similar to Task 5, with just a few changes in the wording (in italic):

1. Initial step for determining accuracy and storage frequency
   - List measurements and performance factors needed for air handler *initial performance testing, periodic testing, and measurement and verification.*
   - Determine plots useful for evaluations.
   - Gather site data, develop plots, and calculate performance factors with real site data.
2. Accuracy and frequency based on energy benefits
   - Determine sensitivity of factors to their input measurements.
   - For each piece of equipment, develop a rough economic evaluation of the effect of varying *performance factors,* parameters, or measurements on energy use.
   - Prioritize the measurements and factors in terms of their effect on building energy use.
   - Considering the cost of instrumentation and calibration, determine the economic level of accuracy for each measurement.
3. Accuracy and frequency based on plots of data
   - Describe how the plots can be used for evaluation of air handler *performance testing, periodic testing, and measurement and verification.*
   - Determine the potential benefits of the plots.
   - Determine the measurement accuracy and storage frequency needed to use the plots for the evaluation.
4. Based on economic analyses and diagnostic plots, determine recommended accuracies and storage frequencies for each measurement.

Conclusions

A method for determining measurement accuracy and storage frequency has been demonstrated on air-handling equipment for operation, control, and diagnostic functions. The required measurements, factors, and plots were determined. Their effect on a building's energy use was calculated. The accuracies and storage frequencies that would enable economic benefits were recommended based on a given building example and on assumptions for instrument capital and calibration costs. The assumptions will have to be reviewed when applying the method to other buildings.

The next step—Task 6—is to check the method's suitability for commissioning functions for air-handling equipment.

References

American Society of Heating, Refrigeration, and Air-Conditioning Engineers. June 1997. ASHRAE Proposed Guideline 14P, "Measurement of Energy and Demand Savings."

——. 1996. *ASHRAE HVAC Systems and Equipment Handbook*, Atlanta, Georgia.

——. 1992. ASHRAE Standard 55–1992, "Thermal Environmental Conditions of Human Occupancy," Atlanta, Georgia.

——. Ongoing. ASHRAE Research Project 980-RPIA, "Techniques for Measuring and Controlling Outside Air Intake Rates in Variable Air Volume Systems," University of Colorado, Moncef Krarti (PI), current project for Indoor Air Quality, Comfort, and Health, B. Seaton at ASHRAE.org.

——. 1999. "Procedures for Determining Heating and Cooling Loads for Computerized Energy Calculations," Technical Committee 4.7, Atlanta, Georgia.

American Society of Mechanical Engineers. 1998. ASME Performance Test Code 19.1, "Test Uncertainty: Instruments and Apparatus," New York.

Brandemuehl, M. In progress. Implementation of On-line Optimal Control of Cooling Plants without Storage," ASHRAE Research Project TRP-823, University of Colorado, Boulder.

Department of Energy and Lawrence Berkeley Laboratory. 1989. DOE-2, California supplement, Version 2: Energy simulation computer program developed by USDOE and LBL based on ASHRAE procedures.

Electric Power Research Institute, and Architectural Energy Corporation. July 1997. *HVAC Diagnostic and Commissioning System.* Final report EPRI CM-108359 prepared by EPRI Customer Systems Group, Palo Alto, California, and Architectural Energy Corporation, Boulder, Colorado.

Kammerud, R., Blanc, S., and Kane, W. 1996. "The Impact of Real-Time Pricing of Electricity on Energy Use, Energy Cost, and Operation of a Major Hotel," *ACEEE Summer Study on Energy Efficiency in Buildings,* Vol. 4, Commercial Buildings: Technologies, Design, and Performance Analysis.

Mazzucchi, R., Gillespie, K., and Lippman, R. 1996. "Energy Data Acquisition and Validation for a Large Office Building," *ACEEE Summer Study on Energy Efficiency in Buildings,* Vol. 3, Commercial Buildings: Technologies, Design, and Performance Analysis.

Smith, S. 1993. *Digital Data Acquisition—Course Notes.* Section 5, "Sampling Theory," Tustin Technical Institute, Inc., Santa Barbara, California.

Appendix A—Performance Factors Considered for Air-Handling Equipment

This appendix contains the performance factors considered for use at the start of Task 5. We decided not to use these factors in our diagnostic plots because most control and operational problems could be solved with plots of measurements. The plots were confusing when we created differences or ratios. Some parameters were much too sensitive to their input measurements and operating conditions to be useful.

Factors Related to Air-Handling Equipment

Economizer

- Measured Outdoor Air Fraction (OAF) = (Mixed T - Return T) / (Outside T - Return T)
- Average Mixed Air Temperature
- Theoretical OAF = f(Outside T or Outside RH)
- Economizer Performance Factor = Measured OAF - Theoretical OAF
- Factors for Damper Positions or Flows

Fans

- Total Air-Handling Unit (AHU) Fan Power
- Space Pressurization Factor = (Supply Fan CFM - Return Fan CFM) / Supply Fan CFM
- Fan Efficiency = Fan Head * Flow / Fan Electrical Power
- Fan Factors (should remain fairly constant)
  - For Constant Volume systems = Fan Power / Rated Fan Power
  - For Variable Volume systems, no Fan Control = Fan Power / Fan Power from Fan Curve based on Fan DP or Fan CFM
  - For Variable Volume with Fan Control = Fan Power is a function of both fan speed and fan DP, which depend on system characteristics. Use the Fan Efficiency and make sure it falls within a band.
- Fan Metric = Total Fan Power / Cooling Effect Supplied, i.e., Supply CFM * (Air Return Enthalpy - Supply Enthalpy) in kW

Coils

- Cooling Coil Differential Temperature (DT) = Cold Deck Temp - Mixed Air Temp
- Heating Coil DT = Hot Deck Temp - Mixed Air Temp
- Cooling Coil Terminal Temp Difference (TTD) = Cold Deck Temp - Chilled Water Supply Temp
- Heating Coil TTD = Hot Water Supply Temp - Hot Deck Temp
- Coil Bypass Factor (DOE2) = $(DBT_S - DBT_L) / (DBT_S - DBT_E)$
- Use these equations: $W_S - DBT_S * (W_E-W_L)/(DBT_E-DBT_L) = W_L - DBT_L * (W_E-W_L)/(DBT_E-DBT_L)$

- L = Leaving, E = Entering, S = Coil Surface and W_S = f(DBT_S @100% RH) on the saturation line to solve for DBT_s, to use in the Bypass Factor equation
- Use only for conditions where $W_L<W_E$

- Coil/Duct DP Factor = (Duct Static P - Fan Discharge P) / Reference DP) * (Reference CFM^k / Measured CFM^k)

Filters

- Filter Factor = (Measured Filter DP / Reference Filter DP) * (Reference CFM^n / Measured CFM^n) (note: n will fall between 1 and 2, depending on the type of filter)

Terminal Units

- Zone Control Indicator = T_{zone} - $T_{setpoint}$
- Discharge Control Indicator = $T_{discharge}$ - $T_{setpoint}$
- Flow Control Indicator = Actual Damper Position / Max Damper Position or Actual Air Flow / Max Air Flow
- Reheater Control Indicator = $T_{discharge}$ - T_{supply}
- Cold Air to Mixed Air Ratio = ($T_{mixed\ air}$ - $T_{hot\ air}$) / ($T_{cold\ air}$ - $T_{hot\ air}$)
  - where: $T_{hot\ air}$ = $T_{return\ air}$ for Recirc Systems
  - $T_{hot\ air}$ = $T_{hot\ duct\ air}$ for Dual Duct Systems

Outdoor Air Fraction

We chose not to use Outdoor Air Fraction (OAF) as an indicator of economizer performance because of the large uncertainty that might occur in OAF with small inaccuracies in Outdoor Air Temperature (OAT) or Mixed Air Temperature (MAT). Charts A-1 and A-2 show that the OAF can vary significantly when the OAT is within a few degrees of the Return Air Temperature (RAT), with OAT or MAT uncertainties of less than 1°F.

For example, if the OAT is 2°F below the RAT, a +0.5°F error in OAT and MAT results in OAFs of 1.3 and .75, respectively, when the OAF should be 1.0. If the OAT is 2°F above the RAT, a +0.5°F error in OAT and MAT results in OAFs of 0.16 and 0.45, respectively, when the OAF should be 0.20.

Stratification of the MAT or inaccurate setup of the OAT instrumentation can easily result in large inaccuracies of the OAF close to the economizer change point, making it difficult to check the economizer's operation.

Instead of using a potentially inaccurate OAF, we chose to compare MAT to the expected MAT to verify the performance of the economizer. However, we cannot verify that the building's ventilation requirements are being met. The outside air flow would need to be measured directly to determine it accurately. ASHRAE Research Project 980-RPIA is intended to determine the preferred ways to verify outside air flow (ASHRAE Ongoing).

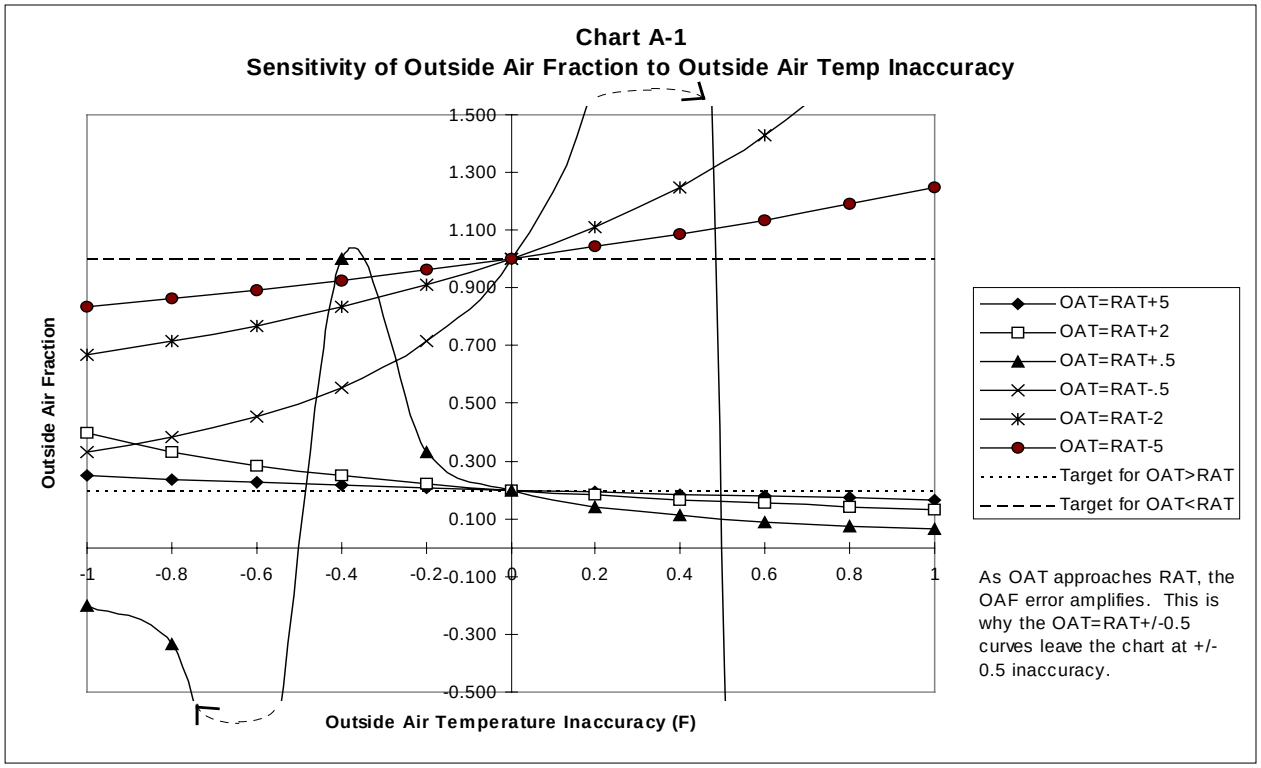


Chart A-1
Sensitivity of Outside Air Fraction to Outside Air Temp Inaccuracy
Outside Air Fraction
Outside Air Temperature Inaccuracy (F)
1.500
1.300
1.100
0.900
0.700
0.500
0.300
0.100
-0.100
-0.300
-0.500
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
OAT=RAT+5
OAT=RAT+2
OAT=RAT+.5
OAT=RAT-.5
OAT=RAT-2
OAT=RAT-5
Target for OAT>RAT
Target for OAT<RAT
As OAT approaches RAT, the OAF error amplifies. This is why the OAT=RAT+/-0.5 curves leave the chart at +/- 0.5 inaccuracy.

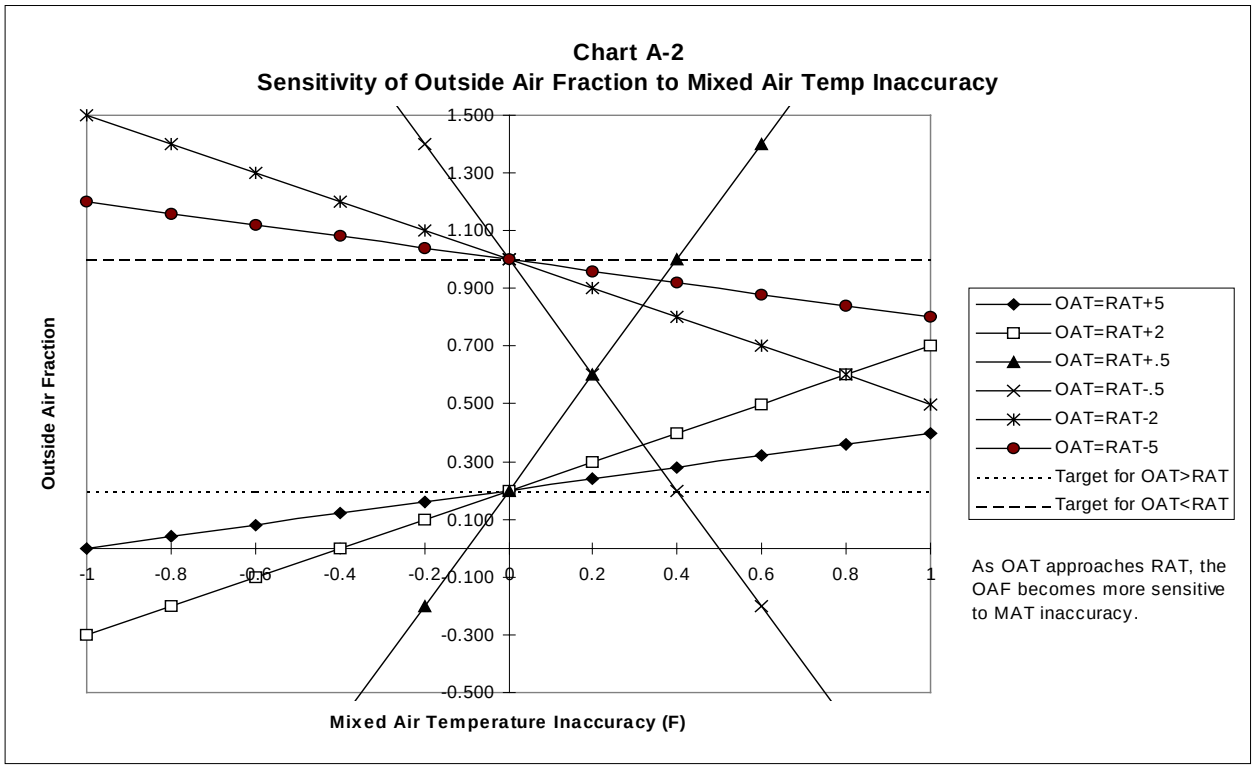


Chart A-2
Sensitivity of Outside Air Fraction to Mixed Air Temp Inaccuracy
Outside Air Fraction
Mixed Air Temperature Inaccuracy (F)
1.500
1.300
1.100
0.900
0.700
0.500
0.300
0.100
-0.100
-0.300
-0.500
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
OAT=RAT+5
OAT=RAT+2
OAT=RAT+.5
OAT=RAT-.5
OAT=RAT-2
OAT=RAT-5
Target for OAT>RAT
Target for OAT<RAT
As OAT approaches RAT, the OAF becomes more sensitive to MAT inaccuracy.

Fan Efficiency

Fan efficiency accuracy is mainly a function of the air flow measurement accuracy. The other parameters (fan static pressure and motor horsepower) directly affect the fan efficiency accuracy, but they are typically more accurate than air flow, whose accuracy may fall between 5% and 10% at best. Table A-1 indicates what we think would be the best achievable fan efficiency accuracy (using monitoring equipment).

Table A-1. Sensitivity of Fan Efficiency to Its Input Parameters

Input Parameters	Base Case Expected Value of Parameter[1]	Base Case Factor's Value	Factor's Value with a 1% Increase in Value of Parameter	Percent Change in Factor with a 1% Increase in Parameter	Desired % Uncertainty[2] of Each Parameter	Affect of Each Parameter's Uncertainty on the Factor (%)
Air Flow (CFM)	50000	0.594	0.600	1.0	5	5.1
Pressure across Fan (inWA)	5	0.594	0.600	1.0	5	4.9
Duct Cross-Sectional Area (ft2)	50	0.594	0.594	0.0	1	0.0
Motor Power (kW)	50	0.594	0.588	-1.0	1	-1.0
Total Factor Uncertainty (%)3						**7.2**

Even with a 5% uncertainty in air flow, the overall fan efficiency uncertainty would be 7%. Air flow monitoring instrumentation will degrade over time unless properly maintained, which will make the fan efficiency accuracy even worse.

We would not expect the fan efficiency to degrade significantly over time because there are few seals that will wear. Motor and fan blade efficiency will not change much unless there is serious damage, at which point mechanical failure is obvious.

Based on the economic analysis in this report, a 10% degradation in fan efficiency would add $1,000 to the building's annual energy cost. For this type of degradation, serious mechanical failure would have to occur. The cost of air flow monitoring equipment might be several thousands of dollars. It would not pay to install expensive air flow equipment just to detect fan degradation—the equipment would not be accurate enough to detect it, and any serious degradation would be the result of obvious mechanical failure.

It is also difficult to say what the fan efficiency (as well as any other fan performance factor listed in Table A-1) should be under any given condition with a VAV system, since the fan efficiency varies with air flow as well as static pressure rise across the fan. Techniques that do not rely on fan air flow or fan efficiency can still be used to optimize fan performance. These are described in the report.

Coil Effectiveness

Coil effectiveness can be calculated two different ways to check and track the heat transfer performance of chilled water to air heat exchangers. With no relative humidity measurement, dry bulb temperatures can be used in the following formula:

$$= (T_{\text{air entering}} - T_{\text{air leaving}}) / (\Delta Tm \text{ Log Mean Temp Difference})$$

where

$$\Delta Tm = [(T_{air\ entering} - T_{fluid\ leaving}) - (T_{air\ leaving} - T_{fluid\ entering})] /$$

$$\ln [(T_{air\ entering} - T_{fluid\ leaving}) / (T_{air\ leaving} - T_{fluid\ entering})]$$

(from ASHRAE 1996)

If relative humidity is available, the coil effectiveness can also be calculated using the following formula:

$$= (h_{air\ entering} - h_{air\ leaving}) / (h_{air\ entering} - h_{average\ coil\ surface})$$

where

$$h_{average\ coil\ surface} \cong (h_{fluid\ in} + h_{fluid\ out}) / 2$$

(from ASHRAE 1996)

These two formulas provide different results. There is also a coil bypass factor described in ASHRAE, but this would be too complicated to calculate for EMCS monitoring. It would require measurements of the humidity before and after the coil.

Table A-2 illustrates the sensitivity of the coil effectivenesses (calculated the two different ways) to their input parameters, using data from the EPRI HVDC program (Project #2, 1994, from 11:00 to 12:00). Even with fairly accurate assumptions for measurement uncertainty (0.5% for temperature and 3% for relative humidity), the total uncertainties for coil effectiveness are 5% for the effectiveness without RH and 21% for the effectiveness with RH.

Table A-2. Sensitivity of Coil Effectiveness to Its Input Parameters

Input Parameters	Base Case Expected Value of Parameter	Base Case Factor's Value	Factor's Value with a 1% Increase in Value of Parameter	Percent Change in Factor with a 1% Increase in Parameter	Desired % Uncertainty of Each Parameter	Affect of Each Parameter's Uncertainty on the Factor (%)
Coil Air Side Effectiveness (no RH measurements)						
Tair entering	67.32	0.669	0.703	5.1	0.5	2.5
Tair leaving	58.85	0.669	0.609	-9.0	0.5	-4.5
Tfluid entering	45.46	0.669	0.681	1.8	0.5	0.9
Tfluid leaving	55.36	0.669	0.685	2.3	0.5	1.2
Total Factor Uncertainty (%)						**5.4**
Coil Air Side Effectiveness (with RH measurements)						
Tair entering	67.32	0.410	0.449	9.6	0.5	4.8
Tair leaving	58.85	0.410	0.347	-15.4	0.5	-7.7
Tfluid entering	45.46	0.410	0.419	2.3	0.5	1.2
Tfluid leaving	55.36	0.410	0.419	2.3	0.5	1.2
RHair entering	0.64	0.410	0.426	3.9	3	11.8
RHair leaving	0.84	0.410	0.389	-5.1	3	-15.2
RHsurface (assume saturated)	1.00	0.410	0.404	-1.5	1	-1.5
Total Factor Uncertainty (%)						**21.4**

Charts A-3, A-4, and A-5 plot the coil effectiveness (without RH measurements) for a single day, using data from EPRI's HVDC program (Project #2, 1994). The LMTD means that the effectiveness is based

on the Log Mean Temperature Difference across the coil. Charts A-3 and A-4 show that the coil effectiveness appears to be a function of both mixed air temperature and supply air flow. This would make it difficult to predict the expected coil performance if one were to monitor the coil for degradation over time. Chart A-5 shows how the coil effectiveness varies over a wide range (from 0.3 to 0.9) throughout a single day of monitoring. Similar results were found using the coil effectiveness with RH measurements (they are not included here).

Because of the high sensitivity of the coil effectiveness to its input parameter accuracy and its large variability to operating conditions, we chose not to use it as a performance indicator for operations and diagnostic functions.

Chart A-3

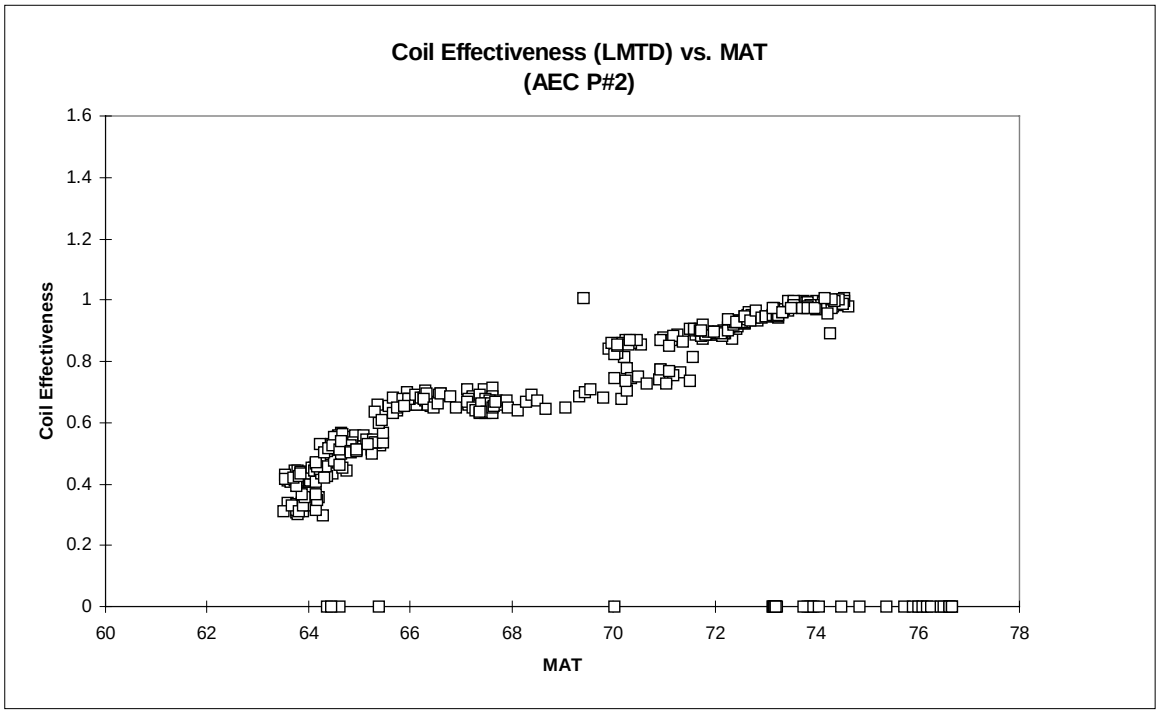


Chart A-4

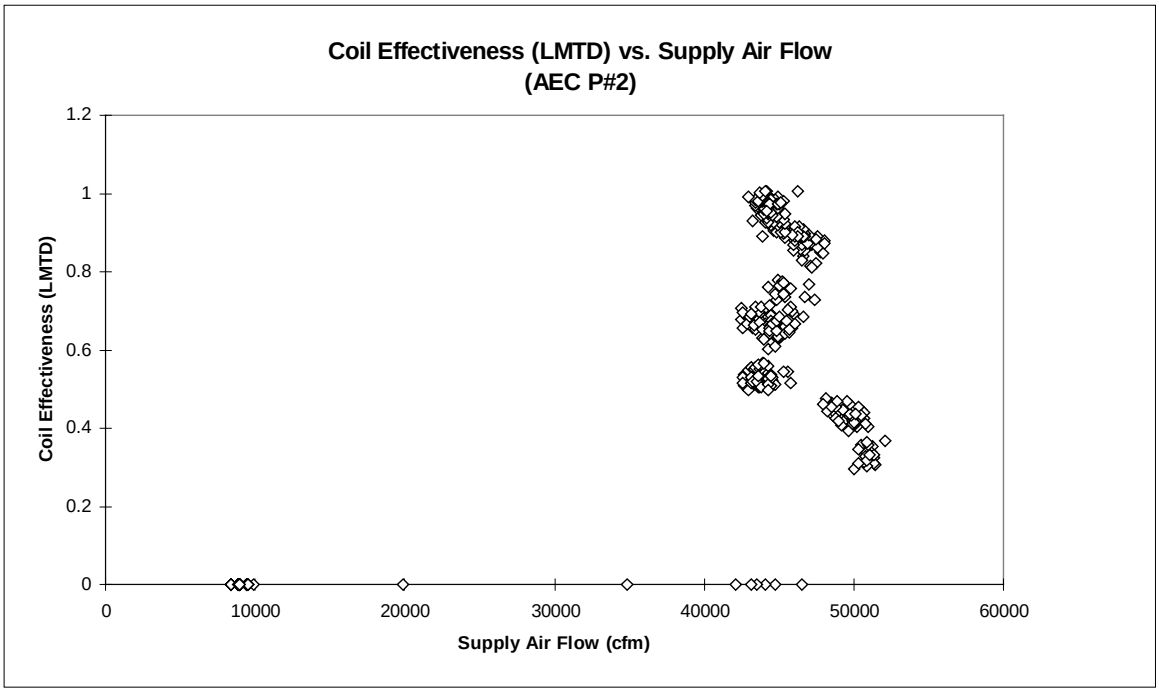
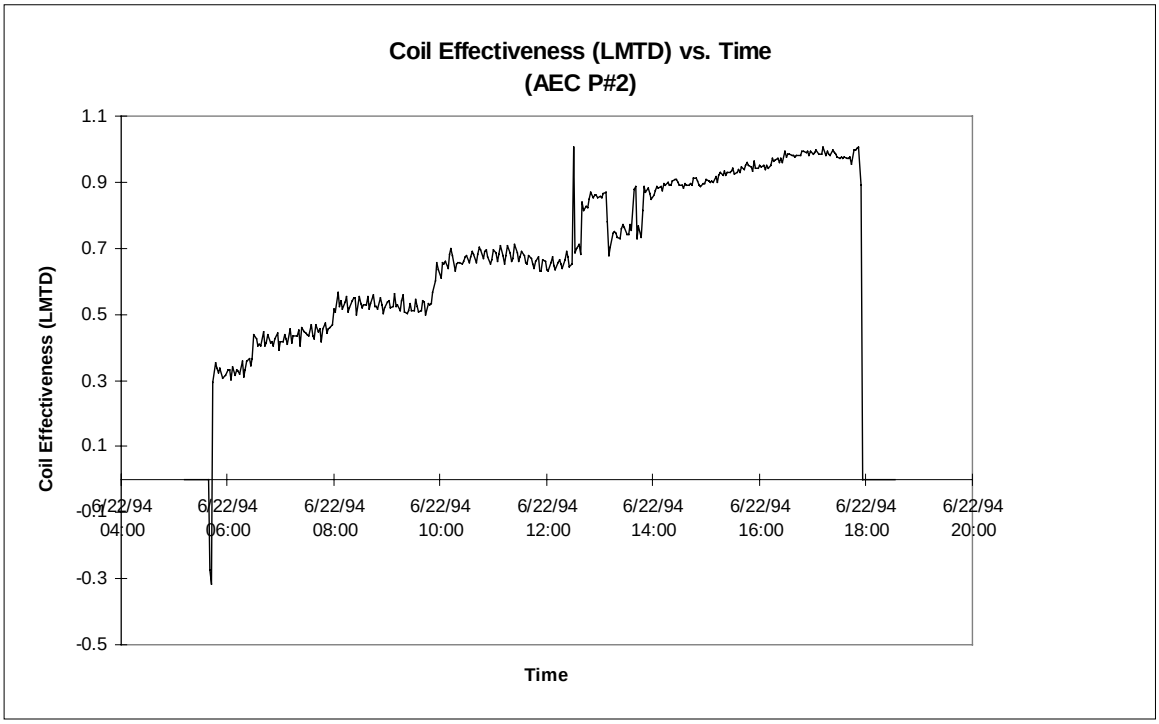


Chart A-5



Filter Factor

The following equation could be used to help monitor the differential pressure across the filters, even at varying air flows. It corrects for flows when they are less than design, or rated, flow rates.

Adjusted Filter DP = (Measured DP) * [(Reference Air Flow or proxy)^n / (Measured Air Flow or proxy)^n]

We chose not to use this factor for several reasons. Supply air flow is typically not available. The exponent “n” varies based on the filter design. (For several filter types for which we had design data, “n” varied from 1.3 to 1.8). The appropriate value of “n” would need to be determined for any particular type of filter. It is not necessary to monitor filter DP continuously because it will not change dramatically. Periodic checks are sufficient. Checks can be made at full fan power because this will be close to design air flow and will indicate the worst case filter DP. This can be used to determine whether the filters warrant cleaning or replacement.

Appendix B—How to Use Diagnostic Plots to Find Problems

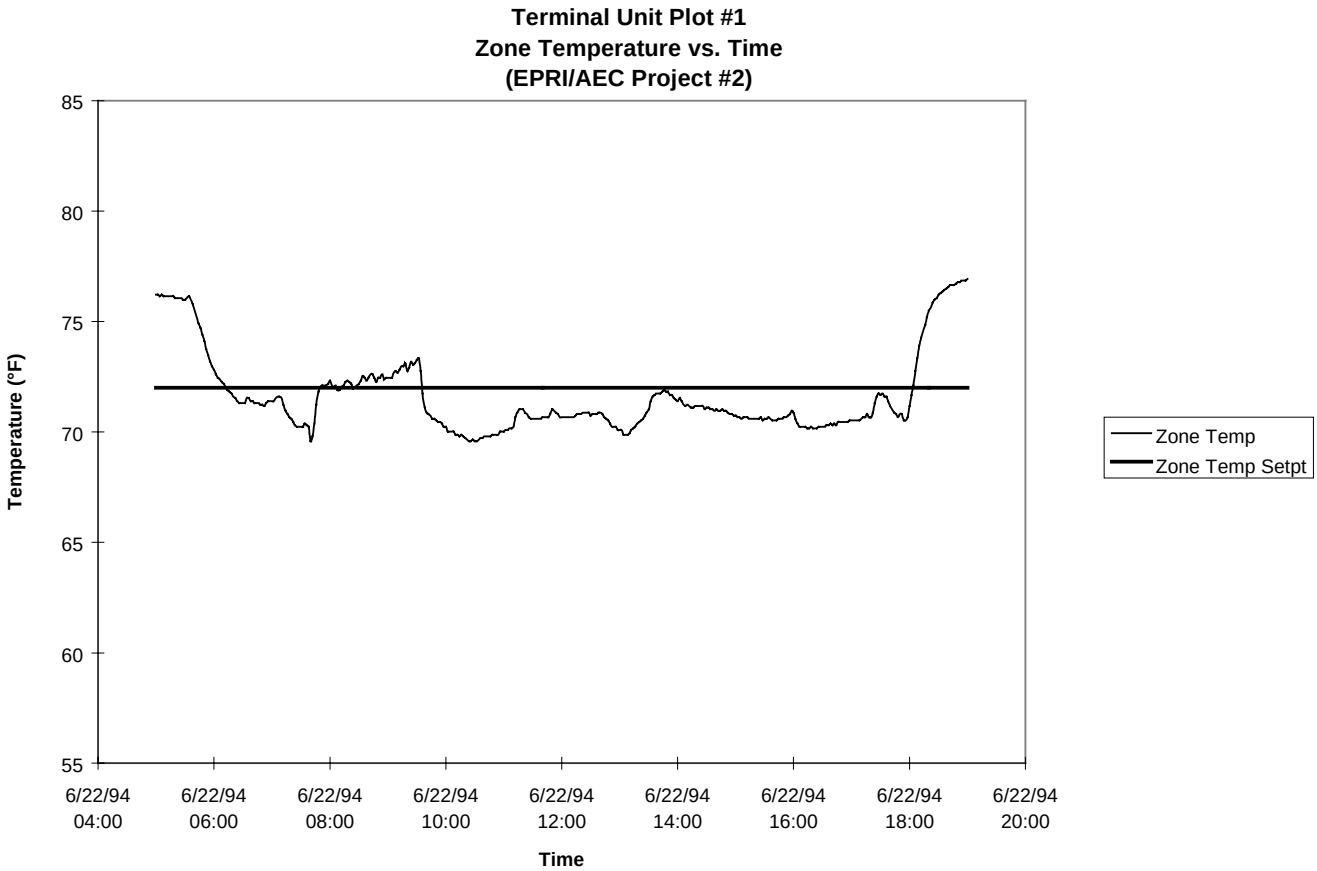
Terminal Unit Operation and Zone Control

1. Zone Temperature vs. Time

   – **Purpose:** To determine if zone temperature is being controlled properly and if occupant comfort is being maintained.

   – **Plot Description:** Plot space temperature and space temperature setpoint vs. time.

   Space temperature and space temperature setpoint are plotted on the y axis, and time is the variable on the x axis (see Terminal Unit Plot #1). The y axis should be constrained between the expected temperatures, usually 55°F to 85°F. Time should be constrained to 24 hours or less. The normal areas of interest are from 2 hours before occupancy until occupancy ends. Beyond these hours, the data is of questionable use. Except for the 2 hours before occupancy, the plot has little meaning unless the supply fan is operating or special control sequences are being employed during the after-hours periods.



- **Discussion:** This plot is a simple representation of the zone controls' operation and their ability to maintain comfort control of the space temperature. The zone temperature setpoint should be a flat line unless zone temperature reset strategies are used. The zone temperature should begin above the setpoint if outside nighttime temperatures are warmer than the setpoint, and it should begin below the setpoint if the nighttime temperatures are cold. The zone temperature should achieve zone setpoint within an hour or two after the supply fan begins operation. The temperature should be maintained throughout the day at ±2°F of the setpoint.

  This plot can also be used to look for control stability problems. A saw tooth pattern of the zone temperature indicates control instability. The easiest way to solve control instability is to widen out the throttling range of the thermostat. If this does not solve the problem, this condition can also be attributed to an oversized terminal unit.

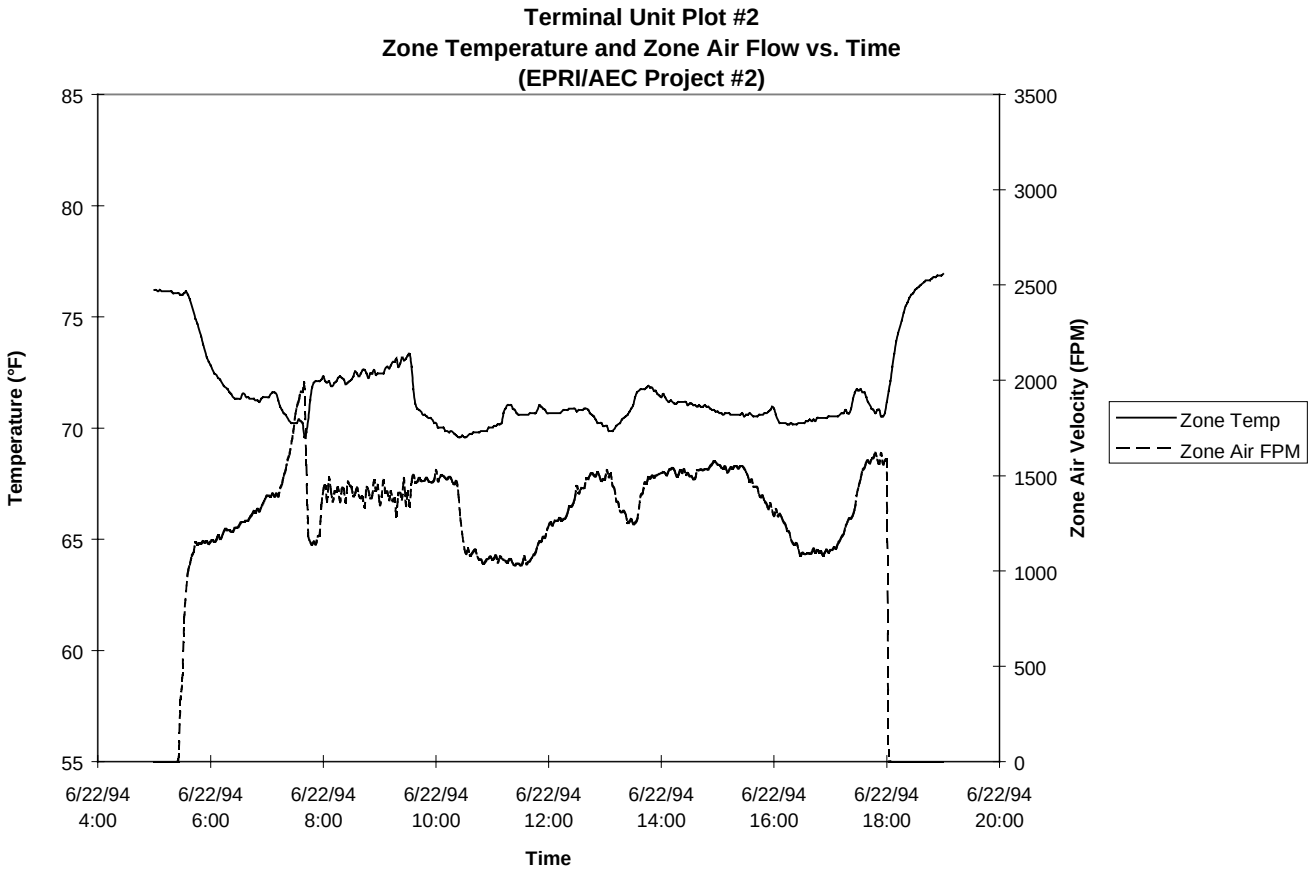
  The third use of this plot is to determine whether the building morning warm-up/cooldown controls are operating properly. At occupancy the zone temperature should be within two degrees of the zone setpoint. If this temperature is not achieved by occupancy time, the morning warm-up/cooldown should be adjusted to start slightly earlier. If the zone temperature achieves zone setpoint more than 15 minutes before occupancy, the morning warm-up/cooldown is starting too early. (Note: Evaluation of morning warm-up/cooldown requires looking at all zones to determine the worst-case zone. The worst-case zone is usually an exterior zone, although interior zones can have difficulty achieving warm-up if no heat source is available at the supply fan or if the warm-up control strategy is faulty.)

- **Analysis:** This plot exhibits two potential problems. From approximately 8:00 a.m. to 10:00 a.m., there appears to be some oscillation, indicating a control stability problem. The other possible problem is the relatively wide deviation—about two degrees—from setpoint. More information is needed about this zone and its occupancy to determine why the deviations exist.

2. Zone Temperature and Zone CFM vs. Time (for interior zones)

   - **Purpose:** To determine if the zone terminal unit is operating properly.

   - **Plot Description:** Plot zone temperature and zone CFM (or a proxy such as zone air velocity feet per minute [FPM]) vs. time. Zone temperature and zone air velocity FPM are plotted on the y axis, and time is the variable on the x axis (see Terminal Unit Plot #2). Two scales should be on the y axis. For the zone temperature, the y axis should be constrained between the expected temperatures, usually 55°F to 85°F. For the CFM, the y axis should be constrained to 100 CFM above and below the maximum zone CFM and the minimum zone CFM. Time should be constrained to the occupancy hours or whenever the fan is operating, and no more than 24 hours should be shown on a single graph. Instead of CFM, percent CFM can be displayed.



– **Discussion:** This plot is a simple representation of the zone terminal unit's operation. As the load in the space increases, the CFM should increase and the temperature maintained within ±2.0°F of the zone setpoint. As zone temperature drops, the CFM should be reduced. Note: There is a long time delay between a change in a zone temperature and the time the thermostat recognizes the change and takes corrective action.

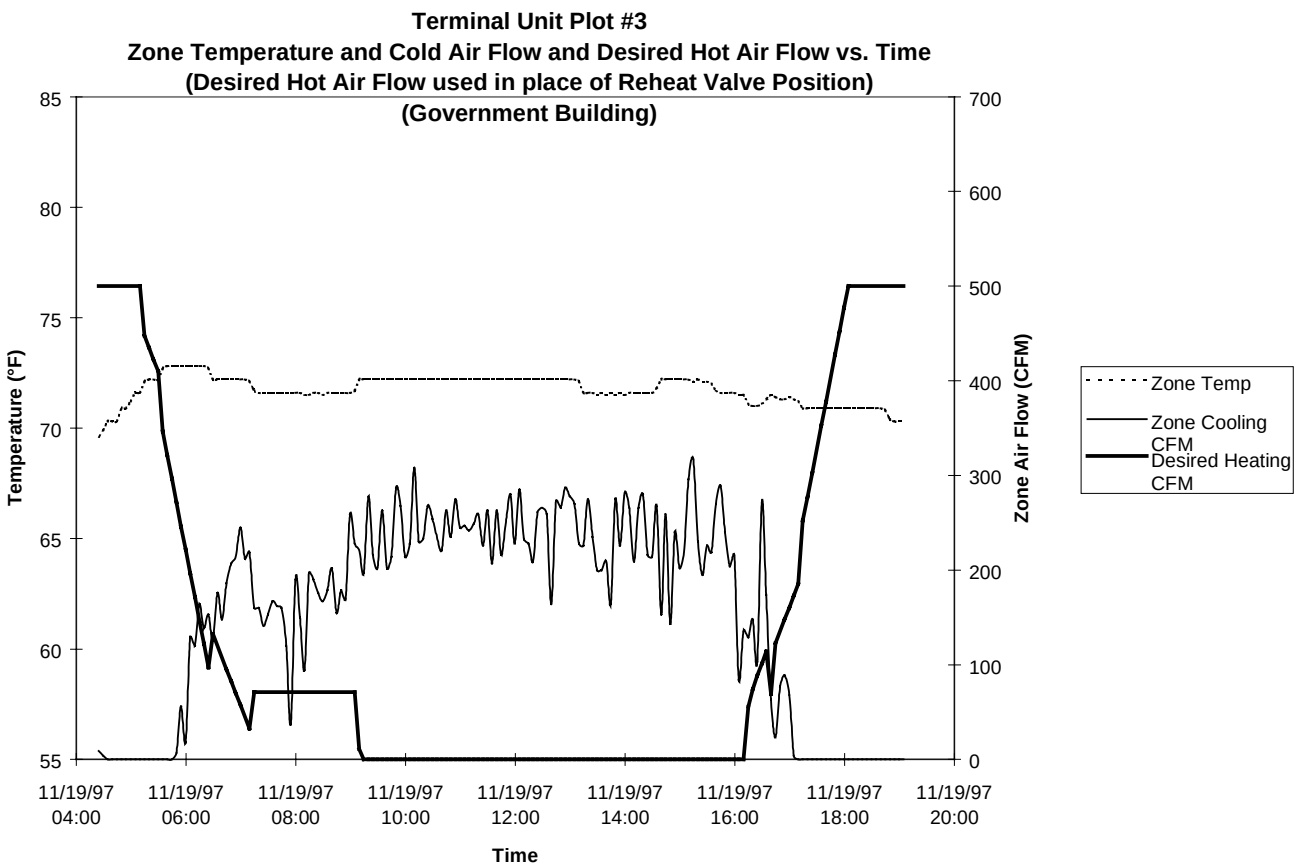
  This plot can also be used to look for control stability problems. A saw tooth pattern of the zone temperature indicates control instability. The easiest way to solve control instability is to widen out the throttling range of the thermostat. If this does not solve the problem, this condition can also be attributed to an oversized terminal unit.

– **Analysis:** From approximately 8:00 a.m. to 10:00 a.m., there appears to be some oscillation, indicating a control stability problem. The oscillations appear in both the temperature and FPM flow plots. The control loops definitely need tuning. These plots also show large 400 FPM swings in the air flow into the zone. This could be control loop tuning or an oversized VAV box. Control loop tuning is a likely answer, as shown by the delay between temperature and flow changes. The integral factor in this loop is probably too slow, requiring long time delays. A change to straight proportional control may determine the problem. Using proportional-only control should result in more rapid response between the temperature and the air flow. The cause of the large changes in flow could also be due to rapid changes in load, such as a large load being turned off and on or the sun going behind the clouds and then reappearing.

3. Zone Temperature, Zone CFM, and Reheat Valve position vs. Time (for exterior zones with reheat)

   – **Purpose:** To determine if the zone terminal unit is operating properly.

   – **Plot Description:** Plot zone temperature, zone (cooling) CFM, and reheat valve position (or a proxy such as desired hot air CFM) vs. time. Zone temperature, zone (cooling) CFM, and desired hot air CFM are plotted on the y axis, and time is the variable on the x axis (see below). Two or three scales should be on the y axis. For the zone temperature, the y axis should be constrained between the expected temperatures, usually 55°F to 85°F. For the CFM, the y axis should be constrained to 100 CFM above and below the maximum zone CFM and the minimum zone CFM. The plot of the reheat valve position should be in terms of percent open. (In Terminal Unit Plot #3, we use desired hot air CFM as a proxy for reheat valve position and the same scale as the zone CFM.) It may be preferable to express both the zone CFM and reheat valve position in terms of percentage to limit the number of scales to two. Time should be constrained to the occupancy hours or whenever the fan is operating.



- **Discussion:** This plot is a simple representation of the zone control terminal unit's operation. As the temperature in the space increases, the zone (cooling) CFM should increase, and the temperature should be maintained within ±2.0°F of the zone setpoint. As the temperature falls, the CFM should be reduced until it reaches the minimum CFM; at that point the heating valve should start to open. (In Terminal Unit Plot #3, the desired hot air CFM is used as a proxy for heating valve position.) As the temperature outside drops, more and more heating should occur until the valve is nearly wide open. The valve may never reach full open because reheat valves are generally oversized. Note: There is a long time delay between a change in a zone temperature and the time the thermostat recognizes the change and takes corrective action.

  This plot can also be used to look for control stability problems. A saw tooth pattern of the zone temperature indicates control instability. The easiest way to solve control instability is to widen out the throttling range of the thermostat. If this does not solve the problem, this condition can also be attributed to an oversized terminal unit.

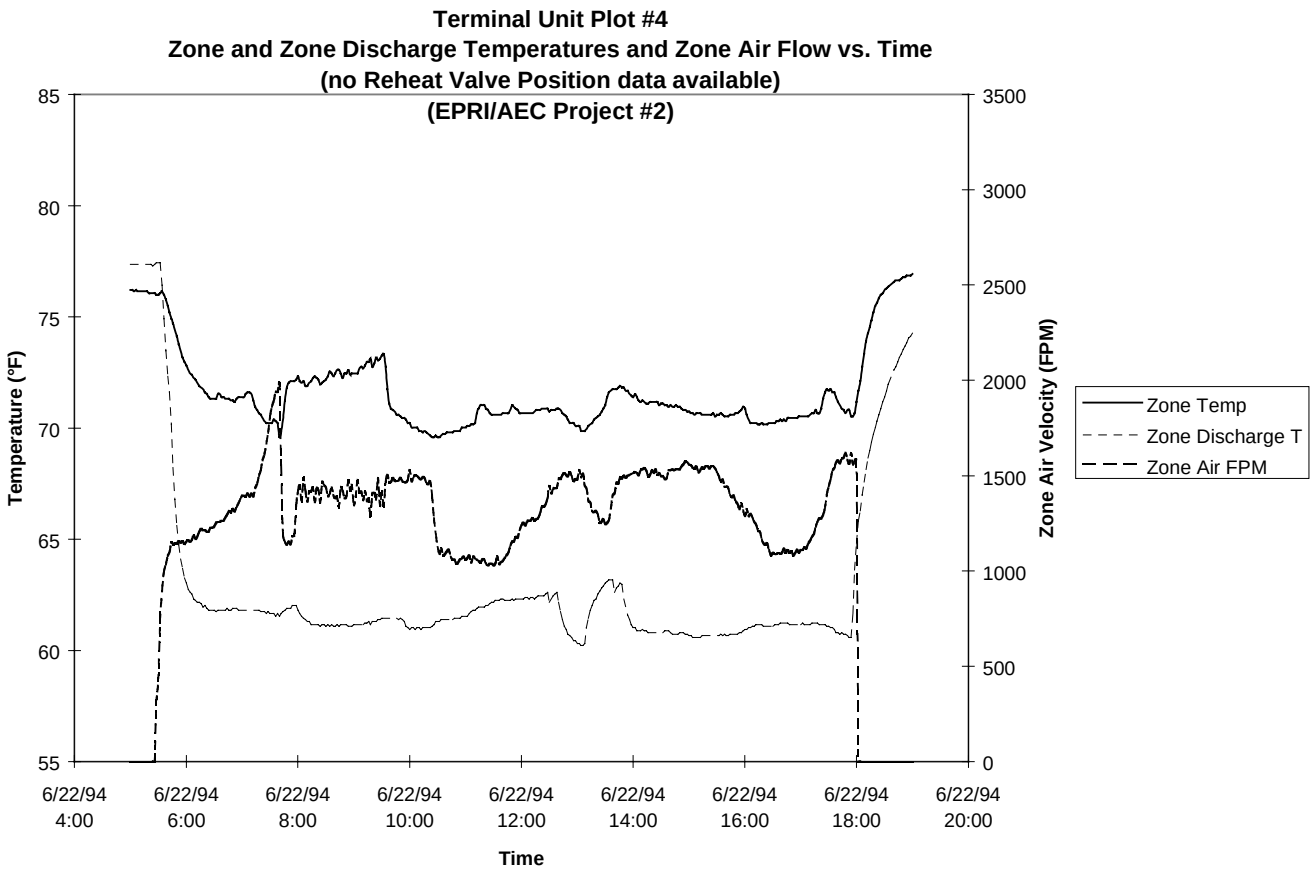
  The third use for this plot is to observe the relative hot water valve position. If all the valves in the system are just barely open, this is an indication that the heating hot water temperature is too high and could be lowered. This would save energy due to heat losses from the piping system and improve controllability of the reheat control valves.

