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High Performance Commercial Building Systems

Development of Fan Diagnostic Methods and Protocols for Short Term Monitoring

Element 5 - Integrated Commissioning and Diagnostics
Project 2.2 - Monitoring and Commissioning of Existing Buildings
Task 2.2.1 - Fault Detection and Diagnosis Procedures

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Introduction

BACKGROUND

For buildings to operate effectively and save energy they must be commissioned properly and operational problems must be detected and diagnosed. Collection of sensor and control data is essential to this process. Likewise, the analysis of this data with effective tools is critical to performing this work in a cost effective manner. In general, the buildings industry lacks consistent methodologies or protocols that make this process of data collection and analysis effective and efficient; the practitioner usually develops his own techniques on a more or less ad hoc basis. Also lacking is a consistent way to accumulate data over time from many projects that could be helpful to the analysis of a particular system. To help remedy this situation (and to serve as an example of this concept) the Center for Environmental Design Research (CEDR) at UC Berkeley developed diagnostic protocols and a software "toolkit" (UCB AHU Toolkit) to help practitioners identify and rectify problems with large built-up air handling units (AHU). [Carter 1998, Webster 1998, 1999]. These tools and protocols rely on short term monitoring and a set of supporting spreadsheet based tools to screen for problems in AHUs and to conduct more in-depth diagnostic studies for problems found.

The work described herein is an extension of the previous work and comprises Task 2.2.1 of Project 2.2 of the High performance Commercial Buildings Systems (HPCBS) project. The goal of Project 2.2, Monitoring and Commissioning for Existing Buildings, is to facilitate the development of diagnostic procedures and commissioning tools needed by owners, operators and the commissioning industry to perform and analyze test results and operate buildings efficiently. All of this work comes under the Integrated Commissioning and Diagnostics (Element 5) of the HPCBS project.

This work was conducted in conjunction with sub-contractor Nexant/Energy Management Group.

PROJECT OBJECTIVES

The overall objectives of this project are to develop and demonstrate diagnostic methods, and establish protocols based on short term monitoring techniques with a focus on finding problems with significant energy impacts. Specifically, the scope of this project is to further the development of protocols for built-up air handlers by testing the efficacy and utility of existing protocols through field testing. Specific technical objectives are to:

1) Identify components of the UCB AHU Toolkit most appropriate for analyzing built-up fan systems.

2) Populate the fan performance database with field data.

3) Refine and modify the protocols based on lessons learned during field-testing.

4) Make recommendations for further development and implementation of the protocols and toolkit.

PROJECT APPROACH

The basic approach for this project was to study three buildings[1] with variable air volume (VAV) systems using the existing UCB AHU Toolkit and measurement protocols apropos to this system type. Since the buildings selected were part of other more comprehensive system studies, large amounts of building management system (BMS) data were available that included most of the parameters required for AHU analysis. The BMS data was supplemented with additional handheld measurements and portable data loggers where necessary. Calibrations were performed for certain parameters where accuracy was uncertain. Two issues were investigated that were not originally part of the scope but are considered critical to successful implementation of these techniques:

1) Accuracy of airflow measurements, in particular airflow monitoring stations (AFMS) (see Appendix V).

2) (Re)assessment of overall potential of these techniques (see Appendix VI).

A summary of the tools used for analysis of these projects is shown in the following section.

FAN DIAGNOSTICS TOOLKIT

The UCB AHU Toolkit is composed of eight Excel spreadsheet tools with over 30 charts and tables for analyzing VAV and CAV systems. They allow a complete, easily accessible, semi-automatic way to calculate various performance metrics and display correlations and trends. The tools provide a standardized way to work with the data and unburden the analyst from tedious computational details. The basic components of the toolkit are listed in Table 1; more detailed descriptions are included in Appendix I; the tools used for this study are shown in bold. Further details about the development of these tools can be found in a series of final reports from previous work [Carter 1998, Webster, 1998]; a complete description of them is provided in the final report for Phase IV of the previous work [Webster 1999]. The UCB AHU Toolkit is publicly available to interested parties by contacting the author. This set of tools represents a "superset" of tools to allow flexibility in how a particular area can be studied and to offer a wide range of options for energy analysts to choose from.