- **Analysis:** This plot shows good temperature control characteristics—the temperature maintains stable control and does not deviate by more than one degree. The air flow plot shows very unstable action, oscillating almost half of the 300 CFM maximum. This is enough oscillation that the occupants may be able to hear the change in air flow. It appears that the oscillation of the cold air CFM also affected the temperature enough to require heating between 7:00 and 9:00 a.m. and again between 4:00 and 5:00 p.m.

4. Zone Temperature, Zone Discharge Temperature, Zone CFM, and Reheat Valve position vs. Time (for exterior zones with reheat)

   - **Purpose:** To determine if the zone terminal unit is operating properly.

   - **Plot Description:** Plot Zone temperature, Zone Discharge Temperature, Zone CFM (or a proxy such as Zone Air Velocity FPM), and Reheat Valve Position (not available in this data set) vs. time. Zone temperature, Zone Discharge Temperature, and Zone Air Velocity FPM are plotted on the y axis, and time is the variable on the x axis (see Terminal Unit Plot #4). Two or three scales should be on the y axis. For the zone temperature, the y axis should be constrained between the expected temperatures, usually 50°F to 110°F. For the CFM, the y axis should be constrained to 100 CFM above and below the maximum zone CFM and the minimum zone CFM. The plot of the reheat valve position should be in terms of percent open. It may be preferable to express both the zone CFM and reheat valve position in terms of percentage. Time should be constrained to the occupancy hours or whenever the fan is operating, within a 24-hour period.



– **Discussion:** This plot is a simple representation of the zone control terminal unit's operation. As the temperature in the space increases, the CFM (or FPM) should increase and the temperature maintained within ±2.0°F of the zone setpoint. As the heat load and temperature fall, the CFM should be reduced until it reaches the minimum CFM; at that point the heating valve should start to open. (Though not shown on Terminal Unit Plot #4, we illustrate heating valve data in Terminal Unit Plot #3.) Proof of the reheat valve's operation is provided by the zone discharge temperature plot. As the temperature outside drops, more and more heating should occur until the valve is nearly wide open. The valve may never reach full open because reheat valves are generally oversized. Note: There is a long time delay between a change in a zone temperature and the time the thermostat recognizes the change and takes corrective action.

This plot can also be used to look for control stability problems. A saw tooth pattern of the zone temperature indicates control instability. The easiest way to solve control instability is to widen out the throttling range of the thermostat. If this does not solve the problem, this condition can also be attributed to an oversized terminal unit.

The third use for this plot is to observe the relative hot water valve position. If all the valves in the system are just barely open, this is an indication that the heating hot water temperature is too high and could be lowered. This would save energy due to heat losses from the piping system and improve controllability of the reheat control valves.

The fourth use for this plot is to observe the heat output from the reheat coil. The temperature of the discharge should rise slowly as the heating load increases. A sudden change in discharge temperature from the supply temperature setpoint can be one of two problems: (1) the hot water

supply temperature is too high and a small opening of the valve produces a large heating output or (2) the reheat valve is oversized. If an oversized valve produces comfort complaints, it should be corrected by installing a valve with a lower Cv.

– **Analysis:** From approximately 8:00 a.m. to 10:00 a.m., there appears to be some oscillation, indicating control stability problems. The oscillations appear in both the temperature and FPM flow plots. The control loops definitely need tuning. These plots also show large 400 FPM swings in the air flow into the zone. This could be control loop tuning or an oversized VAV box. Control loop tuning is a likely answer, as shown by the delay between temperature and flow changes. The integral factor in this loop is probably too slow, requiring long time delays. A change to straight proportional control may determine the problem. Using proportional-only control should result in more rapid response between the temperature and the air flow. The cause of the large changes in flow could also be rapid changes in load, such as a large load's being turned off and on or the sun's going behind the clouds and then reappearing.

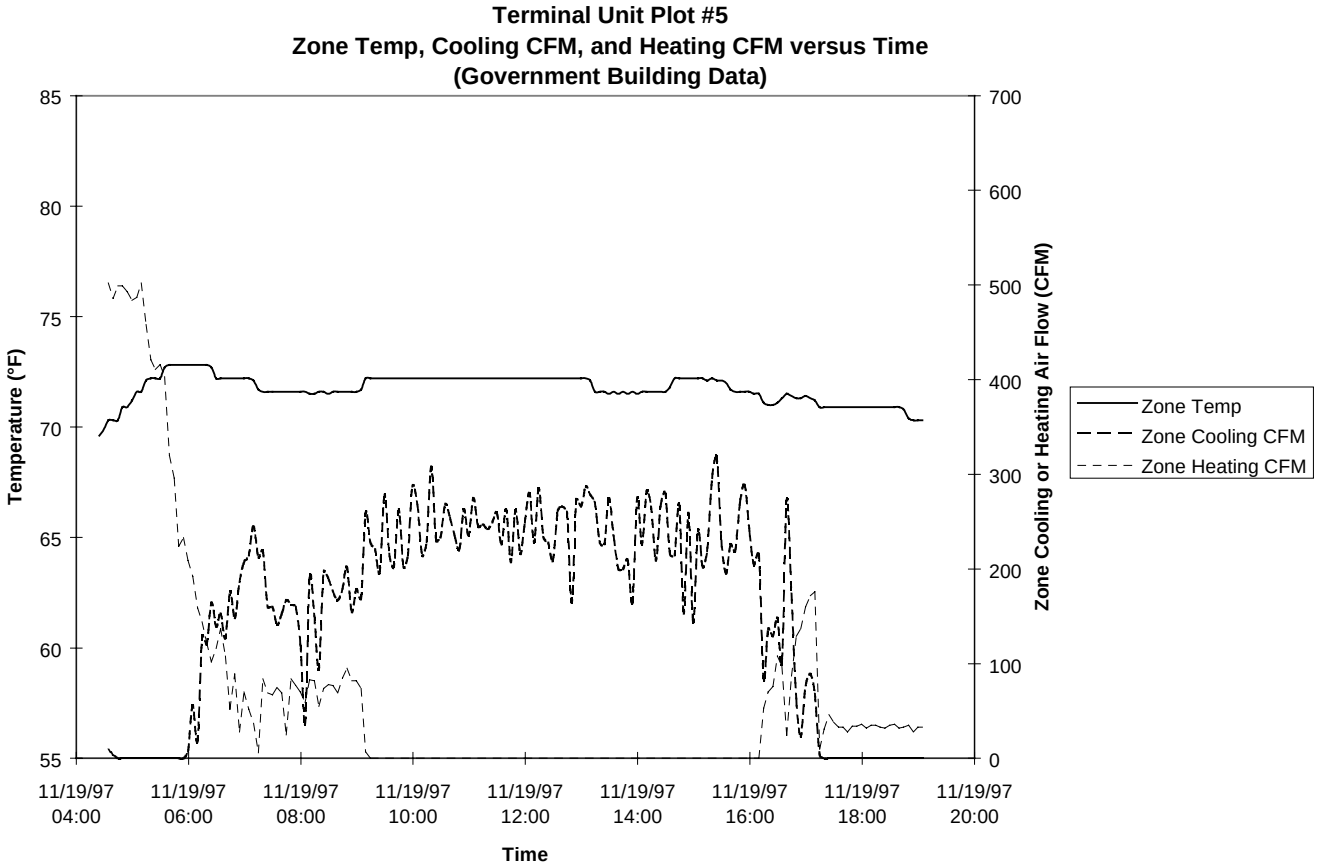
  The relatively high discharge temperature requires some investigation. A VAV system operates more efficiently with supply air temperatures near 55°F. This discharge temperature is maintaining at about 62°F, possibly due to a leaking hot water valve or poor control at the air handler. Note: At about 1:00 p.m. the air flow increases and the zone discharge temperature falls and then the process reverses. This is more indicative of leaking heating coil.

  Another possible problem with this zone may be caused by a high minimum CFM setting. Note that as the zone temperature plot falls, the discharge temperature increases, but the CFM does not drop and stay down.

5. Zone Temperature, Zone Cooling CFM, and Zone Heating CFM vs. Time (for exterior zones with double duct VAV systems)

   – **Purpose:** To determine if the zone terminal unit is operating properly.

   – **Plot Description:** Plot zone temperature, zone cooling CFM, and zone heating CFM vs. time. Zone temperature, zone cooling CFM, and zone heating CFM are plotted on the y axis, and time is the variable on the x axis (see Terminal Unit Plot #5). Two or three scales should be on the y axis. For the zone temperature, the y axis should be constrained between the expected temperatures, usually 55°F to 85°F. For the CFM, the y axis should be constrained to 0 CFM and 100 CFM above the maximum zone cooling (or heating) CFM. Time should be constrained to the occupancy hours or whenever the fan is operating.



– **Discussion:** This plot is a simple representation of the zone control terminal unit's operation. As the temperature in the space increases, the Cooling CFM should increase and the temperature maintained within ±2.0°F of the zone setpoint. With a drop in temperature, the Cooling CFM should be reduced until the Heating CFM starts to increase and then the Cooling CFM should continue to close. As the temperature outside drops, more and more heating should occur until the Heating CFM is at 100%. The Heating CFM may never reach 100% because heating terminal units are generally oversized to handle morning warm-up.

  This plot can also be used to look for control stability problems. A saw tooth pattern of the zone temperature indicates control instability. The easiest way to solve control instability is to widen out the throttling range of the thermostat. If this does not solve the problem, this condition can also be attributed to an oversized terminal unit.

  The third use for this plot is to observe the relative heating CFM percent. If all the heating terminal units in the system are just barely open, this is an indication that the hot duct temperature is too high and could be lowered. This would reduce energy loss from the duct system and improve controllability of the hot duct boxes.

– **Analysis:** Both the heating and cooling control loops have instability. The loops appear to affect each other somewhat with simultaneous heating and cooling. The morning warm-up takes place at about 4:00 to 6:00 a.m. Terminal Unit Plot #5 also shows that the warm-up overshoots the normal occupancy control point by one degree. It also appears that the morning warm-up is starting too early, unless the building is actually occupied at 6:00 a.m.

The box flow sensors need some calibration. There should not be any air flow during nonoccupied hours.

Economizer/Mixed Air Damper Operation

- Mixed Air Temperature, Expected Mixed Air Temperature, Outside Air Temperature, and Return Air Temperature (Optional) vs. Time
  - **Purpose**: To determine if the mixed air/economizer dampers are operating properly.
  - **Plot Description:** Plot $Temp_{MixedAir}$, $Temp_{ExpectedMixAir}$, $Temp_{OutsideAir}$, and $Temp_{ReturnAir}$ (optional on plot) vs. time. $Temp_{Mixed\ Air}$, $Temp_{Expected\ Mix\ Air}$, $Temp_{OutsideAir}$, and $Temp_{Return\ Air}$ (optional) are plotted on the y axis, and time is the variable on the x axis (see below). One scale, from 0 to 100, should be on the y axis. Time should be constrained to the occupancy hours or whenever the fan is operating.

    The expected mixed air temperature is a calculated value derived from the following rules:

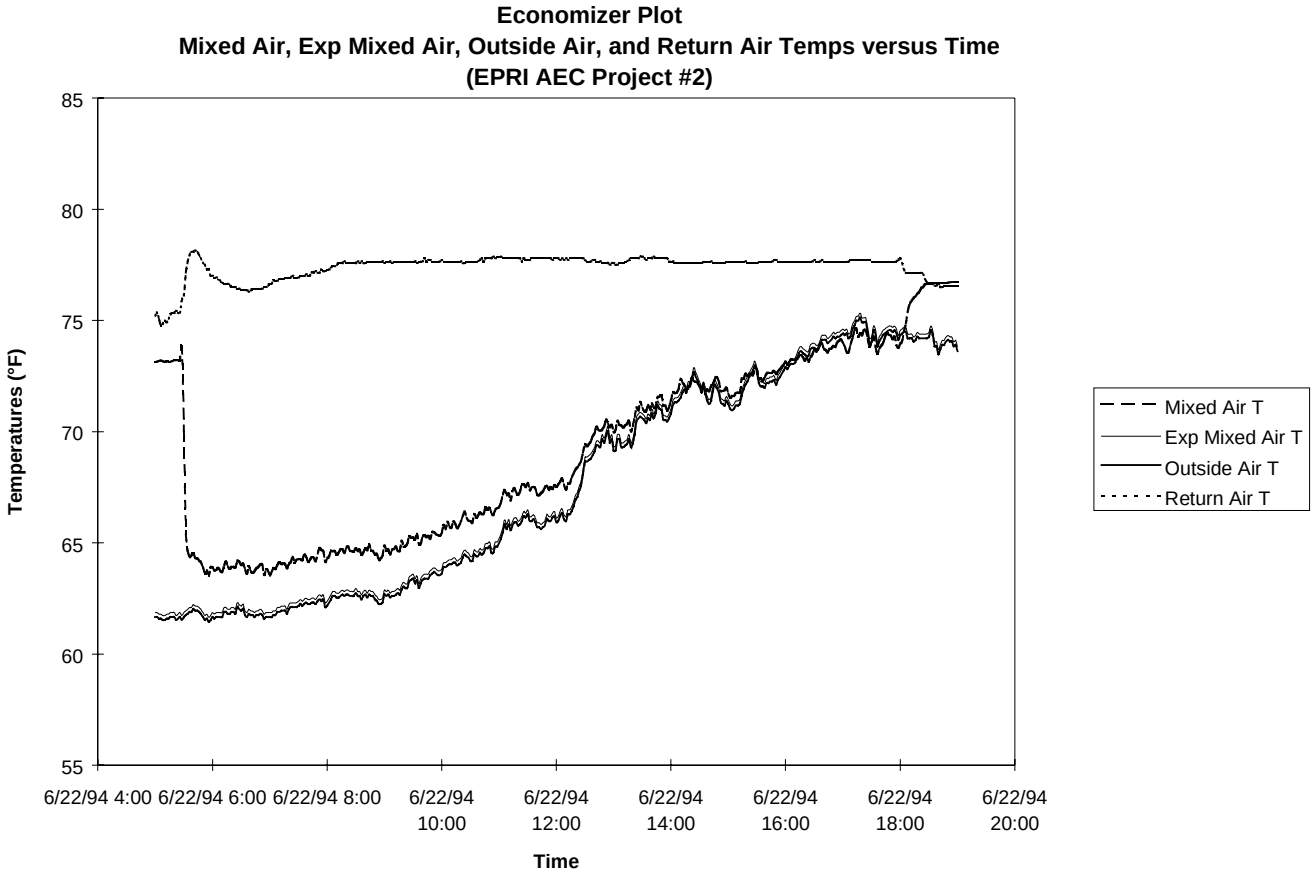
    a. If the outside air temperature is less than the supply air temperature setpoint, the mixed air temperature should equal the supply air temperature or less. If the minimum outside air flow is large or the outside air temperature is very cold, the mixed air temperature should equal the result of the following equation:

       $Temp_{ExpectedMixedAir} = Temp_{ReturnAir} + \%Min_{OSA} * (Temp_{OutsideAir} - Temp_{ReturnAir})$

    b. If the outside air is above the supply air temperature but below the return air, then $Temp_{ExpectedMixedAir} = Temp_{OutsideAir}$

    c. if the outside air temperature is greater than the return air temperature, the mixed air dampers will be in the minimum position and the mixed air temperature will be: $Temp_{ExpectedMixedAir} = Temp_{ReturnAir} + \%\ Min_{OSA}\ (Temp_{OutsideAir} - Temp_{ReturnAir})$

  - **Discussion:** This plot is a representation of the mixed air economizer controls' operation. (Note: If the supply air temperature is being used to control the mixed air dampers instead of mixed air temperature, the expected mixed air temperature plot will not track the supply air temperature plot. At the point mechanical cooling is started, the supply air temperature will deviate from expected mixed air temperature.) The purpose of mixed air economizers is to use cool outside air for cooling for as much of the time as possible and only use mechanical cooling when the outside air is not suitable or to supplement the mixed air when the outside air is too warm to provide all the cooling. The basic operation should follow the rules above; when the outside air temperature is less than the supply air temperature setpoint, the outside air dampers and return air dampers are modulated to maintain the supply air temperature at setpoint. As the outside air temperature rises above the supply air temperature setpoint, mechanical cooling is used to supplement the outside air, the mixed air dampers are at 100% outside air. As the outside air temperature rises above the return air temperature, the outside air is no longer suitable for cooling and the mixed air dampers are returned to the minimum outside air position. $Temp_{MixAir}$ and $Temp_{ExpectedMixAir}$ should track fairly closely. If they deviate consistently by more than 1°F, the controls should be calibrated. (Note: In the following economizer plot, the mixed air temperature deviates by about 2°F all expected mixed air temperature in the morning. The economizer should be open 100% to outside air when the outside air temperature is between the supply air temperature setpoint and the return air temperature.)



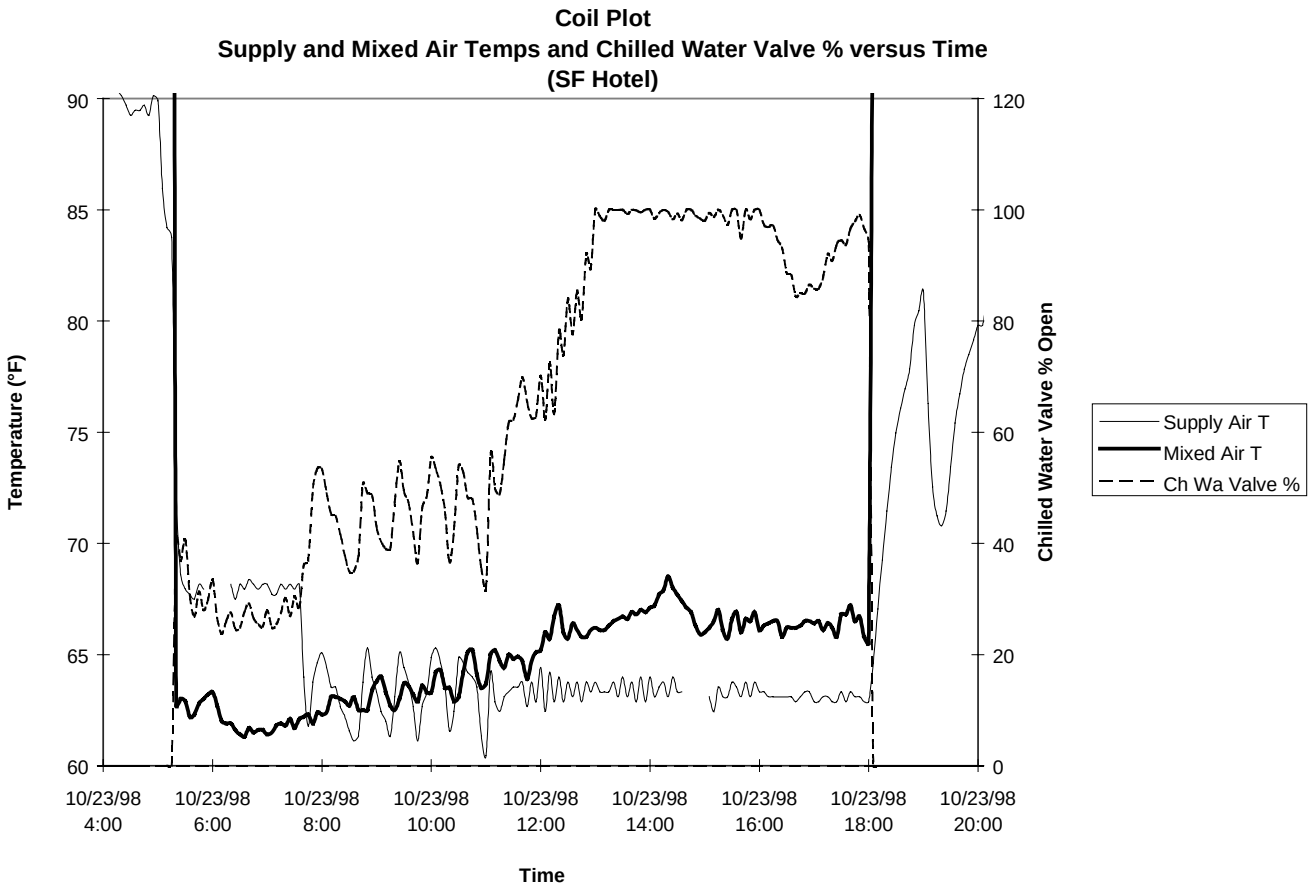
The economizer plot can also be used to look for control stability problems. An oscillating or sawtooth pattern of the mixed air temperature indicates control instability. Mixed air dampers are notoriously unstable controlled devices; the throttling range of the controller may have to be widened to over 20°F to eliminate instability. This is one control loop where Proportional + Integral control is important to remove offset from a large throttling range.

– **Analysis:** The actual mixed air temperature is a couple of degrees above the expected mixed air temperature before 1:00 p.m. This should be investigated. The offset might be due to a proportional-only control loop, in which case integral control action should be added to the control loop to eliminate the offset. It may be due to a leaky return air damper, or the OAT measurement used in the plot may not accurately reflect the temperature of the outside air entering the economizer. A minor amount of control instability can be reduced by retuning the control loop.

Cooling Coils

- Supply Air Temperature, Mixed Air Temperature, and Cooling Loop Output Signal vs. Time
  - **Purpose**: To determine if the cooling coil control is operating properly.

– **Plot Description:** Plot $Temp_{SupplyAir}$, $Temp_{Mixed\ Air}$, and $Signal_{Cooling\ Coil}$ vs. time. $Temp_{Supply\ Air}$, $Temp_{MixedAir}$, and $Signal_{Cooling\ Coil}$ are plotted on the y axis, and time is the variable on the x axis (see Coil Plot, next). One scale, 0 to 100, should be on the y axis that will be within the range of both the expected temperatures and the control output. If dual scales are possible, $Temp_{SupplyAir}$ should be plotted with a restraint between 50°F and 100°F. (Note: A reduced scale can be used if there is no heating coil in the supply fan.) Time should be constrained to the occupancy hours or whenever the fan is operating.



– **Discussion**: This plot is a representation of the supply air controls' operation. The supply air temperature should be stable except during morning warm-up. The main concern is the maintenance of a steady supply air temperature without any significant deviation during the day. (The coil plot shows control stability problems in the morning, exacerbated by economizer instabilities.) The control signal to the cooling coil should increase with an increase in mixed air temperature. The cooling coil control signal may increase slightly without an increase in mixed air temperature, but this is an effect of rising mixed air temperature humidity and should not be considered a problem. There will be varying responses for the control signal depending on what is controlled by that signal. If the mixed air dampers and cooling coil are controlled in sequence (based on supply air temperature), the control signal output from 0 to 50% will control the mixed air dampers and the second 50% from 50 to 100% will control the cooling coil. If a heating coil or preheat coil is controlled by the supply air temperature control, the resulting control output

signal will be split into three sections: 0 to 33% will be the heating coil control, 34 to 66% will be the mixed air damper control, and 67 to 100% will be the cooling coil control. During a typical day, the control signal will never go from 0 to 100% since this would indicate that the weather went from design heating day to design cooling day, almost an impossibility.

This plot can also be used to look for control stability problems. Oscillation of the mixed air temperature, the supply air temperature, and/or the control signals indicates control instability. The oscillations are indicative of various problems depending on where in the output range they take place. For instance, if the control output signal is in its upper ranges, the mixed air temperature should be stable.

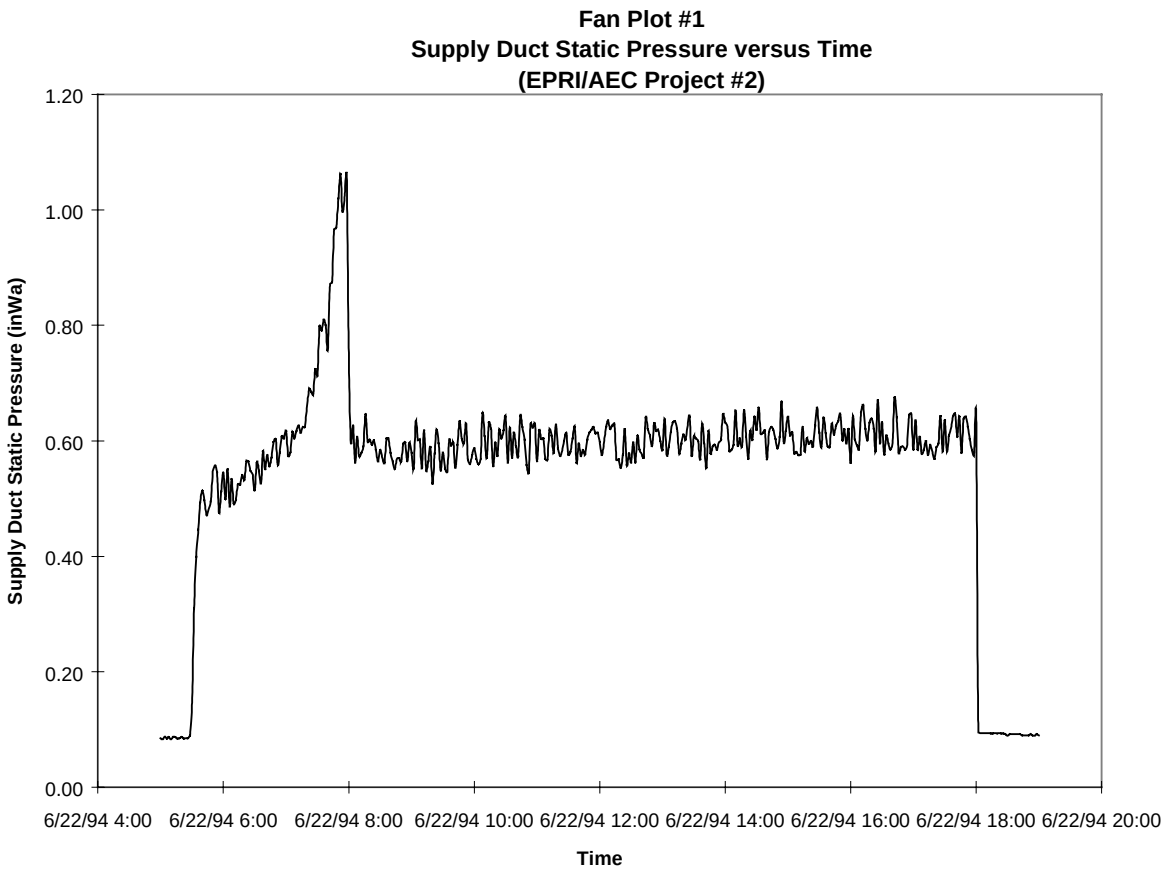
– **Analysis:** The supply air temperature control loop is very unstable and needs tuning, as evidenced by large swings in the chilled water valve position and the resultant swings in the supply air temperature. The oscillation in the mixed air temperature is of some concern in that the mixed air dampers should be at 100% open before the cooling coil starts to open. This may indicate a problem in the sequencing of the two control outputs.

  Another puzzling area is that the cooling coil is 100% open when the mixed air temperature is less than 70°F. The only explanation is that the chiller is not on, or the chilled water supply temperature is not low enough to meet the load.

Fans

1. Supply Duct Static Pressure vs. Time

   – **Purpose**: To determine if the fan is operating on its schedule and to determine if the static pressure control is operating properly.
   – **Plot Description:** Plot $\text{Pressure}_{\text{SupplyAir}}$ vs. time. $\text{Pressure}_{\text{SupplyAir}}$ is plotted on the y axis, and time is the variable on the x axis (see Fan Plot #1). The scale on the y axis should be 0 to 1.0 inH_2O or slightly wider if the control setpoint is higher. Time should be constrained to the occupancy hours or whenever the fan is operating.



– **Discussion**: This plot determines if the fan is operating properly on its normal schedule. The duct static pressure sensor is a good indicator of the status of fan operation.

  This plot can also be used to confirm that the static pressure controls are operating properly. The static pressure should remain constant throughout the normal operation hours. If a morning warm-up control strategy is used, the static pressure may drop significantly during morning warm-up. This is an indication that morning warm-up is not properly controlled and that all zones are probably not receiving the proper CFM.

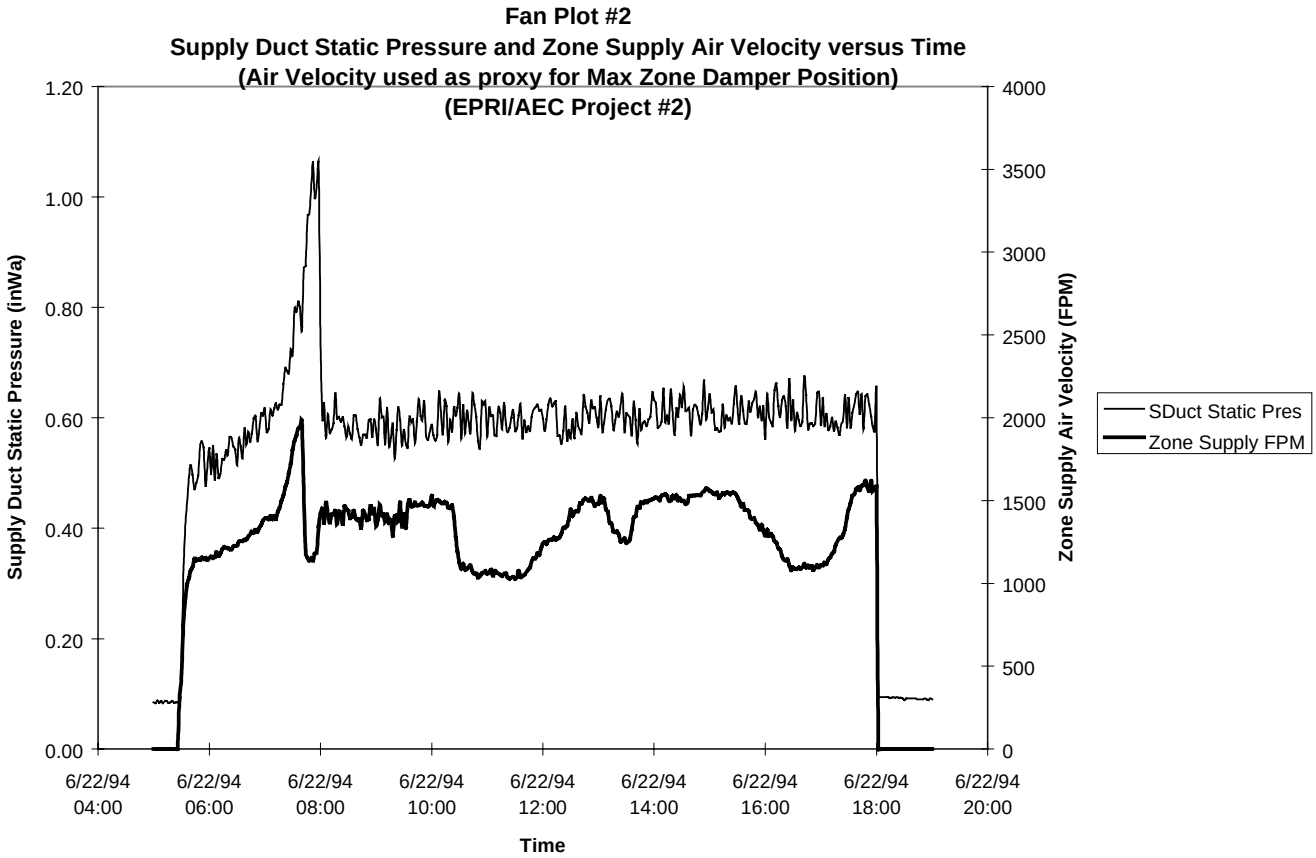
  The third use of this plot is to look for control stability problems. Oscillation of the duct static pressure indicates control instability. Because this is a very fast operating control loop, it is sometimes difficult to remove the oscillations, especially on start-up. Often the sensor signal can be averaged over 5 minutes to “slow down” the control loop response and stabilize the control.

– **Analysis:** . The peak shown at 8:00 a.m. in Fan Plot #1 might have resulted from morning warm-up, but it does not occur until almost 2 hours after the fan starts at 5:30 a.m. The fan turns off at 6:00 p.m.

  The supply duct static pressure appears to be well controlled at about 0.60 inWC, although there is considerable oscillation. Duct static control loops are among the hardest to tune because static pressure travels at close to the speed of sound, and even small changes at the fan are reflected immediately by the static pressure sensor.

2. Supply Duct Static Pressure and Maximum Zone Damper Position vs. Time

- **Purpose**: To determine if the supply duct static pressure is at the lowest pressure possible to maximize fan turn down and reduce energy.
- **Plot Description:** Plot $\text{Pressure}_{\text{SupplyAir}}$ and Damper $\text{Position}_{\text{MaximumZone}}$ (or a proxy such as Zone Supply Air Velocity) vs. time. $\text{Pressure}_{\text{SupplyAir}}$ and Zone Supply Air Velocity are plotted on the y axis, and time is the variable on the x axis (see Fan Plot #2). The scales on the y axis should be 0 to 1.0 inH_2O and 0 to 100%. Time should be constrained to the occupancy hours or whenever the fan is operating.



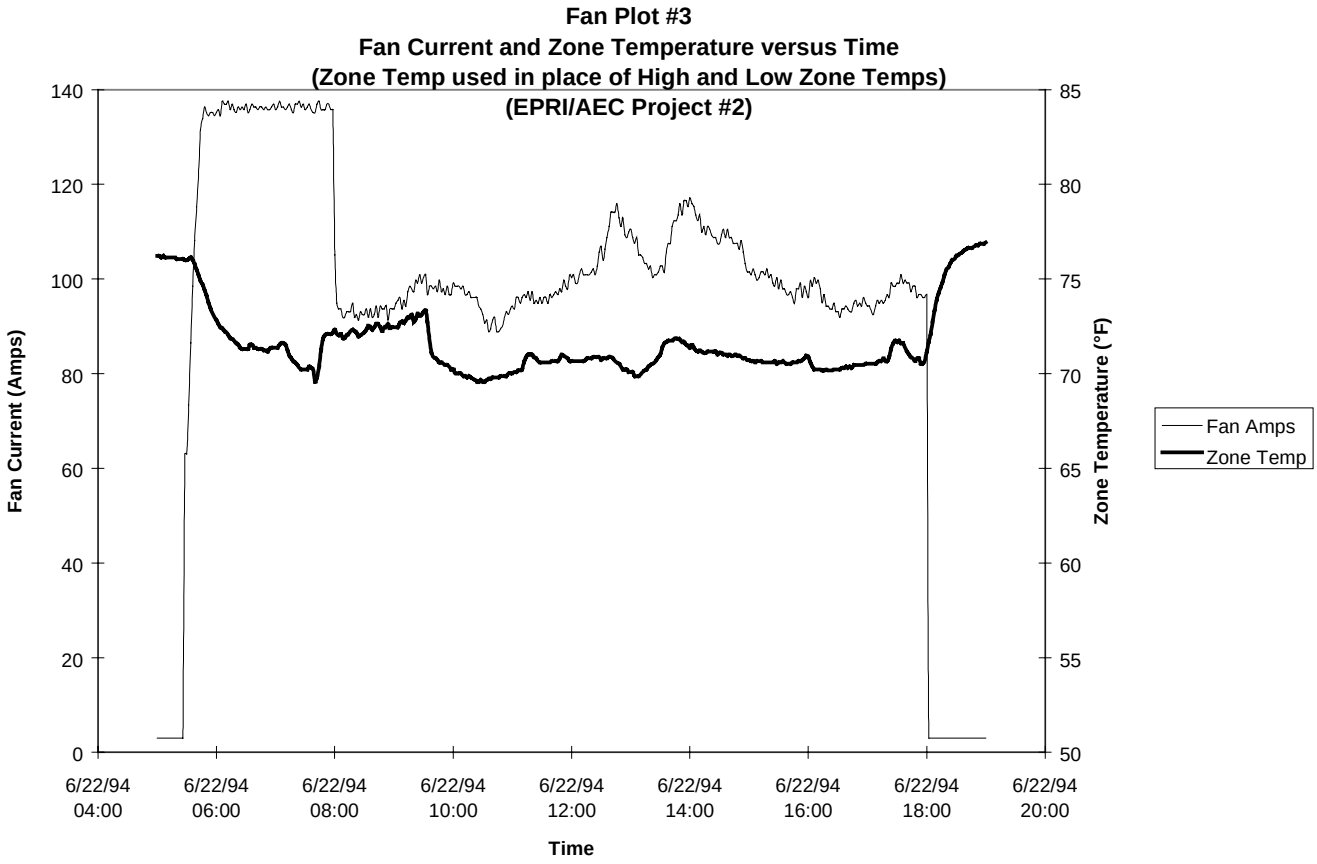
- **Discussion**: Fan Plot #2 enables advanced control strategy using VAV terminal unit feedback to control supply fan capacity. If the VAV terminal unit calling for the most cooling is throttling the supply air to maintain CFM to the zone, the supply duct static pressure is too high. By using a high signal selector to monitor all zones served by the fan system, the operator can determine if the supply duct static pressure is too high. The optimal supply duct static pressure is the pressure that keeps the zone damper on the zone calling for the most cooling wide open at all times. The actual zone will vary as internal and external loads vary, but the static pressure required at the zones should not exceed 0.5 inH_2O. The static pressure will be less than that on days where all zones are lightly loaded.

- **Analysis:** For Fan Plot #2, Maximum Zone Damper Position data was not available. Zone Supply Velocity was plotted instead, though it cannot be used for the advanced control strategy described above. It appears that the velocity reaches a maximum level at 1,500 FPM, which may indicate that the damper position is operating wide open and that the supply air static pressure is at the proper level most of the time. In an advanced control strategy, the supply air static pressure would drop to maintain a wide open damper position when less air is called for at the zone.

3. Supply Fan Status[3], Low Zone Temperature, and High Zone Temperature vs. Time

- **Purpose**: To determine if the morning warm-up (cooldown) program is operating properly.
- **Plot Description:** Plot Supply Fan Status (or a proxy such as Fan Amps), $Temp_{LowZone}$, and $Temp_{HighZone}$ vs. time. The Low Zone and High Zone temperatures were not available, so Fan Plot #3 shows Fan Amps and Zone Temp plotted on the y axis and time plotted on the x axis. The scale on the y axis should be 50 to 85 degrees for the temperatures. Time should be constrained from about 5 hours before occupancy to 2 hours after occupancy.
- **Discussion**: This plot helps determine the efficacy of the morning warm-up/cool down program. The ideal control strategy for starting the air-conditioning fans in the morning is to have a calculation that looks at the worst-case zones (either high or low) and automatically determines what time to start the fan to have the zone temperatures at a temperature suitable for occupancy (70°F for warm-up and 74°F for cooldown) at the time of occupancy. If this plot shows that the zones reach the occupancy temperature before occupancy, the calculation for preconditioning the building needs to be adjusted to a later start time. If this plot shows that the zones reach the occupancy temperature after occupancy, the calculation for preconditioning the building needs to be adjusted to an earlier start time. (The temperature may also be adjusted manually for less advanced control systems.)
- **Analysis:** Morning cooldown starts at about 5:30 a.m., and the zone temperature drops from about 77°F to about 72°F by 6:30 a.m. If the building is not occupied until 8:00 a.m., the morning cooldown could have been started almost one hour later. A more advanced, automatic control strategy could have made a better prediction of the length of time needed for morning cooldown and saved fan energy during that period. In a multi-zone building, the maximum and minimum zone temperatures should be used.

[3]Supply fan status may be indicated using fan differential pressure, duct static pressure presence, fan power, or fan current.


Fan Plot #3
Fan Current and Zone Temperature versus Time
(Zone Temp used in place of High and Low Zone Temps)
(EPRI/AEC Project #2)
Fan Current (Amps)
Zone Temperature (°F)
Time
Fan Amps
Zone Temp
140
120
100
80
60
40
20
0
85
80
75
70
65
60
55
50
6/22/94 04:00
6/22/94 06:00
6/22/94 08:00
6/22/94 10:00
6/22/94 12:00
6/22/94 14:00
6/22/94 16:00
6/22/94 18:00
6/22/94 20:00

Appendix C—Bin Analysis of Energy Use

The bin energy analysis method is a simplified method of energy analysis using Bin Weather Data available from the U.S. Armed Forces Weather Data Handbook, ASHRAE, and PG&E. The method was developed by ASHRAE in a research project sponsored by ASHRAE TC-4.7, Energy Calculations 1999. The basic bin method consists of performing an instantaneous energy calculation at many different outdoor dry bulb and wet bulb temperature conditions, and multiplying the results by the number of hours of occurrence of each condition. The envelope loads are simulated by linear interpolation between the design heating and cooling envelope loads. Internal loads are constant during occupied periods.

Fan Energy

The following formulas are derived from basic fan affinity laws. The kW of the fan is taken from the curves used in DOE-2, California supplement 1989. These curves are based on the static pressure control point being set at one-third of the fan design total static pressure; therefore, an adjustment is made for the various static pressure control points, as follows. The curves are also adjusted for the efficiency penalty of the various control devices.

$$\%KW_{DOE2FanControl} = \frac{KW_{FanDesign}}{Eff_{ControlDevice}} * \left(A + B * \%CFM + C * \%CFM^2\right)$$

Where:

Fan Control Factors from DOE-2						
For	**A**	**B**	**C**	**Min %CFM**	**Min %KW**	**%Eff Cntrl Device**
AF/BI Disch Dampers	0.227143	1.178929	-0.410714	45%	68%	108.1%
AF/BI Inlet Vanes	0.584345	-0.579167	0.970238	30%	48%	103.0%
Forward Curve Disch Dampers	0.190667	0.310000	0.500000	10%	22%	105.7%
Forward Curve Inlet Vanes	0.339619	-0.848139	1.495671	20%	22%	105.7%
Vane Axial Adjust Pitch	0.212048	-0.569286	1.345238	20%	15%	100.0%
Variable Speed	0.219762	-0.874788	1.652597	10%	10%	104.2%

$$\%KW_{Adjusted} = \%KW_{DOE2FanControl} * \left(\frac{\%CFM^2 * \left(Static_{Design} - Static_{Control}\right) + Static_{Control}}{\%CFM^2 * \left| Static_{Design} - \frac{Static_{Design}}{3} \right| + \frac{Static_{Design}}{3}} \right)$$

Chiller Energy

$$Tons_{Supply\ Air} = \frac{\left(Enthalpy_{Mixed\ Air} - Enthalpy_{Supply\ Air\ SetPoint}\right) * 4.45 * CFM}{12,000}$$

or

$$Tons_{Supply\ Air} = \frac{\left(Temp_{Mixed\ Air} - Temp_{Supply\ Air\ SetPoint}\right) * 1.10 * CFM}{12,000}$$

$$kWh_{Chiller} = Tons_{Cooling} * kW/ton * Hours$$

Appendix D—Sensitivity Analysis Using Bin Weather File from McClellan Air Force Base

Fan and Chiller Energy Use vs. Several Air Handler System Parameters

McClelan Air Force Base (Sacramento) Weather File **$/kWh Cost = 0.10**

A - Fan Efficiency

Fan Average Efficiency (%)	Fan Energy (kWh)	Fan Demand (kW)	Added Energy Cost ($/yr)
Baseline	51,877	48.2	-
Baseline - 2%	53,665	49.9	$ 179
Baseline - 4%	55,582	51.7	$ 371
Baseline - 6%	57,641	53.6	$ 576
Baseline - 8%	59,858	55.7	$ 798
Baseline - 10%	62,252	57.9	$ 1,038

B - Clogged Filter

Differential Pressure (in H2O)	Fan Energy (kWh)	Fan Demand (kW)	Added Energy Cost ($/yr)
Baseline	51,877	48.2	-
Baseline+0.25" w.c.	55,582	51.7	$ 371
Baseline+0.5" w.c.	59,287	55.1	$ 741
Baseline+0.75" w.c.	62,993	58.6	$ 1,112
Baseline+1.0" w.c.	66,698	62.0	$ 1,482

C - Outdoor or Return Air Temp Sensor Accuracy

Shift in Economizer Change Point Temperature (°F)	Chiller Energy (kWh)	Chiller Demand (kW)	Added Energy Cost ($/yr)
= RAT+2	133,535	130.3	$ 50
= RAT+1	133,077	130.3	$ 5
= RAT (Baseline)	133,032	130.3	-
= RAT-1	133,135	130.3	$ 10
= RAT-2	133,352	130.3	$ 32

RAT = Return Air Temperature

D - Effect of Zone Temperature on Energy Use

Zone Temperature	Total Energy Use of Fan and Chiller (kWh/yr)	Energy Use Gas-Therms	Added Energy Cost ($/yr)
70.5	257,729	695	$ 4,764
71.0	239,676	715	$ 2,970
71.5	223,671	734	$ 1,382
72.0	209,718	757	-
72.5	196,500	796	$ (1,299)
73.0	185,089	834	$ (2,417)
73.5	174,231	873	$ (3,479)
74.0	164,976	911	$ (4,382)

E - Effect of Leaking Reheat Valve on Energy Use

Zone Supply Temperature	Total Energy Use of Fan and Chiller (kWh/yr)	Total Energy Use Gas Therms	Added Energy Cost ($/yr)
65	220,583	1128	$ 1,309
60	212,843	811	$ 345
55	209,718	757	-

F - Duct Static Pressure Sensor

Static Pressure (in H2O)	Fan Energy Use (kWh)	Fan Demand (kW)	Added Energy Cost ($/yr)
Baseline + 0.3	62,894		$ 294
Baseline + 0.2	61,913		$ 196
Baseline + 0.1	60,932		$ 98
Baseline + 0.0	59,951	50.9	-
Baseline - 0.1	58,970		$ (98)
Baseline - 0.2	57,988		$ (196)
Baseline - 0.3	57,007		$ (294)

G - Reciprocating Chiller - Variable Speed

Supply Air Temperature (°F)	Total Energy Use of Fan and Chiller (kWh)	Total Demand (kW)	Added Energy Cost ($/yr)
50*	189,867	176.8	-
51	190,220	180.4	$ 35
52	191,987	184.7	$ 212
53	195,719	190.1	$ 585
54	201,557	197.0	$ 1,169
55	209,718	205.7	$ 1,985
56	221,551	217.1	$ 3,168
57	239,359	238.9	$ 4,949
58	266,489	268.8	$ 7,662

H - Centrifugal Chiller- Inlet Vanes

Supply Air Temperature (°F)	Total Energy Use of Fan and Chiller (kWh)	Total Demand (kW)	Added Energy Cost ($/yr)
50	242,531	176.8	$ 1,266
51	236,747	180.4	$ 687
52	231,958	184.7	$ 209
53*	229,873	190.1	$ -
54	230,643	197.0	$ 77
55	233,116	205.7	$ 324
56	238,498	217.1	$ 863
57	248,935	238.9	$ 1,906
58	271,352	268.8	$ 4,148

I - Centrifugal Chiller- Variable Speed

Supply Air Temperature (°F)	Total Energy Use of Fan and Chiller (kWh)	Total Demand (kW)	Added Energy Cost ($/yr)
50	165,342	176.8	$ 5
51*	165,296	180.4	-
52	166,289	184.7	$ 99
53	169,290	190.1	$ 399
54	174,666	197.0	$ 937
55	182,120	205.7	$ 1,682
56	192,912	217.1	$ 2,762
57	209,302	238.9	$ 4,401
58	235,338	268.8	$ 7,004

*This temperature is used for the baseline, because it has the minimum energy use in this case.

Assumptions

VAV System
Fan Rated CFM = 50,000
Fan & Drive Efficiency = 60%
Fan Motor Horsepower= 100
Chiller kW/ton = 0.85
VSD Fan Min = 50%

Building
Perimeter Wall Area = 18,000
R-Value of Perimeter 1.5
Floor Area = 50,000
Watts/SqFt Lights = 1.5
Zone Ft2 = 800

W/SqFt Plug Load = 2.3
Nb of Occupants = 300
Internal Load BTUH = 743,001
ASHRAE 0.1% Design °FDB = 105
$0.60 per therm

Appendix IV

Improved Cost-Effectiveness of Building Control Systems' Sensing and Data Collection

Task 6—Method for Determining the Accuracy and Data Storage Frequency for Sensors Applied to Commissioning of Air-Handling Systems

CEC Contract #500-97-010

Project #3

July 1999

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Introduction

This section considers the measurements, factors, and methods needed to test air-handling equipment components from a commissioning perspective. The results that concern us are those that enable the equipment to operate in an energy efficient manner. Those parameters that do not affect energy use will not be considered. The goal is to choose sensor accuracy and storage frequency rates such that one can economically test and maintain energy efficiency of air-handling equipment.

Our focus here is on commissioning and recommissioning of air-handling equipment. Task 5 already covered diagnostics, operations, and control. For this task, we will focus on initial performance testing and ongoing monitoring (or testing) and on measurement and verification (M&V).

The method suggested at the end of Task 5 for determining the measurement accuracy and data storage frequency is summarized below:

A. Initial step for determining accuracy and storage frequency

   1. List measurements and performance factors needed for air handler *initial performance testing, periodic testing, and measurement and verification.*
   2. Determine plots useful for evaluations.
   3. Gather site data, develop plots, and calculate performance factors with real site data.

B. Accuracy and frequency based on energy benefits

   1. Determine sensitivity of factors to their input measurements.
   2. For each piece of equipment, develop a rough economic evaluation of the effect of varying *performance factors*, parameters or measurements on energy use.
   3. Prioritize the measurements and factors in terms of their effect on building energy use.
   4. Considering the cost of instrumentation and calibration, determine the economic level of accuracy for each measurement.

C. Accuracy and frequency based on plots of data

   1. Describe how the plots can be used for the evaluation of air handler *performance testing, periodic testing, and measurement and verification.*
   2. Determine the potential benefits of the plots.
   3. Determine the measurement accuracy and storage frequency needed to use the plots for the evaluation.

D. Based on the economic analyses and diagnostic plots, determine recommended accuracies and storage frequencies for each measurement.

Below, we provide several examples of commissioning functions to which this method is applied. For each of the examples, we proceeded through the method as follows:

1. Perform step A1.
2. Step A2 does not apply, because plots are not needed for tests
3. Step A3 - site data was already collected for the coil and fan performance test examples.
4. Step B1 was already applied to coil and fan performance in Task 5.
5. Step B2 sensitivity analyses were done in Task 5 for all but two of the following examples - (1) terminal unit minimum air flow and (2) minimum outside air flow. Sensitivity analyses will be performed on these parameters.
6. Step B3 - the most relevant factors will be considered.
7. Step B4 - the economic analysis for each example follows this procedure:
   a) determine the acceptable benefit/cost ratio for the task being considered. It should take into account the chance that savings will occur and the acceptable economic risk.
   b) Assume a level of degradation in the factor being measured, and the level to which it can be improved.
   c) Estimate the potential $/yr savings that might result from the improvement or the task (using the level of degradation and the improvement, and the economic sensitivity analysis results).
   d) Estimate the cost for the task, or improvement.
   e) Calculate the benefit/cost ratio.
   f) Compare the benefit/cost ratio to the acceptable B/C ratio. If it is greater, then the task or improvement should be done.
8. Step B5 is added to the method. If average performance factors are calculated, determine the number of data points needed to keep the uncertainty at the desired level.
9. Steps C1 to C3 do not apply because we felt that plots of the data were not useful in determining accuracies and frequencies for the Commissioning purposes covered here. Of course, plots of data during testing can serve other purposes (checking for stability, checking for reasonableness of data, visually comparing data, etc.).
10. For Step D we summarize all the results in a table at the end of this Appendix.

Below are examples of this method applied to commissioning functions on air-handling equipment.

Method Applied to Example Commissioning Functions

Terminal Units

Procedures for testing, adjusting and balancing terminal unit air flows are provided in ASHRAE 111-1988.[1] Measurements should include:

- Flow Rate and Velocity (adjust to within 10% of design)
- Zone Temperature

The importance of maintaining zone temperature accuracy was covered in Task 5. Table 1 shows the costs of a zone temperature that is too low. A deviation of more than about 2°F in either direction could adversely affect comfort as well. This data is based on the bin energy analysis of a 50,000-square-foot office building in Alameda (see Appendix III, Table 3, p. III-20)

Table 1. Effect of Building Average Zone Temperature on Energy Use

Zone Temperature	Total Energy Use of Fan and Chiller (kWh/yr)	Energy Use Gas-Therms	Added Energy Cost ($/yr)
70.5	175,718	37.2	$ 3,859
71.0	161,738	42.6	$ 2,464
71.5	148,157	47.9	$ 1,109
72.0	137,037	53.2	--
72.5	126,270	58.5	$ (1,074)
73.0	117,341	63.8	$ (1,963)
73.5	109,711	69.1	$ (2,723)
74.0	102,300	74.4	$ (3,461)

Determining the individual terminal unit flows to high accuracy is not important, because the flow is self correcting, to maintain the proper zone temperature. The maximum flow should be within 10% of design, to be able to condition the zone during design cooling conditions. If the maximum flow is off, the result is lower comfort to the occupants. The minimum flow is important for energy efficiency and to maintain air quality, so the box should be zeroed periodically.

Economics of Calibrating Minimum Flow Point for Terminal Units

- Assume the minimum acceptable benefit/cost ratio is 5, because only a fraction of the terminal unit flow meters will be off calibration.
- Potential savings: During periods when the outside air and zone temperatures are cool, minimum zone cooling air flow is called for. If the air flow is greater than the design minimum, the reheat coil is used to warm up the extra air, and the fan uses more power to transport the air. Table 2 shows how much extra fan power and reheat energy is used if the minimum air flow on a terminal unit is different from design.

[1] ASHRAE 111-1988, *Practices for Measurement, Testing, Adjusting, and Balancing of Building Heating, Ventilation, Air-Conditioning, and Refrigeration Systems,* Atlanta, GA.

Table 2. Effect of Error in Minimum Zone Flow on Building Energy Use

	Alameda (San Francisco)				McClellan (Sacramento)		
Error in Minimum Zone CFM	Fan (kWh/yr)	Chiller (kWh/yr)	Reheat (Therms/yr)	Added Energy Cost ($/yr)	Fan (kWh/yr)	Reheat (Therms/yr)	Added Energy Cost ($/yr)
-10%	1479	1053	8.15	-3.25	2257	51.56	10.98
-5%	1486	1053	9.69	-1.62	2231	46.24	5.19
0%	1493	1053	11.23	0.00	2208	41.42	0.00
5%	1500	1053	12.77	1.62	2184	36.59	-5.30
10%	1506	1053	14.31	3.15	2160	31.77	-10.59

* Rated zone box flow is 1000 CFM; minimum flow is 150 CFM.

For Sacramento:

- Assume that the minimum flow is likely to be 10% of full flow too high, and can be improved by calibration to 5%.
- Approximate savings is based on an improvement of 5%, or about $5/yr (from Table 2).
- Assumed cost for an annual 5% calibration is $20.
- Benefit/cost ratio is 5/20, or 0.25 .
- It would not pay to annually calibrate the flow sensors at zero flow in each terminal unit at Sacramento.

For Alameda:

- Assume that the minimum flow is likely to be 10% too high, and can be improved by calibration to 5%.
- Approximate savings is based on an improvement of 5%, or about $2/yr (from Table 2).
- Assumed cost for an annual 5% calibration is $20.
- Benefit/cost ratio is 2/20, or 0.1 .
- It would not pay to annually calibrate the flow sensor in each terminal unit at Alameda.

Economics of Installation of New Terminal Unit Flow Sensors

- Assume the minimum acceptable benefit/cost ratio is 5.
- Assume that the minimum flow is likely to be 20% too high, and this could be improved to within 5% of minimum flow.
- Approximate savings would be about $16/yr for Sacramento (see Table 2 above) and $5/yr for Alameda.
- Estimated cost for the flow sensors is $500. Amortized over 5 years, the cost is $100/yr.
- Benefit/cost ratio is 16/100, or 0.16 for Sacramento and 5/100, or 0.05 for Alameda . These are much less than the acceptable B/C ratio of 5.
- It would not pay to install a flow sensor in each terminal unit, in this example.

Air Apparatus (including duct static pressures and DPs, flows, and the economizer)

Procedures for testing, adjusting and balancing air flows are provided in ASHRAE 111-1988. They recommend the following measurements for air flow apparatus:

- Duct or Zone Air Flows (discussed above)
- Fan RPM, Amps, Voltage, Air Flow (ASHRAE says to adjust fan flow to within 5% of design) (Fan flow is covered below under Fan Efficiency)
- Outside and Return Air Flows and Damper Positions (Outside air flow affects energy efficiency and is covered in this section)
- Static Pressure of Duct and Fan Discharge (duct static pressure affects energy efficiency and is covered in this section)
- Fan DP, Filter DP, Coil DPs, other major DPs (DPs affect energy efficiency and are covered in this section)

Duct static pressure accuracy is important for enabling terminal boxes to work properly to get design air flow to the zones under design conditions, and to minimize noise from the boxes. The other DPs are important to check periodically at design air flow, to ensure that fan power is kept to a minimum.

Example Economics of Monitoring DP Across a Coil

- Should the DP across the coil be monitored?
- Assume the minimum acceptable benefit/cost ratio is 2.
- Assume the likely DP increase across the coil over one year would be 0.1 inH_2O, and that this DP can be rectified by cleaning the coil.
- Potential savings are $100/yr for Sacramento (Appendix III page III-D-70) and $129/yr for Alameda (Appendix III page III-20). The savings are based on the extra fan power required. They do not include costs due to possible performance degradation of the coil.
- Estimated cost to add a DP sensor that is 0.05 inH20 accurate would be $300. Amortized over 3 years, this is $100/yr. With annual maintenance costs of $100/yr, the total annual cost is $200/yr.
- The benefit/cost ratio is 100/200, or 0.5 for Sacramento and 129/200, or 0.65 for Alameda . These are less than the acceptable B/C ratio of 2.
- It would not pay to install a DP sensor around the coil for this example.

Example Economics for Measuring and Calibrating the Minimum Outside Air Flow

- Should the Minimum Outside Air Flow of our example building be monitored?
- Assume the minimum acceptable benefit/cost ratio is 2. If air flow is high, energy costs will increase. If it is low, air quality may degrade, even though costs will decrease.
- Assume that the design outside air flow is 15% of full duct flow, and without monitoring, it is about 25%.
- With an outside air flow instrument, the outside air flow can be brought to within 3% (of full flow) of the design outside air flow of 15%.

- Potential savings of reducing outside air flow from 25% to 18% is $7/yr at Alameda, and $194/yr at Sacramento (see Table 3). Since Sacramento has many more hours when the outside air temperature is greater than the return air temperature (of about 75°F) compared to Alameda, more energy is required of the chiller to cool off the excess outside air flow during these minimum flow conditions.
- An outside air flow sensor could cost at least $2,000. Amortized over 3 years, this would be about $700/yr.
- The benefit/cost ratio for Sacramento is 194/700, or 0.28, and 7/700, or 0.01 for Alameda . These are less than the acceptable B/C ratio of 2.
- It would not pay to install an outside air flow monitor in this example.

Table 3. Effect of Error in Minimum Outside Air Flow on Building Energy Use

	Alameda		McClellan (Sacramento)	
% Minimum Outside Air Flow of Max Air Flow	Chiller (kWh/yr)	Added Energy Cost ($/yr)	Chiller (kWh/yr)	Added Energy Cost ($/yr)
10%	69781	-5	130378	-138.6
15% (baseline)	69831	0	131764	0
20%	69880	4.9	133151	138.7
25%	69930	9.9	134538	277.4
30%	69979	14.8	136090	432.6

* Minimum outside air flow is % of 50,000 CFM rated fan flow for Alameda and 60,909 CFM for McClellan.

Reheat Coil

The hot water flow should be balanced according to ASHRAE 111-1988 procedures. The recommended measurements to determine flow or heat transfer rate are:

- Entering and Leaving Water Pressures
- Water DP or meter reading - for water flow rate
- Entering and Leaving Water Temperatures
- Water DT

  or:
- Air Flow rate
- Entering and Leaving Air Temperatures
- Air DT

A high accuracy for the heat transfer rate (or any of the recommended measurements) is not important because the reheat valves are self-correcting based on the heating demand, and energy efficiency is not affected significantly. If the hot water flow is deficient, the zone temperature would be lower than the zone setpoint, and the hot water valve would open more to raise the temperature. In some systems, the hot water temperature can be set back on warm days, to reduce heat loss from the boiler and piping system.

The following example illustrates how a leaking reheat valve will affect energy efficiency.

Example Economics of Monitoring for Reheat Coil Valve Leaks

- Should discharge temperature be monitored to detect reheat coil valve leaks?
- Assume the minimum acceptable benefit/cost ratio is 5, since only a fraction of the terminal units might have valve leaks.
- We will try to detect valve leaks which would raise the zone supply air temperature by 5°F above the supply air temperature of 55°F. We would require a 2°F accuracy to detect a 5°F temperature difference.
- Potential savings from eliminating a leak that results in a 5°F temperature rise are $240/yr for Alameda (Appendix III page III-20) and $345/yr for Sacramento (Appendix III page III-D-70).
- Estimated cost for a 2°F accurate sensor is $300. Amortized over 3 years, the cost would be $100/yr. Annual calibrations are not needed to maintain a 2°F accuracy.
- The benefit/cost ratio is 240/100, or 2.4 for Alameda and 345/100, or 3.5 for Sacramento. These are less than the target B/C ratio of 5.
- It would not pay to install a temperature sensor to detect reheat valve leaks, mainly because of our assumption that not that many terminal units would have that problem (1 out of 5). If the target B/C ratio was less than 5 (i.e. more leaks are expected), then it would pay.

Coils

ASHRAE 111-1988 specifies what to measure during testing and balancing around the cooling or heating coils, ASHRAE 33-78[2] specifies laboratory testing procedures, and ARI Standard 410[3] specifies test procedures for forced-circulation air-cooling and air-heating coils.

In summary, the following measurements are recommended around the coil during testing and balancing:

- Air Flow
- Air Pressure Drop
- Entering and Leaving Dry and Wet Bulbs
- Outside and Return Dry and Wet Bulbs
- Air Temperature Difference
- Water Flow Rate
- Water DP
- Entering and Leaving Water Temps
- Water Temperature Difference
- Refrigerant P and T or Steam P

The Coil Effectiveness for Dry Coils (from ASHRAE S21.12[4]) is defined as follows:

Coil Effectiveness = (Tair entering - Tair leaving) / (Log Mean Temp Difference ΔTm)

[2] ASHRAE, 1978, *Methods of Testing Forced-Circulation Air-Cooling and Air-Heating Coils,* Atlanta, GA.
[3] Air-Conditioning and Refrigeration Institute, 1991, *Standard for Forced-Circulation Air-Cooling and Air-Heating Coils,* Arlington, VA.
[4] ASHRAE Handbook, 1996, *Heating, Ventilation, and Air-Conditioning Systems and Equipment,* inch-pound ed., Atlanta, GA.

where ΔTm = [(Tair entering - Tfluid leaving) - (Tair leaving - Tfluid entering)] /

ln [(Tair entering - Tfluid leaving) / (Tair leaving - Tfluid entering)]

If the coil is to be tested for warranty purposes, the accuracies specified in the test codes or in the test agreement should be used. ASHRAE Standard 111-1988 suggests that the air and water-side heat transfer rates agree within 5%.

It is probably not worthwhile to monitor coil performance over time. If the coil effectiveness degrades, the chilled water flow rate through the coil can increase to make up for the poorer heat transfer. If the degradation is due to air-side blockage, the DP across the coil will increase, so it might be worthwhile to place a pressure sensor across the coil to monitor DP. The measurement would need to be tracked at maximum air flow (such as during morning warm-up/cool-downs). A significant increase should lead to maintenance/cleaning of the coil. (See the Air Apparatus section above for an example economic analysis of the DP across the coil).

The capability of the coil will not affect system performance or energy efficiency significantly, unless the coil cannot maintain the supply air temperature setpoint for a considerable period of time. If a coil performs poorly, the heat transfer rate is self-adjusted by increasing the chilled water flow rate. Usually, poor performance will only affect system efficiency under extreme cooling conditions, when the building load may not be met. When the air conditioning demands are highest, the coil air leaving temperature (or supply air temperature - SAT) may be high. This will require more air flow and fan power to achieve the same amount of cooling. Or, the chilled water temperature (CWT) setpoint could be lowered in order to meet cooling demand. This would also increase energy use. The SAT curves (shown below) indicate how much the annual energy cost increases when the optimum SAT is not maintained. This would only happen a small number of hours a year as a result of a poorly performing coil. The CWT curves (Task 7) show the effect of CWT on annual energy costs. The energy use would be higher for only a small number of hours per year, so the energy cost increase would be small. At less than design loads, CWT and SAT setpoints can usually be maintained.

Coil operating stability can be checked by using the coil plots described in Task 5 (diagnostics).

Example Economics of Monitoring Cooling Coil Effectiveness

- Should cooling coil effectiveness be monitored to detect coil performance degradation?
- Assume the minimum acceptable benefit/cost ratio must be 2.
- If the coil cannot maintain an optimum supply air temperature, our example building's energy use will increase, as shown in Figure 2. For this example, assume that the supply air temperature is 3°F too high for a coil whose effectiveness has degraded by 10%, for 200 out of a total of 2500 operating hours per year.
- A 3°F degradation in supply air temperature would add about $2000/yr to our building's operating costs for Alameda (Figure 1 in Appendix III page III-19), or about $1000/yr for Sacramento (Appendix III, page III-D-70), mainly due to the extra fan energy needed to push more air to supply the same amount of cooling. Since the deficiency would only occur 200 hr/yr, the extra energy costs for our example building in Alameda would roughly be $2,000/yr * (200 hr/yr / 2500 hrs/yr) = $160 /yr, and about $80/yr for Sacramento.
- The potential annual savings are $160/yr for Alameda and $80/yr for Sacramento.

- Tables 4 and 5 show the measurement accuracies required for various levels of uncertainty, and the estimated costs of setting up temperature sensors for testing. (Note: These uncertainties do no include inaccuracies associated with testing under varying or unstable operating conditions or the adjustments needed to correct to conditions that are acceptable for comparisons.)

Table 4. Suggested Measurement Accuracies (%) for Coil Effectiveness Testing

	Total Acceptable Uncertainties (nominal %)					
Measurements	**5**	**10**	**20**	**30**	**40**	**50**
Tair entering	0.5	1	2	3	4	5
Tair leaving	0.5	1	2	3	4	5
Tfluid entering	0.5	1	2	3	4	5
Tfluid leaving	0.5	1	2	3	4	5
Calculated total uncertainty in effectiveness (%)	**5.4**	**10.7**	**21.4**	**32.2**	**42.9**	**53.6**

Note: For other combinations of measurement uncertainties, use the following root-sum-square equation to calculate total uncertainty: Total Uncertainty = (Tair entering^2 + Tair Leaving^2 + Tfluid Entering^2 + Tfluid Leaving^2)$^{1/2}$

Table 5. Example Methods and Costs to Attain Acceptable Uncertainties for Coil Effectiveness Testing

	Total Acceptable Uncertainties (nominal %)					
Measurements	**5**	**10**	**20**	**30**	**40**	**50**
Tair entering	Calibrated HQ Temp Sensor $250	Calibrated Temp Sensor $200	Calibrated Local Sensors $150	Uncalibrated Local Sensors $100	$100	$100
Tair leaving	HQ Averaging Temperature Sensor $1,500	Averaging Temperature Sensor $1,000	Calibrated Multiple HQ Sensors $1,500	Uncalibrated Multiple Sensors $500	Uncalibrated Two Sensors $200	Uncalibrated One Sensor $100
Tfluid entering	$1,000	$1,000	$150	$100	$100	$100
Tfluid leaving	$1,000	$1,000	$150	$100	$100	$100
Total Costs for Testing	**$3,750**	**$3,200**	**$1,950**	**$800**	**$500**	**$400**

Note: The 5% and 10% uncertainty costs include installation through the EMCS, except for the Tair leaving temperature, which is assumed to be installed through the EMCS already. HQ means high quality.

- To test to a 5% accuracy, which is what we would need in order to detect a 10% degradation, the estimated cost would be $3,750. Amortized over a 3 year period, this would cost $1,250/yr. (Note: This example does not account for any cost to correct any problem, if found.)
- The benefit/cost ratio is 160/1250, or 0.13 for Alameda and 80/1250, or 0.07 for Sacramento. It would not pay to test for the coil's effectiveness in this example.
- If the test were to be performed, the number of data points to be taken would need to be determined. Assume the standard deviation of the calculated effectiveness to be about 10%. We can use the next chart (Figure 1) to determine the number of readings required to keep the precision error to 10% of the total acceptable uncertainty of 5%. The number of readings would need to be at least 80.

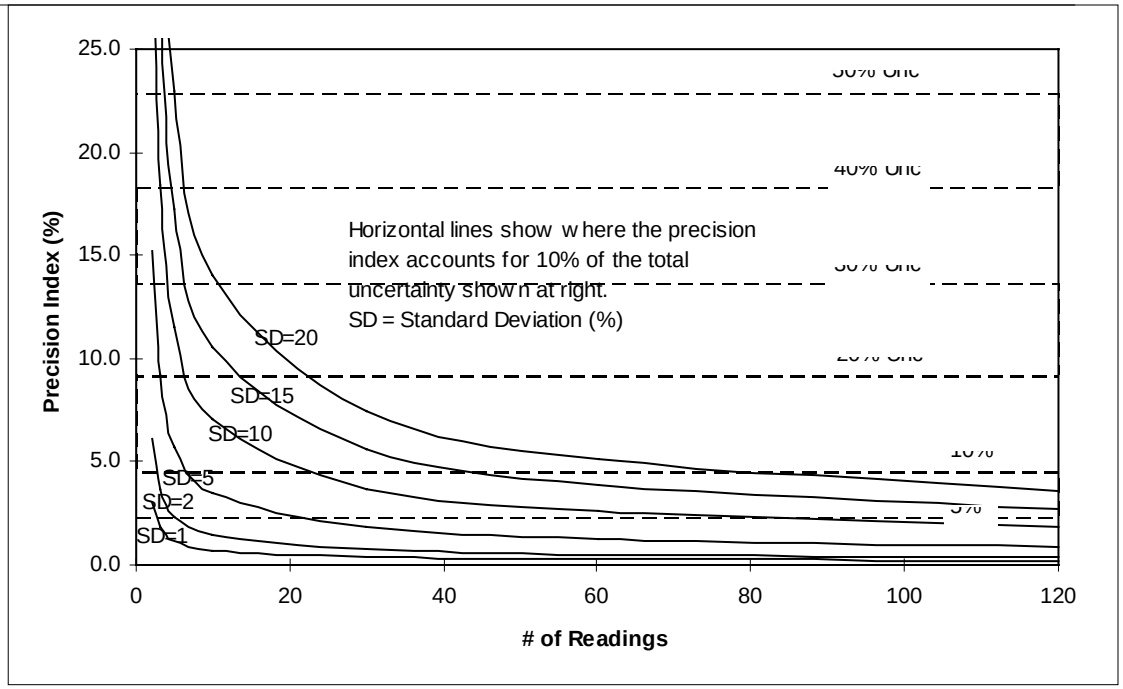

Figure 1. Precision index and total uncertainty as a function of # readings and standard deviation.

- Coil performance, even if less than specified, will usually not affect HVAC performance except under design cooling load conditions. Degradation of performance would have a small effect on annual energy usage. Performance testing would be useful for checking manufacturers' specifications. Results of coil testing are also useful as a check of water and air flow rates during commissioning.

Fans

On-site fan testing should be performed in accordance with AMCA 203-90.[5] The required measurements are:

- Air Flow
- RPM
- Fan Static Pressure
- Discharge and Suction Static Pressures
- Fan Motor Amps, Voltage, Power
- Densities at the inlet, outlet, and velocity measurement station (P, T, and moisture)

Calculation equations:

$$\text{Air Flow (scfm)} = Q_{test} = 1096 * (P_{vel} / \rho)^{0.5} * \text{Area} * (\rho_{des} / \rho_{test})$$

$$\text{Fan Power (hp)} = H_{test} = \text{Motor Power} * \text{Motor Efficiency} * \text{Belt Drive Efficiency}$$

[5] Air Movement and Control Association, Inc., 1990, *Sealed Performance Measurement of Fan Systems*, Arlington Heights, IL.

(Note: Motor and Belt Drive Efficiency need not be included if the manufacturer's design curves include those losses.)

Fan Static Pressure (inH_2O)= $\Delta P_{static\text{-}test} = P_{static\text{-}2} - P_{static\text{-}1} - P_{vel\text{-}1} - SEF_1 + SEF_2$

where:

1 - designates upstream of the fan
2 - designates downstream of the fan
SEF - system effect factor - corrects for installation conditions that affect fan performance - see AMCA 201-90.
$P_{vel\text{-}1} = (fpm/4005)^2$

To compare measured parameters to manufacturer's design curves (such as $\Delta P_{static\text{-}des}$ and H_{des} versus Q_{des}) correct them to design RPM and design density, as follows:

$$Q_{corr} = Q_{test} * (RPM_{des} / RPM_{test})$$

$$\Delta P_{static\text{-}corr} = \Delta P_{static\text{-}test} * (RPM_{des} / RPM_{test})^2 * (\rho_{des} / \rho_{test})$$

$$H_{corr} = H_{test} * (RPM_{des} / RPM_{test})^3 * (\rho_{des} / \rho_{test})$$

To relate fan performance to energy use, the fan efficiency should be used. In Task 5, we plotted the increase in energy cost versus a decrease in fan efficiency. The fan mechanical efficiency equation is:

$$Efficiency = Q_{test}(scfm) * \Delta P_{static\text{-}test}(inH_2O) / (6356 * H_{test}(hp))$$

(this may or may not include motor/drive efficiencies)

The efficiency can be used for comparison to manufacturer's curves (of efficiency versus scfm) for warranty testing. The efficiency is also used to help determine the benefits of upgrading the fan's performance. It can also be used to track performance of installed fans over time, although it is unlikely that fan performance will degrade much. A belt drive system may wear and become less efficient.

Example Economics of Monitoring Fan Efficiency

- Should fan efficiency be measured during commissioning and subsequently monitored to detect fan degradation?
- Assume the minimum acceptable benefit/cost ratio is 2.
- Let's assume that the fan efficiency could be deficient (either as purchased or from degradation) by 10%.
- The energy cost of our example building in Alameda increases by $905/yr for a 10% degradation in fan efficiency (Appendix III Table 3). In Sacramento, the energy cost would increase by $1038/yr (Appendix III, page III-D-70).
- Tables 6 and 7 show the measurement accuracies required for various levels of uncertainty, and the estimated cost of setting up the test. (Note: These uncertainties do no include inaccuracies associated with testing under varying or unstable operating conditions or the adjustments needed to correct to conditions that are acceptable for comparisons.)

- To test to a 5% accuracy, which is what we would need in order to detect a 10% fan degradation, the estimated cost would be $3,850. Amortized over a 3 year period, this would cost $1,300/yr. (Note: This example does not account for any cost to correct any problem, if found.)
- The benefit/cost ratio is 905/1300, or 0.7 for Alameda, and 1038/1300, or 0.8 for Sacramento. It would not pay to test the fan's efficiency in this example.

Table 6. Suggested Measurement Accuracies (%) for Fan Efficiency Testing

	Total Acceptable Uncertainties (nominal %)					
Measurements	**5**	**10**	**20**	**30**	**40**	**50**
Air flow (SCFM)	3	7	16	20	25	35
Pressure across fan (inWA)	3	6	10	20	25	30
Duct cross-sectional area (ft^2)	2	2	5	5	5	5
Motor power (kW)	2	3	5	10	15	15
Calculated total uncertainty in effectiveness (%)	**4.7**	**9.8**	**19.8**	**30.1**	**38.6**	**48.8**

Note: For other combinations of measurement uncertainties, use the following root-sum-square equation to calculate total uncertainty:

$$\text{Total Uncertainty} = (\text{Air Flow Unc}^2 + \text{Pressure Unc}^2 + \text{Area Unc}^2 + \text{Power Unc}^2)^{1/2}$$

Table 7. Example Measurement Techniques and Costs to Attain Acceptable Uncertainties for Fan Efficiency Testing

	Total Acceptable Uncertainties (nominal %)					
Measurements	**5**	**10**	**20**	**30**	**40**	**50**
Air Flow (SCFM)	Averaging Pitot Array $3,000	Pitot Traverse $1,500	Anemometer Traverse $750	Single Point Pitot $1,000	Single Point Anemometer $200	Estimate from RPM $50
Pressure across Fan (inWA)	Hook or Micro Manometer $600	Inclined Manometer $250	Inclined Manometer $250	U-tube Manometer $150	Dial Gage $100	Dial Gage $100
Duct Cross-Sectional Area (ft2)	$50	$50	$25	$25	$25	$25
Motor Power (kW)	CTs, PTs $200	CTs, PTs $200	CTs $150	Local Gage $20	Local Gage $20	Local Gage $20
Total Costs for Testing	**$3,850**	**$2,000**	**$1,175**	**$1,195**	**$345**	**$195**

- If the test were to be performed, the number of data points taken would need to be determined. Assume the standard deviation of the calculated efficiency to be about 5%. We can use Figure 2 to determine the number of readings required to keep the precision error to 10% of the total acceptable uncertainty of 5%. The number of readings would need to be at least 20.

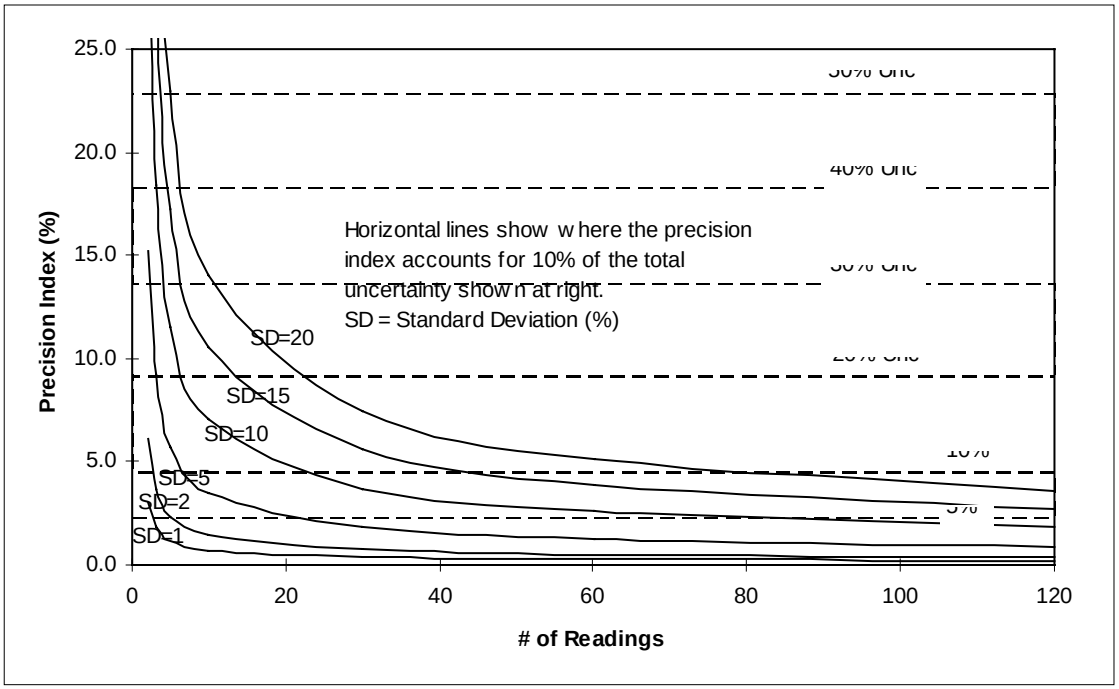

Figure 2. Precision index as a function of # readings and standard deviation.

Results Summary

Table 8 summarizes the results of the economic analyses illustrated thus far in this section. In Task 7, the analyses will be repeated for small, medium and large office buildings and a medium hospital, using the results from the DOE2 model simulation runs.

Table 8. Summary of Example Economic Analyses for Commissioning of Air-Handling Equipment - Bin Analysis - Task 6

Alameda Small Office Building - 50,000 sf

Commissioning Task, Improvement, or Sensor Installation	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings Due to Improvement ($/yr)	Assumed Cost of Improvement	Benefit to Cost Ratio[1]	Acceptable B/C Ratio[2]	Recommend Improvement?[3]	Max Potential Net Savings if Task is Performed[4] ($/yr)
Terminal Unit Min Air Flow Calibration at Zero	High by 10% of full flow	5%	$2	$20/yr	0.10	5	No	-
Terminal Unit Min Air Flow Install New Sensor	High by 20% of full flow	5%	$5	$500/5-yr	0.05	5	No	-
Monitor DP across Coil	High by 0.1 inH2O	0.05 inH_2O	$129	$200/yr	0.65	2	No	-
Measure Minimum Outside Air Flow	MinOAF is 25% of full flow	Target MinOAF is 15%±3% of full flow	$7	$2,000/3-yr	0.01	2	No	-
Detect Leaking Reheat Valves	A typical leak might raise SAT by 5°F	2°F	$240	$300/3-yr	2.4	5	No	-
Test Coil Performance	Effectiveness low by 10% SAT high by 3°F	Effectiveness not degraded. relevant 8% of operating hours	$160	$3,750/3-yr	0.13	2	No	-
Test Fan Performance	Fan Efficiency low by 10%	Fan Efficiency low by 0%	$905	$3,850/3-yr	0.71	2	No	-
Total Potential Annual Savings[5]								$0

Sacramento Small Office Building - 50,000 sf

Commissioning Task, Improvement, or Sensor Installation	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings Due to Improvement ($/yr)	Assumed Cost of Improvement	Benefit to Cost Ratio[1]	Acceptable B/C Ratio[2]	Recommend Improvement?[3]	Max Potential Net Savings if Task is Performed[4] ($/yr)
Terminal Unit Min Air Flow Calibration at Zero	High by 10% of full flow	5%	$5	$20/yr	0.25	5	No	-
Terminal Unit Min Air Flow Install New Sensor	High by 20% of full flow	5%	$16	$500/5-yr	0.16	5	No	-
Monitor DP across Coil	High by 0.1 inH2O	0.05 inH_2O	$100	$200/yr	0.50	2	No	-
Measure Minimum Outside Air Flow	MinOAF is 25% of full flow	Target MinOAF is 15%±3% of full flow	$194	$2,000/3-yr	0.29	2	No	-
Detect Leaking Reheat Valves	A typical leak might raise SAT by 5°F	2°F	$345	$300/3-yr	3.5	5	No	-
Test Coil Performance	Effectiveness low by 10% SAT high by 3°F	Effectiveness not degraded. relevant 8% of operating hours	$80	$3,750/3-yr	0.06	2	No	-
Test Fan Performance	Fan Efficiency low by 10%	Fan Efficiency low by 0%	$1,038	$3,850/3-yr	0.81	2	No	-
Total Potential Annual Savings[5]								$0

[1] The B/C Ratio for the lower table is calculated by: Potential Savings due to Improvement / (Assumed Cost of Improvement / 3 years). The Cost of Improvement is annualized
[2] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is
Where there a many sensors (such as zone sensors), it includes the percentage of zones that might need
[3] The Improved Accuracy or Proposed Improvement is recommended if the B/C ratio is greater than the Acceptable B/C
[4] The Maximum Potential Net Savings is calculated by: (Annual Energy Savings - Annual Cost). The lump sum costs are spread over a 3-year period (I.e. they are
[5] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset

For a procedure to determine the benefits of fan upgrades, see the section on Measurement and Validation (next). In this procedure, the pre- and post-retrofit power versus flow curves are developed, and the post-retrofit fan power is monitored to determine an annual flow profile and energy use. The pre-retrofit annual energy use is then estimated using the post-retrofit flow profile. The difference between pre- and post-retrofit energy uses is the energy savings from the retrofit.

Measurement and Validation of Upgrades in Fan Performance

Background

This section discusses the effects of measurement uncertainty and data storage rates on the uncertainty in the annual energy savings attributed to a specific retrofit on an air-handling fan. The approach taken is illustrated by example of a retrofit of a fan equipped with variable inlet vanes being retrofit with an adjustable speed drive. (This section summarized the more detailed discussion provided in Appendix V.) ASHRAE Draft Guideline 14P[6] provides the procedure that is followed in this example. The annual energy savings achieved with this retrofit is determined by calculating the difference between the fan motor's actual annual energy consumption after the retrofit and what it would have been had the retrofit not been made. The consumption that would have occurred had the retrofit not been made is called the baseline consumption; while the actual consumption after the retrofit is referred to as the post-retrofit or post-test consumption. Each consumption is an integration of the input power to the fan motor over a period of one year. So, the baseline power and post-test power are needed to calculate the savings.

Since the exact consumption pattern is unlikely to occur from one year to the next, the baseline power is calculated from the measured post-test power in this approach. This is made possible by using the relationship between the fan's air flow rate and power during the baseline and post-retrofit period. The baseline relationship is obtained in a short term test prior to the retrofit in which the fan air flow is varied through the range which is expected over the life of the retrofit. The results of this baseline testing, in which 21 data points were taken, is shown as the top plot in Figure 6. The post-retrofit relationship is obtained in a similar manner in the post-test. The results of this test are plotted along the lower curve in Figure 6.

With this information available the one year monitoring period begins. During this period either the flow rate and/or the input power could be monitored. For this example, input power alone is monitored. It is felt that the post-test power is easier to monitor and its measurement is much less susceptible to drift over the year of monitoring. From Figure 6, it can be seen that the fan flow rate is the connection between the post-test power and the baseline power. In this approach, the measured post-test power is used to calculate the air flow rate from the post-test relationship. That air flow rate is used to obtain the baseline power from the baseline relationship. To do this, it is more convenient to use the plot of the post-test relationship shown in Figure 7 to obtain the air flow rate. It, as well as Figure 8, shows the equation which represents the relationship between the two parameters.

[6] ASHRAE, "Proposed Guideline 14P: Measurement of Energy and Demand Savings," June 1999, Atlanta, GA.

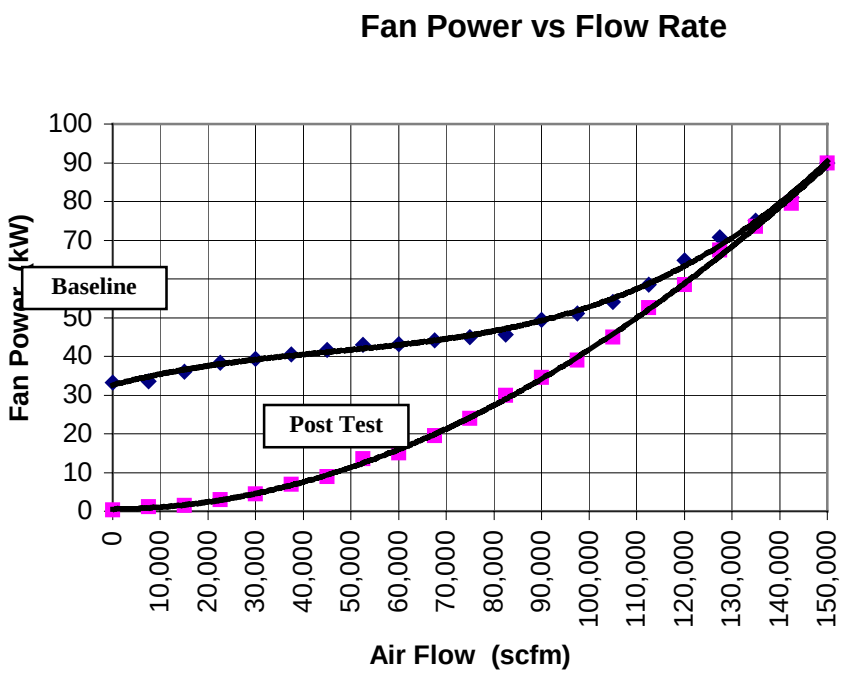

Figure 6. Baseline and post-test relationships.

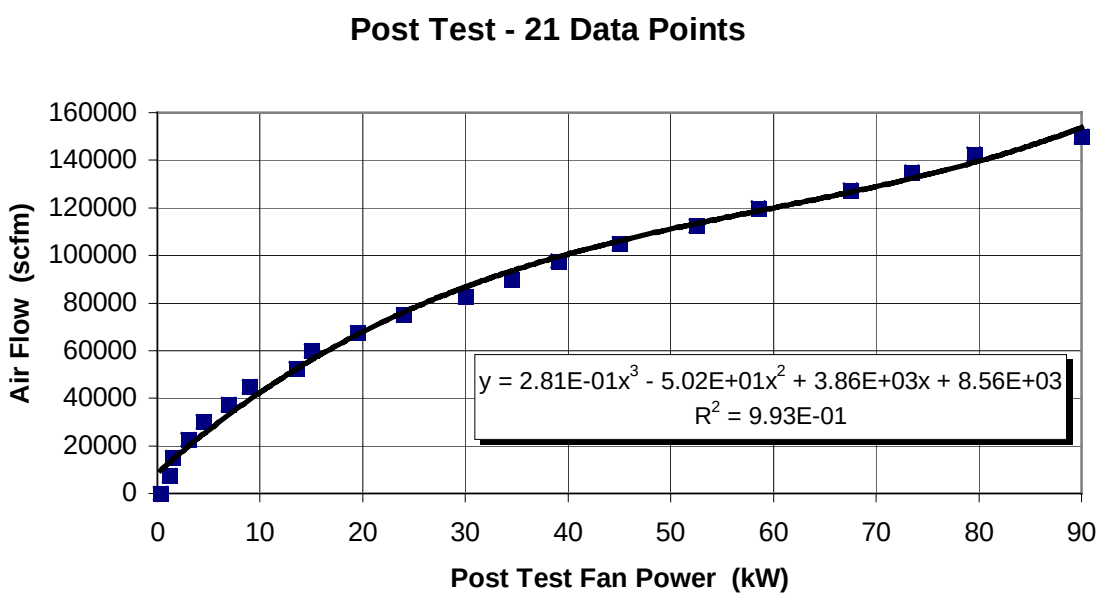

Figure 7. Post-test relationship.

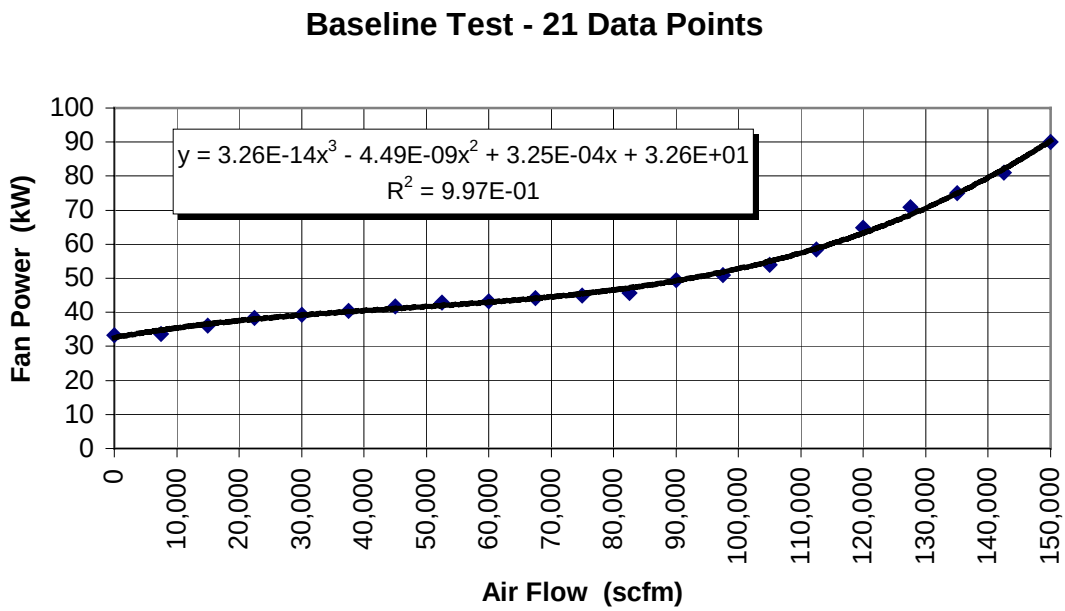

Figure 8. Baseline relationship.

Analysis Process

Determining the uncertainty in the annual energy savings involves several steps. The first is to write the data reduction equation. This is the equation used to determine the annual energy savings.

$$\mathbf{ES} = \sum_{i=1}^{N} \left[(\mathbf{Pb} - \mathbf{Pp}) \Delta \mathbf{t} \right]_i \qquad [1]$$

where:

P_b is the baseline fan motor input power.
P_p is the post-test fan motor input power.
Δt is the time interval between sequential data storage events.
N is the number of times the data is stored during the monitoring period.

The uncertainty in the calculated annual energy saving (ES) due to instrument error, is dependent on the error in the power and the flow measurements and on the sensitivity of the energy saving to errors in these measurements. This is expressed as

$$\mathbf{U_{ES}} = \left[(\mathbf{B_{ES}})^2 + (\mathbf{2 * S_{ES}})^2 \right]^{1/2} \qquad [2]$$

B_{ES} is the systematic portion of the uncertainty and is calculated from

$$\mathbf{B_{ES}} = \left| \begin{array}{l} \left(\theta_{P_b} * U_{P_b}\right)^2 + \left(\theta_{P_p} * U_{P_p}\right)^2 + \left(\theta_{Q_b} * U_{Q_b}\right)^2 + \left(\theta_{Q_p} * U_{Q_p}\right)^2 \\ + \left(2 * \theta_{P_b} * \theta_{P_p} * \rho * U_{P_b} * U_{P_p}\right) + \left(2 * \theta_{Q_b} * \theta_{Q_p} * \rho * U_{Q_b} * U_{Q_p}\right) \end{array} \right|^{1/2} \qquad [3]$$

where:

q represents the sensitivity coefficients which weight the effect of the error in each power and flow rate measurement on the uncertainty in the energy savings.

U represents the error in the power and flow rate measurements.

ρ is the correlation coefficient. It has a value of 1 when the instrumentation has the same error for the baseline and post-test are perfectly correlated for these measurements. Otherwise, its value is zero. Since the product of the two sensitivity coefficients is always negative in the above expressions, the correlation coefficient will decrease the uncertainty when its value is 1.

P is the power measurement.

Q is the flow rate measurement. Q_p and Q_b are involved in the determination of P_b.

B refers to the baseline situation.

p is the post-test and monitoring period.

N is the total number of measurements involved

S_{ES} represents the random portion of the uncertainty. It is calculated from:

$$\mathbf{S_{ES}} = \left[\left| \theta_{P_p} * \frac{SEE_p}{\sqrt{N_p}} * K_1 \right|^2 + \left(\theta_{Q_b} * \frac{SEE_b}{\sqrt{N_b}} * K_2 \right)^2 \right|^{1/2} \qquad [4]$$

where:

SEE refers to the standard error of the estimate, which could be considered the uncertainty in the fit of a curve to the data from the baseline or post-test.

N is the number of points in the each of the short tests. This part of the uncertainty depends on how well the curve fits the data and the number of points in the data set.

K_1 and K_2 are added into the above equation to account for the random portion of the error changes along the length of the fitted curve. At the center of the range these factors would equal 1, however, they could be 2 or 3 for values of the parameter at the extremes of the range. Therefore, the value of both factors was set equal to 1 for this analysis.

The above equations are taken from ASME PTC 19.1-1998 “Test Uncertainty”. They only reflect the contribution of instrument error on the annual energy savings uncertainty. Note that they do not include errors associated with the data storage interval nor the length of the monitoring period. All of these components of uncertainty will be discussed in this section.

The sensitivity coefficients have units of change in energy savings per unit change in the measured parameter. It doesn't matter whether the change is due to a measurement error or a real variation in the parameter. For example, the sensitivity coefficient for the baseline flow rate, Q_b, has the units of ΔkWh per Δscfm. When the sensitivity is multiplied by the error in the measurement, the result has the units of ΔkWh.

The sensitivity coefficients were determined by a process called dithering. In this process, each parameter is changed a small amount to determine the effect of this change on the calculated result. In this example, each parameter was changed 0.5% of full scale while all of the other parameters remained unchanged. The sensitivity coefficient for that parameter was calculated by dividing the change in the energy savings by the change in the parameter. The change in the parameter was determined by changing each value of the parameter data from either the baseline or the post-test by 0.5% of full scale. For example, each value of the post-test flow rate, Qp, was changed by 250 cfm to obtain its sensitivity coefficient. The difference in the calculated energy savings with and without this change in Qp was used to determine the change in the annual energy savings. This dithering process amounted to a shift in the curve fits of baseline and post-test data. The coefficients of these curve fits were used to calculate the change in energy savings.

There are questions how practical aspects of the M&V process could affect the uncertainty of the annual energy savings. For example, how accurate should the measurement of power and air flow rate be to obtain a desired uncertainty in the calculated annual energy savings. Does it make a difference in the uncertainty of energy saving if different instrumentation packages are used for the baseline and post-retrofit tests? How does the number of points taken during the baseline and post-retrofit test affect the energy saving uncertainty? How does the data storage frequency affect that uncertainty? How does the length of the monitoring period affect the uncertainty in the energy savings?

We first define a baseline case and calculate the energy savings and uncertainty in that savings. Then we vary several parameters from the baseline to determine how the energy savings and the uncertainty vary.

Following are the parameters that we studied and their values (bold type indicates the baseline value):

- Number of Test Points for Pre and Post-Retrofit Performance Curves - **21**, 11, 5
- Data Storage Interval (minutes) - 1**5**, 30, 60
- Uncertainties in Power/Flow (%) - **1/3**, 3/5, 5/10, 10/20
- # Weeks in Monitoring Period - **52**, 12(winter), 12(spring), 12(summer), 12(fall), 4(winter), 4(spring), 4(summer), 4(fall), 2(winter), 2(spring), 2(summer), 2(fall). The periods were chosen from the middle of each season.
- Use Different Instruments for Pre- and Post-Retrofit Testing (%) - **no change** (same instruments used pre- and post-retrofit), different Power instruments, different Flow instruments, and different Power and Flow instruments. Power uncertainty is 1% and flow uncertainty is 3%.
- Power Uncertainty (% - same for pre- and post-tests) - **1**, 3, 5, 10
- Flow Uncertainty (% - same for pre- and post-tests) - **3**, 5, 10, 20

Results

Table 10 summarizes the results of our calculations of the energy savings and uncertainty for all of the cases:

Table 10. Measurement and Verification Sensitivity Analysis Results for an Example Fan Retrofit

Number of Test Points for Pre- and Post-Retrofit Performance Curves	Total Fan Energy Saved (kWh)	% Change in Energy from Base Case	Calculated % Uncertainty
21	22,505	0.0	18.6
11	23,395	4.0	30.1
5	16,152	-28.2	63.8
Data Storage Interval (minutes)			
15	22,505	0.0	18.6
30	24,901	10.6	18.8
60	30,892	37.3	19.1
Uncertainty in Power and Flow (%)			
1, 3	22,505		18.6
3, 5	22,505		25.0
5, 10	22,505		34.4
10, 20	22,505		61.6
# Weeks in Monitoring Period			
52	22,505	0.0	19.0
12 (winter)	23,568	4.7	21.0
12 (spring)	26,274	16.7	22.0
12 (summer)	24,300	8.0	17.0
12 (fall)	17,195	-23.6	16.0
4 (winter)	28,413	26.3	22.0
4 (spring)	21,875	-2.8	24.0
4 (summer)	25,167	11.8	17.0
4 (fall)	20,804	-7.6	18.0
2 (winter)	24,784	10.1	25.0
2 (spring)	17,604	-21.8	19.0
2 (summer)	26,341	17.0	17.0
2 (fall)	19,428	-13.7	19.0
Affect of Using Different Instruments for Pre- and Post-Retrofit Testing (%) (Power Uncertainty of 1%, Flow Uncertainty of 3% for all cases)			
Baseline (same instruments for pre- and post-retrofit testing)	22,505		18.6
Different Power Instruments	22,505		23.6
Different Flow Instruments	22,505		59.5
Diff. Power and Flow Instruments	22,505		61.2
Change in Power Uncertainty (Flow uncertainty kept at 3%)			
1	22,505		18.6
3	22,505		25.0
5	22,505		34.3
10	22,505		61.4
Change in Flow Uncertainty (Power uncertainty kept at 1%)			
3	22,505		18.6
5	22,505		18.6
10	22,505		18.8
20	22,505		19.2

Note: **Bold** entries indicate the baseline case value.

There are two types of calculated values that are important in the table:

1. The deviation of the calculated energy savings from the baseline energy savings.
2. The calculated % uncertainty in the energy savings due to instrumentation errors.

We can draw the following conclusions from these results:

1. The number of test points used to define the performance curves should be over 10. The uncertainty increases significantly below 10. The change in energy savings from the base case appears to be accounted for in the increase in calculated uncertainty.
2. In our example, the calculated fan energy saved deviates by 10% if data is stored every 30 minutes, and by 37% at 60 minute intervals, compared to 15 minute intervals. A 15 minute or faster storage rate should be used. The calculated uncertainty does not account for the variation in energy savings due to storage interval. An additional uncertainty term would need to be added.
3. The same instrumentation should be used for pre- and post-retrofit testing, using the same calibration techniques. If flow instrumentation changes, the uncertainty more than triples.
4. Flow measurement accuracy is not important for calculating energy savings, as long as the same instrumentation is used for pre- and post-retrofit testing. Power uncertainty should be kept at 3% or better.
5. No clear pattern emerged from our look at the length of the monitoring period. Large deviations occurred for 2, 4, and 12 week periods during any season (as much as 26% change compared to the 52 week period). We recommend that data be taken for as long a period as possible in order to reduce errors. The calculated uncertainty does not account for the variation in energy savings due to the monitoring period. An additional uncertainty term would need to be added.

Economic Analysis Applied to Example Fan Retrofit

- Should a test be performed to quantify the energy saved from the fan retrofit?
- Assume the minimum acceptable benefit/cost ratio is 1.
- The potential improvement in fan performance is plotted in Figure 6.
- Potential savings from the retrofit (baseline case Table 10) is $2,200/yr (22,505 kWh/yr saved @ 0.10$/kWh)
- For $6,000, the following test can be provided:
  - Power uncertainty of 1%, Flow uncertainty of 10% - same instrumentation for pre- and post-retrofit tests and monitoring.
  - 10 power/flow points for each performance curve (pre- and post-retrofit curves)
  - 15 minute average data points
  - 4 weeks of monitoring
- The test cost amortized over 3 years, is $2,000/yr.
- The benefit/cost ratio is 2,200/2,000, or 1.1. This is greater than the target B/C ratio of 1. The question remains, is the test accuracy good enough to adequately determine the savings from the improvement?
- From Table 10, we can expect a calculated uncertainty of about 20%, and a deviation of the energy savings from the baseline value of up to 26%. Root sum squaring these uncertainties yields an overall uncertainty of about 30%..
- Is a 30% accuracy good enough for this test to proceed? That depends on:
  - The Energy Services Company contract—how do they get paid, what accuracy is specified, how much risk will they take?
  - Building Management's expectations for the job—how much risk will they accept, how comfortable are they with the investment?

- Project Economics—how much room is there in the project for errors in the profitability of the project?

- If 30% accuracy is too good, spend less money on the test. If the accuracy needs to be better, spend more money on testing (which will result in a smaller B/C ratio) or do not perform the test.

Conclusions—Revised Method for Determining Accuracy and Storage Frequency Requirements

As a result of our application of the method for determining accuracy and storage frequency to air-handling commissioning functions, we made a few modifications to the previous version of the method (from Task 5). Following is our revised method, based on our Task 6 work:

A. Initial step for determining accuracy and storage frequency
   1. Define the objective of the test or measurement task.
   2. List measurements, performance factors, and algorithms needed to perform tasks to be accomplished.
   3. Determine what plots, if any, would be useful for evaluations.
   4. Develop plots and algorithms, and calculate performance factors with actual site data.