[1] Novell, Mission Towers, and Broadway building of the Oakland Administrative buildings

Table 1. UCB AHU Toolkit

Tool/tabs	**Description**	**Comments**
Fan analysis & benchmarking (FA_BM_Tool)	Peak load single point analysis	Create a VAV operating curve to extrapolate to a maximum operating point.
System Temperature Analysis (STA_Tool)	AHU airside temperature monitoring	Time series tool to ascertain airside performance problems.
Fan Power Analysis (FPA_Tool)	Power monitoring	Accepts time series power data for creating power histograms
Static Pressure Analysis (DSP_Tool)	Fan discharge static pressure	Accepts duct static pressure (near the fan) time series data to analyze static pressure control problems.
Motor Efficiency (ME_Tool)	Motor efficiency analysis	Single point analysis to evaluate motor efficiency in-situ.
Zone Air Temperature Analysis Tool (ZAT_Tool)	Analyze zone temperatures for up to 4 zones	Helps to determine if zone conditions are being met.
Reheat Analysis Tool (RHT_Tool)	Analyze over/under airing for CAV systems	For CAV systems to determine over and under airing.
Field data sheets	Field data sheets to assist data collection and documentation	Summarizes AHU data for handy reference, and supports pitot traverse measurements.

Project Outcomes

OUTCOMES BY OBJECTIVE

The following are project outcomes listed according to the objectives outlined above.

Objective #1: Identify appropriate tools

Table 1 contains a list and brief description of the toolkit. Tools shown in bold are the ones evaluated in this study and include:

1) Fan Analysis & Benchmarking (FA_BM_Tool) – This tool compares the design intent to an estimate of the peak load operating point based on actual measurements. This tool includes the fan performance database that allows benchmarking of a subject fan to other similar fans in the database population.

2) System Temperature Analysis (STA_Tool) – This tool includes an economizer analysis that allows the minimum outside air fraction to be determined. It also helps to identify calibration errors with SAT, MAT, and OAT sensors and problems with the economizer and SAT controls.

3) Fan Power Analysis (FPA_Tool) – The distribution of fan power (as percent of full load) is shown by this tool to help identify problems with VAV control (e.g., lack of turndown) and unexpected off-hours fan operation. It also includes a projection of annual fan energy consumption.

4) Motor Efficiency (ME_Tool) – In-situ motor efficiency is calculated to identify fan motor problems.

5) Field data sheets – These sheets provide a convenient summary of the fan system attributes and measured and nameplate data in a consistent format.

The tools listed above are all dedicated to analyzing VAV systems, which were the only ones chosen for study in this project since a large fraction of the building stock (at least in California) appears to incorporate VAV systems. Items within each tool marked in bold in Appendix I identify those considered most useful based on work of this study. This does not, however, rule out the potential of the other tools shown; further work would reveal their usefulness. In particular, the DSP_Tool may be useful to understanding VAV turndown and control problems and the ZAT_Tool is a good candidate for further investigation in that it would help identify "bottom line" effects of system problems, i.e., poor zone control. Although not studied in this project, CAV systems could be analyzed effectively with a combination of the ZAT_Tool and the RHT_Tool. The latter provides an analysis of under and over airing by these fans that can lead to poor zone control or excessive reheat and fan energy use, respectively.

Objective #2: Populate fan performance database

The three buildings analyzed for this project comprise the initial population of the benchmarking portion of the FA_BM_Tool. With only three buildings the usefulness is somewhat limited but even with limited experience it is clear that with further population of the database this tool could be very effective in supporting analyses. Table 2 is a summary of results from the testing of the three buildings that was derived from the database information.

Table 2. Fan performance database summary

Project/fan	Manufacturer	Type	Size	Design Efficiency	Measured CFM/SF *	Motor load factor	Fan efficiency ratio**
Novell/SF2	Loren Cook	Plug	66”	58%	.63	40%	.73
Mission Towers/SF1	Loren Cook	Airfoil	49”	73%	.65	80%	.64
Broadway/SF2	Trane	Airfoil	60”	79%	1.28	40%	1.0***

* At maximum monitored operating point
**Ratio of actual fan efficiency to design efficiency
***This value is unrealistically high; see discussion in Appendix III.