B. Engineering and economic sensitivity analysis
   1. Determine sensitivity of factors and algorithms to their input measurements (engineering sensitivity).
   2. For each piece of equipment, develop a rough economic evaluation of the effect of varying parameters or measurements on energy use (economic sensitivity).

C. Accuracy and frequency based on analysis of energy use
   1. Prioritize the measurements and factors in terms of their effect on building energy use.
   2. Considering the cost of instrumentation and calibration, determine the economic level of accuracy for each measurement and parameter.
   3. If test averages are calculated, determine the number of data points needed to keep the uncertainty at the desired level.

D. Accuracy and frequency based on use of plots of data
   1. Describe how each plot can be used to perform the intended evaluation.
   2. Determine the potential benefits of using the plots.
   3. Determine the measurement accuracy and/or storage frequency needed to use the plots for the intended evaluations.

E. Combine the above results and recommend accuracies and storage frequencies for each measurement or parameter.

This is the method that will be presented in the final report for this project.

Appendix V

Detailed Description of Fan Retrofit Measurement and Verification Study from Task 6

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Background …… **V-3**
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Effect of Not Using the Same Instruments for the Baseline and Post Tests ……. **V-14**
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Effect of the Length of the Monitoring Period …….. **V-18**
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Background

This section discusses the effects of measurement uncertainty and data storage rates on the uncertainty in the annual energy savings attributed to a specific retrofit on an air handler fan. The approach taken is illustrated by example of a a fan equipped with variable inlet vanes being retrofit with an adjustable speed drive. This follows an example and the approach discussed in Appendix C of ASHRAE Proposed Guideline 14P, "Measurement of Energy and Demand Savings" (dated June 7, 1999). The annual energy savings achieved with this retrofit is determined by calculating the difference between the fan motor's actual annual energy consumption after the retrofit and what it would have been had the retrofit not been made. The consumption that would have occurred had the retrofit not been made is called the baseline consumption; while the actual consumption after the retrofit is referred to as the post retrofit or post test consumption. Each consumption is an integration of the input power to the fan motor over a period of one year. So, the baseline power and post test power are needed to calculate the savings.

Since the exact consumption pattern is unlikely to occur from one year to the next, the baseline power is calculated from the measured post test power in this approach. This is made possible by using the relationship between the fan's air flow rate and power during both the baseline and post retrofit period. The baseline relationship is obtained in a short term test prior to the retrofit in which the fan air flow is varied through the range which is expected over the life of the retrofit. The results of this baseline testing in which 21 data points where taken is shown as the top plot in Figure 1. The post retrofit relationship is obtained in a similar manner in the post test. The results of this test are plotted along the lower curve in Figure 1.

With this information available, the one year monitoring period begins. During this period either the flow rate and/or the input power could be monitored. For this example, input power alone is monitored. It is felt that the post test power is easier to monitor and its measurement is much less susceptible to drift over the year of monitoring. From Figure 1, it can be seen that the fan flow rate is the connection between the post test power and the baseline power. In this approach, the measured post test power is used to calculate the air flow rate from the post test relationship. That air flow rate is used to obtain the baseline power from the baseline relationship. To do this, it is more convenient to use the plot of the post test relationship shown in Figure 2 to obtain the air flow rate. It, as well as Figure 3, shows the equation which represents the relationship between the two parameters.

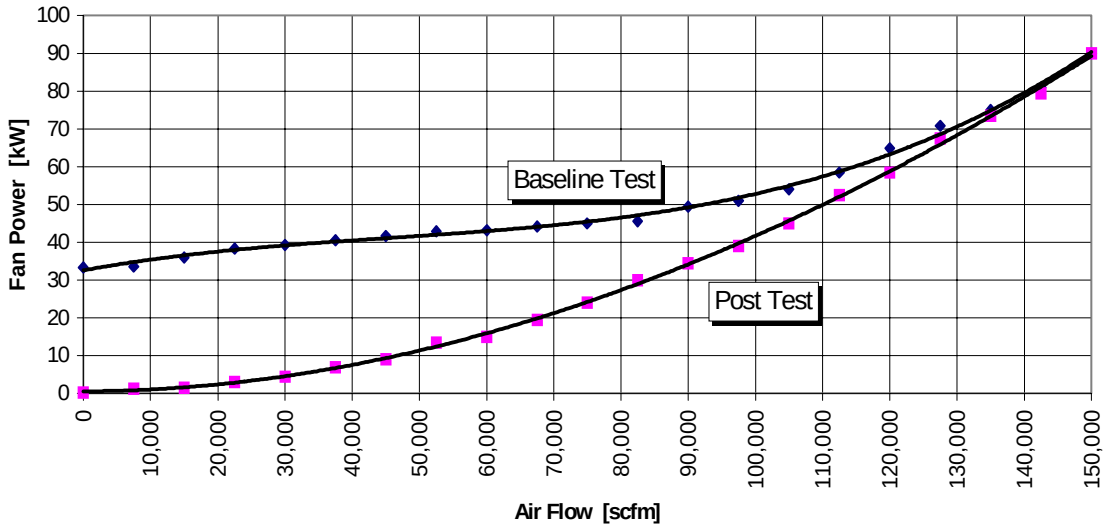


Figure 1. Baseline and Post Test Relationships

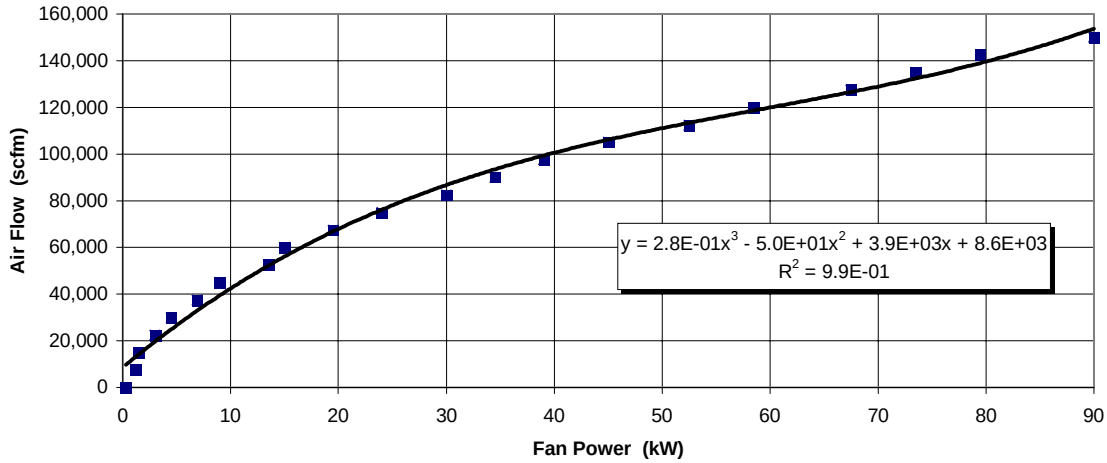


Figure 2. Post Test Relationships

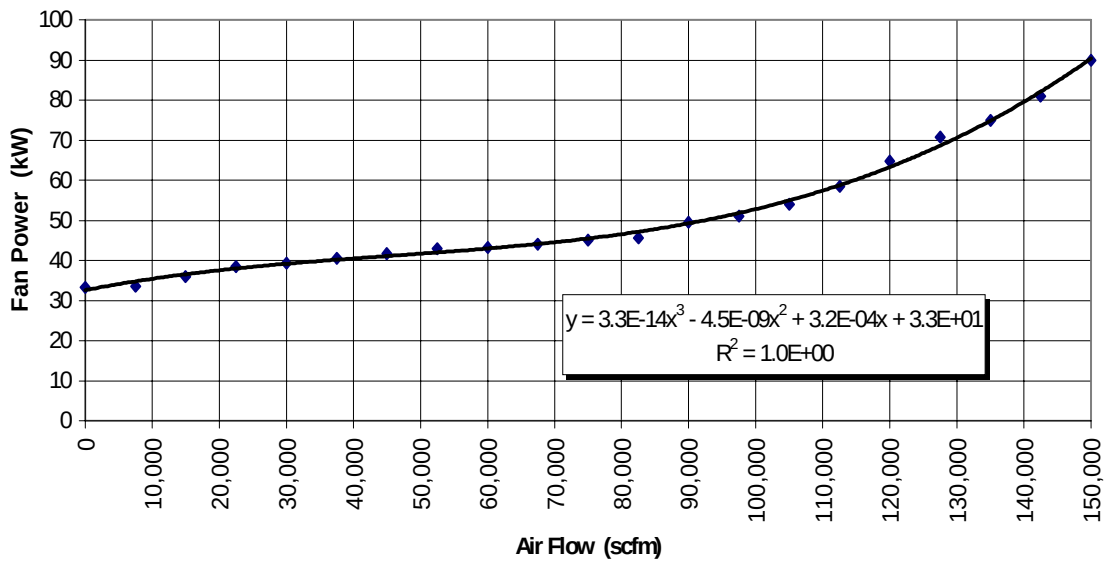


Figure 3. BaselineTest Relationships

Analysis Process

Determining the uncertainty in the annual energy savings involves several steps. The first is to write the data reduction equation. This is the equation used to determine the annual energy savings.

$$\mathbf{ES} = \sum_{i=1}^{N} \left[(\mathbf{Pb} - \mathbf{Pp}) \Delta \mathbf{t} \right]_i \qquad [1]$$

P_b is the baseline fan motor input power, P_p is the post test fan motor input power and Δt is the time interval between sequential data storage events. N is the number of times the data is stored during the monitoring period.

The uncertainty in the calculated annual energy saving, ES, due to instrument uncertainty is dependent on the error in the power and the flow measurements and on the sensitivity of the energy saving to errors in these measurements. This is expressed as

$$\mathbf{U_{ES}} = \left[(\mathbf{B_{ES}})^2 + (2 * \mathbf{S_{ES}})^2 \right]^{1/2} \qquad [2]$$

B_{ES} is the systematic portion of the uncertainty and is calculated from

$$\mathbf{B_{ES}} = \left[\begin{array}{l} \left(\theta_{P_b} * U_{P_b}\right)^2 + \left(\theta_{P_p} * U_{P_p}\right)^2 + \left(\theta_{Q_b} * U_{Q_b}\right)^2 + \left(\theta_{Q_p} * U_{Q_p}\right)^2 \\ + \left(2 * \theta_{P_b} * \theta_{P_p} * \rho * U_{P_b} * U_{P_p}\right) + \left(2 * \theta_{Q_b} * \theta_{Q_p} * \rho * U_{Q_b} * U_{Q_p}\right) \end{array} \right]^{1/2} \quad [3]$$

In the above equations, the "θ"s represent the sensitivity coefficients which weight the effect of the error in each power and flow rate measurement on the uncertainty in the energy savings. The "U"s represent the error in the power and flow rate measurements. The "ρ" is the correlation coefficient. It has a value of 1 when the instrumentation errors for both the baseline and post test are perfectly correlated. That is, the same instrument is used for both sets of tests or different instruments are used which have been calibrated against the same standard at the same time. Otherwise, its value is zero. Since the product of the two sensitivity coefficients is always negative in the above expressions; the correlation coefficient will decrease the uncertainty when its value is 1. P refers to the power measurement and Q to the flow rate measurement. "b" refers to the baseline situation and "p" to the post test and monitoring period. N is the total number of measurements involved. Although, not explicitly shown in the first equation, Q_p and Q_b are involved in the determination of P_b.

S_{ES} represents the random portion of the uncertainty. It is calculated from:

$$\mathbf{S_{ES}} = \left[\left(\theta_{P_p} * \frac{SEE_p}{\sqrt{N_p}} * K_1 \right)^2 + \left(\theta_{Q_b} * \frac{SEE_b}{\sqrt{N_b}} * K_2 \right)^2 \right]^{1/2} \quad [4]$$

SEE refers to the standard error of the estimate, which could be considered the uncertainty in the fit of a curve to the data from the baseline or post test. N is the number of points in each of the short tests. This part of the uncertainty depends on how well the curve fits the data and the number of points in the data set. Two factors, K_1 and K_2 are added into the above equation to account for the random portion of the error changes along the length of the fitted curve. At the center of the range these factors would equal 1, however, they could be 2 or 3 for values of the parameter at the extremes of the range. Most of the data in this analysis is near the center of the range; so , the value of both factors was set equal to 1.

The above equations are taken from ASME PTC 19.1-1998 "Test Uncertainty". They only reflect the contribution of instrument error on the uncertainty in the annual energy savings. Note that they do not include errors associated with the data storage interval nor

the length of the monitoring period. These components of uncertainty will be discussed later in this section.

The sensitivity coefficients have units of change in energy savings per unit change in the measured parameter. It doesn't matter whether the change is due to a measurement error or a real variation in the parameter. For example, the sensitivity coefficient for the baseline flow rate, Q_b, has the units of ΔkWh per Δscfm. When the sensitivity is multiplied by the error in the measurement, the result has the units of ΔkWh.

The sensitivity coefficients were determined by a process called dithering. In this process, each parameter is changed a small amount to determine the effect of this change on the calculated result. In this example, each parameter was changed 0.5% of full scale while all of the other parameters remained unchanged. The sensitivity coefficient for that parameter was calculated by dividing the change in the energy savings by the change in the parameter. The change in the parameter was determined by changing each value of the parameter data from either the baseline or the post test by 0.5% of full scale. For example, each value of the post test flow rate, Qp, was changed by 750 cfm to obtain its sensitivity coefficient. The difference in the calculated energy savings with and without this change in Qp was used to determine the change in the annual energy savings. This dithering process amounted to a shift in the curve fits of baseline and post test data. The coefficients of these curve fits were used to calculate the change in energy savings.

There are questions how practical aspects of the M&V process could affect the uncertainty of the annual energy savings. For example, how accurate should the measurement of power and air flow rate be to obtain a desired uncertainty in the calculated annual energy savings. Does it make a difference in the uncertainty of energy saving if different instrumentation packages are used for the baseline and post retrofit tests? How does the number of points taken during the baseline and post retrofit test affect the energy saving uncertainty? How does the data storage interval affect that uncertainty? How does the length of the monitoring period affect the uncertainty in the energy savings? Several measurement options highlighted by these questions are discussed in this section. They are summarized by the cases shown in Table 1.

	Cases								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Baseline Test									
Instrument Package	"A"	"A"	"A"	"A"	"A"	"A"	"A"	"A"	"A"
Number Data Points	21	11	5	21	21	21	21	21	21
Post Test									
Instrument Package	"A"	"A"	"A"	"B"	"A"	"A"	"A"	"A"	"A"
Number Data Points	21	11	5	21	21	21	21	21	21
Monitoring Period									
Instrument Package	"A"	"A"	"A"	"B"	"A"	"A"	"A"	"A"	"A"
Data Storage Interval (min)	15	15	15	15	30	60	15	15	15
Test Period (days)	365	365	365	365	365	365	14	28	84

Table 1. Measurement Cases

Comparing the results of cases 1, 2 and 3 shows the effect of the number of data points taken during the baseline and post retrofit tests. Case 4 shows the effect of changing instrument packages between the baseline test and post retrofit short test. The results of cases 5 and 6 would highlight the effect of data storage interval when compared with case 1. Similarly, cases 7, 8 and 9 shows the impact of the duration of the post retrofit monitoring period. These cases are generic combinations of the measurement options. Cases where the error in the power and flow measurements are varied over a specific ranges of errors is discussed later. For example, the instrument error for packages “A” and “B” are varied from 1% to 10% for power and 3% to 20% for flow to show the effects of those variations. Note that case 1 represents the base case for comparison purposes. It incorporates the most data points taken during the short term tests, the fastest data storage rate, the same instrument package used for all tests and the longest monitoring period. It’s expected that all other cases will cause the uncertainty in the annual energy consumption to increase when compared with this case.

Results and Discussion

An uncertainty analysis was carried out to determine the effect of changing various aspects of the testing and monitoring. The results of the analysis are discussed below.

Effect of Instrument Error Level and Number of Data Points.

Table 2 shows the results of changing the data storage interval and, for a given storage interval, the number of data points in the baseline and post test. Note that the same instrumentation is used for all of the tests including the monitoring period. The upper

right portion of the table shows the instrument error levels which are combinations of individual

Assumptions:

Same instrumentation used for both short tests and monitoring period
Monitoring period: 365 days

Instrument Uncertainties				
Level	**1**	**2**	**3**	**4**
Pb	**1%**	**3%**	**5%**	**10%**
Qb	**3%**	**5%**	**10%**	**20%**
Pp	**1%**	**3%**	**5%**	**10%**
Qp	**3%**	**5%**	**10%**	**20%**

Data Storage Interval [min]	Number of Points in Data Set	Total Energy Saved [kWh]	Change from Base Case [kWh]	Uncertainty in Savings [kWh]			
15	21	22,505	0	4,192	5,623	7,734	13,852
15	11	23,395	890	6,782	7,885	9,728	15,705
15	5	16,152	-6,353	14,363	15,186	16,714	22,532
30	21	24,901	2,396	4,221	5,766	8,013	14,464
30	11	25,874	3,369	6,803	7,992	9,957	16,258
30	5	18,657	-3,848	14,373	15,257	16,890	23,048
60	21	30,892	8,387	4,288	6,010	8,466	15,434
60	11	31,931	9,426	6,862	8,186	10,341	17,145
60	5	24,833	2,328	14,446	15,407	17,170	23,749

Data Storage Interval [min]	Number of Points in Data Set	Total Energy Saved * [kWh]	Change from Base Case [%]	PercentUncertainty in Base Case Savings [%]			
15	21	22,505	0%	19%	25%	34%	62%
15	11	23,395	4%	30%	35%	43%	70%
15	5	16,152	-28%	64%	67%	74%	100%
30	21	24,901	11%	19%	26%	36%	64%
30	11	25,874	15%	30%	36%	44%	72%
30	5	18,657	-17%	64%	68%	75%	102%
60	21	30,892	37%	19%	27%	38%	69%
60	11	31,931	42%	30%	36%	46%	76%
60	5	24,833	10%	64%	68%	76%	106%

Table 2. Effect of the Number of Data Points and Data Storage Intervals

instrument errors assumed for this analysis. The results in each column correspond to the combination of errors in this portion of the table. This table also shows the difference in uncertainty corresponding to different data storage rates. Note that the base case is the one in which the data storage interval is 15 minutes and in which 21 data points are taken in the short tests. The uncertainty in the energy savings is a minimum for this case.

There are two components to the uncertainty shown in this table. One is that calculated based on the data storage interval, number of data points and the combination of individual instrument errors. This is shown on the right side of the table. The second is shown under the column labeled "Change from Base Case". This column shows an kWh difference between the calculated Base Case Energy Savings and the energy savings calculated for other combinations of data storage interval and number of data points.

The information from the right side of this table is plotted in Figure 4. The base case used for comparison purposes is denoted by "15, 21" which represents 15 minute data storage interval and 21 data points. From this plot several trends are apparent. First, for a given data storage interval and number of data points; the uncertainty increases with increasing instrument error. Secondly, as the number of data points decrease, especially from 11 to 5, the uncertainty increases rapidly. Less obvious is that for all cases where only 5 data points are taken, the instrument error has little effect on the energy savings uncertainty. Note that the effect of data storage rate is almost negligible compared to the effect of the number of points and the instrument error levels.

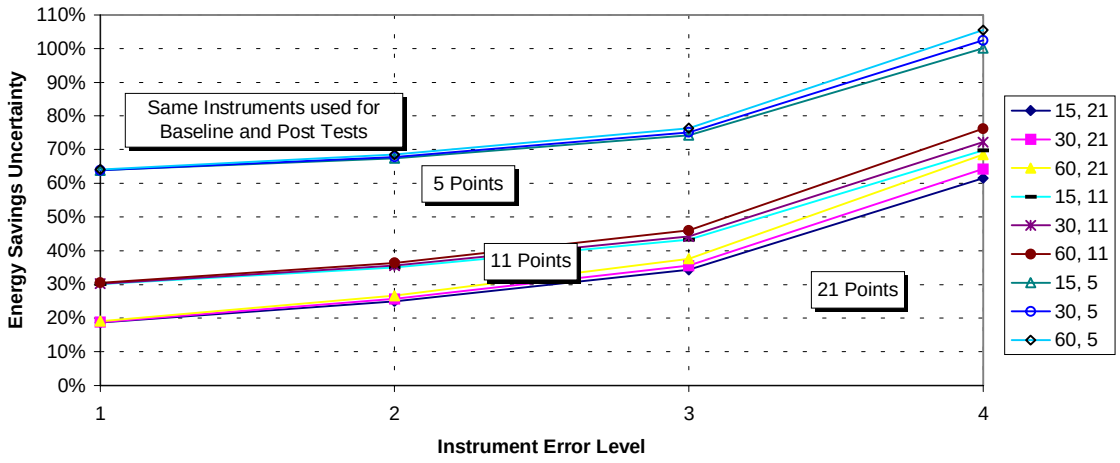


Figure 4. Effect of Number of Data Points and Data Storage Intervals at Different Instrument Error Levels

There are a number of errors which are not reflected in the calculated uncertainties presented in Table 2. These are noted in the "Total Energy Saved Column". For a given data storage interval the total energy saved calculated in this analysis changes with the

number of data points. Also, for a given number of data points, as the data storage interval increases the calculated energy savings increases especially between 30 and 60 minutes. Table 3 shows the combined effect of both aspect of the testing. It also indicates a pattern that shows the effect of each. Note that the deviations for all of the savings associated with the 30 minute storage interval are all 11%; while all of those for the 60 minute intervals are approximately 38%. These deviations are associated with the averaging effect attributed to the longer storage intervals. The effect associated with the 11 and 5 data points is +4% and -28% , respectively. This effect is likely due to the difference in the curve fit coefficients obtained from the 21, 11 and 5 point tests.

Data Storage Interval [min]	Number of Points in Data Set	Total Energy Saved [kWh]	Change from Base Case [kWh]	Change from Base Case [%]	Net Change from Base Case [%]
15	21	22,505	0	0%	
15	11	23,395	890	4%	
15	5	16,152	-6,353	-28%	
30	21	24,901	2,396	11%	11%
30	11	25,874	3,369	15%	11%
30	5	18,657	-3,848	-17%	11%
60	21	30,892	8,387	37%	37%
60	11	31,931	9,426	42%	38%
60	5	24,833	2,328	10%	39%

Table 3. Combined Effect of Number of Data Points and Data Storage Interval

The effect of the data storage interval can be seen in Figures 5 and 6. Figure 5 is a plot of one week of post power data stored at 15 minute intervals. This data is an average of the power during the previous 15 minutes. Figure 6 is a plot of the same data for a single day. Added to this are plots of the same data averaged over 30 minutes and 60 minutes to simulated these data storage intervals. The three plots follow one another closely except during times when there are large changes in power, especially over short periods of time when the fans are turned on or off. During those periods, the 60 minute data is much lower than the 15 minute and 30 minute traces. This is significant. As noted in Figure 1, the energy savings is largest for when the input power is lower. The net effect of the 60 minute (and to some extent the 30 minute) data is to reduce the stored post power. This lower post power corresponds to a larger difference between it and the baseline power. So, it appears that the 60 minute data will create larger differences and correspondingly larger energy savings than the 15 minute or 30 minute data. Figures 6A, 6B and 6C show the effect during different parts of the day. Assuming the base case is the best estimate of the actual annual energy savings and its uncertainty, these errors are considerable when compared to the calculated uncertainty. The table shows that the error is especially large for the 60 minute data storage rate.

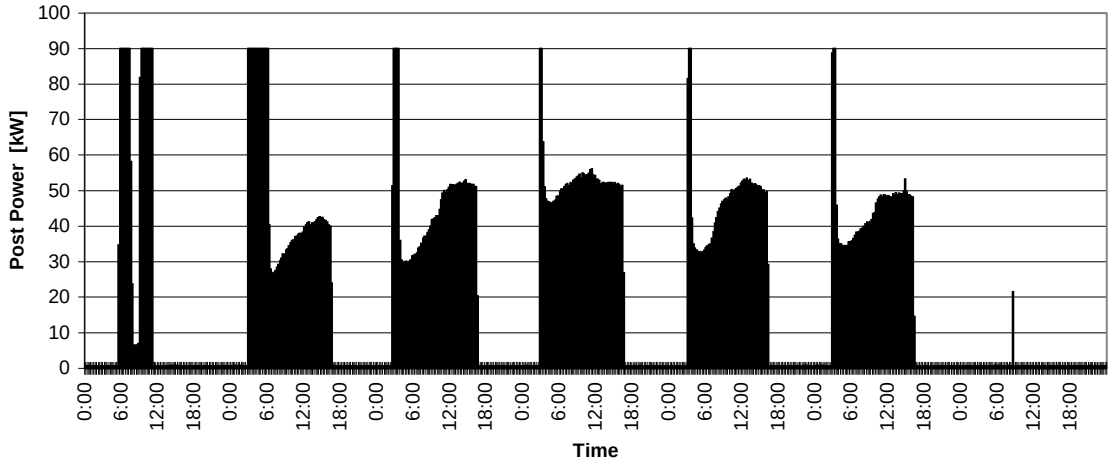


Figure 5. Sample from Monitoring Period Post Retrofit Power Data Set - 1/21/96 (Sun.) through 1/27/96 (Sat.)

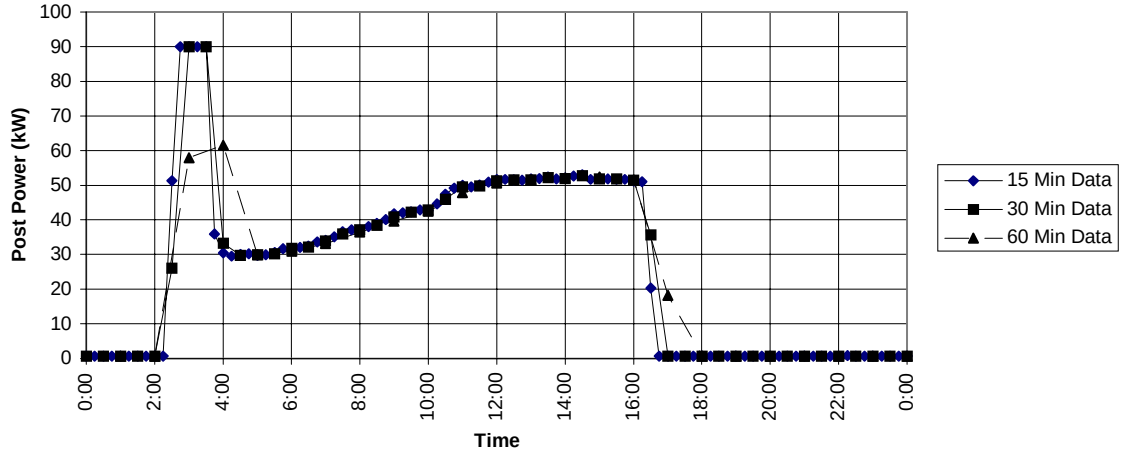


Figure 6. Effect of Longer Data Storage Intervals - 1/23/96

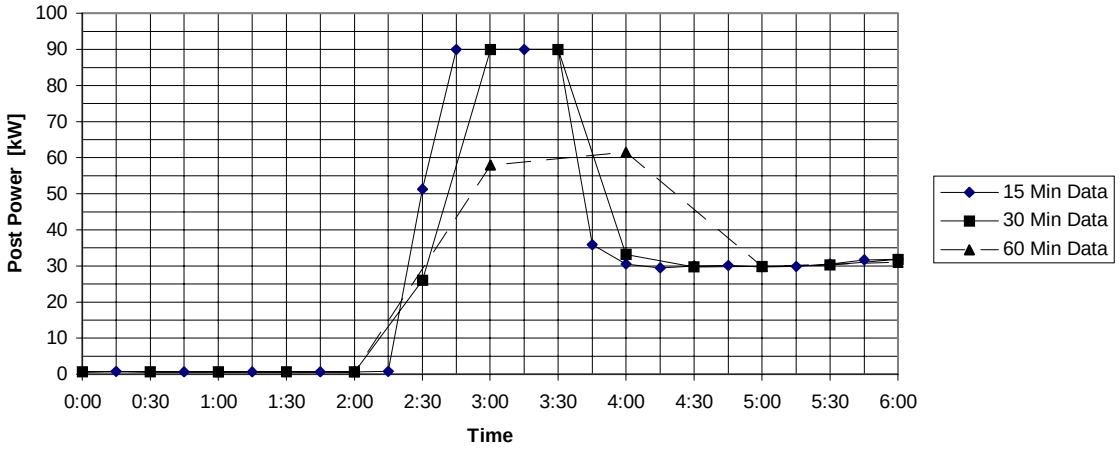


Figure 6A. Effect of Longer Data Storage Intervals - Rapid Power Ramp Up (1/23/96)

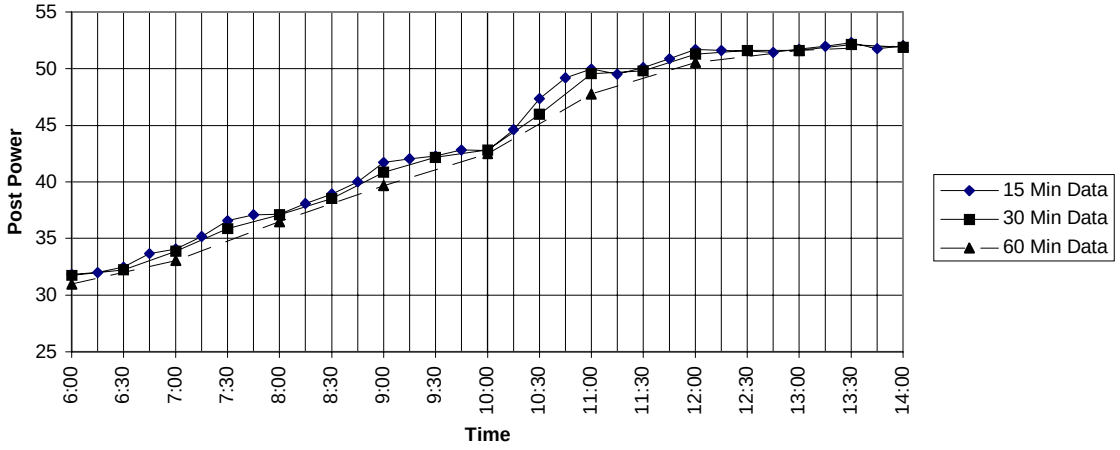


Figure 6B. Effect of Longer Data Storage Intervals - Gradual Power Ramp Up (1/23/96)

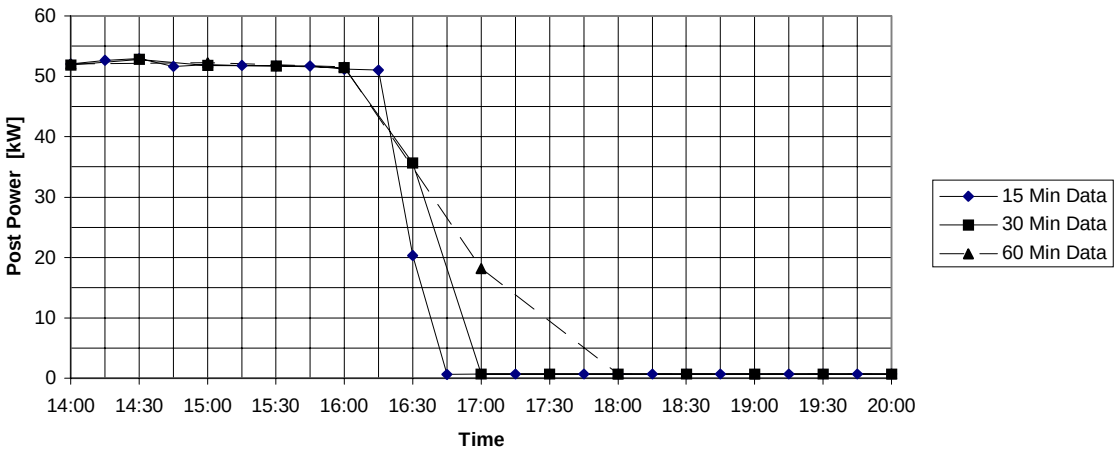


Figure 6C. Effect of Longer Data Storage Intervals - Rapid Power Ramp Down (1/23/96)

Effect of Not Using the Same Instruments for the Baseline and Post Tests

If the period of time between the baseline test and the post retrofit test is short, it's assumed that the same power and flow instrumentation would be used for both tests. The power measurement instrumentation would be left in place for the long term monitoring period. There are, however, some instances when the same instrumentation may not be used for both short tests. Table 4 (and Figure 7) show the effect of changing the instrument error between tests. Three cases are compared with the base case. In the base case, both the power and flow instrument errors are correlated; so the value of ρ is 1 for both instruments. In Case 1A, ρ is 1 for the power instruments; but it's equal to 0 for the flow instruments. In Case B the opposite is true: ρ is 1 for the flow instruments; but it's equal to 0 for the power instruments. Two completely different instrument packages are simulated in Case 1C. In that case, ρ is 0 for the both the flow and power instrument errors. This analysis was done for the same data storage rate and number of data points in the base case. Note the assumptions listed at the top of the table.

As in Table 2, the uncertainty in energy savings increases as the individual instrument error increases. However, the increase is much greater than when the same instrument packages were used for both short tests. The results also show that the flow measurement instrument error has a greater effect on the uncertainty (Cases 1B and 1C) than the power instrument error. Note, there is little difference between Case 1B and Case 1C. There is little added effect from the instrument errors from both packages not being correlated. The levels refer to the combinations shown at the top of Table 4.

Assumptions:

Data Storage Frequency: 15 Minutes
Monitoring period: 365 days
All case test data points: **21**
Instrument errors same for all cases as follows:

Instrument Errors				
Level	**1**	**2**	**3**	**4**
Pb	**1%**	**3%**	**5%**	**10%**
Qb	**3%**	**5%**	**10%**	**20%**
Pp	**1%**	**3%**	**5%**	**10%**
Qp	**3%**	**5%**	**10%**	**20%**

Correlation of Instrument Errors:

Base Case: Power instrument errors correlated (ρ=1);
Flow instrument errors correlated (ρ=1)

Case #1A: Power instrument errors correlated (ρ=1);
Flow instrument errors not correlated (ρ=0)

Case #1B: Power instrument errors not correlated (ρ=0);
Flow instrument errors correlated (ρ=1)

Case #1C: Power instrument errors not correlated (ρ=0);
Flow instrument errors not correlated (ρ=0)

	Total Energy Saved [kWh]	Change from Base Case [kWh]	Uncertainty in Savings [kWh]			
Level			1	2	3	4
Base	22,505	0	4,192	5,623	7,734	13,852
1A	22,505	0	5,305	11,258	18,002	35,340
1B	22,505	0	13,394	21,936	43,105	85,934
1C	22,505	0	13,783	24,006	46,068	91,879

	Total Energy Saved * [kWh]	Change from Base Case [%]	PercentUncertainty in Base Case Savings [%]			
Level			1	2	3	4
Base Case	22,505	0%	19%	25%	34%	62%
Case 1A	22,505	0%	24%	50%	80%	157%
Case 1B	22,505	0%	60%	97%	192%	382%
Case 1C	22,505	0%	61%	107%	205%	408%

Table 4. Effect of Using Different Instrument Packages for Baseline and Post Tests

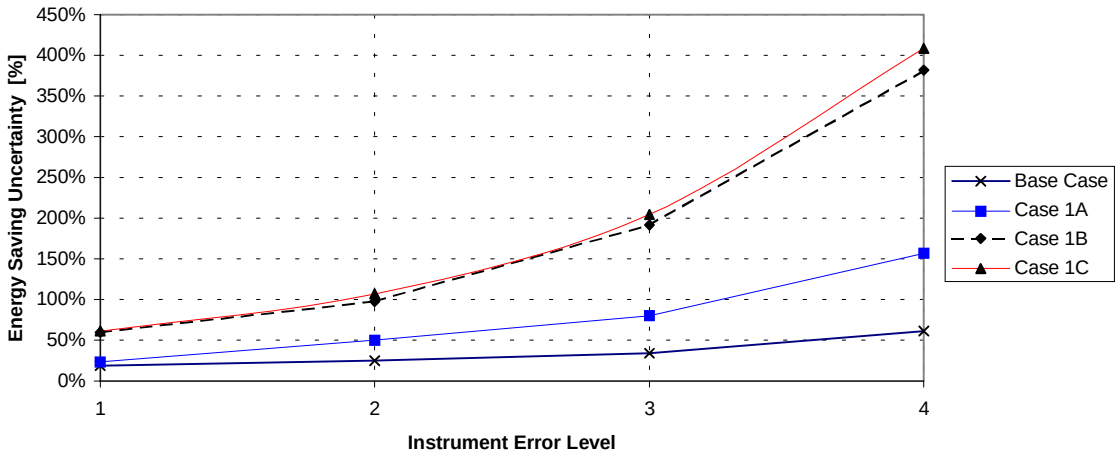


Figure 7. Effect of Using Different Instrument Packages for Baseline and Post Tests

<u>Effect of Individual Instrument Errors.</u>

The last section shows that it is not advisable to use different instrument packages for baseline and post tests. Assuming this is the case, does the flow or power instruments have the greatest effect on the uncertainty in energy savings? This is a practical question, since the answer may allow less accurate instruments to be chosen for the testing.

An analysis was done by creating five cases as shown in Table 5. Case 1 is the base case that has been discussed above. The instrument combinations for Case 1 are shown in the table. The remaining cases consists of the same combinations with one exception. The purpose was to see, by comparison with Case 1, how each variation affected the energy savings uncertainty. The lower half of the table shows the results.

In Case 2, the baseline and post flow error are 3% for all levels. The error in the remaining instrument errors is the same as in Case 1. Baseline and post power increase from levels 1 through 4. The results shows that there is virtually no change in the energy savings uncertainty from the base case inferring the flow measurement errors have little to no effect on the energy savings uncertainty. Assuming the flow measurement error is not large enough to show its effect, it was raised to 30% in Case 3. The result is the same. Possibly there is some interaction between the two sets of errors. So, in Case 4, the power measurement errors are fixed at 1%; while the flow measurement errors are allowed to increase as in Case 1. The same is done in Case 5 except the error is set at 10% for the power measurement errors. The results of these two cases indicate that the energy savings uncertainty is virtually dependent only on the errors in the power measurements. This is true for flow measurement error up to 30%. Above 30% the errors in the flow measurements begin to have a small effect on the energy savings uncertainty. Note, the

results presented here are based on the assumption that the instrument errors for the baseline and post test packages are perfectly correlated.

Assumptions:

Same instrumentation used for all tests
Monitoring period: 365 days
Number data points: 21
Data storage interval: 15

Case 1: Base Case Instrument Errors:

Instrument Uncertainties				
Level	**1**	**2**	**3**	**4**
Pb	**1%**	**3%**	**5%**	**10%**
Qb	**3%**	**5%**	**10%**	**20%**
Pp	**1%**	**3%**	**5%**	**10%**
Qp	**3%**	**5%**	**10%**	**20%**

Case 2: Same as Case 1 except Qb=Qp=3% for all levels
Case 3: Same as Case 1 except Qb=Qp=30% for all levels
Case 4: Same as Case 1 except Pb=Pp=1% for all levels
Case 5: Same as Case 1 except Pb=Pp=10% for all levels

Case	Total Energy Saved [kWh]	Uncertainty in Savings [kWh]			
	Level	**1**	**2**	**3**	**4**
Case 1	22,505	4,192	5,623	7,734	13,852
Case 2	22,505	4,192	5,619	7,719	13,815
Case 3	22,505	4,459	5,821	7,867	13,899
Case 4	22,505	4,192	4,197	4,220	4,311
Case 5	22,505	13,815	13,817	13,824	13,852

Case	Total Energy Saved [kWh]	PercentUncertainty in Base Case Savings [%]			
	Level	**1**	**2**	**3**	**4**
Case 1	22,505	19%	25%	34%	62%
Case 2	22,505	19%	25%	34%	61%
Case 3	22,505	20%	26%	35%	62%
Case 4	22,505	19%	19%	19%	19%
Case 5	22,505	61%	61%	61%	62%

Table 5. Effect of Individual Instrument Errors on Energy Savings Uncertainty

Effect of the Length of the Monitoring Period.

It would be desirable to shorten the monitoring period. But to do so may increase the uncertainty in the calculated savings. In the analysis, sensitivity coefficients were calculated for 2 week, 4 week and 12 week monitoring periods for the four seasons of the year. The weeks were chosen near the middle of each season for the 2 week and 4 week periods.The energy savings was also calculated on a per day basis for each period. It was then annualized for comparison with the base case which represented savings for a 365 day year. The sensitivity coefficients were annualized in a similar manner.

Table 6 compares the base case (1 year) results with those for the 2 week, 4 week and 12 week monitoring periods. The left side of the table shows the percent uncertainty in the base case energy savings associated with each seasonal monitoring period. The right side of the table presents the deviation of each of these percentages from the percent uncertainty associated with the base case. These deviations are plotted by length of monitoring period and level of instrument error in Figures 8, 9,10, and 11. They show that the uncertainty due to instrument error is not greatly affected by the length of the monitoring period. It does appear that the deviation from the base case uncertainty is within 8% for all but two periods where the instrument error level was at a maximum (Level 4). Although the deviations were smallest for the summer and fall monitoring periods, there is no clear pattern to indicate that it is better to monitor during one particular season.

Figure 13 shows the deviation in the calculated energy saving for each seasonal monitoring period from the calculated base case energy savings. The plot shows that using summer and winter data always overestimate the annual savings for all monitoring periods. Likewise, fall data consistently underestimates annual savings. A wide variation in savings resulted from using spring data. There appears to be no advantage in estimating the annual energy savings by lengthening the monitoring period up to 12 weeks. Depending on the time of year monitored, the energy savings could be different by as much as 26% for this example.

Level	1	2	3	4
Pb	1%	3%	5%	10%
Qb	3%	5%	10%	20%
Pp	1%	3%	5%	10%
Qp	3%	5%	10%	20%

2 Week Monitor

	Total Energy Saved [kWh]	Change from Base Case [%]	PercentUncertainty in Base Case Savings [%]			
Level			1	2	3	4
Base	22,505	0%	19%	25%	34%	62%
Winter	24,784	10%	25%	31%	40%	68%
Spring	17,604	-22%	19%	24%	32%	55%
Summer	26,341	17%	17%	25%	35%	65%
Fall	19,428	-14%	19%	25%	35%	62%

2 Week Monitor

	Deviation from Base Case Savings Uncertainty [%]			
Level	1	2	3	4
Base	0%	0%	0%	0%
Winter	7%	6%	6%	6%
Spring	0%	-1%	-3%	-6%
Summer	-2%	0%	1%	4%
Fall	0%	0%	0%	0%

4 Week Monitor

	Total Energy Saved [kWh]	Change from Base Case [%]	PercentUncertainty in Base Case Savings [%]			
Level			1	2	3	4
Base	22,505	0%	19%	25%	34%	62%
Winter	28,413	26%	22%	28%	38%	66%
Spring	21,875	-3%	24%	31%	42%	75%
Summer	25,167	12%	17%	25%	36%	65%
Fall	20,804	-8%	18%	24%	34%	61%

4 Week Monitor

	Deviation from Base Case Savings Uncertainty [%]			
Level	1	2	3	4
Base	0%	0%	0%	0%
Winter	3%	3%	3%	4%
Spring	5%	6%	8%	13%
Summer	-1%	0%	1%	4%
Fall	-1%	-1%	-1%	0%

12 Week Monitor

	Total Energy Saved [kWh]	Change from Base Case [%]	PercentUncertainty in Base Case Savings [%]			
Level			1	2	3	4
Base	22,505	0%	19%	25%	34%	62%
Winter	23,568	5%	21%	27%	35%	61%
Spring	26,274	17%	22%	30%	41%	73%
Summer	24,300	8%	17%	25%	35%	65%
Fall	17,195	-24%	16%	22%	30%	53%

12 Week Monitor

	Deviation from Base Case Savings Uncertainty [%]			
Level	1	2	3	4
Base	0%	0%	0%	0%
Winter	2%	2%	1%	0%
Spring	4%	5%	6%	11%
Summer	-1%	0%	1%	3%
Fall	-2%	-3%	-5%	-8%

Table 6. Effect of Length of Seasonal Monitoring Period on Energy Savings Uncertainty

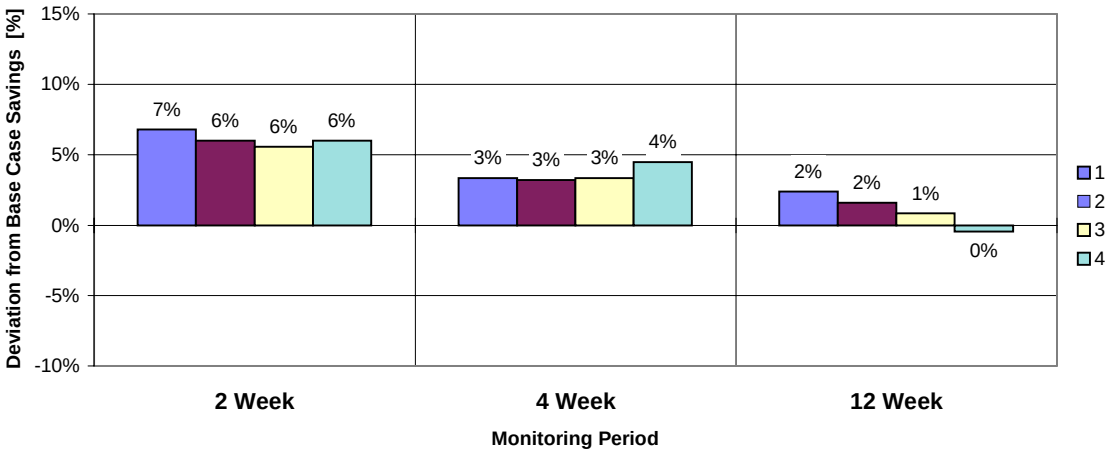


Figure 8. Deviation from Base Case Savings by Instrument Level - Winter Monitoring Periods.

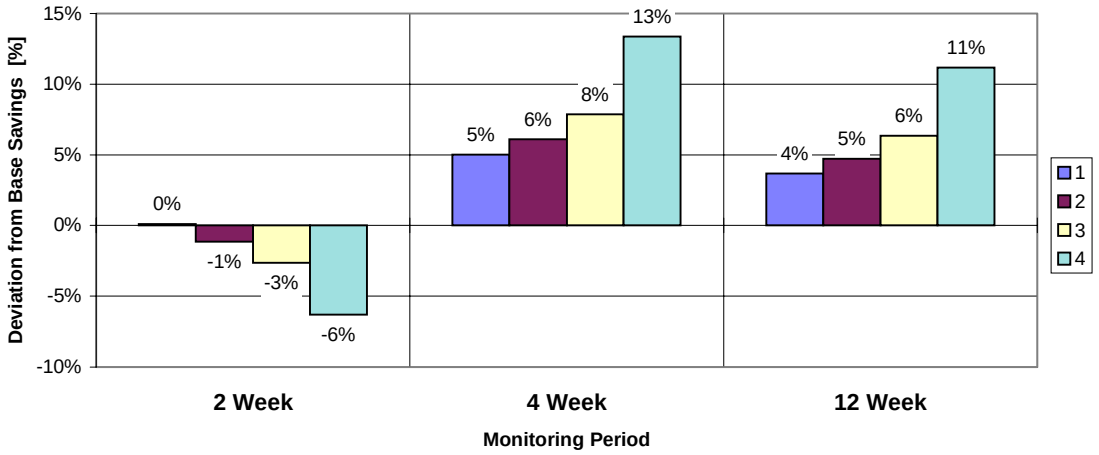


Figure 9. Deviation from Base Case Savings by Instrument Level - Spring Monitoring Periods.

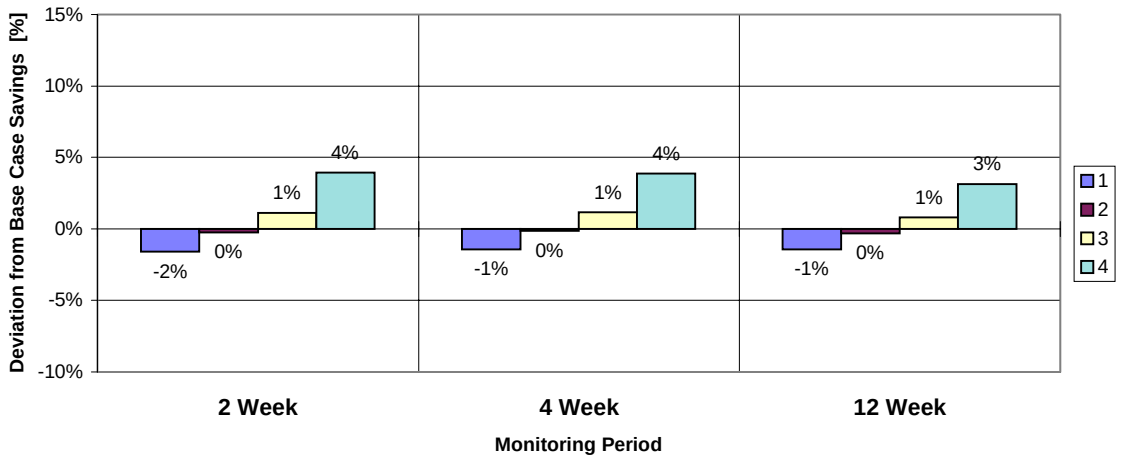


Figure 10. Deviation from Base Case Savings by Instrument Level - Summer Monitoring Periods.

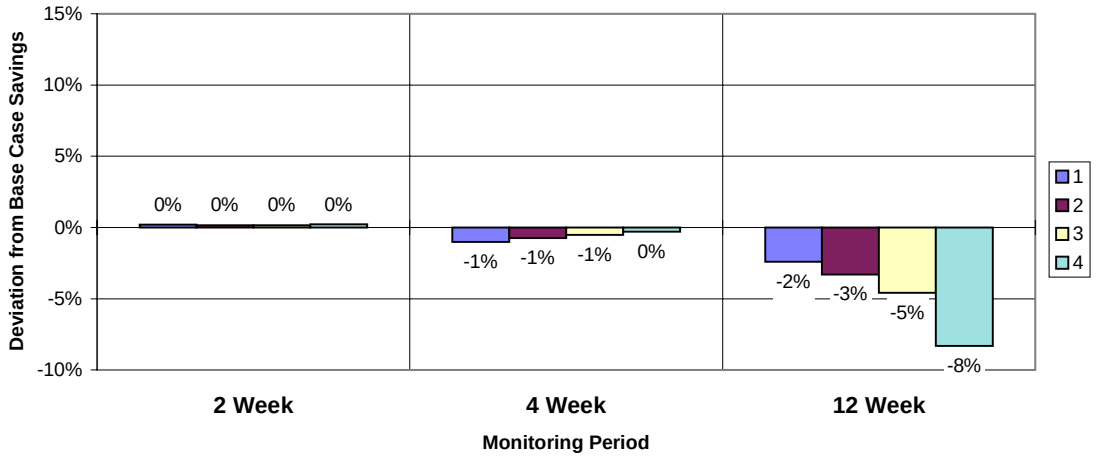


Figure 11. Deviation from Base Case Savings by Instrument Level - Fall Monitoring Periods.

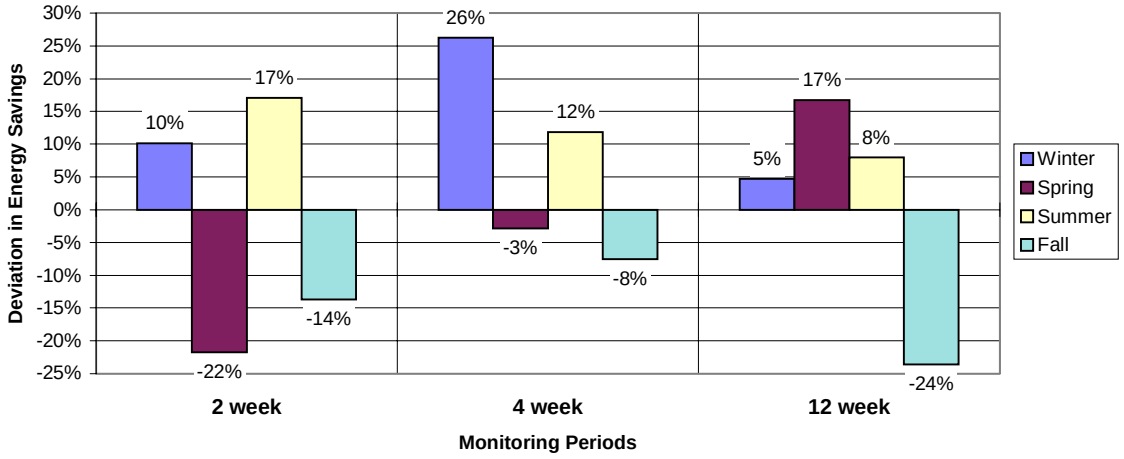


Figure 12. Deviation in Energy Savings from Base Case Savings Due to Length of Monitoring Period.

Conclusions and Recommendations

This section has discussed by example estimating the uncertainty in energy savings from retrofitting an air handling fan. The retrofit consisted of replacing variable inlet vanes with an adjustable speed drive. The purpose of the measurement and verification process is to determine the amount of annual energy savings that have been realized from this retrofit project. Details of accomplishing this were discussed in the "Background" section.

The purpose of the uncertainty analysis was to answer practical questions regarding how the level of instrumentation error and the data storage intervals affect the uncertainty in annual energy savings. The results of this analysis show that there are two components of the uncertainty in annual energy savings. One is based on the error in the power and flow measurements and the sensitivity of the calculated savings to those errors. It's expressed as a percentage uncertainty in the base case energy savings. This component is also affected by the number of points generated during the baseline and post test and the data storage interval. The other component of uncertainty is a result of the effect of the number of points and data storage interval on the energy savings calculation. It is expressed as a deviation from the calculated base case energy savings.

Most of this analysis was performed assuming that the same instrument package would be used for the baseline test, the post test and the monitoring period. In this part of analysis it was shown that the uncertainty in annual energy saving increases with the level of instrument error. And for a given level of instrument error the energy savings uncertainty

increases with decreasing number of short test data points. The increase was not linear with number of data points. That is, the increased uncertainty due to decreasing the number of points from 21 to 5 was greater than twice the increase due to decreasing the number from 21 to 11. Contrary to this trend, the increase in the length of the data storage interval while keeping the number of data points constant was associated with little to no change in the energy savings uncertainty.

Related to this was the question whether the power or the flow instrument error had a greater effect on the energy savings uncertainty. It was found through the analysis that, at least up to a flow instrument error of 30%, the energy savings uncertainty was affected mainly by the power instrument error. This assumes the same instruments were used for all tests.

In addition to the instrument error-related energy savings uncertainty a deviation from the base case energy savings was observed. This component of uncertainty was due to the number of points and the length of the data storage interval. Non-linear effects of both were noted. The largest effect was noted for the decrease in the number of points from 11 to 5 and for the increase in the storage interval from 30 minutes to 60 minutes. These deviations appear to be caused by the averaging process in which lower post test power values are generated by longer storage intervals (relative to the base case storage intervals) and different curve fit coefficients resulting from fits with a smaller number of points. The lower post test power values are associated with larger difference between baseline and post test power. This can often result in greater savings calculated for a given time interval. These differences occur most often where there are large changes in the post test power such as when the fan motor is started or stopped.

Given the desire to keep the monitoring period as short as possible, the results for various monitoring periods were compared with the base case results. Two, four and twelve week monitoring periods for each season of the year were analyzed to see whether they could be used to predict annual energy savings and the uncertainty in those savings. This comparison for the instrument error related component of uncertainty showed that for other than level 4 instrument errors, the uncertainty of the annual energy savings due to instrument error was within 8% of the base case estimate. However, the energy savings predicted from data taken during these monitoring periods varied widely. The predicted savings values could only be confined to a band of ± 26% around the baseline energy savings. Taken together with the instrument related uncertainty, all short monitoring period produced results that were within approximately 30% of the base case estimates.

As mentioned earlier, for most of this analysis it was assumed that the same instrument packages were used for all tests. The effect of not using the same packages was considered. The same basic trends as discussed above were found to be true, however, the level of uncertainty related to instrument error was found to increase from two to five times the amount determined assuming the same instrument packages. This depended on

whether the flow, the power instrument or both instrument packages changed. As a result, it was determined that the same power and flow instrumentation packages should be used for all testing to keep the energy savings uncertainty from becoming excessive.

This analysis is based on this specific example. The sensitivity coefficients and the calculated energy savings depended on the curve fit of the data from the baseline and post retrofit relationship between input power to the fan motor and air flow. These relationships will be different for different retrofits. They also depend on the frequency distribution of the post test power acquired during the monitoring period. Different buildings and building operations may produced different frequency distributions of power. This analysis did not attempt to generalize the effect of different distributions on the energy savings and sensitivity coefficients. The data used in this analysis represented usage of a fan approximately 14 hours per day, 5 days per week. The savings are relatively small compared to what might have been achieved in a building where the fan operates every hour of the year. So, the percentage uncertainty may be larger than a similar retrofit in another operation. However, having performed an analysis for only one operation, it hasn't been verified that this is true.

This is a post test analysis. It is important to be able to estimate the uncertainty before the testing is performed. Fortunately, the basic steps for performing a pre test analysis are presented in this example. The missing information includes the effect of the curve fit coefficient on the calculation of the sensitivity coefficients and on the energy savings. Also missing is the post test power profile and its effect on the energy savings and sensitivity coefficient calculations. If this profile could be assumed with a good degree of confidence, the analysis could be performed prior to the testing.

Appendix VI

CEC Sensor Project - Task 7

Verification of Results - Application of Results to Small, Medium, and Large Office Buildings and a Medium Size Hospital for Fresno and San Francisco Climates

Simulation Method

Simulations were performed by Eley Assoc. with DOE2.1E, version 83 from JJ Hirsch & Associates. DOE2.1E performs an hourly energy calculation using a full year of typical weather data (8760 hours). The weather data include drybulb and wetbulb temperature as well as wind speed and solar radiation.
The calculation takes place in four steps. First, hourly thermal loads are calculated for each zone accounting for exterior conduction, radiation, and infiltration as well as internal lighting, equipment and occupant heat gains. Next, the air handling system is simulated to determine fan energy and to calculate heating and cooling loads for the central plant (including ventilation air load). Third, the system loads are passed to the central plant model where chiller and boiler energy consumption are calculated. Finally, the energy costs are calculated based on a utility rate specified by the user.

Baseline models were developed with VisualDOE 2.6, and macro variables were added to the input files to allow the parameters to be easily adjusted. The simulations use weather data for the San Francisco Bay area (CEC03RV2) and Fresno (CEC13RV2).

Four different building types were modeled.

- Two-story office of 50,000 ft^2 served by a single chiller and a VAV reheat system.
- Ten-story office of 250,000 ft^2 with two chillers and a VAV reheat system
- Forty-story office of 1,000,000 ft^2 served by three equally sized chillers and a VAV reheat system.
- Five-story hospital of 250,000 ft^2 with two chillers and a constant-volume (CV) reheat system.

The following tables describe the model assumptions in more detail. Supply air flow and chiller capacity depend on the climate, otherwise all assumptions are the same for San Francisco and Fresno.

BUILDING TYPE	Baseline Office	Baseline Office	Large Office	Large Office	Medium Office	Medium Office	Hospital	Hospital
LOCATION	San Francisco	Fresno	San Francisco	Fresno	San Francisco	Fresno	San Francisco	Fresno
Construction								
number of stories	2	2	40	40	10	10	5	5
front orientation	SE	SE	SE	SE	SE	SE	SE	SE
width	250	250	250	250	250	250	500	500
depth	100	100	100	100	100	100	100	100
shape	rect	rect	rect	rect	rect	rect	rect	rect
total floor area	50000	50000	1000000	1000000	250000	250000	250000	250000
Floor to Floor Height	13	13	13	13	13	13	14	14
Plenum	3	3	3	3	3	3	4	4
wall area	18200	18200	364000	364000	91000	91000	84000	84000
window-wall ratio	0.35	0.35	0.35	0.35	0.35	0.35	0.15	0.15
window type	single bronze	single bronze	single bronze	single bronze	single bronze	single bronze	single bronze	single bronze
window shading	med. blinds	med. blinds	med. blinds	med. blinds	med. blinds	med. blinds	med. blinds	med. blinds
wall type	R-11 mtl. frm.	R-11 mtl. frm.	R-11 mtl. frm.	R-11 mtl. frm.	R-11 mtl. frm.	R-11 mtl. frm.	R-11 mass	R-11 mass
roof type	R-19 mass	R-19 mass	R-19 mass	R-19 mass	R-19 mass	R-19 mass	R-19 mass	R-19 mass
floor type	R-11 mass	R-11 mass	R-11 mass	R-11 mass	R-11 mass	R-11 mass	R-11 mass	R-11 mass
wall absorp.	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
roof absorp.	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Loads								
lighting power	1.5	1.5	1.5	1.5	1.5	1.5	1.6	1.6
equipment power	0.75	0.75	0.75	0.75	0.75	0.75	1	1
occupant density (sf/person)	250	250	250	250	250	250	200	200
infiltration (perim.)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
infiltration (int.)	0	0	0	0	0	0	0	0
Operating Schedules								
Cooling setpoint (occupied)	73	73	73	73	73	73	73	73
Cooling setpoint (unoccupied)	99	99	99	99	99	99	n.a.	n.a.
Heating setpoint (occupied)	70	70	70	70	70	70	70	70
Heating setpoint (unoccupied)	55	55	55	55	55	55	n.a.	n.a.
Fan schedule	6am -7pm	6am -7pm	6am -7pm	6am -7pm	6am -7pm	6am -7pm	24 hr	24 hr
Lighting schedule	7am - 7pm	7am - 7pm	7am - 7pm	7am - 7pm	7am - 7pm	7am - 7pm	7am - 6pm	7am - 6pm
Lighting off-hour fraction	0.2	0.2	0.2	0.2	0.2	0.2	0.7	0.7
Misc. equip. schedule	7am - 6pm	7am - 6pm	7am - 6pm	7am - 6pm	7am - 6pm	7am - 6pm	7am - 6pm	7am - 6pm
Equip. off-hour fraction	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.7
Occupants	8am -6pm	8am -6pm	8am -6pm	8am -6pm	8am -6pm	8am -6pm	24 hr	24 hr

BUILDING TYPE	Baseline Office	Baseline Office	Large Office	Large Office	Medium Office	Medium Office	Hospital	Hospital
LOCATION	San Francisco	Fresno	San Francisco	Fresno	San Francisco	Fresno	San Francisco	Fresno
System								
System type	VAV reheat	VAV reheat	VAV reheat	VAV reheat	VAV reheat	VAV reheat	CV reheat	CV reheat
Economizer	yes	yes	yes	yes	yes	yes	yes	yes
Economizer setpoint	74	74	74	74	74	74	74	74
Fan cfm	50000	70000	1000000	1600000	250000	350000	250000	350000
Fan SP	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
Fan eff	0.62	0.62	0.62	0.62	0.62	0.62	0.62	0.62
Fan motor eff	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
Fan drive eff	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Fan control	speed	speed	speed	speed	speed	speed	constant	constant
OA cfm/person	37.5	37.5	37.5	37.5	37.5	37.5	30	30
SAT setpoint	55	55	55	55	55	55	55	55
SAT control	OA reset	OA reset	OA reset	OA reset	OA reset	OA reset	OA reset	OA reset
Coil oversize ratios	na	na	na	na	na	na	na	na
Night cycle control	cycle on any	cycle on any	cycle on any	cycle on any	cycle on any	cycle on any	cycle on any	cycle on any
Zone Air								
Min. air flow frac.	0.5	0.5	0.5	0.5	0.5	0.5	1.0	
Zone Reheat	yes	yes	yes	yes	yes	yes	yes	
Reheat delta T	45	45	45	45	45	45	45	
Source	hot-water	hot-water	hot-water	hot-water	hot-water	hot-water	hot-water	
Baseboard heat	none	none	none	none	none	none	none	
Central Plant								
Boiler - Type	fuel hw power	fuel hw power	fuel hw power	fuel hw power	fuel hw power	fuel hw power	fuel hw power	fuel hw power
Boiler - Efficiency	80%	80%	80%	80%	80%	80%	80%	80%
Boiler - Sizing	Auto	Auto	Auto	Auto	Auto	Auto	Auto	Auto
Hot Water Pump	100ft, fixed spe	100ft, fixed spe	100ft, fixed spe	100ft, fixed spe	100ft, fixed spe	100ft, fixed spe	100ft, fixed spe	100ft, fixed spee
Chiller								
Number	1	1	3	3	2	2	2	2
Size (tons)	125	175	850	1200	300	450	400	550
Size (sf/ton)	400	286	392	278	417	278	313	227
Efficiency - kW/ton	0.85	0.85	0.65	0.65	0.65	0.65	0.65	0.65
Entering Cond Water T	80	80	80	80	80	80	80	80
Chilled Water Supply T	44	44	44	44	44	44	44	44
Condenser Head	50 ft	50 ft	65	65	65	65	65	65
Condenser Flow - gpm/ton	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Chilled Water Pump	90 ft, fixed	90 ft, fixed	100, var speed	100, var speed	100, var speed	100, var speed	100, fixed	100, fixed
Evaporator Head *	0 ft	0 ft	30	30	30	30	0	0
Evaporator Flow - gpm/ton *	0	0	2	2	2	2	0	0

* Evaporator inputs for VisualDOE only relevant for primary/secondary pumping

The impact of nine different parameters was estimated with the simulation models.

Filter pressure drop. The static pressure across the supply fan was increased from a base of 6 in. w.c. to represent increased filter pressure drop of 0.25 in, 0.5 in., 0.75 in., and 1.0 in.

Economizer setpoint. A function was added to DOE2 so that the economizer limit temperature is set each hour to a constant offset from the return air temperature. The offset is varied from +3 to -6 degrees F. In the +3 case, the outside air dampers remain fully open as the outdoor air temperature rises up to a point where it is 3 degrees warmer than the return air. Then the damper returns to minimum.

Zone temperature setpoint. Baseline thermostat setpoints are 73F for cooling and 70F for heating. Setpoints in the model were varied by -3F, -2F, -1F, +1F, and +2F.

Duct static pressure setpoint. Changes in duct static pressure setpoint were represented in the model by a change in the static pressure across the supply fan. These variations are -0.3, -0.2, -0.1, +0.1, +0.2, and +0.3 in. w.c.

Supply air temperature. Baseline supply air temperature setpoint is 55F, and the value is varied between 50F and 58F. In the simulation, this is the minimum setpoint, and the supply air temperature varies based on an outdoor air reset schedule. When outdoor air is 55F or below, then supply air is 60F. When outdoor air rises above 60F, then the supply air is at its minimum temperature. If outdoor air is between 55 and 60, then the supply air temperature varies linearly between 60 and the minimum setpoint. This parameter is studied with two different chiller types: the baseline centrifugal chiller with inlet vane unloading, and a centrifugal chiller with variable speed compressor unloading.

Chilled water supply temperature. The baseline is 44F, and the setpoint is varied between 40F and 47F. When the ChWSTemp setpoint is above 44F, the air supply temperature minimum setpoint of 55F may not be achieved by the coil. This would result in higher fan energy use, that would offset lower chiller energy use. To model this, we increased the air supply temperature minimum setpoint by 1 degree F for every

degree the ChWSTemp is increased above 44F. Chilled water supply temperature is studied with two different chiller types: the baseline centrifugal chiller with inlet vane unloading, and a centrifugal chiller with variable speed compressor unloading.
Outside air quantity. The baseline ventilation air quantity is 0.15 cfm/ft^2, which is approximately the code minimum. Results are also simulated for 0.05, 0.10, 0.20 and 0.30 cfm/ft^2.
Minimum VAV box flow fraction. In the three buildings with VAV reheat systems, the minimum airflow fraction is 0.5 in the base case. The minimum is also modeled at 0.20, 0.35, 0.65 and 0.80.
Leaking reheat control valve. Baseboard heaters are added to each zone to represent the heat gain caused by a leaking reheat valve. This method represents both the added cooling load for the zone as well as the added heating load on the boiler. Two heat output levels of the heaters are modeled to approximate the heat equivalent to a 5F and 10F rise in supply air temperature. These heaters are on whenever the fans are operating.

Discussion

Several of the building assumptions do not meet present California standards for building construction (Title 24) because our intent is for the results to apply to existing as well as new buildings. Title 24 calls for R13 wall insulation; we used R11. Title 24 calls for 1.2 watts/ft^2; we used 1.5 watts/ft^2. Title 24 calls for 0.15 cfm/ft2; we used the same. Our assumptions are based on what is typical, not just new construction. For the hospital, the lighting multiplier is 1.0 for 12 hours per day, and 0.7 for the remaining hours. Also, the fan design cfm was chosen to meet the peak demand for the buildings, and are not based just on building area. Since the fans are VFD, the air flow varies with building demand. The size has a very small effect on our sensitivity analyses.

The increased energy use for a leaking reheat valve for the hospital case is much smaller than for the office buildings, which is counter-intuitive. The reason is that the hospital's constant volume system is in reheat mode most of the time anyway. Therefore, the added baseboard heat (representing a leaking reheat valve) just offsets existing reheat consumption. So the affect of a leaking valve on a constant volume system is much smaller than on a VAV system, where it affects fan energy and cooling energy significantly.

Another hospital result that is counter-intuitive is that lower zone temperature setpoints lead to cooling savings, which is the opposite of the result for the VAV office buildings. Since the zones are in reheat mode most of the time, with a constant volume of air flow, if the cooling setpoint is lowered, the amount of reheat needed to maintain zone temperature is reduced. Therefore, the energy cost of maintaining a lower zone temperature is less, which is opposite what one would expect in a VAV building.

The chilled water supply temperature results usually lead to a U-shape curve, because the chiller energy increases below the 44F setpoint, and the fan energy increases above the 44F setpoint, since the supply air temperature minimum setpoint is increased by 1 degree for every degree that the chilled water supply temperature setpoint is increased. This assumption is an attempt to model the coil’s limitations in maintaining supply air temperature when the chilled water temperature increases. In the hospitals, the curve is not U-shaped. The cost continues to drop as chilled water temperature and supply air temperature rise. The fan energy doesn't increase as supply air temperature increases because the hospital is constant volume, whereas the chiller energy drops as CHWS rises. At some point the loads will not be met due to high supply air temperature, but we are not reaching that point in this model. The fan sizing for the hospital is probably generous in the baseline, because loads are still satisfied with 58F supply air. The other building types do have some problems meeting the loads as the supply air temperature increases.

The economizer change point results are interesting. For the office buildings in Fresno, the results form a "smiley face", with the lowest cost at zero or -1 deg error. (By error we mean an offset of the economizer change point, where the economizer switches from minimum to maximum outside air flow. That point is typically where the outdoor air temperature is equal to the return air temperature.) In San Francisco, there is also a "smiley face", but the lowest cost occurs at about a -4 deg error. The hospitals behave differently compared to the office buildings. In Fresno, it is a smile with the low point at -4, while in SF we don't reach the low point even at -6 deg.

We investigated the reasons for the lowest cost points falling below the zero degree offset change point. There are many hours in San Francisco and at night in Fresno when the enthalpy of outdoor air is higher than return air, even when the drybulb temperature is lower outdoors. Therefore, if the economizer is controlled only based on drybulb temperature, then a lower setpoint is better in SF. The same is true even for the Fresno hospital, because it runs 24 hours per day and encounters many nighttime hours of mild temperature (i.e. 60 to 70 deg) at high relative humidity. It would be valuable to investigate this effect more.

Results

The remainder of this appendix contains the detailed results of the building simulations, and the economic analyses (that are based on these results) that determine sensor accuracies and whether or not to initiate certain commissioning tests. The tables and figures are as follows:

Tables 1 to 8 - Sensor Accuracies and Commissioning Tests based on Energy Benefits (for all 8 buildings)
Table 9 - Summary of Recommended Sensor Accuracies for All DOE-2 Example Sites - Task 7
Table 10 - Summary of Potential Savings for AllDOE-2 Example Sites - Task 7
Figures 1 to 8 - Detailed tabular results of the DOE-2 sensitivity runs, including chiller and fan energy and capacity, building energy costs, and the change in energy costs from baseline conditions.
Charts 1 to 32 - Plots of the DOE-2 sensitivity run results. Four plots for each of the eight building scenarios.

Table 1

Sensor Accuracies and Other Improvements based on Energy Benefits

(Fresno Small Office Building - 50,000 sf)

Air Handler Operation and Control - Sensors	No. of Sensors	Added Annual Energy Cost with Baseline Accuracy (2°F or 0.5 inH_2O)	Energy Cost with Improved Accuracy (0.5°F or 0.2 inH_2O)	Annual Energy Savings from Improved Accuracy	Assumed Annualized Cost of Improvement	Benefit to Cost Ratio	Acceptable B/C Ratio[1]	Recommended Sensor Accuracy[2]	Maximum Potential Net Savings if Sensors are Improved[3]
		($/yr)	($/yr)	($/yr)	($/yr)				($/yr)
Supply Air Temperature	1	$505	$58	$447	$150	3.0	1	0.5°F	$297
Zone Temps (one per 1000 sf)	50	$1,686	$307	$1,379	$1,000	1.4	5	2°F	-
Duct Static Pressure	1	$1,100	$437	$663	$150	4.4	2	0.2 inH_2O	$513
Filter Differential Pressure	1	$1,100	$437	$663	$150	4.4	2	0.2 inH_2O	$513
Outside Air Temperature[4]	1	$26	$4	$22	$150	0.1	1	1°F	-
Return Air Temperature	1	$26	$4	$22	$150	0.1	1	2°F	-
Chilled Water Temperature	1	$708	$124	$584	$150	3.9	1	0.5°F	$434

Commissioning Activity, Improvement, or Sensor Installation	No. of Sensors	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings Due to Improvement ($/yr)	Assumed Cost of Improvement	Benefit to Cost Ratio[5]	Acceptable B/C Ratio[1]	Recommend Improvement?[2]	Max Potential Net Savings if Task is Performed[3] ($/yr)
Calibrate Zone Min Air Flow at Zero	50	High by 10% of full flow	5%	$3,133	$1,000/yr	3.1	5	No	-
Install New Zone Air Flow Sensor	50	High by 20% of full flow	5%	$9,400	$30,000/3-yr	0.9	5	No	-
Monitor Coil Differential Pressure	1	High by 0.1 inH2O	0.05 inH_2O	$109	$150/yr	0.7	2	No	-
Install an Outside Air Flow Sensor	1	High by 1/3 of min flow	5% of min flow	$871	$3,000/3-yr	0.9	2	No	-
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	50	High by 5°F,chance of leak = 20%	2°F	$21,930	$15,000/3-yr	4.4	5	No	-
Test Coil Performance		Effectiveness low by 10%, SAT high by 3°F	5% Eff.	$952	$3,750/3-yr	0.8	2	No	-
Test Fan Efficiency		Fan Efficiency low by 10%	5%	$427	$3,850/3-yr	0.3	2	No	-

Total Potential Annual Savings[6] $1,756

[1] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is acceptable. Where there a many sensors (such as zone sensors), it includes the percentage of zones that might need improvement.

[2] The Improved Accuracy or Proposed Improvement is recommended if the B/C ratio is greater than the Acceptable B/C Ratio.

[3] The Maximum Potential Net Savings is calculated by: (Annual Energy Savings - Annual Cost). The lump sum costs are spread over a 3-year period (I.e. they are divided by 3).

[4] Outside air temperature should be 1°F accurate, in order to use the diagnostic plots shown in Task 5. Depending on the energy analysis results, the OAT accuracy is set to 1°F or better.

[5] The B/C Ratio for the lower table is calculated by: Potential Savings due to Improvement / (Assumed Cost of Improvement / 3 years). The Cost of Improvement is annualized over 3 years. The B/C ratio does not include the cost of fixing the problem, which could lead to a different economic decision.

[6] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset of them.

Table 2

Sensor Accuracies and Other Improvements based on Energy Benefits

(Fresno Medium Office Building - 250,000 sf)

Air Handler Operation and Control - Sensors	No. of Sensors	Added Annual Energy Cost with Baseline Accuracy (2°F or 0.5 inH_2O)	Energy Cost with Improved Accuracy (0.5°F or 0.2 inH_2O)	Annual Energy Savings from Improved Accuracy	Assumed Annualized Cost of Improvement	Benefit to Cost Ratio	Acceptable B/C Ratio[1]	Recommended Sensor Accuracy[2]	Maximum Potential Net Savings if Sensors are Improved[3]
		($/yr)	($/yr)	($/yr)	($/yr)				($/yr)
Supply Air Temperature	2	$2,346	$307	$2,040	$300	6.8	1	0.5°F	$1,740
Zone Temps (one per 1000 sf)	250	$9,872	$1,924	$7,948	$5,000	1.6	5	2°F	-
Duct Static Pressure	2	$5,912	$2,369	$3,543	$300	11.8	2	0.2 inH_2O	$3,243
Filter Differential Pressure	2	$5,912	$2,369	$3,543	$300	11.8	2	0.2 inH_2O	$3,243
Outside Air Temperature[4]	2	$161	$22	$139	$300	0.5	1	1°F	-
Return Air Temperature	2	$161	$22	$139	$300	0.5	1	2°F	-
Chilled Water Temperature	2	$3,547	$588	$2,960	$300	9.9	1	0.5°F	$2,660

Commissioning Activity, Improvement, or Sensor Installation	No. of Sensors	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings Due to Improvement ($/yr)	Assumed Cost of Improvement	Benefit to Cost Ratio[5]	Acceptable B/C Ratio[1]	Recommend Improvement?[2]	Max Potential Net Savings if Task is Performed[3] ($/yr)
Calibrate Zone Min Air Flow at Zero	250	High by 10% of full flow	5%	$16,542	$5,000/yr	3.3	5	No	-
Install New Zone Air Flow Sensor	250	High by 20% of full flow	5%	$49,625	$150,000/3-yr	1.0	5	No	-
Monitor Coil Differential Pressure	2	High by 0.1 inH2O	0.05 inH_2O	$590	$300/yr	2.0	2	No	-
Install an Outside Air Flow Sensor	2	High by 1/3 of min flow	5% of min flow	$4,548	$6,000/3-yr	2.3	2	Yes	$2,548
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	250	High by 5°F,chance of leak = 20%	2°F	$108,139	$75,000/3-yr	4.3	5	No	-
Test Coil Performance		Effectiveness low by 10%, SAT high by 3°F	5% Eff.	$4,931	$8,000/3-yr	1.8	2	No	-
Test Fan Efficiency		Fan Efficiency low by 10%	5%	$2,264	$8,000/3-yr	0.8	2	No	-

Total Potential Annual Savings[6] $13,433

[1] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is acceptable. Where there a many sensors (such as zone sensors), it includes the percentage of zones that might need improvement.

[2] The Improved Accuracy or Proposed Improvement is recommended if the B/C ratio is greater than the Acceptable B/C Ratio.

[3] The Maximum Potential Net Savings is calculated by: (Annual Energy Savings - Annual Cost). The lump sum costs are spread over a 3-year period (I.e. they are divided by 3).

[4] Outside air temperature should be 1°F accurate, in order to use the diagnostic plots shown in Task 5. Depending on the energy analysis results, the OAT accuracy is set to 1°F or better.

[5] The B/C Ratio for the lower table is calculated by: Potential Savings due to Improvement / (Assumed Cost of Improvement / 3 years). The Cost of Improvement is annualized over 3 years. The B/C ratio does not include the cost of fixing the problem, which could lead to a different economic decision.

[6] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset of them.

Table 3

Sensor Accuracies and Other Improvements based on Energy Benefits

(Fresno Large Office Building - 1,000,000 sf)

Air Handler Operation and Control - Sensors	No. of Sensors	Added Annual Energy Cost with Baseline Accuracy (2°F or 0.5 inH_2O)	Energy Cost with Improved Accuracy (0.5°F or 0.2 inH_2O)	Annual Energy Savings from Improved Accuracy	Assumed Annualized Cost of Improvement	Benefit to Cost Ratio	Acceptable B/C Ratio[1]	Recommended Sensor Accuracy[2]	Maximum Potential Net Savings if Sensors are Improved[3]
		($/yr)	($/yr)	($/yr)	($/yr)				($/yr)
Supply Air Temperature	3	$10,821	$1,380	$9,442	$450	21.0	1	0.5°F	$8,992
Zone Temps (one per 1000 sf)	1000	$27,154	$4,573	$22,581	$20,000	1.1	5	2°F	-
Duct Static Pressure	3	$26,395	$10,558	$15,837	$450	35.2	2	0.2 inH_2O	$15,387
Filter Differential Pressure	3	$26,395	$10,558	$15,837	$450	35.2	2	0.2 inH_2O	$15,387
Outside Air Temperature[4]	3	$700	$75	$625	$450	1.4	1	0.5°F	$175
Return Air Temperature	3	$700	$75	$625	$450	1.4	1	0.5°F	$175
Chilled Water Temperature	3	$12,519	$1,826	$10,693	$450	23.8	1	0.5°F	$10,243

Commissioning Activity, Improvement, or Sensor Installation	No. of Sensors	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings Due to Improvement ($/yr)	Assumed Cost of Improvement	Benefit to Cost Ratio[5]	Acceptable B/C Ratio[1]	Recommend Improvement?[2]	Max Potential Net Savings if Task is Performed[3] ($/yr)
Calibrate Zone Min Air Flow at Zero	1000	High by 10% of full flow	5%	$80,390	$20,000/yr	4.0	5	No	-
Install New Zone Air Flow Sensor	1000	High by 20% of full flow	5%	$241,169	$600,000/3-yr	1.2	5	No	-
Monitor Coil Differential Pressure	3	High by 0.1 inH2O	0.05 inH_2O	$2,630	$450/yr	5.8	2	Yes	$2,180
Install an Outside Air Flow Sensor	3	High by 1/3 of min flow	5% of min flow	$18,501	$9,000/3-yr	6.2	2	Yes	$15,501
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	1000	High by 5°F,chance of leak = 20%	2°F	$394,199	$300,000/3-yr	3.9	5	No	-
Test Coil Performance		Effectiveness low by 10%, SAT high by 3°F	5% Eff.	$15,973	$12,000/3-yr	4.0	2	Yes	$11,973
Test Fan Efficiency		Fan Efficiency low by 10%	5%	$10,315	$12,000/3-yr	2.6	2	Yes	$6,315

Total Potential Annual Savings[6] $86,327

[1] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is acceptable. Where there a many sensors (such as zone sensors), it includes the percentage of zones that might need improvement.

[2] The Improved Accuracy or Proposed Improvement is recommended if the B/C ratio is greater than the Acceptable B/C Ratio.

[3] The Maximum Potential Net Savings is calculated by: (Annual Energy Savings - Annual Cost). The lump sum costs are spread over a 3-year period (I.e. they are divided by 3).

[4] Outside air temperature should be 1°F accurate, in order to use the diagnostic plots shown in Task 5. Depending on the energy analysis results, the OAT accuracy is set to 1°F or better.

[5] The B/C Ratio for the lower table is calculated by: Potential Savings due to Improvement / (Assumed Cost of Improvement / 3 years). The Cost of Improvement is annualized over 3 years. The B/C ratio does not include the cost of fixing the problem, which could lead to a different economic decision.

[6] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset of them.

Table 4

Sensor Accuracies and Other Improvements based on Energy Benefits

(Fresno Medium Hospital Building - 250,000 sf - Constant Volume Air Handler)

Air Handler Operation and Control - Sensors	No. of Sensors	Added Annual Energy Cost with Baseline Accuracy (2°F or 0.5 inH_2O)	Energy Cost with Improved Accuracy (0.5°F or 0.2 inH_2O)	Annual Energy Savings from Improved Accuracy	Assumed Annualized Cost of Improvement	Benefit to Cost Ratio	Acceptable B/C Ratio[1]	Recommended Sensor Accuracy[2]	Maximum Potential Net Savings if Sensors are Improved[3]
		($/yr)	($/yr)	($/yr)	($/yr)				($/yr)
Supply Air Temperature	2	$65,087	$16,328	$48,759	$300	162.5	2	0.5°F	$48,459
Zone Temps (one per 1000 sf)	250	$72,690	$18,050	$54,641	$5,000	10.9	5	0.5°F	$49,641
Duct Static Pressure	2	$43,907	$16,663	$27,244	$300	90.8	2	0.2 inH_2O	$26,944
Filter Differential Pressure	2	$43,907	$16,663	$27,244	$300	90.8	2	0.2 inH_2O	$26,944
Outside Air Temperature[4]	2	$3,291	$942	$2,350	$300	7.8	2	0.5°F	$2,050
Return Air Temperature	2	$3,291	$942	$2,350	$300	7.8	2	0.5°F	$2,050
Chilled Water Temperature	2	$10,953	$2,605	$8,348	$300	27.8	2	0.5°F	$8,048

Commissioning Activity, Improvement, or Sensor Installation	No. of Sensors	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings Due to Improvement ($/yr)	Assumed Cost of Improvement	Benefit to Cost Ratio[5]	Acceptable B/C Ratio[1]	Recommend Improvement?[2]	Max Potential Net Savings if Task is Performed[3] ($/yr)
Calibrate Zone Min Air Flow at Zero	250	High by 10% of full flow	5%	N/A	-	-	-	No	-
Install New Zone Air Flow Sensor	250	High by 20% of full flow	5%	N/A	-	-	-	No	-
Monitor Coil Differential Pressure	2	High by 0.1 inH2O	0.05 inH_2O	$4,245	$300/yr	14.1	2	Yes	$3,945
Install an Outside Air Flow Sensor	2	High by 1/3 of min flow	5% of min flow	$3,951	$6,000/3-yr	2.0	2	No	-
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	250	High by 5°F,chance of leak = 20%	2°F	$1,705	$75,000/3-yr	0.1	5	No	-
Test Coil Performance		Effectiveness low by 10%, SAT high by 3°F	5% Eff.	-$42,430	$8,000/3-yr	-15.9	2	No	-
Test Fan Efficiency		Fan Efficiency low by 10%	5%	$19,108	$8,000/3-yr	7.2	2	Yes	$16,441

Total Potential Annual Savings[6] $184,520

[1] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is acceptable. Where there a many sensors (such as zone sensors), it includes the percentage of zones that might need improvement.

[2] The Improved Accuracy or Proposed Improvement is recommended if the B/C ratio is greater than the Acceptable B/C Ratio.

[3] The Maximum Potential Net Savings is calculated by: (Annual Energy Savings - Annual Cost). The lump sum costs are spread over a 3-year period (I.e. they are divided by 3).

[4] Outside air temperature should be 1°F accurate, in order to use the diagnostic plots shown in Task 5. Depending on the energy analysis results, the OAT accuracy is set to 1°F or better.

[5] The B/C Ratio for the lower table is calculated by: Potential Savings due to Improvement / (Assumed Cost of Improvement / 3 years). The Cost of Improvement is annualized over 3 years. The B/C ratio does not include the cost of fixing the problem, which could lead to a different economic decision.

[6] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset of them.

Table 5

Sensor Accuracies and Other Improvements based on Energy Benefits

(San Francisco Small Office Building - 50,000 sf)

Air Handler Operation and Control - Sensors	No. of Sensors	Added Annual Energy Cost with Baseline Accuracy (2°F or 0.5 inH_2O)	Energy Cost with Improved Accuracy (0.5°F or 0.2 inH_2O)	Annual Energy Savings from Improved Accuracy	Assumed Annualized Cost of Improvement	Benefit to Cost Ratio	Acceptable B/C Ratio[1]	Recommended Sensor Accuracy[2]	Maximum Potential Net Savings if Sensors are Improved[3]
		($/yr)	($/yr)	($/yr)	($/yr)				($/yr)
Supply Air Temperature	1	$368	$54	$314	$150	2.1	1	0.5°F	$164
Zone Temps (one per 1000 sf)	50	$1,491	$232	$1,259	$1,000	1.3	5	2°F	-
Duct Static Pressure	1	$721	$289	$432	$150	2.9	2	0.2 inH_2O	$282
Filter Differential Pressure	1	$721	$289	$432	$150	2.9	2	0.2 inH_2O	$282
Outside Air Temperature[4]	1	$958	$264	$694	$150	4.6	2	0.5°F	$544
Return Air Temperature	1	$958	$264	$694	$150	4.6	2	0.5°F	$544
Chilled Water Temperature	1	$329	$75	$254	$150	1.7	1	0.5°F	$104

Commissioning Activity, Improvement, or Sensor Installation	No. of Sensors	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings Due to Improvement ($/yr)	Assumed Cost of Improvement	Benefit to Cost Ratio[5]	Acceptable B/C Ratio[1]	Recommend Improvement?[2]	Max Potential Net Savings if Task is Performed[3] ($/yr)
Calibrate Zone Min Air Flow at Zero	50	High by 10% of full flow	5%	$2,561	$1,000/yr	2.6	5	No	-
Install New Zone Air Flow Sensor	50	High by 20% of full flow	5%	$7,684	$30,000/3-yr	0.8	5	No	-
Monitor Coil Differential Pressure	1	High by 0.1 inH2O	0.05 inH_2O	$72	$150/yr	0.5	2	No	-
Install an Outside Air Flow Sensor	1	High by 1/3 of min flow	5% of min flow	$414	$3,000/3-yr	0.4	2	No	-
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	50	High by 5°F,chance of leak = 20%	2°F	$22,785	$15,000/3-yr	4.6	5	No	-
Test Coil Performance		Effectiveness low by 10%, SAT high by 3°F	5% Eff.	$352	$3,750/3-yr	0.3	2	No	-
Test Fan Efficiency		Fan Efficiency low by 10%	5%	$265	$3,850/3-yr	0.2	2	No	-

Total Potential Annual Savings[6] $1,919

[1] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is acceptable. Where there a many sensors (such as zone sensors), it includes the percentage of zones that might need improvement.

[2] The Improved Accuracy or Proposed Improvement is recommended if the B/C ratio is greater than the Acceptable B/C Ratio.

[3] The Maximum Potential Net Savings is calculated by: (Annual Energy Savings - Annual Cost). The lump sum costs are spread over a 3-year period (I.e. they are divided by 3).

[4] Outside air temperature should be 1°F accurate, in order to use the diagnostic plots shown in Task 5. Depending on the energy analysis results, the OAT accuracy is set to 1°F or better.

[5] The B/C Ratio for the lower table is calculated by: Potential Savings due to Improvement / (Assumed Cost of Improvement / 3 years). The Cost of Improvement is annualized over 3 years. The B/C ratio does not include the cost of fixing the problem, which could lead to a different economic decision.

[6] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset of them.

Table 6

Sensor Accuracies and Other Improvements based on Energy Benefits

(San Francisco Medium Office Building - 250,000 sf)

Air Handler Operation and Control - Sensors	No. of Sensors	Added Annual Energy Cost with Baseline Accuracy (2°F or 0.5 inH_2O)	Energy Cost with Improved Accuracy (0.5°F or 0.2 inH_2O)	Annual Energy Savings from Improved Accuracy	Assumed Annualized Cost of Improvement	Benefit to Cost Ratio	Acceptable B/C Ratio[1]	Recommended Sensor Accuracy[2]	Maximum Potential Net Savings if Sensors are Improved[3]
		($/yr)	($/yr)	($/yr)	($/yr)				($/yr)
Supply Air Temperature	2	$1,630	$233	$1,397	$300	4.7	1	0.5°F	$1,097
Zone Temps (one per 1000 sf)	250	$8,311	$1,850	$6,462	$5,000	1.3	5	2°F	-
Duct Static Pressure	2	$4,056	$1,626	$2,430	$300	8.1	2	0.2 inH_2O	$2,130
Filter Differential Pressure	2	$4,056	$1,626	$2,430	$300	8.1	2	0.2 inH_2O	$2,130
Outside Air Temperature[4]	2	$4,108	$1,072	$3,036	$300	10.1	2	0.5°F	$2,736
Return Air Temperature	2	$4,108	$1,072	$3,036	$300	10.1	2	0.5°F	$2,736
Chilled Water Temperature	2	$1,345	$262	$1,083	$300	3.6	2	0.5°F	$783

Commissioning Activity, Improvement, or Sensor Installation	No. of Sensors	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings Due to Improvement ($/yr)	Assumed Cost of Improvement	Benefit to Cost Ratio[5]	Acceptable B/C Ratio[1]	Recommend Improvement?[2]	Max Potential Net Savings if Task is Performed[3] ($/yr)
Calibrate Zone Min Air Flow at Zero	250	High by 10% of full flow	5%	$12,075	$5,000/yr	2.4	5	No	-
Install New Zone Air Flow Sensor	250	High by 20% of full flow	5%	$36,226	$150,000/3-yr	0.7	5	No	-
Monitor Coil Differential Pressure	2	High by 0.1 inH2O	0.05 inH_2O	$408	$300/yr	1.4	2	No	-
Install an Outside Air Flow Sensor	2	High by 1/3 of min flow	5% of min flow	$2,209	$6,000/3-yr	1.1	2	No	-
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	250	High by 5°F,chance of leak = 20%	2°F	$104,621	$75,000/3-yr	4.2	5	No	-
Test Coil Performance		Effectiveness low by 10%, SAT high by 3°F	5% Eff.	$1,339	$8,000/3-yr	0.5	2	No	-
Test Fan Efficiency		Fan Efficiency low by 10%	5%	$1,436	$8,000/3-yr	0.5	2	No	-

Total Potential Annual Savings[6] $11,612

[1] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is acceptable. Where there a many sensors (such as zone sensors), it includes the percentage of zones that might need improvement.

[2] The Improved Accuracy or Proposed Improvement is recommended if the B/C ratio is greater than the Acceptable B/C Ratio.

[3] The Maximum Potential Net Savings is calculated by: (Annual Energy Savings - Annual Cost). The lump sum costs are spread over a 3-year period (I.e. they are divided by 3).

[4] Outside air temperature should be 1°F accurate, in order to use the diagnostic plots shown in Task 5. Depending on the energy analysis results, the OAT accuracy is set to 1°F or better.

[5] The B/C Ratio for the lower table is calculated by: Potential Savings due to Improvement / (Assumed Cost of Improvement / 3 years). The Cost of Improvement is annualized over 3 years. The B/C ratio does not include the cost of fixing the problem, which could lead to a different economic decision.

[6] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset of them.

Table 7

Sensor Accuracies and Other Improvements based on Energy Benefits

(San Francisco Large Office Building - 1,000,000 sf)

Air Handler Operation and Control - Sensors	No. of Sensors	Added Annual Energy Cost with Baseline Accuracy (2°F or 0.5 inH_2O)	Energy Cost with Improved Accuracy (0.5°F or 0.2 inH_2O)	Annual Energy Savings from Improved Accuracy	Assumed Annualized Cost of Improvement	Benefit to Cost Ratio	Acceptable B/C Ratio[1]	Recommended Sensor Accuracy[2]	Maximum Potential Net Savings if Sensors are Improved[3]
		($/yr)	($/yr)	($/yr)	($/yr)				($/yr)
Supply Air Temperature	3	$4,125	$411	$3,714	$450	8.3	2	0.5°F	$3,264
Zone Temps (one per 1000 sf)	1000	$29,893	$6,102	$23,792	$20,000	1.2	5	2°F	-
Duct Static Pressure	3	$18,808	$7,420	$11,388	$450	25.3	2	0.2 inH_2O	$10,938
Filter Differential Pressure	3	$18,808	$7,420	$11,388	$450	25.3	2	0.2 inH_2O	$10,938
Outside Air Temperature[4]	3	$24,244	$7,321	$16,924	$450	37.6	2	0.5°F	$16,474
Return Air Temperature	3	$24,244	$7,321	$16,924	$450	37.6	2	0.5°F	$16,474
Chilled Water Temperature	3	$9,802	$2,396	$7,406	$450	16.5	2	0.5°F	$6,956

Commissioning Activity, Improvement, or Sensor Installation	No. of Sensors	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings Due to Improvement ($/yr)	Assumed Cost of Improvement	Benefit to Cost Ratio[5]	Acceptable B/C Ratio[1]	Recommend Improvement?[2]	Max Potential Net Savings if Task is Performed[3] ($/yr)
Calibrate Zone Min Air Flow at Zero	1000	High by 10% of full flow	5%	$49,089	$20,000/yr	2.5	5	No	-
Install New Zone Air Flow Sensor	1000	High by 20% of full flow	5%	$147,268	$600,000/3-yr	0.7	5	No	-
Monitor Coil Differential Pressure	3	High by 0.1 inH2O	0.05 inH_2O	$1,847	$450/yr	4.1	2	Yes	$1,397
Install an Outside Air Flow Sensor	3	High by 1/3 of min flow	5% of min flow	$9,591	$9,000/3-yr	3.2	2	Yes	$6,591
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	1000	High by 5°F,chance of leak = 20%	2°F	$402,200	$300,000/3-yr	4.0	5	No	-
Test Coil Performance		Effectiveness low by 10%, SAT high by 3°F	5% Eff.	$730	$12,000/3-yr	0.2	2	No	-
Test Fan Efficiency		Fan Efficiency low by 10%	5%	$6,097	$12,000/3-yr	1.5	2	No	-

Total Potential Annual Savings[6] $73,031

[1] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is acceptable. Where there a many sensors (such as zone sensors), it includes the percentage of zones that might need improvement.

[2] The Improved Accuracy or Proposed Improvement is recommended if the B/C ratio is greater than the Acceptable B/C Ratio.

[3] The Maximum Potential Net Savings is calculated by: (Annual Energy Savings - Annual Cost). The lump sum costs are spread over a 3-year period (I.e. they are divided by 3).

[4] Outside air temperature should be 1°F accurate, in order to use the diagnostic plots shown in Task 5. Depending on the energy analysis results, the OAT accuracy is set to 1°F or better.

[5] The B/C Ratio for the lower table is calculated by: Potential Savings due to Improvement / (Assumed Cost of Improvement / 3 years). The Cost of Improvement is annualized over 3 years. The B/C ratio does not include the cost of fixing the problem, which could lead to a different economic decision.

[6] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset of them.

Table 8

Sensor Accuracies and Other Improvements based on Energy Benefits

(San Francisco Medium Hospital Building - 250,000 sf - Constant Volume Air Handler)

Air Handler Operation and Control - Sensors	No. of Sensors	Added Annual Energy Cost with Baseline Accuracy (2°F or 0.5 inH_2O)	Energy Cost with Improved Accuracy (0.5°F or 0.2 inH_2O)	Annual Energy Savings from Improved Accuracy	Assumed Annualized Cost of Improvement	Benefit to Cost Ratio	Acceptable B/C Ratio[1]	Recommended Sensor Accuracy[2]	Maximum Potential Net Savings if Sensors are Improved[3]
		($/yr)	($/yr)	($/yr)	($/yr)				($/yr)
Supply Air Temperature	2	$37,174	$9,208	$27,966	$300	93.2	2	0.5°F	$27,666
Zone Temps (one per 1000 sf)	250	$47,638	$11,894	$35,744	$5,000	7.1	5	0.5°F	$30,744
Duct Static Pressure	2	$33,507	$12,094	$21,413	$300	71.4	2	0.2 inH_2O	$21,113
Filter Differential Pressure	2	$33,507	$12,094	$21,413	$300	71.4	2	0.2 inH_2O	$21,113
Outside Air Temperature[4]	2	$1,276	$325	$951	$300	3.2	2	0.5°F	$651
Return Air Temperature	2	$1,276	$325	$951	$300	3.2	2	0.5°F	$651
Chilled Water Temperature	2	$5,216	$1,218	$3,998	$300	13.3	2	0.5°F	$3,698

Commissioning Activity, Improvement, or Sensor Installation	No. of Sensors	Assumed Deviation without Sensor or Improvement	Assumed Deviation with Sensor or Improvement	Potential Savings Due to Improvement ($/yr)	Assumed Cost of Improvement	Benefit to Cost Ratio[5]	Acceptable B/C Ratio[1]	Recommend Improvement?[2]	Max Potential Net Savings if Task is Performed[3] ($/yr)
Calibrate Zone Min Air Flow at Zero	250	High by 10% of full flow	5%	N/A	-	-	-	No	-
Install New Zone Air Flow Sensor	250	High by 20% of full flow	5%	N/A	-	-	-	No	-
Monitor Coil Differential Pressure	2	High by 0.1 inH2O	0.05 inH_2O	$2,955	$300/yr	9.9	2	Yes	$2,655
Install an Outside Air Flow Sensor	2	High by 1/3 of min flow	5% of min flow	-$343	$6,000/3-yr	-0.2	2	No	-
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	250	High by 5°F,chance of leak = 20%	2°F	$3,059	$75,000/3-yr	0.1	5	No	-
Test Coil Performance		Effectiveness low by 10%, SAT high by 3°F	5% Eff.	-23,967	$8,000/3-yr	-9.0	2	No	-
Test Fan Efficiency		Fan Efficiency low by 10%	5%	$13,648	$8,000/3-yr	5.1	2	Yes	$10,981

Total Potential Annual Savings[6] $119,272

[1] The acceptable benefit/cost ratio includes the risk that savings will not occur, as well as the margin of economic uncertainty that is acceptable. Where there a many sensors (such as zone sensors), it includes the percentage of zones that might need improvement.

[2] The Improved Accuracy or Proposed Improvement is recommended if the B/C ratio is greater than the Acceptable B/C Ratio.

[3] The Maximum Potential Net Savings is calculated by: (Annual Energy Savings - Annual Cost). The lump sum costs are spread over a 3-year period (I.e. they are divided by 3).

[4] Outside air temperature should be 1°F accurate, in order to use the diagnostic plots shown in Task 5. Depending on the energy analysis results, the OAT accuracy is set to 1°F or better.

[5] The B/C Ratio for the lower table is calculated by: Potential Savings due to Improvement / (Assumed Cost of Improvement / 3 years). The Cost of Improvement is annualized over 3 years. The B/C ratio does not include the cost of fixing the problem, which could lead to a different economic decision.

[6] The Total Potential Annual Savings includes all of the improvements listed. In reality, most sites would benefit from just a subset of them.