Objective #3: Refine and modify the protocols

Some of the changes made as a result of this research are the following.

- Maximum operating point - A *new method* was developed for determining the maximum operating point for VAV systems. It is important to establish the maximum operating point so actual performance can be compared to design intent and to gauge actual performance of the system relative to other similar systems, both of which help identify problems with fan performance. The new technique relies on scatter plots of logged airflow, fan static pressure (FSP), speed, and power data extrapolated to an appropriate assumed maximum operating condition by regression. This requires that an effective way be found to monitor airflow and fan speed with short-term techniques. (For a suggested modification of this technique, please refer to Objective #4 outcome section.)

  The new procedure replaces the *original method* wherein the maximum airflow operating point was achieved by resetting the supply air temperature (SAT) upwards thus driving the VAV boxes open. This procedure proved cumbersome and ineffective due to the difficulty involved with a trial and error process of monitoring VAV box positions to prevent saturation (i.e., all boxes 100% open). There are also significant delays due to the response time required for the boxes to adjust to a new volume condition for a given temperature control point.

  The new method also allows comparison to the design operating point to be improved. In this case the regression for speed is used to extrapolate to the design speed and the corresponding airflow is used to find the corresponding FSP and power.[2]

[2] The summary table for the FA_BM_Tool needs to be changed to reflect these improvements. The new table will replace the label “Field Measured Data” with “Maximum Field Measured data,” and the column labeled “Corrected to Design Speed” with “Extrapolated to Design Speed.” These values are derived from regressions of the time series of measurements and represent the maximum condition found for *the monitoring period*, which is assumed to be

- Procedures for tracer gas calibration of airflow monitoring stations (AFMS) were developed; these relied on using a tracer gas injection system at the fan inlet and sampled measurements of concentration downstream of the outlet, known as the constant injection tracer gas (CITG) technique; see Appendix V.

- Although data was collected using the BMS in this study it is still important to focus on short term monitoring using data loggers as the default assumption for these protocols. Experience on this project indicates that if good BMS data is available the tools can be used just as effectively.

- The Fan Power Analysis tool was modified to use a different chart type with occupied and unoccupied bars next to one another and to filter out data below 1 kW in the summary calculations.

- The motor efficiency tool was modified to calculate motor input kW when data for volts, amps and power factor are lacking. Now the measured power input is used to find the motor load factor if the detailed measurements are not included.

Objective #4: Make recommendations

The following are recommendations to improve the measurement protocol and certain aspects of the toolkit.

Protocol -

- New methods for airflow measurement need to be developed or additional research conducted to prove that manufacturers fan curves are accurate enough in actual installations to be used to determine airflow from FSP and speed measurements. To accurately identify problems with fans, efficiency must be measured in the field-installed condition.

  Investigate methods by which the measured maximum operating point can be extrapolated from a normalized system operating curve characterized by field test data (using flow and pressure coefficients) for particular fan types. By passing this curve through a FSP measured point a system operating curve for a particular fan can be assumed that would allow extrapolation to the maximum condition at the equivalent design speed.

- Further research needs to be done to verify that the fan static pressure methodology is accurate in the general case or new methods developed to measure this important parameter.

- Develop methods and instrumentation to log speed with a portable data logger.

- Determine how many built-up CAV systems still exist in the California and the national building stock to evaluate the need for further development and support for the CAV protocol and tools.

- Conduct detailed inspection of the fans that show low efficiency to determine causes.

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representative of actual maximum operating conditions, and for the *equivalent design* conditions, which is found by extrapolation to the design speed.

Toolkit interface and presentation enhancements -

- Add automatic project titling to all charts along with certain metrics (e.g., automatic percent outside air on the MAT-OAT Chart of the STA_Tool).

- Further refine and reduce the number of charts to those most useful. For example, the charts for the tools studied not indicated in bold in Table 1 were found not to be particularly useful.

- Power analysis tool - Change the format to include input horsepower and efficiency to determine input kW for load factor analysis since power factor is not always available (especially on variable speed motors).