Table 9. Summary of Recommended Sensor Accuracies for All DOE-2 Example Sites - Task 7

Air Handler Operation and Control - Sensors	Fresno Small Office	Fresno Medium Office	Fresno Large Office	Fresno Medium Hospital	S.F. Small Office	S.F. Medium Office	S.F. Large Office	S.F. Medium Hospital	Recommended Storage Frequency (from Diagnostic Plots)
Supply Air Temperature	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	2 min
Single Zone Temp (1000 sf)	2°F	2°F	2°F	0.5°F	2°F	2°F	2°F	0.5°F	2 min
Duct Static Pressure	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	1 min
Filter Differential Pressure	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	0.2 inH_2O	Every 3 months
Outside Air Temperature	1°F	1°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	5 min
Return Air Temperature	2°F	2°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	1 min
Chilled Water Temperature	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	0.5°F	2 min
Commissioning Activity, Improvement, or Sensor Installation									
Calibrate Zone Min Air Flow at Zero	-	-	-	-	-	-	-	-	N/A
Install New Zone Air Flow Sensor	-	-	-	-	-	-	-	-	N/A
Monitor Coil Differential Pressure	-	-	0.05 inH_2O	0.05 inH_2O	-	-	0.05 inH_2O	0.05 inH_2O	Every 3 months.
Install an Outside Air Flow Sensor	-	5% of min flow	5% of min flow	-	-	-	5% of min flow	-	Every 5 minutes
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	-	-	-	-	-	-	-	-	N/A
Test Coil Performance	-	-	5% Eff.	-	-	-	-	-	Test every few years
Test Fan Efficiency	-	-	5% Eff.	5% Eff.	-	-	-	5% Eff.	Initial Test Only

Table 10. Summary of Potential Savings for All DOE-2 Example Sites - Task 7

Air Handler Operation and Control - Sensors	Fresno Small Office	Fresno Medium Office	Fresno Large Office	Fresno Medium Hospital	S.F. Small Office	S.F. Medium Office	S.F. Large Office	S.F. Medium Hospital
Supply Air Temperature	$297	$1,740	$8,992	$48,459	$164	$1,097	$3,264	$27,666
Single Zone Temp (1000 sf)	-	-	-	$49,641	-	-	-	$30,744
Duct Static Pressure	$513	$3,243	$15,387	$26,944	$282	$2,130	$10,938	$21,113
Filter Differential Pressure	$513	$3,243	$15,387	$26,944	$282	$2,130	$10,938	$21,113
Outside Air Temperature	-	-	$175	$2,050	$544	$2,736	$16,474	$651
Return Air Temperature	-	-	$175	$2,050	$544	$2,736	$16,474	$651
Chilled Water Temperature	$434	$2,660	$10,243	$8,048	$104	$783	$6,956	$3,698
Commissioning Task, Improvement, or Sensor Installation								
Calibrate Zone Min Air Flow at Zero	-	-	-	-	-	-	-	-
Install New Zone Air Flow Sensor	-	-	-	-	-	-	-	-
Monitor Coil Differential Pressure	-	-	$2,180	$3,945	-	-	$1,397	$2,655
Install an Outside Air Flow Sensor	-	$2,548	$15,501	-	-	-	$6,591	-
Zone Supply Air Temp Sensor to Detect Reheat Valve Leaks	-	-	-	-	-	-	-	-
Test Coil Performance	-	-	$11,973	-	-	-	-	-
Test Fan Efficiency	-	-	$6,315	$16,441	-	-	-	$10,981
Total Potential Annual Savings	$1,756	$13,433	$86,327	$184,520	$1,919	$11,612	$73,031	$119,272
Total Building Energy Use (MWh/yr)	752	3,546	14,820	11,207	620	2,941	11,829	8,785
Total Building Energy Cost (k$/yr)	$94k	$439k	$1,872k	$1,597k	$77k	$364k	$1,497k	$1,215k
% Savings vs. Total Energy Cost	1.9 %	3.1 %	4.6 %	11.6 %	2.5 %	3.2 %	4.9 %	9.8 %

Note: The Total Potential Annual Savings includes all improvements listed. In reality, most sites would require only a subset of them.

Figure 1 - Fresno Small Office Building - 50,000 sf

	kWh			kw		Cost	
	chiller	fan	total	chiller	fan	Total	Change
Baseline	168,136	85,461	752,773	109.1	54.7	$94,048	$0
Filter + 0.25 inches	168,731	88,997	756,903	109.7	56.9	$94,595	$547
Filter + 0.5 inches	169,361	92,532	761,136	110.3	59.1	$95,148	$1,100
Filter + 0.75 inches	169,966	96,059	765,286	110.9	61.4	$95,696	$1,648
Filter + 1.0 inches	170,562	99,589	769,413	111.5	63.6	$96,241	$2,193
Econo Err 3	168,690	85,474	753,346	109.1	10.5	$94,109	$86
Econo Err 2	168,397	85,467	753,040	109.1	10.5	$94,081	$58
Econo Err 1	168,132	85,462	752,768	109.1	10.5	$94,048	$25
Econo Err 0	167,975	85,455	752,600	109.1	10.5	$94,023	$0
Econo Err -1	167,955	85,452	752,577	109.1	10.5	$94,021	-$2
Econo Err -2	168,044	85,452	752,667	109.1	10.5	$94,033	$10
Econo Err -3	168,235	85,458	752,867	109.1	10.5	$94,045	$22
Econo Err -4	168,495	85,471	753,141	109.1	10.5	$94,061	$38
Econo Err -5	168,819	85,487	753,483	109.1	10.5	$94,089	$66
Econo Err -6	169,179	85,506	753,861	109.1	10.5	$94,109	$86
Setpoint - 3.0 deg (70.0/67.0)	177,406	111,481	782,685	118.5	78.5	$97,249	$3,201
Setpoint - 2.0 deg (71.0/68.0)	173,578	100,699	769,645	115.7	71.2	$95,734	$1,686
Setpoint - 1.0 deg (72.0/69.0)	170,566	92,092	759,887	113.0	64.4	$94,662	$614
Baseline	168,136	85,461	752,773	109.1	54.7	$94,048	$0
Setpoint + 1.0 deg (74.0/71.0)	166,353	80,442	747,835	105.7	46.9	$93,852	-$196
Setpoint + 2.0 deg (75.0/72.0)	165,249	76,738	745,062	102.6	40.5	$94,044	-$4
Duct SP + 0.3 inches	168,850	89,704	757,730	109.8	57.3	$94,704	$656
Duct SP + 0.2 inches	168,612	88,290	756,078	109.6	56.4	$94,485	$437
Duct SP + 0.1 inches	168,374	86,876	754,425	109.3	55.6	$94,266	$218
Baseline	168,136	85,461	752,773	109.1	54.7	$94,048	$0
Duct SP - 0.1 inches	167,899	84,046	751,121	108.9	53.8	$93,829	-$219
Duct SP - 0.2 inches	167,661	82,631	749,467	108.6	52.8	$93,610	-$438
Duct SP - 0.3 inches	167,424	81,216	747,816	108.4	51.9	$93,391	-$657
SAT 50 deg - cent/vane	184,158	72,605	760,513	106.2	31.0	$95,230	$1,182
SAT 51 deg - cent/vane	180,368	74,209	757,405	106.5	34.3	$94,642	$594
SAT 52 deg - cent/vane	176,781	76,168	754,830	106.9	38.1	$94,131	$83
SAT 53 deg - cent/vane	173,450	78,576	752,907	107.4	42.7	$93,845	-$203
SAT 54 deg - cent/vane	170,634	81,606	752,290	108.2	48.1	$93,838	-$210
Baseline	168,136	85,461	752,773	109.1	54.7	$94,048	$0
SAT 56 deg - cent/vane	165,910	90,351	754,453	110.3	62.7	$94,489	$441
SAT 57 deg - cent/vane	163,938	96,375	757,638	110.7	69.2	$95,219	$1,171
SAT 58 deg - cent/vane	161,830	103,381	760,968	110.8	76.4	$96,079	$2,031
ChW 40, min SAT 55, Cent/Vane	180,733	85,461	765,407	119.1	54.7	$95,915	$1,867
ChW 41, min SAT 55, Cent/Vane	176,876	85,461	761,539	116.1	54.7	$95,345	$1,297
ChW 42, min SAT 55, Cent/Vane	173,489	85,461	758,142	113.4	54.7	$94,843	$795

ChW 43, min SAT 55, Cent/Vane	170,574	85,461	755,218	111.1	54.7	$94,411	$363
ChW 44, min SAT 55, Cent/Vane	168,136	85,461	752,773	109.1	54.7	$94,048	$0
ChW 45, min SAT 56, Cent/Vane	163,972	90,351	752,509	108.7	62.7	$94,195	$147
ChW 46, min SAT 57, Cent/Vane	160,593	96,375	754,283	107.7	69.2	$94,703	$655
ChW 47, min SAT 58, Cent/Vane	157,576	103,381	756,702	106.8	76.4	$95,410	$1,362
SAT 50 deg - cent/vsd	162,764	72,605	739,069	116.9	31.0	$93,868	$1,675
SAT 51 deg - cent/vsd	157,496	74,209	734,480	117.4	34.3	$93,132	$939
SAT 52 deg - cent/vsd	152,636	76,168	730,627	118.0	38.1	$92,490	$297
SAT 53 deg - cent/vsd	148,218	78,576	727,615	118.7	42.7	$92,102	-$91
SAT 54 deg - cent/vsd	144,454	81,606	726,048	119.9	48.1	$92,024	-$169
Baseline	141,252	85,461	725,825	121.2	54.7	$92,193	$0
SAT 56 deg - cent/vsd	138,598	90,351	727,076	123.1	62.7	$92,623	$430
SAT 57 deg - cent/vsd	136,392	96,375	730,027	123.6	69.2	$93,361	$1,168
SAT 58 deg - cent/vsd	134,505	103,381	733,579	123.8	76.4	$94,279	$2,086
ChW 40, min SAT 55, Cent/VSD	151,834	85,461	736,441	130.0	54.7	$94,114	$1,921
ChW 41, min SAT 55, Cent/VSD	148,608	85,461	733,204	132.9	54.7	$93,607	$1,414
ChW 42, min SAT 55, Cent/VSD	145,805	85,461	730,392	128.5	54.7	$93,069	$876
ChW 43, min SAT 55, Cent/VSD	143,369	85,461	727,948	124.6	54.7	$92,602	$409
ChW 44, min SAT 55, Cent/VSD	141,252	85,461	725,825	121.2	54.7	$92,193	$0
ChW 45, min SAT 56, Cent/VSD	136,816	90,351	725,288	120.1	62.7	$92,268	$75
ChW 46, min SAT 57, Cent/VSD	133,153	96,375	726,777	117.9	69.2	$92,698	$505
ChW 47, min SAT 58, Cent/VSD	130,049	103,381	729,108	115.8	76.4	$93,341	$1,148
SAT 50 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 51 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 52 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 53 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 54 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
Baseline	0	0	0	0.0	0.0	$0	$0
SAT 56 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 57 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 58 deg - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 40 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 41 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 42 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 43 - recip/vsd	0	0	0	0.0	0.0	$0	$0
Baseline	0	0	0	0.0	0.0	$0	$0
CHWS 45 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 46 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 47 - recip/vsd	0	0	0	0.0	0.0	$0	$0
Min OA 0.05 cfm/sf	161,615	84,903	745,007	91.3	53.9	$92,185	-$1,863
Min OA 0.10 cfm/sf	164,791	85,185	748,846	100.0	54.5	$93,069	-$979
Baseline	168,136	85,461	752,773	109.1	54.7	$94,048	$0
Min OA 0.20 cfm/sf	171,577	85,738	756,800	118.8	55.1	$95,074	$1,026
Min OA 0.30 cfm/sf	178,747	86,013	764,895	139.4	55.7	$97,190	$3,142

VAV min 0.20	154,952	60,453	704,317	109.1	52.8	$85,370	-$8,678
VAV min 0.35	159,048	64,530	716,914	108.8	53.5	$88,285	-$5,763
VAV min 0.50	168,136	85,461	752,773	109.1	54.7	$94,048	$0
VAV min 0.65	183,421	129,977	818,457	109.8	56.7	$103,447	$9,399
VAV min 0.80	207,464	201,515	919,696	128.2	66.0	$117,519	$23,471
Zone SAT 65	350,300	277,191	1,168,997	147.4	91.1	$166,958	$72,910
Zone SAT 60	232,834	164,020	925,849	145.4	88.9	$130,597	$36,549
Zone SAT 55	168,136	85,461	752,773	109.1	54.7	$94,048	$0

Figure 2 - Fresno Medium Office Building - 250,000 sf

	kWh			kw		Cost	
	chiller	fan	total	chiller	fan	Total	Change
medium	591,349	452,741	3,545,611	428.2	291.7	$438,791	$0
Filter + 0.25 inches	594,309	471,454	3,568,323	430.8	303.7	$441,760	$2,969
Filter + 0.5 inches	597,256	490,173	3,590,760	433.4	315.8	$444,703	$5,912
Filter + 0.75 inches	600,218	508,857	3,613,496	435.9	327.9	$447,666	$8,875
Filter + 1.0 inches	603,157	527,564	3,636,161	438.5	339.9	$450,621	$11,830
Econo Err 3	593,941	452,800	3,548,979	428.2	125.6	$439,281	$650
Econo Err 2	592,097	452,759	3,546,566	428.2	125.6	$438,905	$274
Econo Err 1	591,028	452,734	3,545,080	428.2	125.6	$438,757	$126
Econo Err 0	590,323	452,706	3,544,053	428.2	125.6	$438,631	$0
Econo Err -1	590,204	452,691	3,543,911	428.2	125.6	$438,625	-$6
Econo Err -2	590,823	452,694	3,544,605	428.2	125.6	$438,708	$77
Econo Err -3	591,995	452,734	3,545,894	428.2	125.6	$438,815	$184
Econo Err -4	593,352	452,801	3,547,467	428.2	125.6	$438,913	$282
Econo Err -5	595,414	452,900	3,549,901	428.2	125.6	$439,052	$421
Econo Err -6	597,483	453,002	3,552,354	428.2	125.6	$439,199	$568
Setpoint - 3.0 deg (70.0/67.0)	633,099	584,621	3,715,235	456.7	390.6	$455,943	$17,152
Setpoint - 2.0 deg (71.0/68.0)	616,573	531,525	3,645,105	449.8	364.4	$448,663	$9,872
Setpoint - 1.0 deg (72.0/69.0)	602,466	487,675	3,589,048	438.0	327.5	$442,639	$3,848
medium	591,349	452,741	3,545,611	428.2	291.7	$438,791	$0
Setpoint + 1.0 deg (74.0/71.0)	583,150	426,305	3,516,645	418.0	256.4	$437,155	-$1,636
Setpoint + 2.0 deg (75.0/72.0)	577,161	406,091	3,497,532	405.8	221.9	$437,218	-$1,573
Duct SP + 0.3 inches	594,895	475,205	3,572,759	431.3	306.2	$442,344	$3,553
Duct SP + 0.2 inches	593,718	467,703	3,563,711	430.3	301.3	$441,160	$2,369
Duct SP + 0.1 inches	592,532	460,222	3,554,598	429.2	296.5	$439,971	$1,180
medium	591,349	452,741	3,545,611	428.2	291.7	$438,791	$0
Duct SP - 0.1 inches	590,146	445,235	3,536,194	427.2	286.9	$437,577	-$1,214
Duct SP - 0.2 inches	588,958	437,751	3,527,088	426.2	282.0	$436,382	-$2,409
Duct SP - 0.3 inches	587,771	430,263	3,518,031	425.1	277.2	$435,198	-$3,593
SAT 50 deg - cent/vane	672,638	381,513	3,606,429	418.3	169.1	$445,680	$6,889
SAT 51 deg - cent/vane	652,553	390,241	3,582,487	419.7	186.1	$441,976	$3,185
SAT 52 deg - cent/vane	634,771	401,253	3,564,248	421.5	207.3	$439,152	$361
SAT 53 deg - cent/vane	617,973	414,553	3,549,866	424.2	232.5	$437,851	-$940
SAT 54 deg - cent/vane	603,736	431,454	3,544,050	427.4	262.5	$437,612	-$1,179
medium	591,349	452,741	3,545,611	428.2	291.7	$438,791	$0
SAT 56 deg - cent/vane	580,138	478,744	3,553,395	428.6	323.0	$441,012	$2,221
SAT 57 deg - cent/vane	570,654	510,151	3,570,297	430.9	354.4	$445,006	$6,215
SAT 58 deg - cent/vane	562,724	545,324	3,590,853	430.1	381.2	$449,121	$10,330
ChW 40, min SAT 55, Cent/Vane	645,695	452,741	3,612,240	467.2	291.7	$447,692	$8,901
ChW 41, min SAT 55, Cent/Vane	629,478	452,741	3,592,255	455.4	291.7	$445,074	$6,283
ChW 42, min SAT 55, Cent/Vane	615,010	452,741	3,574,643	445.0	291.7	$442,764	$3,973

ChW 43, min SAT 55, Cent/Vane	602,282	452,741	3,558,813	435.9	291.7	$440,515	$1,724
ChW 44, min SAT 55, Cent/Vane	591,349	452,741	3,545,611	428.2	291.7	$438,791	$0
ChW 45, min SAT 56, Cent/Vane	571,147	478,744	3,541,405	422.2	323.0	$439,493	$702
ChW 46, min SAT 57, Cent/Vane	554,832	510,151	3,549,835	419.3	354.4	$442,368	$3,577
ChW 47, min SAT 58, Cent/Vane	542,027	545,324	3,564,279	414.7	381.2	$445,633	$6,842
SAT 50 deg - cent/vsd	665,070	381,513	3,615,365	460.4	169.1	$447,999	$7,039
SAT 51 deg - cent/vsd	645,027	390,241	3,591,174	462.4	186.1	$444,336	$3,376
SAT 52 deg - cent/vsd	627,608	401,253	3,572,575	465.1	207.3	$441,532	$572
SAT 53 deg - cent/vsd	611,167	414,553	3,557,180	469.2	232.5	$440,154	-$806
SAT 54 deg - cent/vsd	595,973	431,454	3,549,780	474.1	262.5	$440,040	-$920
medium	582,672	452,741	3,549,620	475.2	291.7	$440,960	$0
SAT 56 deg - cent/vsd	571,305	478,744	3,555,819	475.8	323.0	$442,993	$2,033
SAT 57 deg - cent/vsd	560,220	510,151	3,569,956	479.2	354.4	$446,734	$5,774
SAT 58 deg - cent/vsd	550,514	545,324	3,587,830	478.0	381.2	$450,737	$9,777
ChW 40, min SAT 55, Cent/VSD	607,094	452,741	3,605,236	509.9	291.7	$449,766	$8,806
ChW 41, min SAT 55, Cent/VSD	597,119	452,741	3,589,140	521.1	291.7	$447,471	$6,511
ChW 42, min SAT 55, Cent/VSD	591,009	452,741	3,574,656	503.6	291.7	$445,065	$4,105
ChW 43, min SAT 55, Cent/VSD	587,036	452,741	3,561,526	488.5	291.7	$442,895	$1,935
ChW 44, min SAT 55, Cent/VSD	582,672	452,741	3,549,620	475.2	291.7	$440,960	$0
ChW 45, min SAT 56, Cent/VSD	567,001	478,744	3,545,149	464.2	323.0	$441,299	$339
ChW 46, min SAT 57, Cent/VSD	551,106	510,151	3,550,017	457.3	354.4	$443,494	$2,534
ChW 47, min SAT 58, Cent/VSD	537,679	545,324	3,560,108	447.3	381.2	$446,170	$5,210
SAT 50 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 51 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 52 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 53 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 54 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
medium	0	0	0	0.0	0.0	$0	$0
SAT 56 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 57 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 58 deg - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 40 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 41 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 42 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 43 - recip/vsd	0	0	0	0.0	0.0	$0	$0
medium	0	0	0	0.0	0.0	$0	$0
CHWS 45 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 46 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 47 - recip/vsd	0	0	0	0.0	0.0	$0	$0
Min OA 0.05 cfm/sf	560,174	449,725	3,488,846	360.0	288.9	$427,324	-$11,467
Min OA 0.10 cfm/sf	575,727	451,234	3,517,420	393.2	291.2	$433,471	-$5,320
medium	591,349	452,741	3,545,611	428.2	291.7	$438,791	$0
Min OA 0.20 cfm/sf	606,751	454,217	3,571,339	465.1	293.3	$444,151	$5,360
Min OA 0.30 cfm/sf	637,576	455,714	3,619,988	544.6	295.6	$454,567	$15,776

VAV min 0.20	515,279	318,871	3,272,427	425.2	282.0	$394,568	-$44,223
VAV min 0.35	541,933	342,601	3,348,695	426.4	285.8	$409,807	-$28,984
VAV min 0.50	591,349	452,741	3,545,611	428.2	291.7	$438,791	$0
VAV min 0.65	671,384	684,044	3,919,066	431.5	302.4	$488,416	$49,625
VAV min 0.80	782,673	1,055,015	4,482,799	483.5	349.7	$561,892	$123,101
Zone SAT 65	1,344,870	1,378,172	5,588,539	581.7	455.6	$797,609	$358,818
Zone SAT 60	873,545	820,516	4,430,267	557.9	440.9	$619,022	$180,231
Zone SAT 55	591,349	452,741	3,545,611	428.2	291.7	$438,791	$0

Figure 3 - Fresno Large Office Building - 1,000,000 sf

	kWh			kw		Cost	
	chiller	fan	total	chiller	fan	Total	Change
large	2,594,469	2,062,972	14,820,210	1897.8	1266.2	$1,871,818	$0
Filter + 0.25 inches	2,607,238	2,148,256	14,921,120	1909.5	1318.5	$1,884,993	$13,175
Filter + 0.5 inches	2,620,165	2,233,582	15,022,750	1921.1	1370.8	$1,898,213	$26,395
Filter + 0.75 inches	2,633,061	2,318,823	15,124,020	1932.8	1423.0	$1,911,486	$39,668
Filter + 1.0 inches	2,646,068	2,404,166	15,225,390	1944.5	1475.2	$1,924,765	$52,947
Econo Err 3	2,506,973	2,023,921	14,613,530	1897.1	516.1	$1,836,210	$1,360
Econo Err 2	2,500,301	2,023,752	14,605,240	1897.1	516.1	$1,835,601	$751
Econo Err 1	2,496,747	2,023,664	14,600,960	1897.1	516.1	$1,835,110	$260
Econo Err 0	2,494,203	2,023,565	14,597,820	1897.1	516.1	$1,834,850	$0
Econo Err -1	2,494,325	2,023,539	14,598,220	1897.1	516.1	$1,834,888	$38
Econo Err -2	2,496,709	2,023,517	14,604,120	1897.1	516.1	$1,835,498	$648
Econo Err -3	2,503,244	2,023,723	14,617,940	1897.1	516.1	$1,836,566	$1,716
Econo Err -4	2,510,190	2,023,993	14,630,550	1897.1	516.1	$1,837,390	$2,540
Econo Err -5	2,518,833	2,024,466	14,644,210	1897.1	516.1	$1,838,247	$3,397
Econo Err -6	2,530,592	2,024,986	14,661,040	1897.1	516.1	$1,839,430	$4,580
Setpoint - 3.0 deg (70.0/67.0)	2,749,262	2,559,062	15,396,880	2059.8	1752.7	$1,924,571	$52,753
Setpoint - 2.0 deg (71.0/68.0)	2,684,794	2,355,482	15,149,450	2003.5	1578.2	$1,898,972	$27,154
Setpoint - 1.0 deg (72.0/69.0)	2,633,293	2,192,358	14,959,900	1945.3	1430.0	$1,880,964	$9,146
large	2,594,469	2,062,972	14,820,210	1897.8	1266.2	$1,871,818	$0
Setpoint + 1.0 deg (74.0/71.0)	2,568,162	1,960,741	14,727,860	1856.2	1133.8	$1,870,634	-$1,184
Setpoint + 2.0 deg (75.0/72.0)	2,553,060	1,883,319	14,686,110	1822.5	1023.6	$1,879,708	$7,890
Duct SP + 0.3 inches	2,609,844	2,165,310	14,941,340	1911.8	1329.0	$1,887,560	$15,742
Duct SP + 0.2 inches	2,604,618	2,131,230	14,901,190	1907.1	1308.0	$1,882,376	$10,558
Duct SP + 0.1 inches	2,599,511	2,097,084	14,860,560	1902.5	1287.1	$1,877,078	$5,260
large	2,594,469	2,062,972	14,820,210	1897.8	1266.2	$1,871,818	$0
Duct SP - 0.1 inches	2,589,157	2,028,825	14,779,880	1893.2	1245.3	$1,866,053	-$5,765
Duct SP - 0.2 inches	2,584,005	1,994,653	14,739,700	1888.5	1224.3	$1,860,777	-$11,041
Duct SP - 0.3 inches	2,578,845	1,960,444	14,699,170	1883.9	1203.4	$1,855,506	-$16,312
SAT 50 deg - cent/vane	3,019,976	1,792,623	15,187,340	1883.8	795.2	$1,919,335	$47,517
SAT 51 deg - cent/vane	2,917,536	1,824,829	15,068,060	1887.8	872.7	$1,900,742	$28,924
SAT 52 deg - cent/vane	2,824,460	1,866,338	14,969,410	1898.5	973.6	$1,886,199	$14,381
SAT 53 deg - cent/vane	2,740,357	1,918,184	14,896,070	1904.1	1064.3	$1,875,221	$3,403
SAT 54 deg - cent/vane	2,662,267	1,982,680	14,843,740	1897.8	1157.5	$1,870,858	-$960
large	2,594,469	2,062,972	14,820,210	1897.8	1266.2	$1,871,818	$0
SAT 56 deg - cent/vane	2,535,628	2,160,970	14,825,470	1901.6	1399.4	$1,876,653	$4,835
SAT 57 deg - cent/vane	2,489,028	2,280,112	14,869,380	1912.4	1531.0	$1,886,995	$15,177
SAT 58 deg - cent/vane	2,446,560	2,417,078	14,929,500	1927.9	1697.7	$1,901,764	$29,946
ChW 40, min SAT 55, Cent/Vane	2,837,872	2,062,972	15,087,750	2078.2	1266.2	$1,910,907	$39,089
ChW 41, min SAT 55, Cent/Vane	2,764,718	2,062,972	15,008,910	2023.9	1266.2	$1,899,442	$27,624

ChW 42, min SAT 55, Cent/Vane	2,700,127	2,062,972	14,937,460	1975.8	1266.2	$1,888,334	$16,516
ChW 43, min SAT 55, Cent/Vane	2,643,286	2,062,972	14,874,460	1933.8	1266.2	$1,879,479	$7,661
ChW 44, min SAT 55, Cent/Vane	2,594,469	2,062,972	14,820,210	1897.8	1266.2	$1,871,818	$0
ChW 45, min SAT 56, Cent/Vane	2,495,798	2,160,970	14,779,930	1871.5	1399.4	$1,870,207	-$1,611
ChW 46, min SAT 57, Cent/Vane	2,418,788	2,280,112	14,788,290	1857.5	1531.0	$1,875,339	$3,521
ChW 47, min SAT 58, Cent/Vane	2,353,944	2,417,078	14,818,630	1853.5	1697.7	$1,885,802	$13,984
SAT 50 deg - cent/vsd	3,192,216	1,792,623	15,406,210	2158.6	795.2	$1,956,432	$55,322
SAT 51 deg - cent/vsd	3,079,782	1,824,829	15,269,050	2164.6	872.7	$1,937,103	$35,993
SAT 52 deg - cent/vsd	2,972,932	1,866,338	15,153,250	2180.8	973.6	$1,921,339	$20,229
SAT 53 deg - cent/vsd	2,870,902	1,918,184	15,058,900	2189.4	1064.3	$1,909,203	$8,093
SAT 54 deg - cent/vsd	2,778,857	1,982,680	14,988,690	2179.8	1157.5	$1,902,272	$1,162
large	2,695,871	2,062,972	14,947,960	2179.8	1266.2	$1,901,110	$0
SAT 56 deg - cent/vsd	2,621,729	2,160,970	14,938,760	2185.6	1399.4	$1,905,663	$4,553
SAT 57 deg - cent/vsd	2,564,392	2,280,112	14,971,410	2201.8	1531.0	$1,915,166	$14,056
SAT 58 deg - cent/vsd	2,512,916	2,417,078	15,020,940	2225.2	1697.7	$1,929,599	$28,489
ChW 40, min SAT 55, Cent/VSD	2,867,384	2,062,972	15,211,000	2118.2	1266.2	$1,937,825	$36,715
ChW 41, min SAT 55, Cent/VSD	2,817,636	2,062,972	15,135,590	2175.8	1266.2	$1,929,098	$27,988
ChW 42, min SAT 55, Cent/VSD	2,773,575	2,062,972	15,066,840	2222.6	1266.2	$1,918,681	$17,571
ChW 43, min SAT 55, Cent/VSD	2,735,974	2,062,972	15,005,540	2244.9	1266.2	$1,910,797	$9,687
ChW 44, min SAT 55, Cent/VSD	2,695,871	2,062,972	14,947,960	2179.8	1266.2	$1,901,110	$0
ChW 45, min SAT 56, Cent/VSD	2,586,760	2,160,970	14,888,460	2128.4	1399.4	$1,897,428	-$3,682
ChW 46, min SAT 57, Cent/VSD	2,501,388	2,280,112	14,879,660	2093.3	1531.0	$1,901,614	$504
ChW 47, min SAT 58, Cent/VSD	2,426,589	2,417,078	14,893,410	2070.0	1697.7	$1,909,218	$8,108
SAT 50 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 51 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 52 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 53 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 54 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
large	0	0	0	0.0	0.0	$0	$0
SAT 56 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 57 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 58 deg - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 40 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 41 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 42 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 43 - recip/vsd	0	0	0	0.0	0.0	$0	$0
large	0	0	0	0.0	0.0	$0	$0
CHWS 45 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 46 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 47 - recip/vsd	0	0	0	0.0	0.0	$0	$0
Min OA 0.05 cfm/sf	2,468,034	2,052,283	14,637,570	1605.0	1257.1	$1,830,191	-$41,627
Min OA 0.10 cfm/sf	2,529,888	2,057,517	14,726,530	1747.9	1265.7	$1,851,457	-$20,361
large	2,594,469	2,062,972	14,820,210	1897.8	1266.2	$1,871,818	$0
Min OA 0.20 cfm/sf	2,657,846	2,068,167	14,914,270	2055.0	1271.6	$1,893,623	$21,805

Min OA 0.30 cfm/sf	2,785,696	2,076,106	15,104,760	2321.7	1284.5	$1,937,353	$65,535
VAV min 0.20	2,159,332	1,406,791	13,339,460	1883.7	1219.2	$1,635,915	-$235,903
VAV min 0.35	2,330,939	1,511,028	13,804,780	1889.0	1237.4	$1,721,830	-$149,988
VAV min 0.50	2,594,469	2,062,972	14,820,210	1897.8	1266.2	$1,871,818	$0
VAV min 0.65	3,013,442	3,214,657	16,632,590	1915.1	1319.5	$2,112,987	$241,169
VAV min 0.80	3,568,746	5,014,092	19,302,870	2260.7	1554.9	$2,463,620	$591,802
Zone SAT 65	5,507,064	5,252,293	22,305,690	2326.8	2082.7	$3,234,829	$1,363,011
Zone SAT 60	3,655,108	3,189,963	17,821,330	2326.8	1902.0	$2,528,816	$656,998
Zone SAT 55	2,594,469	2,062,972	14,820,210	1897.8	1266.2	$1,871,818	$0

Figure 4 - Fresno Medium Hospital Building - 250,000 sf - Constant Volume Air Handler

	kWh			kw		Cost	
	chiller	fan	total	chiller	fan	Total	Change
hosp	1,895,728	3,821,548	11,207,530	688.3	436.2	$1,596,599	$0
Filter + 0.25 inches	1,917,632	3,980,978	11,392,950	688.4	454.4	$1,618,047	$21,448
Filter + 0.5 inches	1,941,390	4,139,622	11,582,630	688.5	472.6	$1,640,506	$43,907
Filter + 0.75 inches	1,962,417	4,299,056	11,763,550	688.6	490.8	$1,662,067	$65,468
Filter + 1.0 inches	1,985,838	4,458,735	11,951,460	688.7	509.0	$1,683,882	$87,283
Econo Err 3	1,906,898	3,821,548	11,218,610	688.3	70.2	$1,598,140	$4,840
Econo Err 2	1,895,724	3,821,548	11,207,530	688.3	70.2	$1,596,591	$3,291
Econo Err 1	1,885,172	3,821,548	11,196,900	688.3	70.2	$1,595,183	$1,883
Econo Err 0	1,871,405	3,821,548	11,183,130	643.7	70.2	$1,593,300	$0
Econo Err -1	1,865,891	3,821,548	11,177,480	639.8	70.2	$1,592,575	-$725
Econo Err -2	1,857,178	3,821,548	11,170,140	542.4	70.2	$1,591,544	-$1,756
Econo Err -3	1,855,116	3,821,548	11,171,250	542.4	70.2	$1,591,416	-$1,884
Econo Err -4	1,851,253	3,821,548	11,169,640	486.7	70.2	$1,590,830	-$2,470
Econo Err -5	1,853,623	3,821,548	11,174,490	471.3	70.2	$1,590,957	-$2,343
Econo Err -6	1,860,153	3,821,548	11,184,520	471.3	70.2	$1,591,782	-$1,518
Setpoint - 3.0 deg (70.0/67.0)	1,785,104	3,821,548	11,011,240	687.0	436.2	$1,484,062	-$112,537
Setpoint - 2.0 deg (71.0/68.0)	1,819,333	3,821,548	11,080,800	687.4	436.2	$1,522,110	-$74,489
Setpoint - 1.0 deg (72.0/69.0)	1,854,520	3,821,548	11,143,350	687.8	436.2	$1,559,433	-$37,166
hosp	1,895,728	3,821,548	11,207,530	688.3	436.2	$1,596,599	$0
Setpoint + 1.0 deg (74.0/71.0)	1,934,942	3,821,548	11,264,290	688.8	436.2	$1,632,698	$36,099
Setpoint + 2.0 deg (75.0/72.0)	1,976,610	3,821,548	11,324,530	689.3	436.2	$1,669,289	$72,690
Duct SP + 0.3 inches	1,923,174	4,012,222	11,433,210	688.5	458.1	$1,622,895	$26,296
Duct SP + 0.2 inches	1,911,012	3,948,681	11,348,440	688.4	450.8	$1,613,262	$16,663
Duct SP + 0.1 inches	1,904,012	3,885,088	11,279,790	688.4	443.5	$1,605,088	$8,489
hosp	1,895,728	3,821,548	11,207,530	688.3	436.2	$1,596,599	$0
Duct SP - 0.1 inches	1,886,027	3,758,004	11,130,960	688.3	429.0	$1,587,645	-$8,954
Duct SP - 0.2 inches	1,878,503	3,694,404	11,061,210	688.3	421.7	$1,579,085	-$17,514
Duct SP - 0.3 inches	1,870,227	3,630,544	10,989,060	688.2	414.4	$1,570,797	-$25,802
SAT 50 deg - cent/vane	2,427,441	3,821,548	11,839,060	695.9	436.2	$1,745,515	$148,916
SAT 51 deg - cent/vane	2,321,000	3,821,548	11,714,900	696.0	436.2	$1,716,743	$120,144
SAT 52 deg - cent/vane	2,214,291	3,821,548	11,587,460	696.1	436.2	$1,687,192	$90,593
SAT 53 deg - cent/vane	2,107,133	3,821,548	11,460,290	696.2	436.2	$1,657,332	$60,733
SAT 54 deg - cent/vane	1,999,945	3,821,548	11,334,450	689.1	436.2	$1,627,205	$30,606
hosp	1,895,728	3,821,548	11,207,530	688.3	436.2	$1,596,599	$0
SAT 56 deg - cent/vane	1,799,715	3,821,548	11,101,200	687.7	436.2	$1,570,525	-$26,074
SAT 57 deg - cent/vane	1,707,116	3,821,548	10,980,030	655.7	436.2	$1,542,466	-$54,133
SAT 58 deg - cent/vane	1,614,153	3,821,548	10,852,020	604.2	436.2	$1,512,459	-$84,140
ChW 40, min SAT 55, Cent/Vane	2,068,404	3,821,548	11,387,090	704.5	436.2	$1,621,475	$24,876
ChW 41, min SAT 55, Cent/Vane	2,016,668	3,821,548	11,333,290	698.3	436.2	$1,614,025	$17,426
ChW 42, min SAT 55, Cent/Vane	1,970,642	3,821,548	11,285,660	692.8	436.2	$1,607,431	$10,832

ChW 43, min SAT 55, Cent/Vane	1,930,359	3,821,548	11,244,640	689.8	436.2	$1,601,735	$5,136
ChW 44, min SAT 55, Cent/Vane	1,895,728	3,821,548	11,207,530	688.3	436.2	$1,596,599	$0
ChW 45, min SAT 56, Cent/Vane	1,772,813	3,821,548	11,072,570	688.2	436.2	$1,566,563	-$30,036
ChW 46, min SAT 57, Cent/Vane	1,659,700	3,821,548	10,918,820	636.7	436.2	$1,533,869	-$62,730
ChW 47, min SAT 58, Cent/Vane	1,550,912	3,821,548	10,768,900	576.2	436.2	$1,500,586	-$96,013
SAT 50 deg - cent/vsd	2,541,853	3,821,548	11,955,020	751.3	436.2	$1,764,872	$172,593
SAT 51 deg - cent/vsd	2,397,196	3,821,548	11,795,130	751.6	436.2	$1,730,901	$138,622
SAT 52 deg - cent/vsd	2,255,896	3,821,548	11,632,730	751.9	436.2	$1,696,227	$103,948
SAT 53 deg - cent/vsd	2,115,557	3,821,548	11,474,300	752.2	436.2	$1,661,719	$69,440
SAT 54 deg - cent/vsd	1,978,751	3,821,548	11,317,890	752.5	436.2	$1,626,984	$34,705
hosp	1,845,371	3,821,548	11,163,600	752.9	436.2	$1,592,279	$0
SAT 56 deg - cent/vsd	1,726,808	3,821,548	11,034,020	753.2	436.2	$1,562,793	-$29,486
SAT 57 deg - cent/vsd	1,615,998	3,821,548	10,907,010	753.5	436.2	$1,533,850	-$58,429
SAT 58 deg - cent/vsd	1,534,880	3,821,548	10,802,920	694.5	436.2	$1,507,500	-$84,779
ChW 40, min SAT 55, Cent/VSD	2,006,547	3,821,548	11,337,150	660.7	436.2	$1,617,132	$24,853
ChW 41, min SAT 55, Cent/VSD	1,958,716	3,821,548	11,285,820	684.8	436.2	$1,609,781	$17,502
ChW 42, min SAT 55, Cent/VSD	1,917,923	3,821,548	11,241,120	708.1	436.2	$1,603,352	$11,073
ChW 43, min SAT 55, Cent/VSD	1,880,076	3,821,548	11,200,440	730.8	436.2	$1,597,561	$5,282
ChW 44, min SAT 55, Cent/VSD	1,845,371	3,821,548	11,163,600	752.9	436.2	$1,592,279	$0
ChW 45, min SAT 56, Cent/VSD	1,703,124	3,821,548	11,006,940	774.7	436.2	$1,559,001	-$33,278
ChW 46, min SAT 57, Cent/VSD	1,614,742	3,821,548	10,884,430	734.0	436.2	$1,530,795	-$61,484
ChW 47, min SAT 58, Cent/VSD	1,575,406	3,821,548	10,795,750	650.4	436.2	$1,507,291	-$84,988
SAT 50 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 51 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 52 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 53 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 54 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
hosp	0	0	0	0.0	0.0	$0	$0
SAT 56 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 57 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 58 deg - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 40 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 41 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 42 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 43 - recip/vsd	0	0	0	0.0	0.0	$0	$0
hosp	0	0	0	0.0	0.0	$0	$0
CHWS 45 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 46 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 47 - recip/vsd	0	0	0	0.0	0.0	$0	$0
Min OA 0.05 cfm/sf	1,872,150	3,821,548	11,185,300	687.4	436.2	$1,592,851	-$3,748
Min OA 0.10 cfm/sf	1,882,904	3,821,548	11,195,360	687.9	436.2	$1,594,779	-$1,820
hosp	1,895,728	3,821,548	11,207,530	688.3	436.2	$1,596,599	$0
Min OA 0.20 cfm/sf	1,917,573	3,821,548	11,231,920	688.8	436.2	$1,601,256	$4,657
Min OA 0.30 cfm/sf	1,966,447	3,821,548	11,279,780	689.8	436.2	$1,611,227	$14,628

VAV min 0.20	na	na	na	na	na	na	na
VAV min 0.35	na	na	na	na	na	na	na
VAV min 0.50	na	na	na	na	na	na	na
VAV min 0.65	na	na	na	na	na	na	na
VAV min 0.80	na	na	na	na	na	na	na
Zone SAT 65	1,941,222	3,821,548	11,255,500	688.9	436.2	$1,618,086	$21,487
Zone SAT 60	1,899,503	3,821,548	11,209,250	688.4	436.2	$1,599,441	$2,842
Zone SAT 55	1,895,728	3,821,548	11,207,530	688.3	436.2	$1,596,599	$0

Figure 5 - San Francisco Small Office Building - 50,000 sf

	kWh			kw		Cost	
	chiller	fan	total	chiller	fan	Total	Change
Baseline	89,622	52,956	620,341	80.8	35.3	$77,300	$0
Filter + 0.25 inches	90,038	55,155	622,965	81.2	36.8	$77,661	$361
Filter + 0.5 inches	90,460	57,356	625,609	81.7	38.2	$78,021	$721
Filter + 0.75 inches	90,882	59,555	628,252	82.2	39.6	$78,381	$1,081
Filter + 1.0 inches	91,290	61,755	630,861	82.6	41.0	$78,740	$1,440
Econo Err 3	91,179	53,006	621,969	103.7	7.4	$78,609	$1,384
Econo Err 2	90,583	52,984	621,341	103.7	7.4	$78,183	$958
Econo Err 1	90,066	52,962	620,795	103.5	7.4	$77,753	$528
Econo Err 0	89,346	52,944	620,057	80.7	7.4	$77,225	$0
Econo Err -1	89,086	52,931	619,779	80.7	7.4	$77,198	-$27
Econo Err -2	88,829	52,918	619,508	80.7	7.4	$77,166	-$59
Econo Err -3	88,723	52,911	619,396	78.9	7.4	$77,025	-$200
Econo Err -4	88,743	52,917	619,419	78.9	7.4	$77,021	-$204
Econo Err -5	89,020	52,948	619,727	78.9	7.4	$77,046	-$179
Econo Err -6	89,479	52,996	620,226	78.9	7.4	$77,087	-$138
Setpoint - 3.0 deg (70.0/67.0)	99,370	69,012	641,571	103.4	53.9	$80,081	$2,781
Setpoint - 2.0 deg (71.0/68.0)	95,185	61,978	631,774	101.3	47.8	$78,791	$1,491
Setpoint - 1.0 deg (72.0/69.0)	91,979	56,742	624,819	88.9	40.8	$77,764	$464
Baseline	89,622	52,956	620,341	80.8	35.3	$77,300	$0
Setpoint + 1.0 deg (74.0/71.0)	87,844	50,256	617,652	75.8	29.8	$77,308	$8
Setpoint + 2.0 deg (75.0/72.0)	86,573	48,385	616,308	73.2	25.9	$77,727	$427
Duct SP + 0.3 inches	90,120	55,594	623,485	81.3	37.0	$77,732	$432
Duct SP + 0.2 inches	89,956	54,715	622,446	81.1	36.5	$77,589	$289
Duct SP + 0.1 inches	89,786	53,835	621,385	81.0	35.9	$77,444	$144
Baseline	89,622	52,956	620,341	80.8	35.3	$77,300	$0
Duct SP - 0.1 inches	89,438	52,077	619,245	80.6	34.8	$77,154	-$146
Duct SP - 0.2 inches	89,262	51,197	618,166	80.4	34.2	$77,008	-$292
Duct SP - 0.3 inches	89,091	50,315	617,100	80.2	33.6	$76,862	-$438
SAT 50 deg - cent/vane	104,781	47,506	633,370	84.0	21.5	$79,371	$2,071
SAT 51 deg - cent/vane	101,511	48,156	630,140	83.3	23.2	$78,723	$1,423
SAT 52 deg - cent/vane	98,357	48,979	627,181	82.6	25.1	$78,246	$946
SAT 53 deg - cent/vane	95,299	50,028	624,478	82.0	27.5	$77,779	$479
SAT 54 deg - cent/vane	92,417	51,334	622,220	81.3	31.0	$77,454	$154
Baseline	89,622	52,956	620,341	80.8	35.3	$77,300	$0
SAT 56 deg - cent/vane	86,699	54,956	618,577	80.7	39.2	$77,305	$5
SAT 57 deg - cent/vane	83,870	57,516	617,496	82.5	45.2	$77,554	$254
SAT 58 deg - cent/vane	80,645	60,658	615,956	83.2	49.8	$77,795	$495
ChW 40, min SAT 55, Cent/Vane	95,950	52,956	626,686	88.2	35.3	$78,480	$1,180
ChW 41, min SAT 55, Cent/Vane	94,015	52,956	624,746	85.9	35.3	$78,120	$820
ChW 42, min SAT 55, Cent/Vane	92,313	52,956	623,039	84.0	35.3	$77,803	$503

ChW 43, min SAT 55, Cent/Vane	90,848	52,956	621,570	82.2	35.3	$77,530	$230
ChW 44, min SAT 55, Cent/Vane	89,622	52,956	620,341	80.8	35.3	$77,300	$0
ChW 45, min SAT 56, Cent/Vane	85,740	54,956	617,615	79.5	39.2	$77,122	-$178
ChW 46, min SAT 57, Cent/Vane	82,248	57,516	615,869	80.3	45.2	$77,235	-$65
ChW 47, min SAT 58, Cent/Vane	78,610	60,658	613,916	80.2	49.8	$77,384	$84
SAT 50 deg - cent/vsd	86,054	47,506	614,600	95.2	21.5	$78,408	$2,629
SAT 51 deg - cent/vsd	81,732	48,156	610,315	94.1	23.2	$77,615	$1,836
SAT 52 deg - cent/vsd	77,651	48,979	606,428	93.0	25.1	$77,024	$1,245
SAT 53 deg - cent/vsd	73,820	50,028	602,949	92.1	27.5	$76,445	$666
SAT 54 deg - cent/vsd	70,232	51,334	599,984	91.0	31.0	$76,017	$238
Baseline	66,857	52,956	597,523	90.3	35.3	$75,779	$0
SAT 56 deg - cent/vsd	63,631	54,956	595,456	90.2	39.2	$75,724	-$55
SAT 57 deg - cent/vsd	60,670	57,516	594,243	92.9	45.2	$75,944	$165
SAT 58 deg - cent/vsd	57,683	60,658	592,942	93.9	49.8	$76,171	$392
ChW 40, min SAT 55, Cent/VSD	70,485	52,956	601,162	96.8	35.3	$76,880	$1,101
ChW 41, min SAT 55, Cent/VSD	69,361	52,956	600,035	98.5	35.3	$76,630	$851
ChW 42, min SAT 55, Cent/VSD	68,394	52,956	599,065	95.4	35.3	$76,306	$527
ChW 43, min SAT 55, Cent/VSD	67,565	52,956	598,233	92.7	35.3	$76,024	$245
ChW 44, min SAT 55, Cent/VSD	66,857	52,956	597,523	90.3	35.3	$75,779	$0
ChW 45, min SAT 56, Cent/VSD	63,081	54,956	594,904	88.1	39.2	$75,517	-$262
ChW 46, min SAT 57, Cent/VSD	59,737	57,516	593,307	88.8	45.2	$75,563	-$216
ChW 47, min SAT 58, Cent/VSD	56,492	60,658	591,747	87.9	49.8	$75,654	-$125
SAT 50 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 51 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 52 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 53 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 54 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
Baseline	0	0	0	0.0	0.0	$0	$0
SAT 56 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 57 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 58 deg - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 40 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 41 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 42 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 43 - recip/vsd	0	0	0	0.0	0.0	$0	$0
Baseline	0	0	0	0.0	0.0	$0	$0
CHWS 45 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 46 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 47 - recip/vsd	0	0	0	0.0	0.0	$0	$0
Min OA 0.05 cfm/sf	88,387	52,820	618,581	77.2	34.0	$76,533	-$767
Min OA 0.10 cfm/sf	89,009	52,889	619,462	79.1	34.7	$76,888	-$412
Baseline	89,622	52,956	620,341	80.8	35.3	$77,300	$0
Min OA 0.20 cfm/sf	90,270	53,023	621,247	86.7	35.9	$77,788	$488
Min OA 0.30 cfm/sf	91,622	53,147	622,916	103.7	36.8	$78,919	$1,619

VAV min 0.20	80,097	34,025	582,201	78.7	34.1	$70,595	-$6,705
VAV min 0.35	83,046	37,997	593,231	78.7	34.6	$72,842	-$4,458
VAV min 0.50	89,622	52,956	620,341	80.8	35.3	$77,300	$0
VAV min 0.65	101,083	84,375	668,675	92.8	38.5	$84,984	$7,684
VAV min 0.80	119,472	135,468	743,028	103.4	46.5	$96,940	$19,640
Zone SAT 65	215,417	235,114	968,649	104.7	65.1	$144,065	$66,765
Zone SAT 60	136,350	141,348	782,998	104.8	65.1	$115,275	$37,975
Zone SAT 55	89,622	52,956	620,341	80.8	35.3	$77,300	$0

Figure 6 - San Francisco Medium Office Building - 250,000 sf

	kWh			kw		Cost	
	chiller	fan	total	chiller	fan	Total	Change
medium	285,590	287,174	2,941,157	340.3	203.8	$364,154	$0
Filter + 0.25 inches	287,580	299,043	2,955,489	342.7	212.0	$366,187	$2,033
Filter + 0.5 inches	289,569	310,957	2,969,778	345.0	220.2	$368,210	$4,056
Filter + 0.75 inches	291,571	322,880	2,984,287	347.3	228.5	$370,251	$6,097
Filter + 1.0 inches	293,564	334,804	2,998,719	349.7	236.7	$372,282	$8,128
Econo Err 3	293,705	287,553	2,951,296	382.7	83.4	$370,338	$6,566
Econo Err 2	291,016	287,400	2,947,880	382.7	83.4	$367,880	$4,108
Econo Err 1	288,556	287,263	2,944,740	382.7	83.4	$365,916	$2,144
Econo Err 0	284,668	287,117	2,939,580	340.2	83.4	$363,772	$0
Econo Err -1	283,331	287,028	2,937,397	340.2	83.4	$363,563	-$209
Econo Err -2	281,644	286,908	2,934,287	340.2	83.4	$363,209	-$563
Econo Err -3	280,999	286,849	2,933,138	328.0	83.4	$362,571	-$1,201
Econo Err -4	281,078	286,875	2,933,152	328.0	83.4	$362,521	-$1,251
Econo Err -5	282,579	287,050	2,935,101	328.0	83.4	$362,681	-$1,091
Econo Err -6	285,414	287,344	2,938,880	328.0	83.4	$362,969	-$803
Setpoint - 3.0 deg (70.0/67.0)	334,432	378,928	3,071,713	381.1	288.8	$378,893	$14,739
Setpoint - 2.0 deg (71.0/68.0)	314,638	340,612	3,015,474	381.0	256.3	$372,465	$8,311
Setpoint - 1.0 deg (72.0/69.0)	298,180	310,050	2,972,289	380.7	230.9	$367,853	$3,699
medium	285,590	287,174	2,941,157	340.3	203.8	$364,154	$0
Setpoint + 1.0 deg (74.0/71.0)	275,540	270,060	2,918,343	314.2	176.1	$362,137	-$2,017
Setpoint + 2.0 deg (75.0/72.0)	268,051	258,025	2,904,620	301.9	150.0	$362,305	-$1,849
Duct SP + 0.3 inches	287,975	301,427	2,958,315	343.1	213.7	$366,590	$2,436
Duct SP + 0.2 inches	287,178	296,657	2,952,591	342.2	210.4	$365,780	$1,626
Duct SP + 0.1 inches	286,392	291,948	2,946,919	341.2	207.1	$364,970	$816
medium	285,590	287,174	2,941,157	340.3	203.8	$364,154	$0
Duct SP - 0.1 inches	284,788	282,405	2,935,441	339.4	200.5	$363,345	-$809
Duct SP - 0.2 inches	283,982	277,635	2,929,644	338.4	197.1	$362,530	-$1,624
Duct SP - 0.3 inches	283,169	272,860	2,923,691	337.5	193.8	$361,702	-$2,452
SAT 50 deg - cent/vane	357,247	250,374	3,007,849	349.7	122.3	$371,487	$7,333
SAT 51 deg - cent/vane	341,325	255,090	2,989,739	347.3	132.2	$368,773	$4,619
SAT 52 deg - cent/vane	326,258	260,861	2,974,055	345.3	143.6	$366,762	$2,608
SAT 53 deg - cent/vane	311,942	267,899	2,960,071	342.5	160.5	$364,986	$832
SAT 54 deg - cent/vane	298,382	276,500	2,949,261	340.6	181.4	$364,118	-$36
medium	285,590	287,174	2,941,157	340.3	203.8	$364,154	$0
SAT 56 deg - cent/vane	273,325	300,261	2,935,946	344.1	227.4	$365,009	$855
SAT 57 deg - cent/vane	262,073	316,330	2,934,980	347.0	244.1	$366,143	$1,989
SAT 58 deg - cent/vane	251,227	335,749	2,936,007	333.1	273.5	$367,137	$2,983
ChW 40, min SAT 55, Cent/Vane	310,676	287,174	2,968,630	373.4	203.8	$369,363	$5,209
ChW 41, min SAT 55, Cent/Vane	303,167	287,174	2,960,780	363.4	203.8	$367,831	$3,677
ChW 42, min SAT 55, Cent/Vane	296,490	287,174	2,953,542	354.6	203.8	$366,451	$2,297

ChW 43, min SAT 55, Cent/Vane	290,624	287,174	2,946,786	346.9	203.8	$365,209	$1,055
ChW 44, min SAT 55, Cent/Vane	285,590	287,174	2,941,157	340.3	203.8	$364,154	$0
ChW 45, min SAT 56, Cent/Vane	269,335	300,261	2,931,358	338.5	227.4	$364,147	-$7
ChW 46, min SAT 57, Cent/Vane	255,287	316,330	2,927,148	336.8	244.1	$364,583	$429
ChW 47, min SAT 58, Cent/Vane	242,715	335,749	2,926,002	320.3	273.5	$365,176	$1,022
SAT 50 deg - cent/vsd	350,982	250,374	3,005,355	406.8	122.3	$374,674	$9,006
SAT 51 deg - cent/vsd	332,021	255,090	2,984,274	406.9	132.2	$371,622	$5,954
SAT 52 deg - cent/vsd	314,675	260,861	2,965,396	404.4	143.6	$369,216	$3,548
SAT 53 deg - cent/vsd	297,350	267,899	2,948,654	400.3	160.5	$367,144	$1,476
SAT 54 deg - cent/vsd	281,229	276,500	2,934,623	397.4	181.4	$365,984	$316
medium	265,980	287,174	2,924,028	397.0	203.8	$365,668	$0
SAT 56 deg - cent/vsd	251,528	300,261	2,916,812	402.6	227.4	$366,314	$646
SAT 57 deg - cent/vsd	238,782	316,330	2,913,953	406.9	244.1	$367,178	$1,510
SAT 58 deg - cent/vsd	226,462	335,749	2,913,067	386.3	273.5	$367,861	$2,193
ChW 40, min SAT 55, Cent/VSD	284,128	287,174	2,948,876	352.8	203.8	$369,829	$4,161
ChW 41, min SAT 55, Cent/VSD	278,590	287,174	2,941,569	366.9	203.8	$368,666	$2,998
ChW 42, min SAT 55, Cent/VSD	274,051	287,174	2,935,044	379.9	203.8	$367,612	$1,944
ChW 43, min SAT 55, Cent/VSD	269,687	287,174	2,929,206	393.6	203.8	$366,799	$1,131
ChW 44, min SAT 55, Cent/VSD	265,980	287,174	2,924,028	397.0	203.8	$365,668	$0
ChW 45, min SAT 56, Cent/VSD	248,780	300,261	2,912,556	392.3	227.4	$365,171	-$497
ChW 46, min SAT 57, Cent/VSD	233,595	316,330	2,906,404	387.1	244.1	$365,072	-$596
ChW 47, min SAT 58, Cent/VSD	219,705	335,749	2,903,201	360.3	273.5	$365,140	-$528
SAT 50 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 51 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 52 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 53 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 54 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
medium	0	0	0	0.0	0.0	$0	$0
SAT 56 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 57 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 58 deg - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 40 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 41 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 42 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 43 - recip/vsd	0	0	0	0.0	0.0	$0	$0
medium	0	0	0	0.0	0.0	$0	$0
CHWS 45 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 46 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 47 - recip/vsd	0	0	0	0.0	0.0	$0	$0
Min OA 0.05 cfm/sf	279,849	286,277	2,929,882	323.7	196.5	$359,802	-$4,352
Min OA 0.10 cfm/sf	282,796	286,733	2,936,302	332.4	200.2	$361,875	-$2,279
medium	285,590	287,174	2,941,157	340.3	203.8	$364,154	$0
Min OA 0.20 cfm/sf	288,493	287,603	2,946,067	362.2	207.1	$366,757	$2,603
Min OA 0.30 cfm/sf	294,630	288,446	2,954,786	384.9	213.6	$371,711	$7,557

VAV min 0.20	246,431	191,274	2,753,527	326.9	198.1	$332,197	-$31,957
VAV min 0.35	257,905	212,027	2,807,316	327.7	200.2	$342,567	-$21,587
VAV min 0.50	285,590	287,174	2,941,157	340.3	203.8	$364,154	$0
VAV min 0.65	337,225	442,122	3,183,979	380.8	212.7	$400,380	$36,226
VAV min 0.80	419,237	695,897	3,561,236	381.2	250.5	$454,663	$90,509
Zone SAT 65	829,896	1,179,480	4,692,107	384.9	325.4	$689,392	$325,238
Zone SAT 60	486,010	706,989	3,710,312	384.9	325.4	$538,522	$174,368
Zone SAT 55	285,590	287,174	2,941,157	340.3	203.8	$364,154	$0

Figure 7 - San Francisco Large Office Building - 1,000,000 sf

	kWh			kw		Cost	
	chiller	fan	total	chiller	fan	Total	Change
large	1,156,611	1,219,406	11,829,220	1513.4	930.9	$1,497,297	$0
Filter + 0.25 inches	1,165,545	1,270,082	11,890,890	1525.0	969.4	$1,506,589	$9,292
Filter + 0.5 inches	1,174,391	1,320,628	11,952,990	1536.6	1007.9	$1,516,105	$18,808
Filter + 0.75 inches	1,183,250	1,371,262	12,015,060	1548.2	1046.4	$1,525,701	$28,404
Filter + 1.0 inches	1,192,235	1,421,884	12,076,520	1559.7	1084.9	$1,534,985	$37,688
Econo Err 3	1,197,048	1,221,634	11,884,890	1626.5	357.6	$1,526,722	$30,975
Econo Err 2	1,185,517	1,220,853	11,868,490	1626.5	356.6	$1,519,991	$24,244
Econo Err 1	1,173,091	1,220,089	11,850,830	1626.5	356.6	$1,510,388	$14,641
Econo Err 0	1,153,803	1,219,249	11,825,650	1513.4	358.0	$1,495,747	$0
Econo Err -1	1,146,856	1,218,755	11,815,730	1513.1	358.0	$1,494,797	-$950
Econo Err -2	1,138,756	1,218,152	11,805,240	1513.0	358.0	$1,493,249	-$2,498
Econo Err -3	1,132,157	1,217,742	11,797,550	1380.7	358.0	$1,489,714	-$6,033
Econo Err -4	1,131,998	1,217,768	11,797,490	1380.8	358.0	$1,489,390	-$6,357
Econo Err -5	1,136,135	1,218,440	11,805,060	1380.8	358.0	$1,490,016	-$5,731
Econo Err -6	1,147,150	1,219,888	11,823,850	1380.8	358.0	$1,491,328	-$4,419
Setpoint - 3.0 deg (70.0/67.0)	1,367,874	1,587,747	12,387,890	1619.2	1284.4	$1,555,387	$58,090
Setpoint - 2.0 deg (71.0/68.0)	1,285,853	1,438,506	12,160,680	1618.9	1149.4	$1,527,190	$29,893
Setpoint - 1.0 deg (72.0/69.0)	1,215,502	1,315,656	11,971,790	1618.1	1031.5	$1,509,500	$12,203
large	1,156,611	1,219,406	11,829,220	1513.4	930.9	$1,497,297	$0
Setpoint + 1.0 deg (74.0/71.0)	1,109,047	1,146,329	11,727,170	1366.1	830.3	$1,487,375	-$9,922
Setpoint + 2.0 deg (75.0/72.0)	1,072,236	1,090,686	11,659,380	1307.4	745.2	$1,481,652	-$15,645
Duct SP + 0.3 inches	1,167,370	1,280,217	11,903,310	1527.3	977.1	$1,508,457	$11,160
Duct SP + 0.2 inches	1,163,761	1,259,951	11,878,400	1522.7	961.7	$1,504,717	$7,420
Duct SP + 0.1 inches	1,160,205	1,239,677	11,853,710	1518.1	946.3	$1,500,990	$3,693
large	1,156,611	1,219,406	11,829,220	1513.4	930.9	$1,497,297	$0
Duct SP - 0.1 inches	1,153,054	1,199,160	11,804,520	1508.8	915.5	$1,493,590	-$3,707
Duct SP - 0.2 inches	1,149,527	1,178,925	11,779,490	1504.1	900.1	$1,489,859	-$7,438
Duct SP - 0.3 inches	1,146,011	1,158,650	11,754,740	1499.4	884.6	$1,486,149	-$11,148
SAT 50 deg - cent/vane	1,468,089	1,056,091	12,124,420	1510.4	582.4	$1,521,937	$24,640
SAT 51 deg - cent/vane	1,399,232	1,077,001	12,042,890	1501.8	639.7	$1,511,406	$14,109
SAT 52 deg - cent/vane	1,333,678	1,103,283	11,973,190	1491.7	715.6	$1,504,119	$6,822
SAT 53 deg - cent/vane	1,271,606	1,135,298	11,915,710	1490.9	791.6	$1,500,383	$3,086
SAT 54 deg - cent/vane	1,212,267	1,173,261	11,864,910	1492.2	853.0	$1,497,356	$59
large	1,156,611	1,219,406	11,829,220	1513.4	930.9	$1,497,297	$0
SAT 56 deg - cent/vane	1,104,864	1,274,559	11,807,200	1502.0	1008.4	$1,496,068	-$1,229
SAT 57 deg - cent/vane	1,054,373	1,339,490	11,796,550	1436.0	1095.1	$1,496,965	-$332
SAT 58 deg - cent/vane	1,004,774	1,414,916	11,789,900	1375.8	1190.3	$1,498,168	$871
ChW 40, min SAT 55, Cent/Vane	1,264,947	1,219,406	11,952,260	1653.3	930.9	$1,521,307	$24,010
ChW 41, min SAT 55, Cent/Vane	1,232,828	1,219,406	11,915,250	1617.9	930.9	$1,514,354	$17,057
ChW 42, min SAT 55, Cent/Vane	1,204,008	1,219,406	11,882,980	1578.0	930.9	$1,508,167	$10,870

ChW 43, min SAT 55, Cent/Vane	1,178,546	1,219,406	11,854,030	1543.2	930.9	$1,502,177	$4,880
ChW 44, min SAT 55, Cent/Vane	1,156,611	1,219,406	11,829,220	1513.4	930.9	$1,497,297	$0
ChW 45, min SAT 56, Cent/Vane	1,087,389	1,274,559	11,787,370	1477.4	1008.4	$1,492,253	-$5,044
ChW 46, min SAT 57, Cent/Vane	1,024,691	1,339,490	11,762,690	1394.5	1095.1	$1,489,634	-$7,663
ChW 47, min SAT 58, Cent/Vane	967,636	1,414,916	11,745,920	1324.0	1190.3	$1,488,303	-$8,994
SAT 50 deg - cent/vsd	1,504,480	1,056,091	12,187,350	1729.3	582.4	$1,543,725	$28,956
SAT 51 deg - cent/vsd	1,433,687	1,077,001	12,099,030	1729.5	639.7	$1,533,077	$18,308
SAT 52 deg - cent/vsd	1,361,094	1,103,283	12,019,640	1729.7	715.6	$1,525,045	$10,276
SAT 53 deg - cent/vsd	1,288,937	1,135,298	11,950,250	1729.8	791.6	$1,519,933	$5,164
SAT 54 deg - cent/vsd	1,220,618	1,173,261	11,890,200	1729.7	853.0	$1,516,353	$1,584
large	1,156,371	1,219,406	11,844,830	1729.6	930.9	$1,514,769	$0
SAT 56 deg - cent/vsd	1,094,888	1,274,559	11,811,980	1729.7	1008.4	$1,511,981	-$2,788
SAT 57 deg - cent/vsd	1,035,587	1,339,490	11,792,090	1671.8	1095.1	$1,511,111	-$3,658
SAT 58 deg - cent/vsd	978,964	1,414,916	11,776,580	1582.4	1190.3	$1,511,353	-$3,416
ChW 40, min SAT 55, Cent/VSD	1,223,696	1,219,406	11,955,730	1495.8	930.9	$1,532,584	$17,815
ChW 41, min SAT 55, Cent/VSD	1,201,375	1,219,406	11,922,930	1555.8	930.9	$1,528,261	$13,492
ChW 42, min SAT 55, Cent/VSD	1,185,867	1,219,406	11,894,340	1614.1	930.9	$1,523,503	$8,734
ChW 43, min SAT 55, Cent/VSD	1,169,823	1,219,406	11,868,120	1672.5	930.9	$1,519,474	$4,705
ChW 44, min SAT 55, Cent/VSD	1,156,371	1,219,406	11,844,830	1729.6	930.9	$1,514,769	$0
ChW 45, min SAT 56, Cent/VSD	1,084,209	1,274,559	11,792,630	1723.9	1008.4	$1,507,484	-$7,285
ChW 46, min SAT 57, Cent/VSD	1,015,405	1,339,490	11,757,560	1591.6	1095.1	$1,502,091	-$12,678
ChW 47, min SAT 58, Cent/VSD	951,286	1,414,916	11,730,660	1477.6	1190.3	$1,499,678	-$15,091
SAT 50 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 51 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 52 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 53 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 54 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
large	0	0	0	0.0	0.0	$0	$0
SAT 56 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 57 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 58 deg - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 40 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 41 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 42 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 43 - recip/vsd	0	0	0	0.0	0.0	$0	$0
large	0	0	0	0.0	0.0	$0	$0
CHWS 45 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 46 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 47 - recip/vsd	0	0	0	0.0	0.0	$0	$0
Min OA 0.05 cfm/sf	1,130,707	1,215,160	11,781,890	1412.4	922.6	$1,476,237	-$21,060
Min OA 0.10 cfm/sf	1,144,004	1,217,304	11,805,510	1472.9	927.9	$1,487,284	-$10,013
large	1,156,611	1,219,406	11,829,220	1513.4	930.9	$1,497,297	$0
Min OA 0.20 cfm/sf	1,168,974	1,221,458	11,850,210	1551.4	933.7	$1,508,601	$11,304
Min OA 0.30 cfm/sf	1,194,673	1,225,424	11,889,250	1635.7	939.1	$1,529,045	$31,748

VAV min 0.20	985,510	828,634	11,041,680	1466.3	907.9	$1,363,300	-$133,997
VAV min 0.35	1,041,213	904,266	11,266,810	1483.9	916.7	$1,409,458	-$87,839
VAV min 0.50	1,156,611	1,219,406	11,829,220	1513.4	930.9	$1,497,297	$0
VAV min 0.65	1,378,129	1,867,593	12,860,900	1618.1	957.1	$1,644,565	$147,268
VAV min 0.80	1,704,736	2,898,514	14,416,130	1619.8	1064.6	$1,860,151	$362,854
Zone SAT 65	3,176,979	4,557,252	18,347,760	1635.6	1301.7	$2,742,025	$1,244,728
Zone SAT 60	1,873,386	2,579,788	14,631,200	1635.8	1301.7	$2,167,631	$670,334
Zone SAT 55	1,156,611	1,219,406	11,829,220	1513.4	930.9	$1,497,297	$0

Figure 8 - San Francisco Medium Hospital Building - 250,000 sf - Constant Volume Air Handler

	kWh			kw		Cost	
	chiller	fan	total	chiller	fan	Total	Change
hosp	954,036	2,729,539	8,784,498	504.3	311.6	$1,214,797	$0
Filter + 0.25 inches	970,000	2,843,273	8,915,809	504.3	324.6	$1,230,104	$15,307
Filter + 0.5 inches	994,319	2,957,092	9,071,387	504.4	337.6	$1,248,304	$33,507
Filter + 0.75 inches	1,013,388	3,070,558	9,209,216	504.5	350.6	$1,264,511	$49,714
Filter + 1.0 inches	1,031,405	3,184,398	9,343,949	504.6	363.5	$1,280,375	$65,578
Econo Err 3	960,511	2,729,539	8,790,839	508.6	49.6	$1,215,479	$1,958
Econo Err 2	954,034	2,729,539	8,784,496	504.3	48.5	$1,214,797	$1,276
Econo Err 1	948,305	2,729,539	8,778,755	504.3	48.5	$1,214,171	$650
Econo Err 0	942,526	2,729,539	8,773,100	504.3	48.5	$1,213,521	$0
Econo Err -1	930,343	2,729,539	8,760,795	454.9	48.5	$1,212,076	-$1,445
Econo Err -2	924,031	2,729,539	8,754,831	435.2	48.5	$1,211,355	-$2,166
Econo Err -3	916,489	2,729,539	8,747,338	423.2	48.5	$1,210,226	-$3,295
Econo Err -4	910,037	2,729,539	8,740,878	398.1	48.5	$1,209,171	-$4,350
Econo Err -5	906,432	2,729,539	8,737,519	389.6	48.5	$1,208,394	-$5,127
Econo Err -6	904,669	2,729,539	8,736,216	367.9	48.5	$1,207,842	-$5,679
Setpoint - 3.0 deg (70.0/67.0)	947,518	2,729,539	8,732,454	503.4	311.6	$1,143,009	-$71,788
Setpoint - 2.0 deg (71.0/68.0)	949,252	2,729,539	8,752,074	503.6	311.6	$1,167,146	-$47,651
Setpoint - 1.0 deg (72.0/69.0)	949,687	2,729,539	8,765,520	503.9	311.6	$1,190,541	-$24,256
hosp	954,036	2,729,539	8,784,498	504.3	311.6	$1,214,797	$0
Setpoint + 1.0 deg (74.0/71.0)	958,162	2,729,539	8,802,067	504.6	311.6	$1,238,585	$23,788
Setpoint + 2.0 deg (75.0/72.0)	962,776	2,729,539	8,820,818	504.9	311.6	$1,262,435	$47,638
Duct SP + 0.3 inches	974,970	2,866,108	8,947,749	504.3	327.2	$1,233,943	$19,146
Duct SP + 0.2 inches	966,432	2,820,710	8,888,496	504.3	322.0	$1,226,891	$12,094
Duct SP + 0.1 inches	959,972	2,774,924	8,835,336	504.3	316.8	$1,220,707	$5,910
hosp	954,036	2,729,539	8,784,498	504.3	311.6	$1,214,797	$0
Duct SP - 0.1 inches	947,136	2,684,247	8,730,892	504.2	306.4	$1,208,482	-$6,315
Duct SP - 0.2 inches	940,999	2,638,786	8,679,478	504.2	301.2	$1,202,296	-$12,501
Duct SP - 0.3 inches	934,252	2,593,012	8,625,946	504.2	296.0	$1,196,116	-$18,681
SAT 50 deg - cent/vane	1,304,612	2,729,539	9,194,472	506.4	311.6	$1,302,443	$87,646
SAT 51 deg - cent/vane	1,232,977	2,729,539	9,109,312	506.4	311.6	$1,284,239	$69,442
SAT 52 deg - cent/vane	1,161,635	2,729,539	9,025,695	505.6	311.6	$1,266,598	$51,801
SAT 53 deg - cent/vane	1,091,072	2,729,539	8,944,639	505.6	311.6	$1,249,397	$34,600
SAT 54 deg - cent/vane	1,021,470	2,729,539	8,863,313	504.7	311.6	$1,232,011	$17,214
hosp	954,036	2,729,539	8,784,498	504.3	311.6	$1,214,797	$0
SAT 56 deg - cent/vane	888,448	2,729,539	8,709,558	503.8	311.6	$1,198,532	-$16,265
SAT 57 deg - cent/vane	825,544	2,729,539	8,639,997	477.1	311.6	$1,183,179	-$31,618
SAT 58 deg - cent/vane	765,957	2,729,539	8,572,381	438.7	311.6	$1,168,068	-$46,729
ChW 40, min SAT 55, Cent/Vane	1,040,179	2,729,539	8,873,379	515.2	311.6	$1,227,196	$12,399
ChW 41, min SAT 55, Cent/Vane	1,014,412	2,729,539	8,846,892	510.9	311.6	$1,223,496	$8,699

ChW 42, min SAT 55, Cent/Vane	991,472	2,729,539	8,823,237	507.5	311.6	$1,220,195	$5,398
ChW 43, min SAT 55, Cent/Vane	971,335	2,729,539	8,802,409	505.3	311.6	$1,217,287	$2,490
ChW 44, min SAT 55, Cent/Vane	954,036	2,729,539	8,784,498	504.3	311.6	$1,214,797	$0
ChW 45, min SAT 56, Cent/Vane	875,308	2,729,539	8,695,946	504.0	311.6	$1,196,635	-$18,162
ChW 46, min SAT 57, Cent/Vane	804,130	2,729,539	8,617,022	463.1	311.6	$1,179,953	-$34,844
ChW 47, min SAT 58, Cent/Vane	740,110	2,729,539	8,543,037	422.4	311.6	$1,163,925	-$50,872
SAT 50 deg - cent/vsd	1,357,397	2,729,539	9,250,119	546.2	311.6	$1,312,098	$101,375
SAT 51 deg - cent/vsd	1,265,195	2,729,539	9,144,154	545.9	311.6	$1,290,950	$80,227
SAT 52 deg - cent/vsd	1,173,639	2,729,539	9,040,743	546.4	311.6	$1,270,442	$59,719
SAT 53 deg - cent/vsd	1,084,504	2,729,539	8,940,550	547.0	311.6	$1,250,470	$39,747
SAT 54 deg - cent/vsd	995,484	2,729,539	8,839,958	547.6	311.6	$1,230,341	$19,618
hosp	910,898	2,729,539	8,744,165	547.7	311.6	$1,210,723	$0
SAT 56 deg - cent/vsd	831,900	2,729,539	8,655,470	547.8	311.6	$1,192,510	-$18,213
SAT 57 deg - cent/vsd	755,606	2,729,539	8,572,443	545.9	311.6	$1,175,291	-$35,432
SAT 58 deg - cent/vsd	684,653	2,729,539	8,494,245	505.3	311.6	$1,158,755	-$51,968
ChW 40, min SAT 55, Cent/VSD	983,730	2,729,539	8,823,148	481.3	311.6	$1,222,031	$11,308
ChW 41, min SAT 55, Cent/VSD	961,995	2,729,539	8,799,835	499.2	311.6	$1,218,695	$7,972
ChW 42, min SAT 55, Cent/VSD	943,261	2,729,539	8,779,351	515.8	311.6	$1,215,756	$5,033
ChW 43, min SAT 55, Cent/VSD	926,374	2,729,539	8,760,900	531.9	311.6	$1,213,103	$2,380
ChW 44, min SAT 55, Cent/VSD	910,898	2,729,539	8,744,165	547.7	311.6	$1,210,723	$0
ChW 45, min SAT 56, Cent/VSD	821,008	2,729,539	8,643,155	562.1	311.6	$1,190,747	-$19,976
ChW 46, min SAT 57, Cent/VSD	739,111	2,729,539	8,553,191	535.0	311.6	$1,172,555	-$38,168
ChW 47, min SAT 58, Cent/VSD	673,348	2,729,539	8,476,572	472.5	311.6	$1,156,318	-$54,405
SAT 50 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 51 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 52 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 53 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 54 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
hosp	0	0	0	0.0	0.0	$0	$0
SAT 56 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 57 deg -recip/vsd	0	0	0	0.0	0.0	$0	$0
SAT 58 deg - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 40 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 41 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 42 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 43 - recip/vsd	0	0	0	0.0	0.0	$0	$0
hosp	0	0	0	0.0	0.0	$0	$0
CHWS 45 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 46 - recip/vsd	0	0	0	0.0	0.0	$0	$0
CHWS 47 - recip/vsd	0	0	0	0.0	0.0	$0	$0
Min OA 0.05 cfm/sf	953,608	2,729,539	8,784,180	502.9	311.6	$1,215,010	$213
Min OA 0.10 cfm/sf	953,734	2,729,539	8,784,168	503.6	311.6	$1,214,951	$154
hosp	954,036	2,729,539	8,784,498	504.3	311.6	$1,214,797	$0
Min OA 0.20 cfm/sf	952,934	2,729,539	8,782,800	504.7	311.6	$1,214,393	-$404

Min OA 0.30 cfm/sf	947,718	2,729,539	8,776,863	475.2	311.6	$1,212,717	-$2,080
VAV min 0.20	na	na	na	na	na	na	na
VAV min 0.35	na	na	na	na	na	na	na
VAV min 0.50	na	na	na	na	na	na	na
VAV min 0.65	na	na	na	na	na	na	na
VAV min 0.80	na	na	na	na	na	na	na
Zone SAT 65	969,684	2,729,539	8,805,003	506.1	311.6	$1,247,290	$32,493
Zone SAT 60	956,791	2,729,539	8,790,984	504.7	311.6	$1,219,896	$5,099
Zone SAT 55	954,036	2,729,539	8,784,498	504.3	311.6	$1,214,797	$0

Chart 1

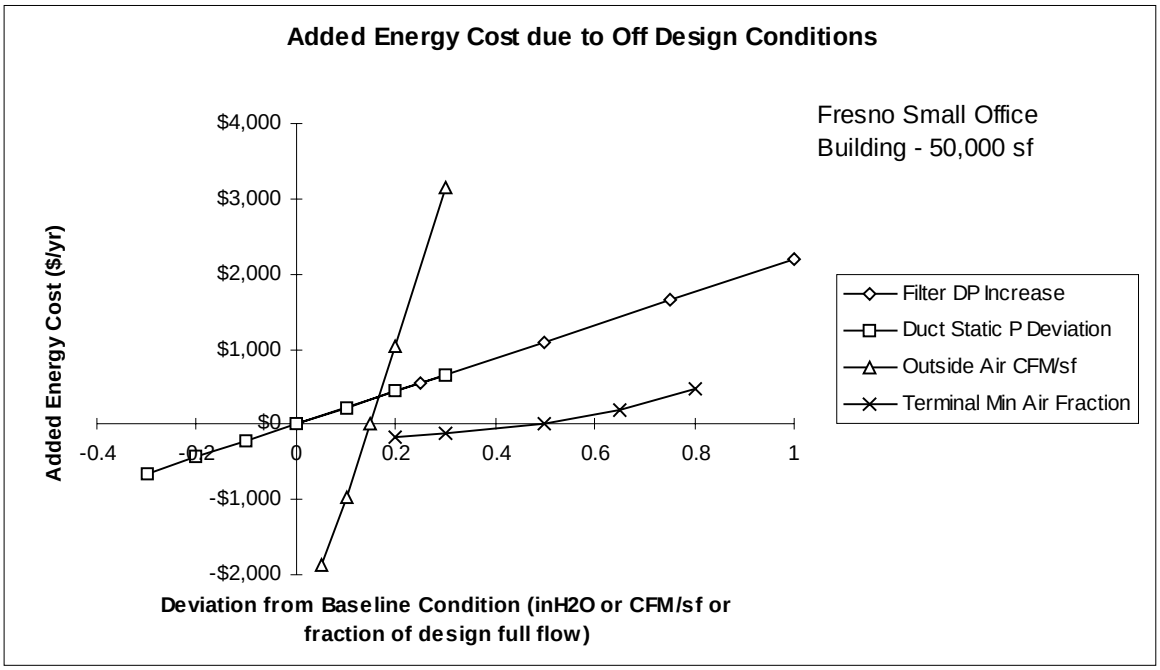


Chart 2

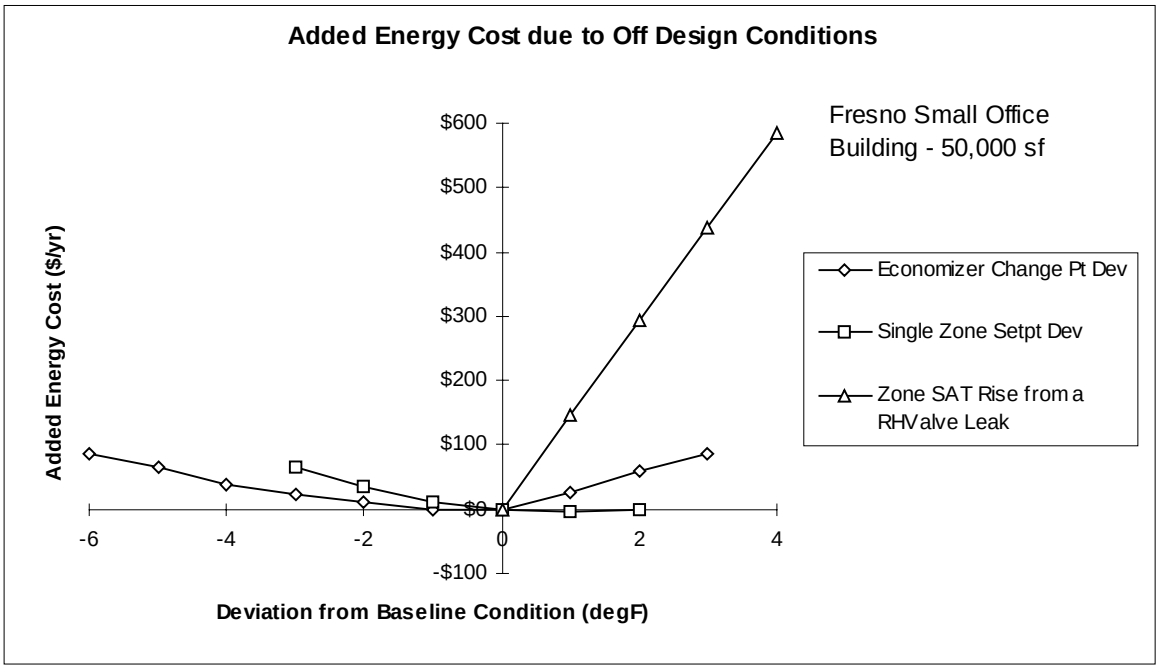


Chart 3

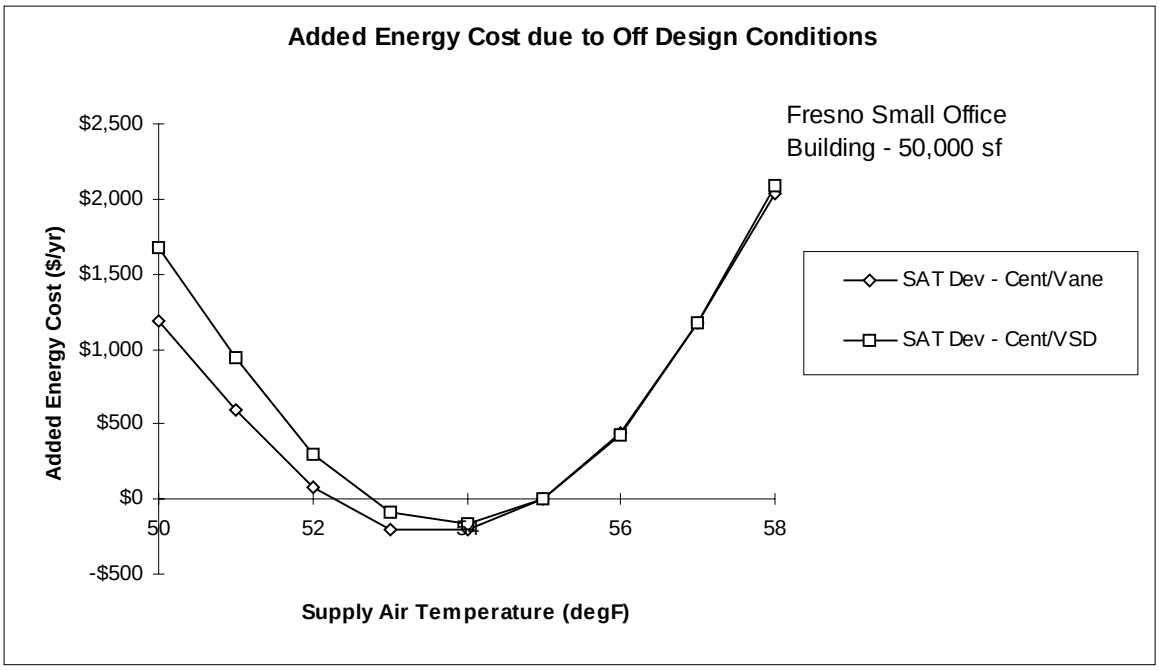


Chart 4

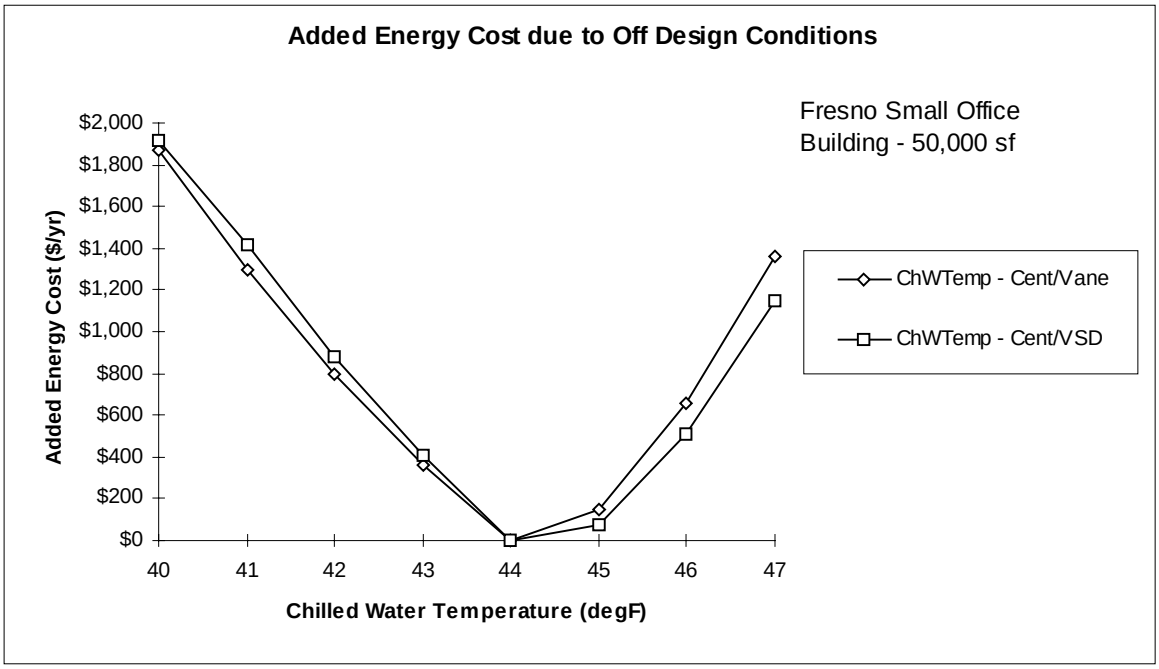


Chart 5

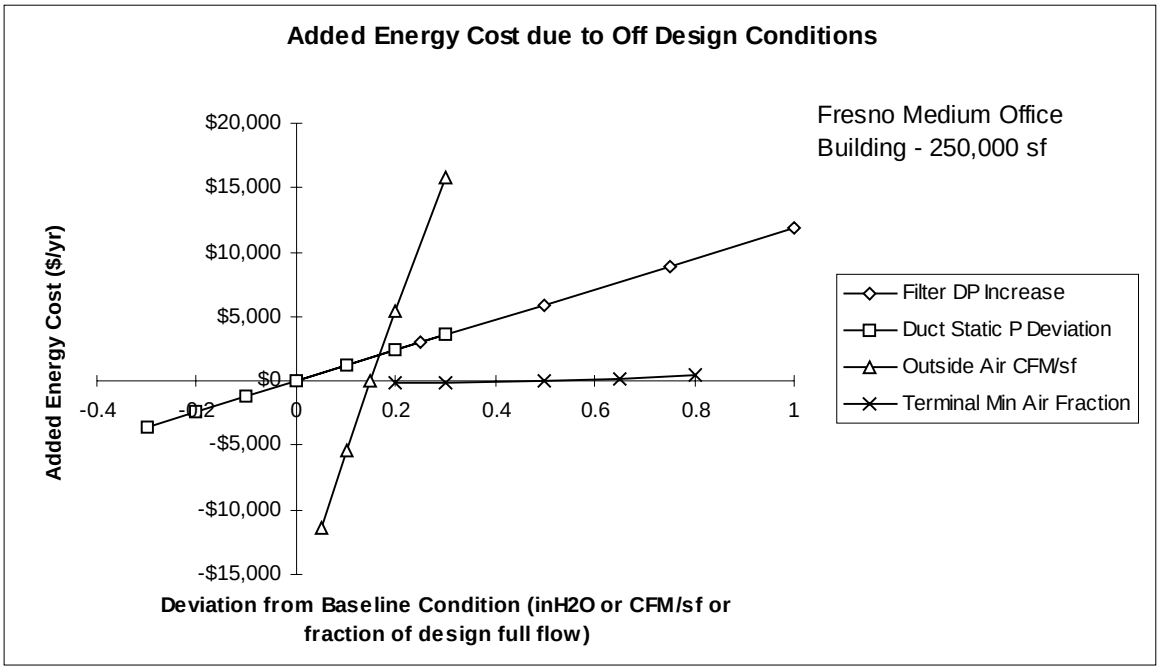


Chart 6

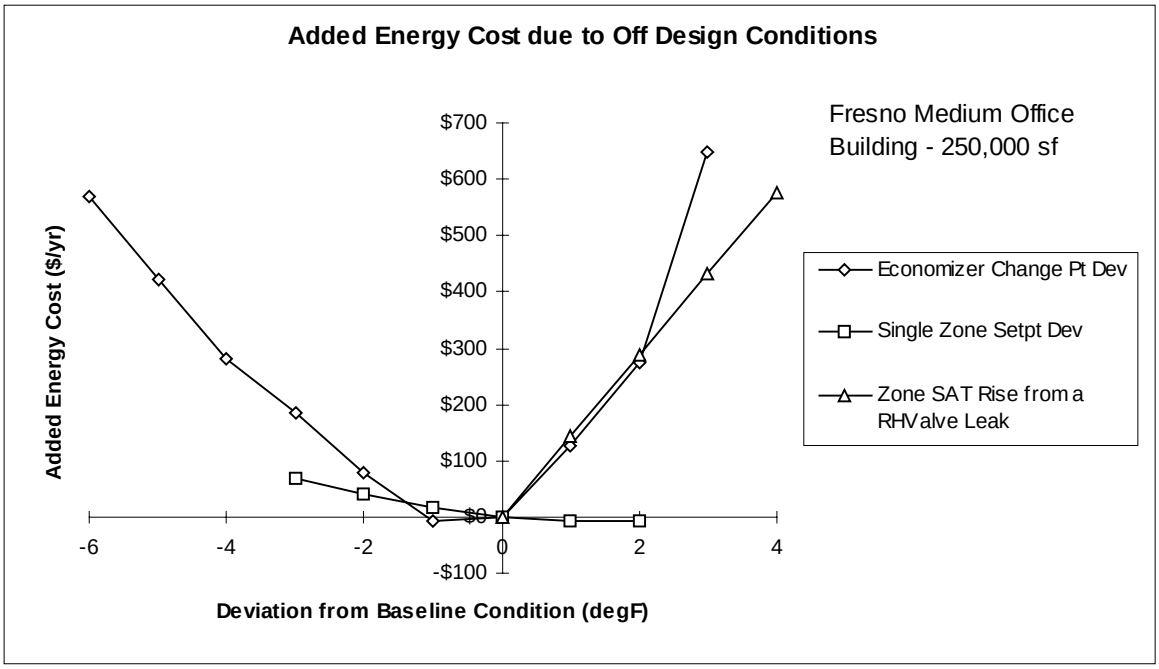


Chart 7

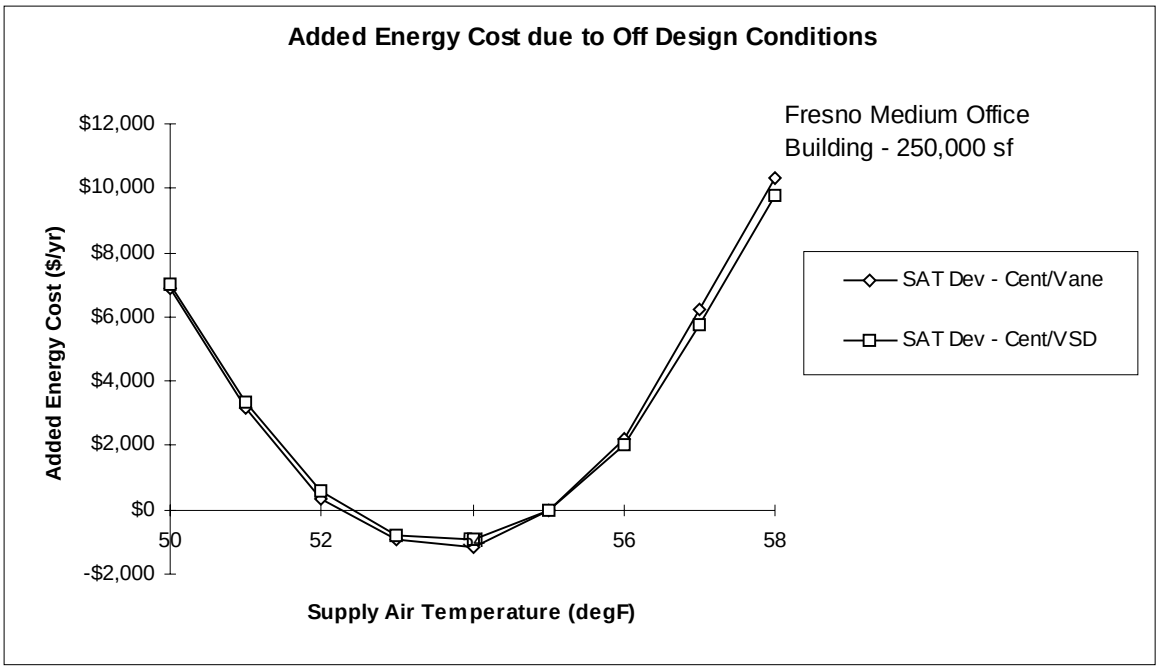


Chart 8

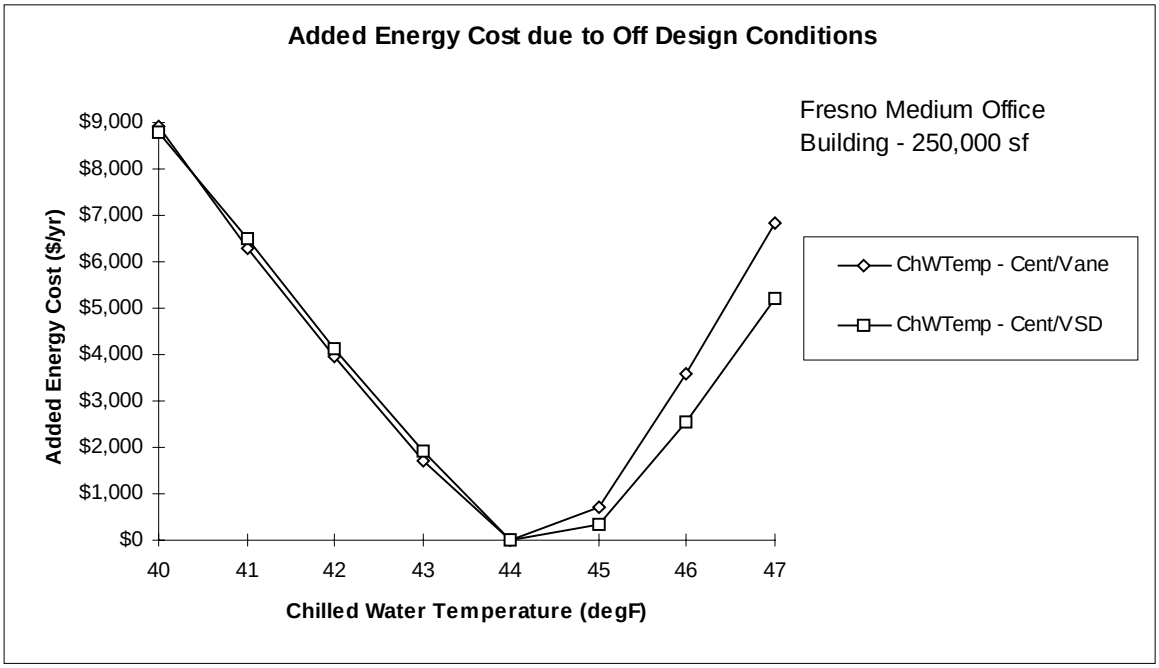


Chart 9

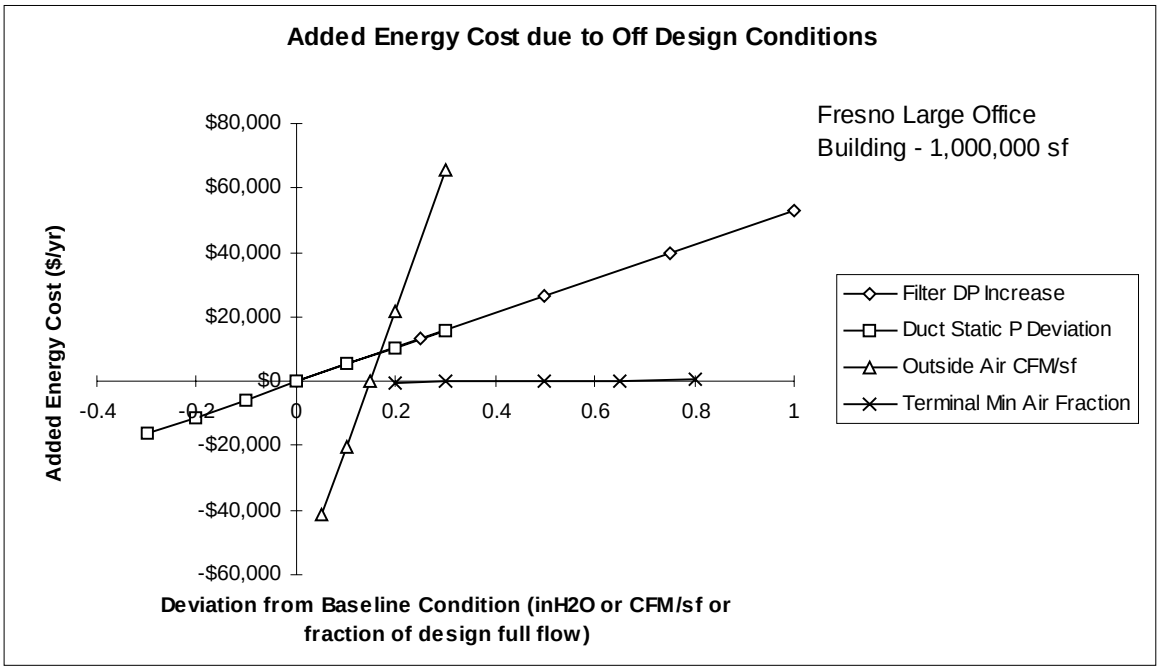
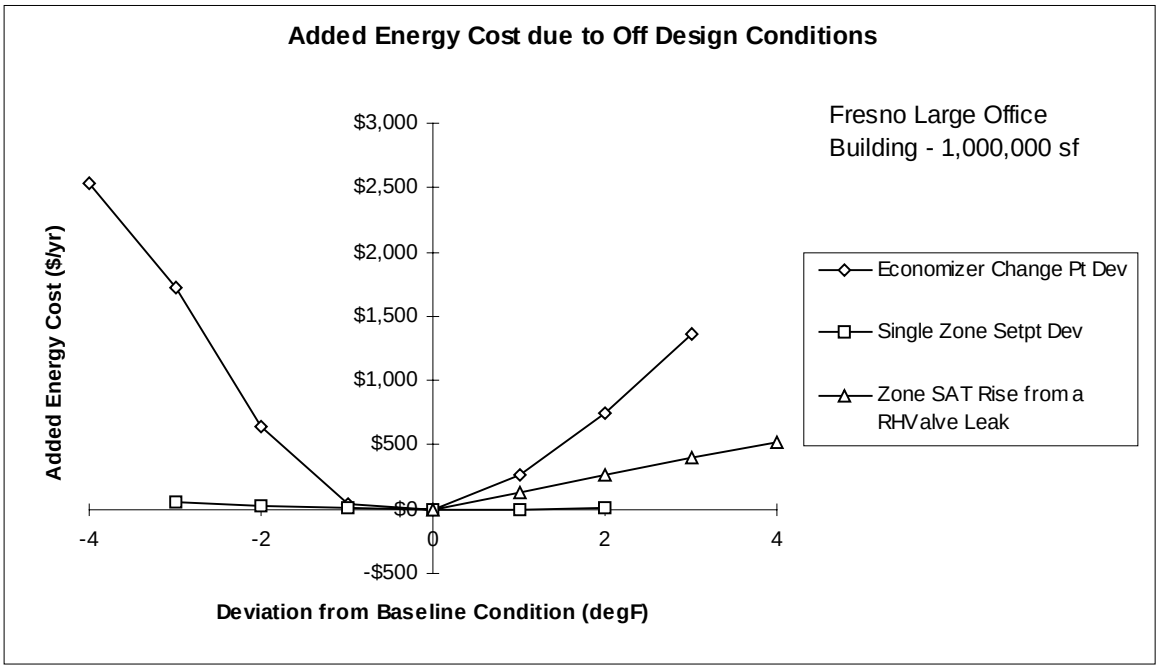


Chart 10



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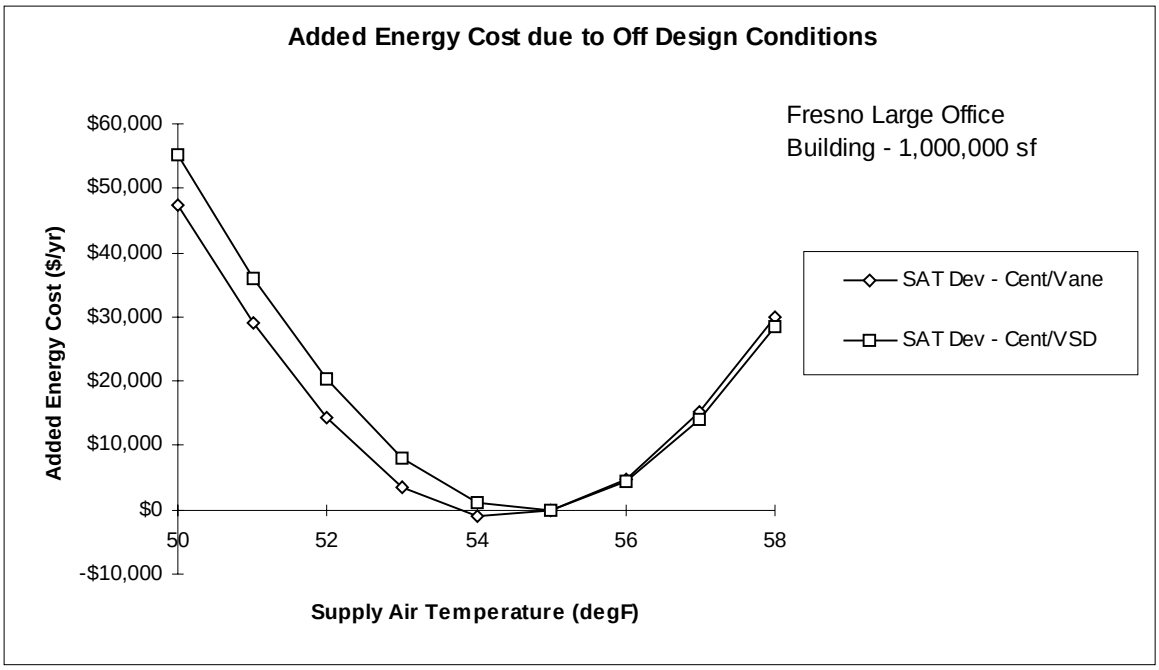