  The power analysis would be more general if the histogram for power was presented in percent of hours rather than actual measured hours. Also, the load factor time of day analysis could provide more insight if each day was presented as a separate series as was suggested below for the economizer analysis.

  The presentation could be improved by removing the large number of hours in the 0% band; these values result from power signal noise when the system is off and should be filtered out.

Toolkit technical improvements –

- Include a more accurate model of drive efficiencies, especially for VFDs.

- Expand tools to better accommodate parallel fans and lead-lag performance.

- System Temperature Analysis Tool - The economizer analysis would be simplified if the MAT vs OAT and RAT vs SAT charts were made selectable by day or all days or showed each day in a separate series. This would allow easier tracking of performance as the economizer changes operation during the day and would help identify operating conditions that cause problems.

  The Summary Sheet and SAT charts could benefit from the addition of a chiller lockout temperature input. A filter for percentage of time when SAT is not being controlled to setpoint for systems that do not use SAT reset would also be helpful. For systems that do use reset, there should be another plot based on the how the reset is controlled (e.g., RAT or OAT).

  All charts except the last, should have weekdays and weekends indicated separately.

- Load factor chart – support both combined and single fan power for dual fan systems.

- All the tools that use motor input (FA_BM_Tool, ME_Tool, and FPA_Tool) should be combined or coordinated better to avoid duplication of effort and confusion between tools in inputs and calculated values. The motor efficiency tool relies on the nameplate power factor, which rarely is listed especially on variable speed motors. Also, VFDs generally have power factor correction so the power factors typically equal to one.

  Add motor efficiency for variable speed motors versus load factor. Also, add an explicit drive ratio in these tools (which can be determined easily with a hand held tachometer) and calculate motor speed from measured fan speed.

- Develop a new tool that automatically calculates the maximum operating point from the tools data set and integrate this capability in the FA_BM _Tool (i.e., add a time series capability). Modify the maximum operating point procedure (and associated summary table) to include extrapolation to the design speed along the system operating curve, as discussed above.
- Consider combining Fan Power Analysis into FA_BM_Tool to allow comparison of normalized power distributions between projects/systems.

OTHER OUTCOMES

Outcome #5: Airflow measurements

Airflow monitoring stations were calibrated for all three sites using tracer gas techniques. These calibrations resulted in a 17% average error that was applied to all airflow data; see Appendix V.

Outcome #6: Potential

A detailed analysis was made of the maximum energy savings potential from application of these protocols based on assumptions about probability of occurrence of 11 problems and estimates of energy savings for each for the four building types where these systems exist most frequently. See Appendix VI for details.

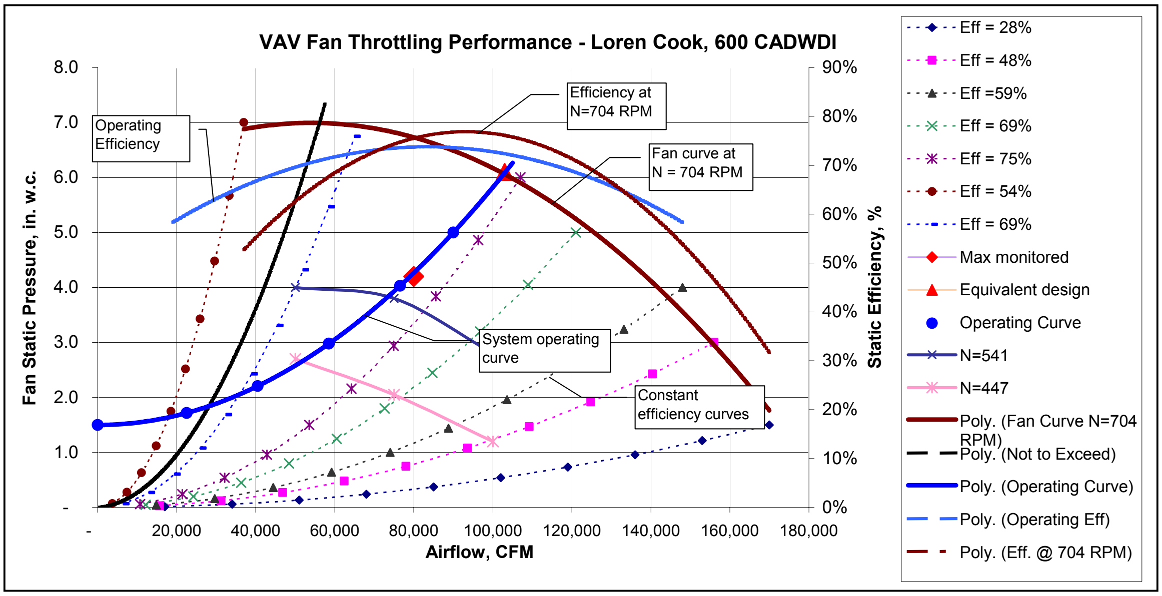
DISCUSSION

Fan performance

The results for Novell and Mission Towers showed fan efficiencies about ~ 60-70% of catalog ratings. These results could be the result of a systematic error in the measurements or due to real problems with the fans. Cursory inspection of the fans does not suggest that there is a signification problem with them, but closer inspection may be warranted. However, the Mission Towers and Broadway outlet conditions were complicated (e.g., duct splits and a closely coupled elbow at the outlet) suggesting the possibility of significant system effect factors. Likewise the Novell system had back draft dampers on the inlet, which can also cause system effect issues. In addition, the Novell fans are operated mostly in the "extended" range of operation, which can cause poor performance, and unstable fan operation. For the Broadway building the fan output (FSP and airflow) are lower than predicted for the measured fan speed, yet the power input is low as well causing the fan efficiency to indicate high despite the low output. This is a contradictory situation that suggests an undetected problem with the measurements.

Possible errors in measurements for these systems could result from FSP and airflow measurements. One significant issue is measurement of FSP. FSP was measured at the outlet of a fan , which is known to be problematic due to the high turbulence at that location. However, at Mission the static pressure was measured at each of the four taps. There was very little difference between these readings suggesting that the turbulence is not a significant factor. At Novell, there is no housing so the static pressure is relatively easy to measure and was corroborated with a hand held pressure transducer.

From these results we conclude that the low performance of Novell and Mission Towers is due to either system effect and/or operational problems (perhaps exacerbated by other factors only to be revealed by a further inspections). The results from Broadway, however, are inconclusive, at least for fan performance.



Maximum operating condition

Figure 1: Typical VAV system performance

For reference purposes in the report, Figure 1 shows a theoretical performance map of a typical VAV system using catalog data from a representative large airfoil fan. This chart emphasizes how the system operating curve dominates the performance discussion about these systems. It represents an empirical characteristic that results from the interaction of the fan with the particular system in which it is installed, and the load characteristics of the building. Two maximum operating conditions are indicated; one typical of actual monitored maximum operating conditions and the other for the equivalent design point that can be extrapolated from a regression of system operating data. Establishing this system operating curve is the essential to the successful application of the VAV system fan performance analysis tools.

For this reason, it is important that fan airflow be accurately measured and monitored for VAV systems. The toolkit does not currently include tracking of airflow since the original method relied on a single point determination of airflow. It was determined that simulating a peak load condition by increasing the SAT is time consuming and difficult. It is better to track airflow over a peak cooling load time of year and generate the operating curve as exemplified in the analyses in the Appendices. However, this requires an accurate airflow monitoring station that in turn needs to be calibrated. The protocol for determining the maximum operating condition needs to be improved to allow determination by extrapolation along the system operating curve to the design speed rather than using the fan laws as is currently done in the FA_BM_Tool. This more accurately reflects the maximum operating condition based on the actual performance of the system.

A related issue occurs if only one fan of a set is monitored. As exemplified by the Mission Towers project where analysis focused on one supply fan, problems with the other fan were found to influence the results of the monitored unit. For example, at Mission Towers it was discovered that SF2 did not modulate after June 19, 2002 due to a problem with its VFD. This would not have been easily detected by the protocols because monitoring fan speed was not included in the protocol. In this case if the speed problem was not identified the analysis of the data would have yielded inaccurate results. Potentially this type of problem could be found via the fan power analysis if both fans were monitored or possibly during single point tests if they were made (but not now recommended).