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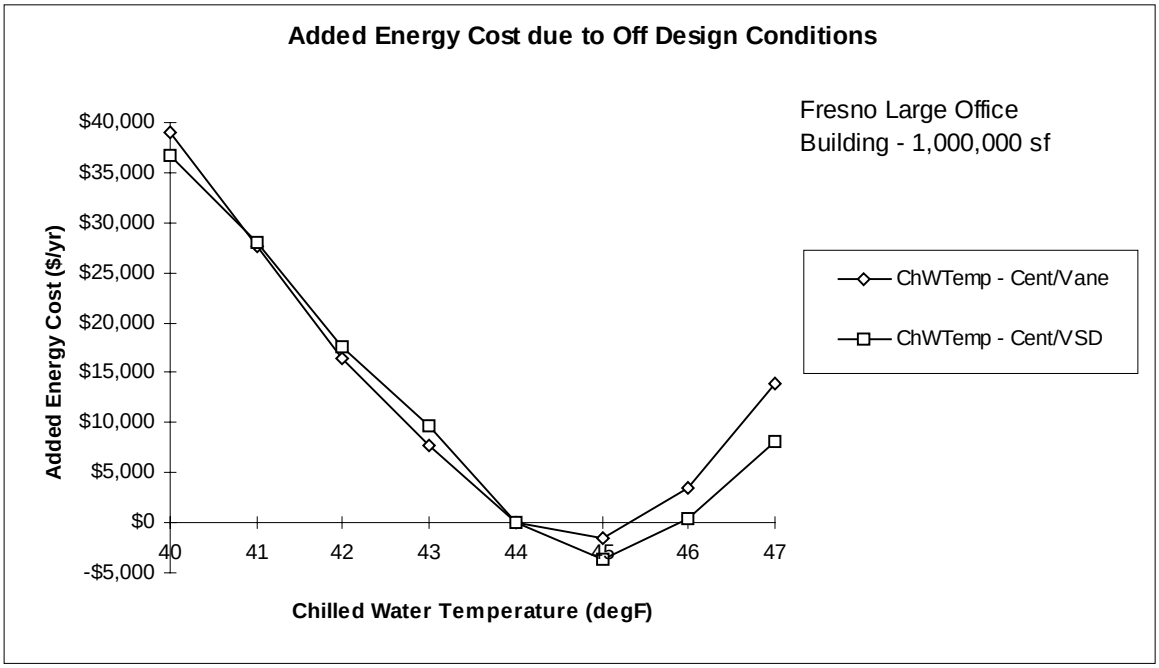

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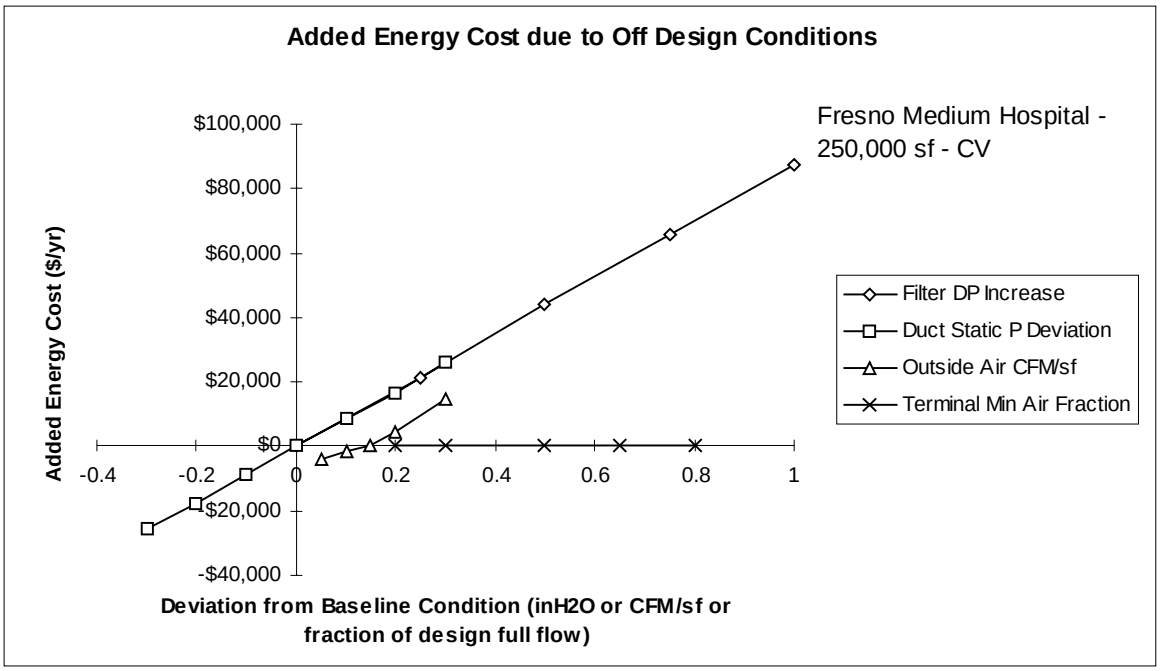

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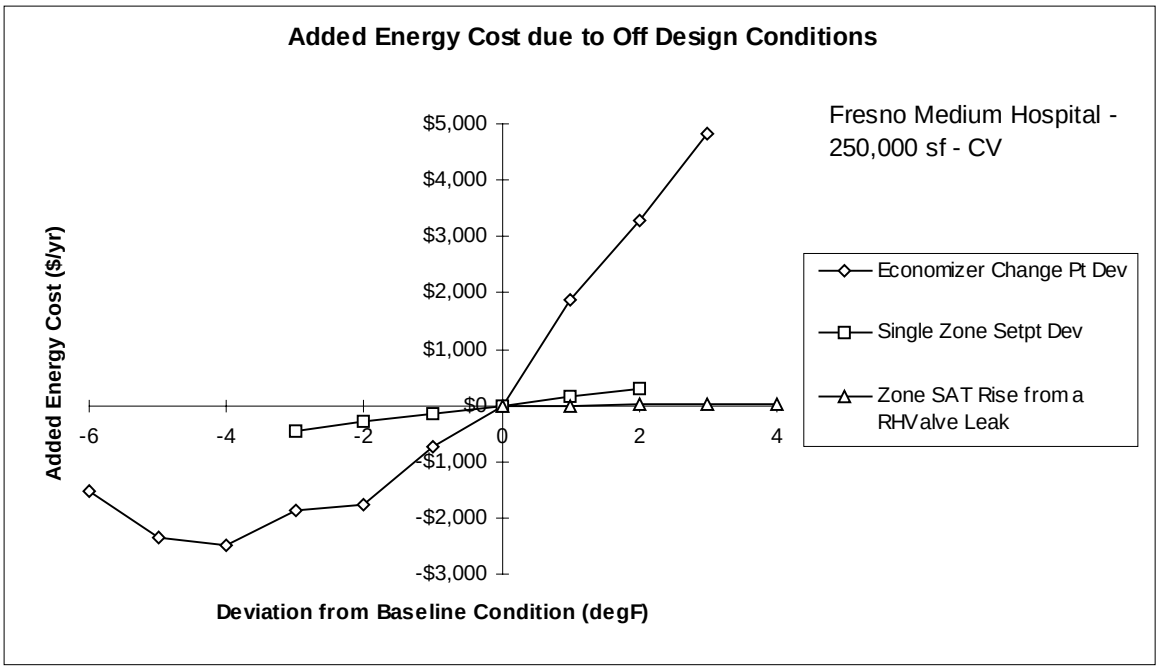

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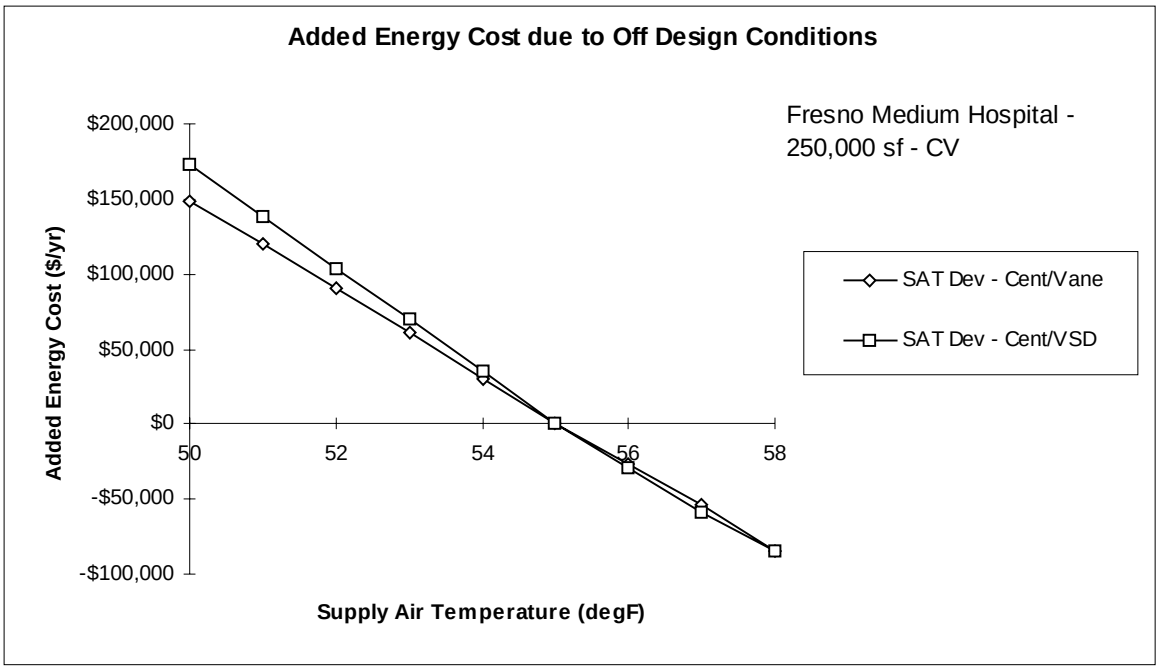

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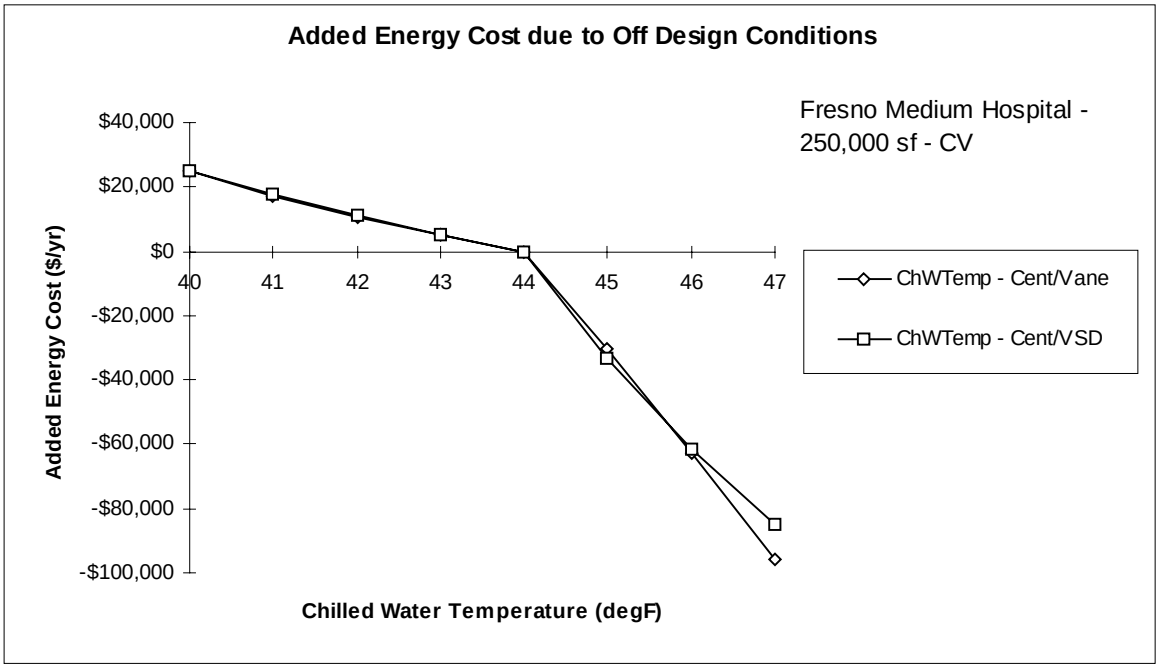

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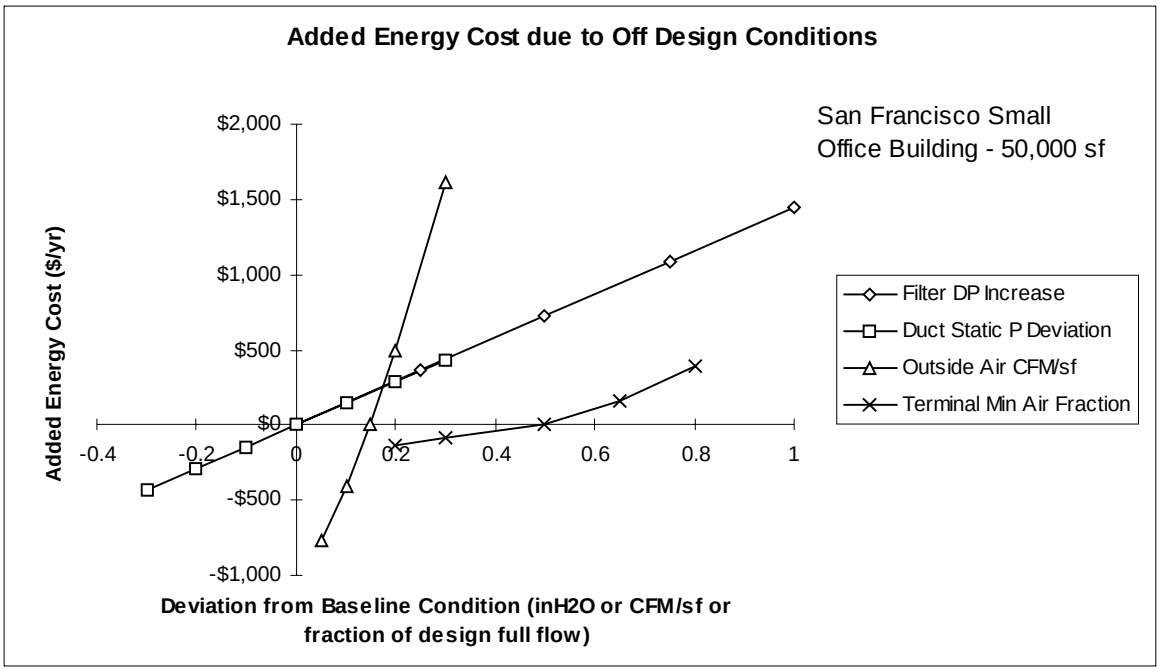

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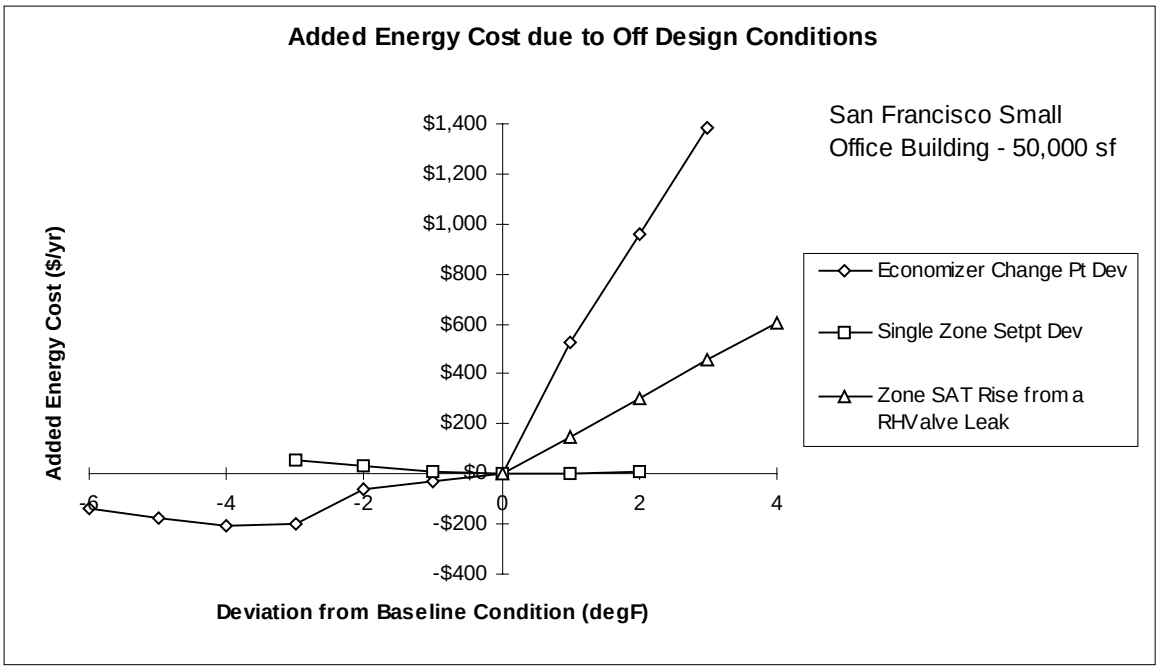

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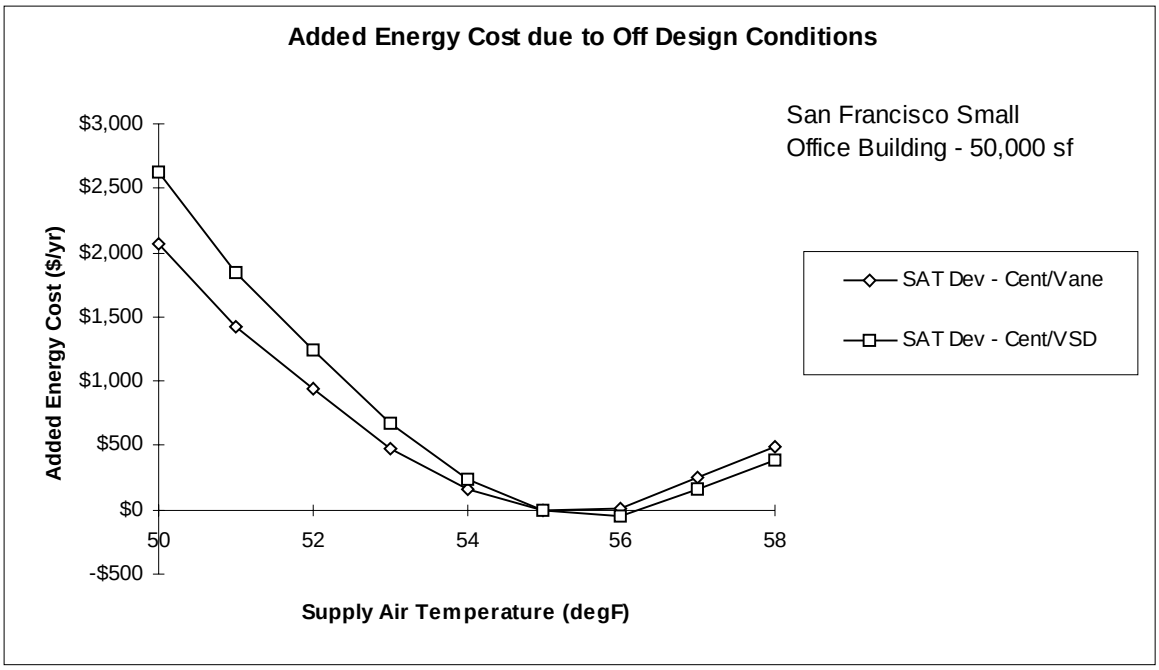

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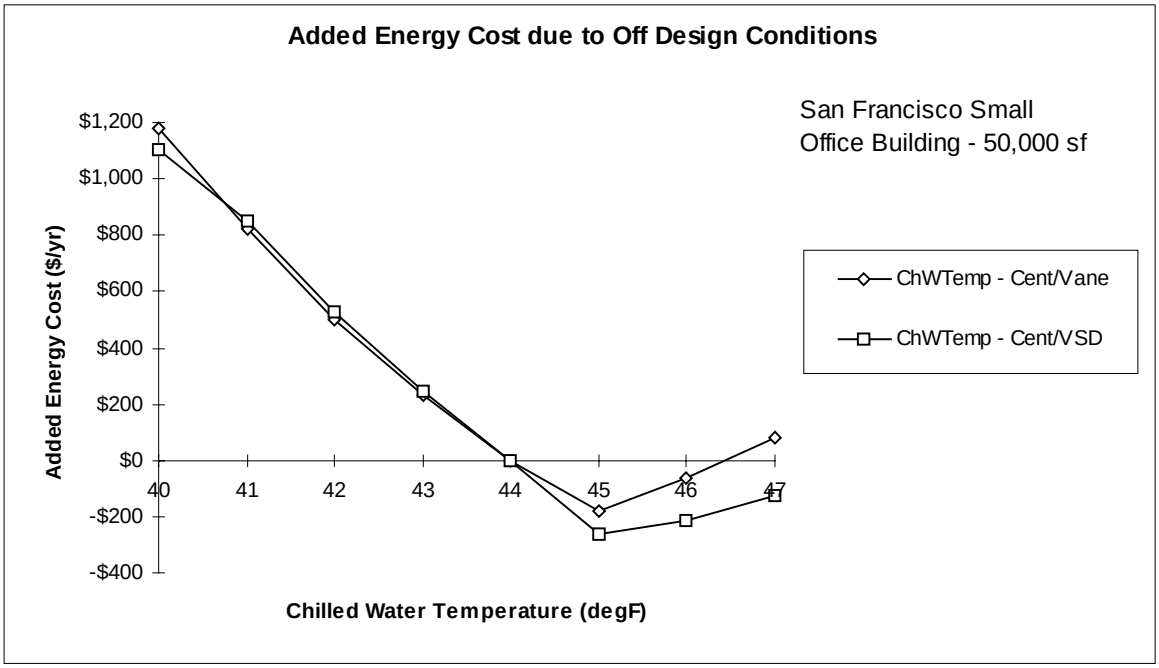

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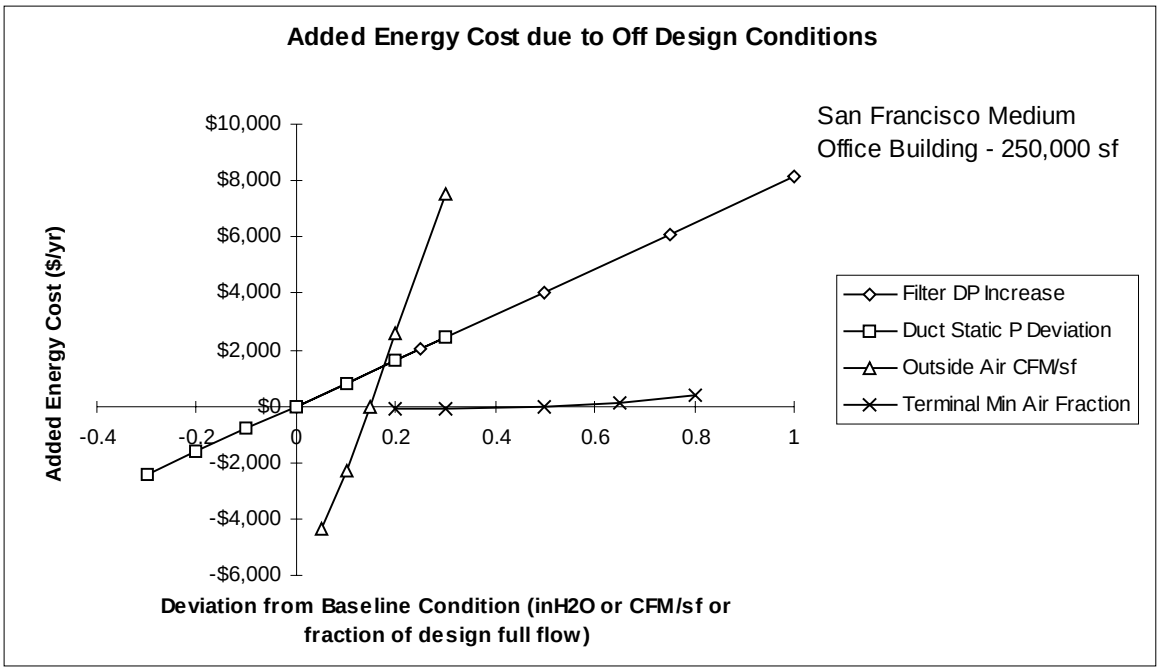

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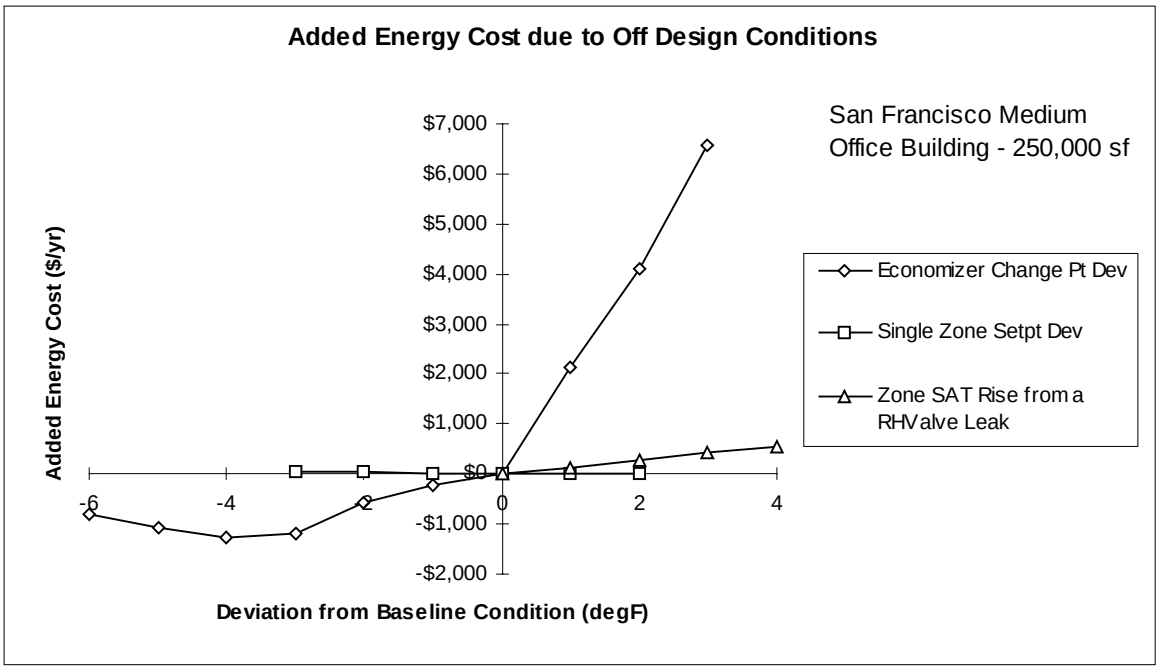

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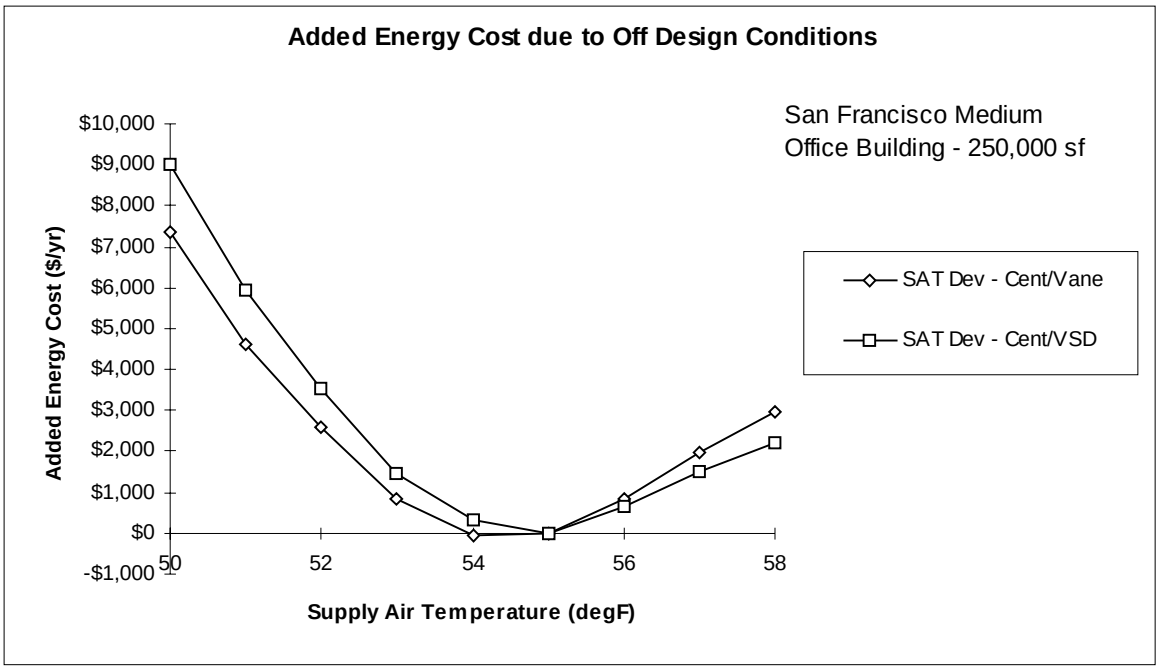

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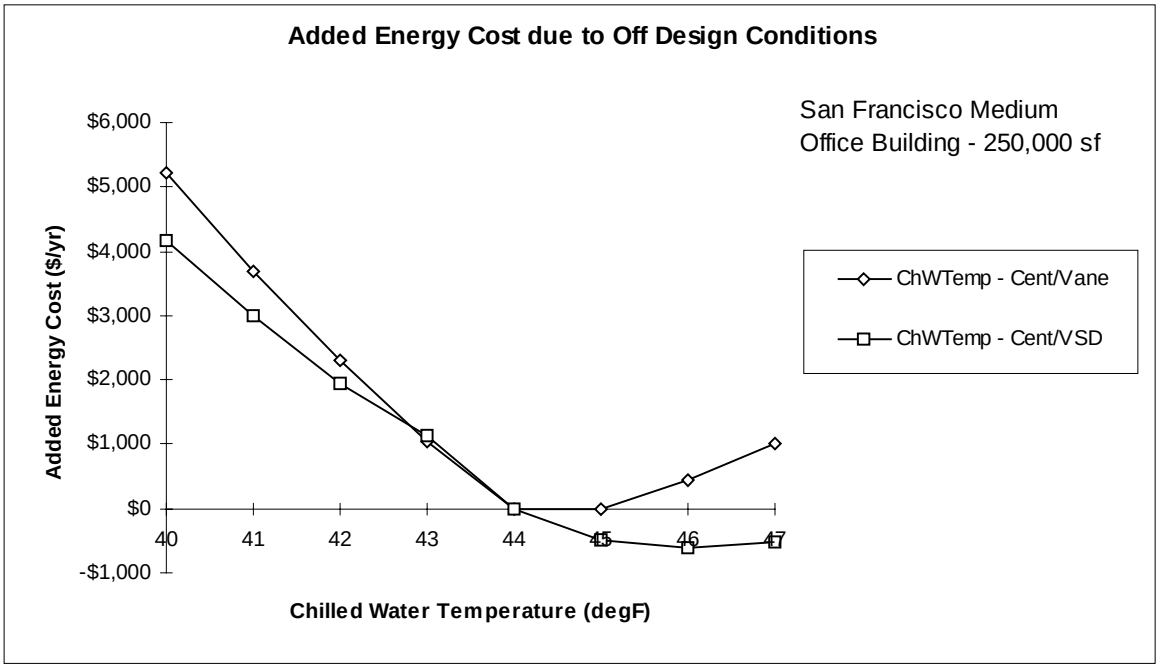

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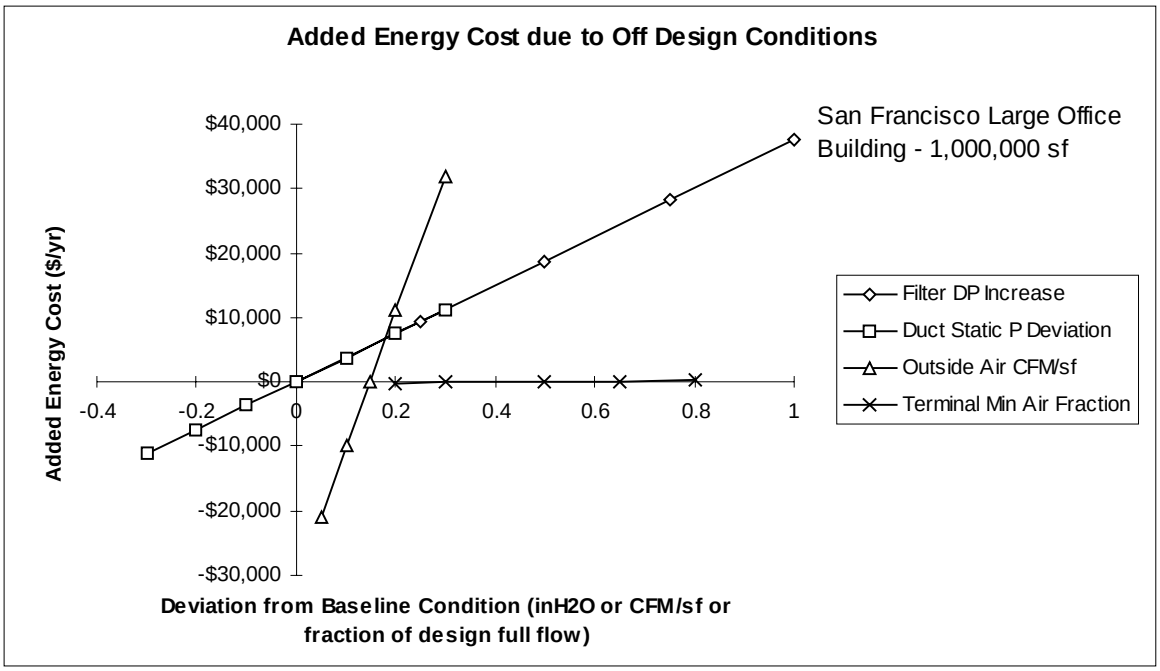

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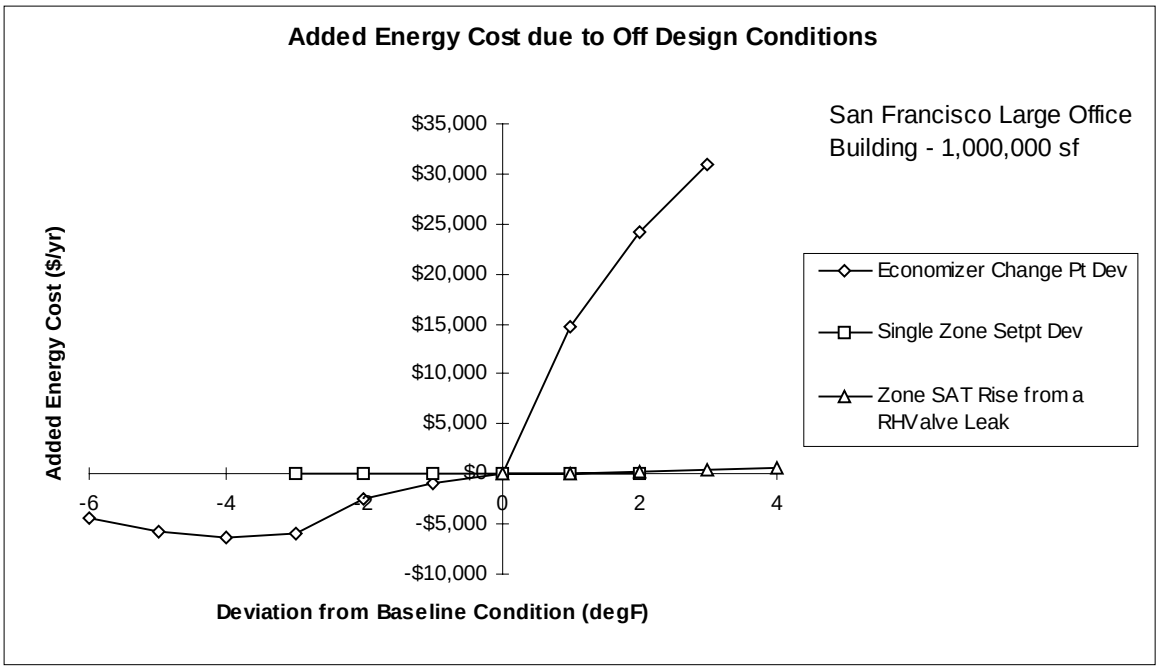

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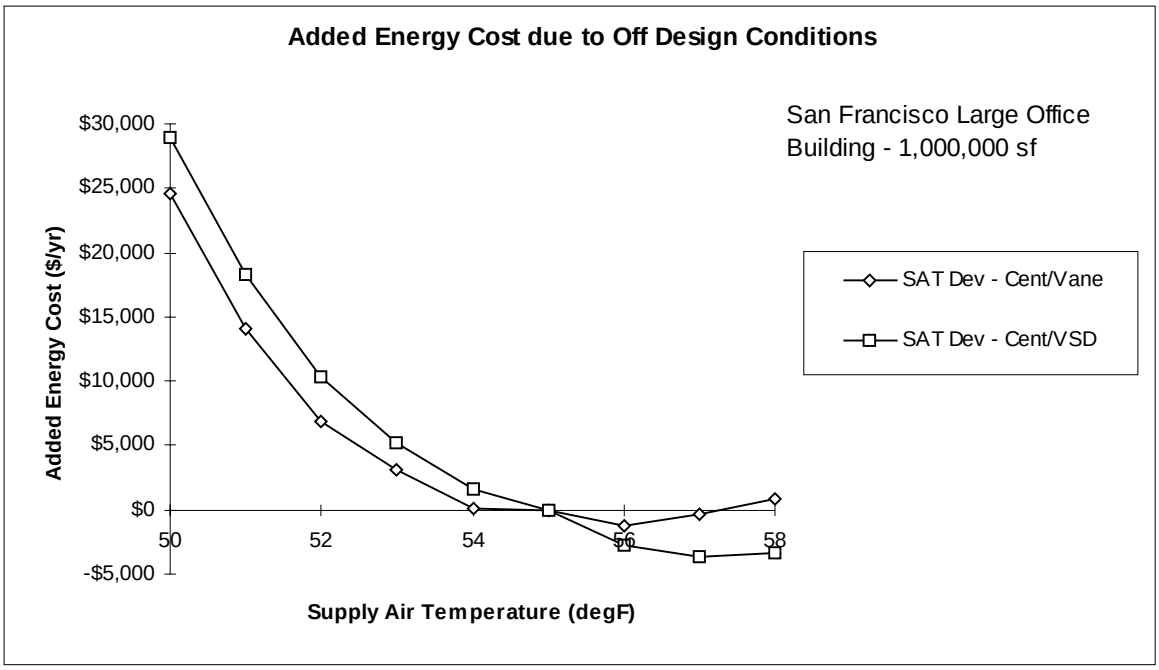

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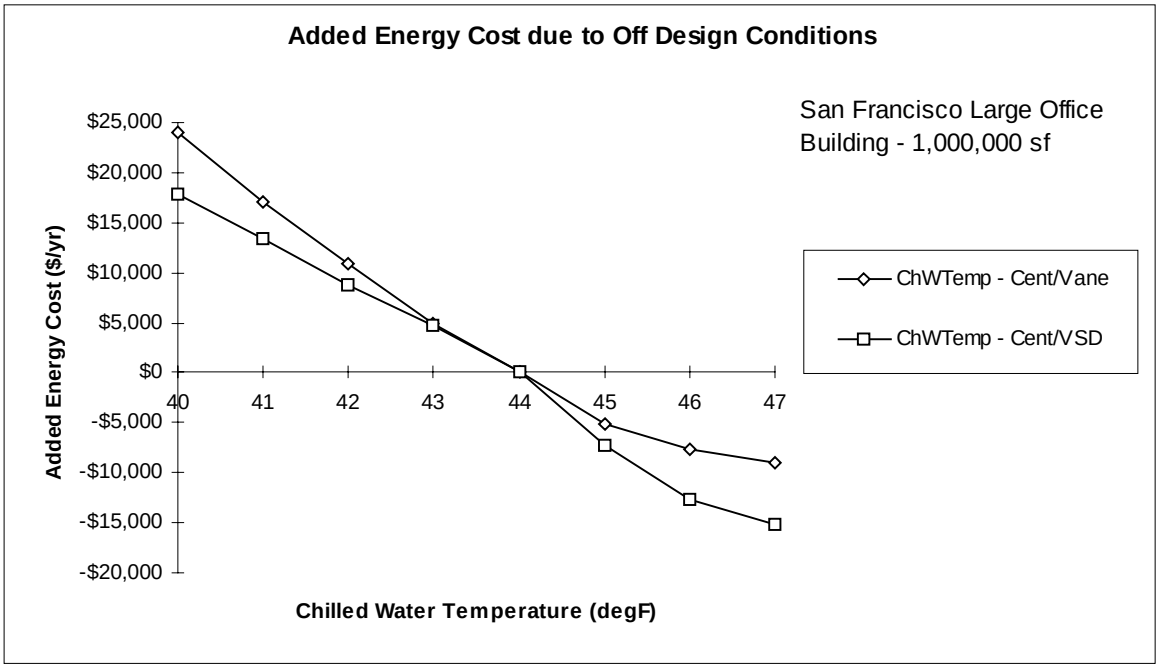

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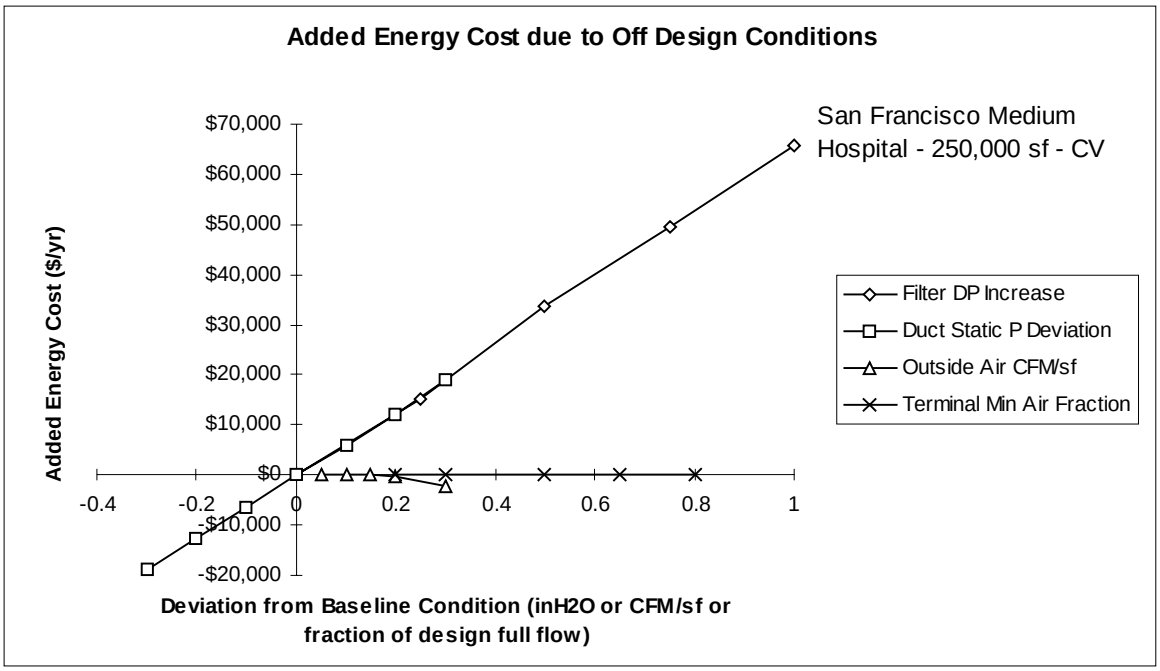

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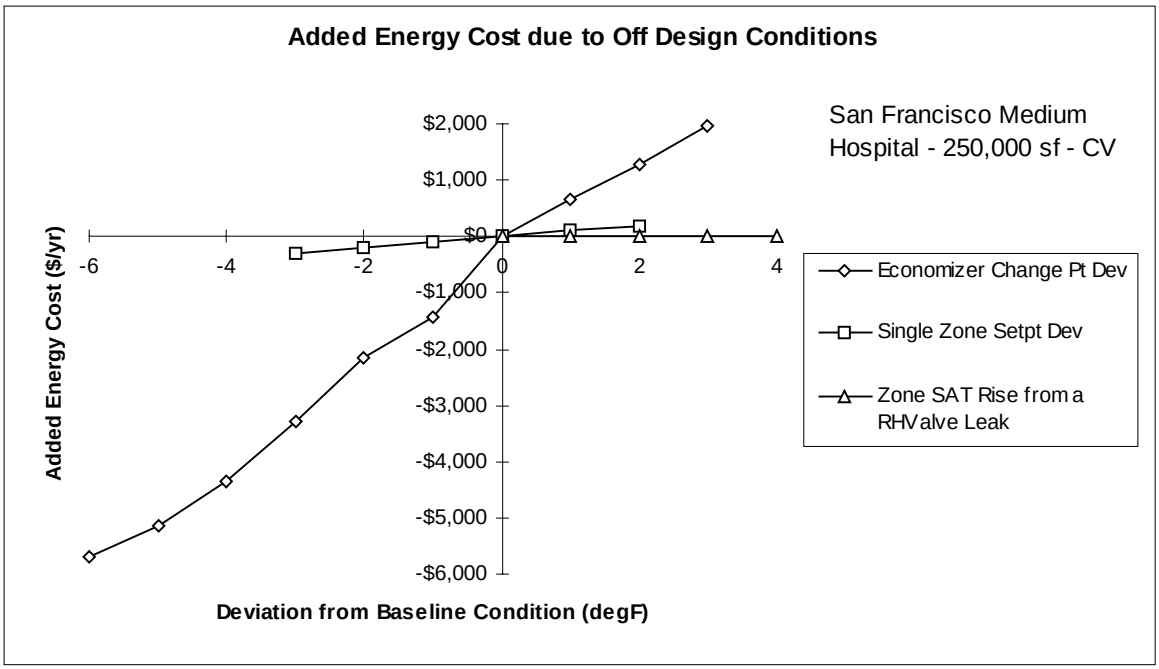

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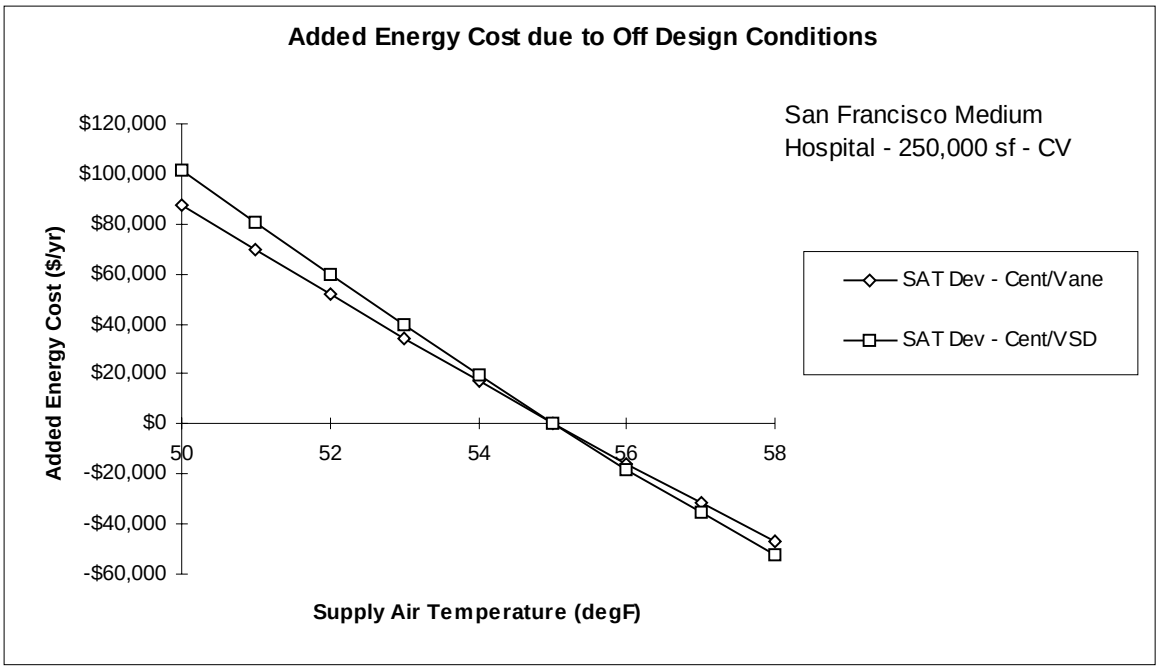
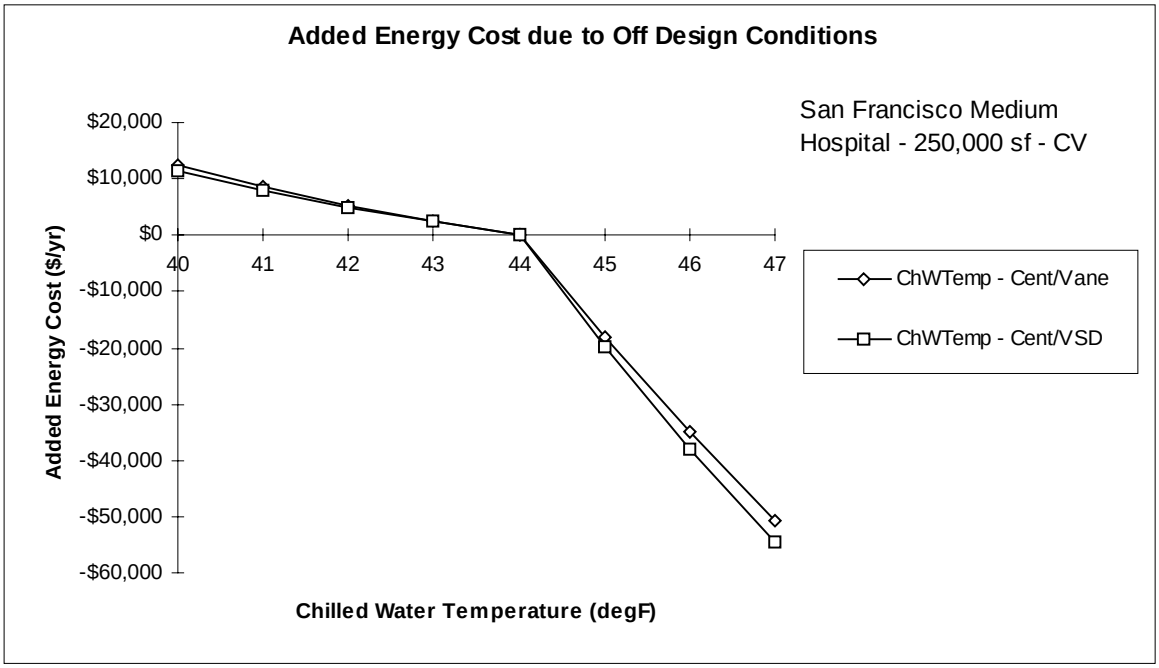
Chart 32