From this discussion it is apparent that both fans of a set need to be monitored and additional comparisons be made between fans to identify any differences in operation.

Motor efficiency analysis

Fan/motor speed - Unexpected difficulty was encountered measuring fan speed, a parameter that should be easily accessible. Care has to be exercised when using strobe tachometers. Although these instruments have significant advantages in terms of accuracy and safety (ability to measure speeds without contact), the strobe synchronization occurs at a number of multiples of the true speed making it difficult to know that the actual speed is being measured. Contact tachometers seemed better in this regard.

In addition, discovering the underlying methodology used for reporting speed in the BMS was difficult. Ultimately this required a separate calibration procedure.

A method needs to be devised for short term monitoring of fan speed.

VFD efficiency – Figure 2 shows a typical VFD efficiency curve versus speed [Hydeman 2003]. As shown, VFD efficiency starts to drop significantly at speeds of 50% of full speed. Although most systems due not turn down much below 50%, adding this calculation to the motor/drive efficiency calculations would improve the overall accuracy of the tools.

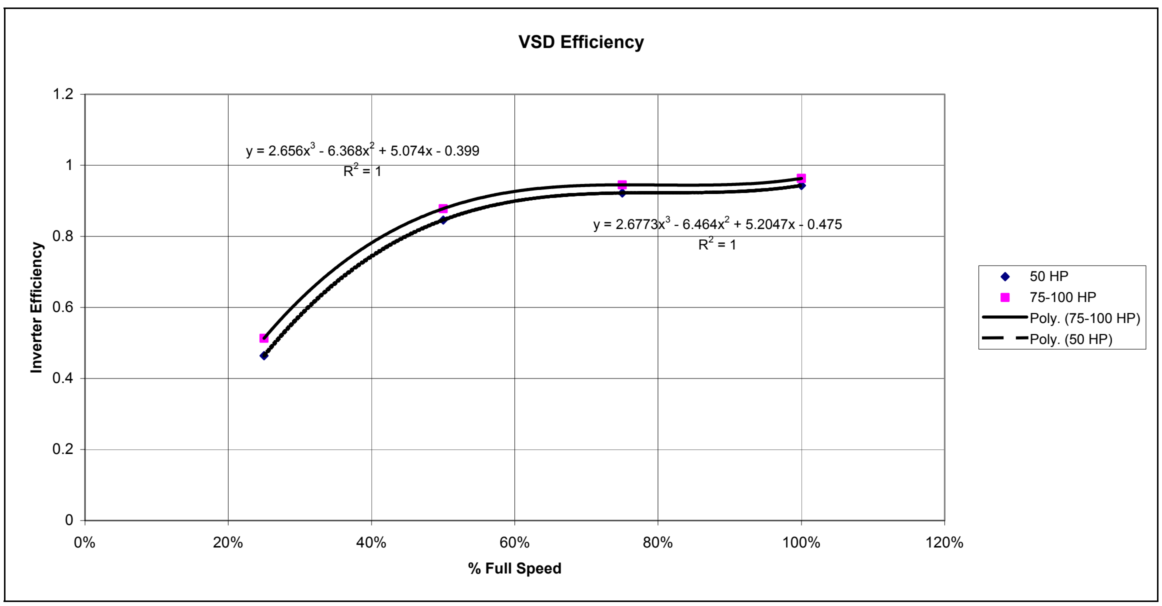


Figure 2: VFD efficiency

BMS vs short term data

BMS data was used for this project. In two cases some of the data was derived from a separate data acquisition system so the quality was considered to be as good or better than could be obtained using portable data loggers. However, using this data was complicated by several problems, including missing records for various data points (e.g., large portions of the speed records were missing), and lack of calibration of some sensors at the outset. This was again complicated by the fact that some data came from the BMS and some from the independent monitoring system, or in the case of Broadway, supplemented with some portable logger data. Long periods of stable operation in warm weather with complete data records were difficult to find in many instances. This led to an extensive effort to filter and analyze the data sets to yield subsets suitable for analyses with the toolkit. In hindsight, it would have been better to use portable loggers (including airflow by addition of a pressure sensor on the AFMSs). However, this experience also emphasized the deficiencies in (modified) the protocol due to the inability to track airflow and fan speed.

SUMMARY AND CONCLUSIONS

Overall substantial progress was made in development of the fan diagnostic protocols. Experience in monitoring and analyzing three buildings facilitated a critical examination of the protocols. Changes were made where feasible, and a comprehensive list of changes and additions was developed that would improve the tools and protocols significantly. This experience emphasized the kind of iterative effort it takes to bring the development of tools like these to viability. Among specific conclusions are the following:

- Accurate monitoring of airflow, fan static pressure, and fan speed are the only significant barriers to achieving a robust set of tools.

- Portable data logger monitoring (augmented by a few crucial additional parameters) has been reaffirmed as the right choice for these procedures. There are benefits to knowing the accuracy, placement, consistency and format of the data sets that argue strongly for use of portable loggers vs BMS trended data (at least those that typically exist in the installed base). However, as demonstrated by this project, the there is no inherent restriction against using BMS data in the tools

- In-situ performance of fans needs further investigation. The analyses of these buildings indicate that fan efficiencies can be lower than anticipated. Whether this is due to problems inherent to the methods used or is a real condition such as system effect needs further study.

- Further development of the single point analysis using monitored airflow, FSP, speed, and power would significantly enhance the analysis capability of the FA_BM_Tool.

- Once appropriate data sets are provided the toolkit can be easily used. By modifying input assumptions, the data can be viewed in alternative ways.

- Although the database contains only three fans as the result of this work, it has been helpful in understanding the performance issues discussed herein and in the Appendices.

With further development, as described in the recommendations contained in this report, the protocol and toolkit could become a very powerful method for screening for the types of problems in VAV (and potentially CAV) systems identified in Appendix VI and discussed in Webster [Webster 1999].

BENEFITS AND COMMERCIALIZATION POTENTIAL

Practitioners will benefit from the use of these tools because tedious ad hoc methods can be replaced with a standardized protocol that uses preformatted analysis charts and summaries. However, experience on this project indicates that these analyses are not simple and can require much time and effort to achieve meaningful results. Without simple and reliable tools it is unlikely that operations or energy service companies will conduct these types of studies.

These techniques are oriented toward large built-up fan systems. This limits the ultimate potential since these systems predominately occur in large buildings of certain types. Appendix VI provides a detailed analysis of the potential energy savings associated with utilization of these tools. Savings of 18% of total aggregate fan/pump energy is shown to be possible for the four major building types to which these protocols are most applicable. However, some of these tools could be effectively applied to smaller systems,[3] which would expand the utility and potential significantly.

RECOMMENDATIONS

The bulk of our recommendations are contained in the detailed enumerations captured in Objective #4 outcomes and in the discussion section. In general they emphasize the need for:

- Additional research on fan in-situ performance.
- Development of short term airflow and fan speed monitoring techniques.
- Making suggested improvements in the toolkit.
- Populating the fan performance database.

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[3] Smaller systems tend to use packaged equipment, which may complicate the ability to make the appropriate measurements and may limit the ability to make corrective changes. However, there is no inherent reason that these tools could not be used for these systems.

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Appendix I: UCB AHU Toolkit

Tools used in this study are shown in bold.

Tool/tabs	Description	Comments
Fan analysis & benchmarking (FA_BM_Tool)	Peak load single point analysis	Use VAV operating curve to extrapolate to maximum operating point
Summary	Design versus measured single point comparison	Compares original design intent to measurements extrapolated to design speed.
Fan Plot	System curve plot of design & measured data	Ditto
SFPI plot	Efficiency plot of design and measured data	SFPI = Specific fan power, individual fan, Watts/cfm Includes motor and drive efficiencies. Provides insight into problems of system resistance and fan efficiency.
Benchmarking	Set fan performance database filtering criteria	Filters database for fans similar to a subject fan.
Benchmark chart	Normalized distribution comparing subject fan to filtered sample population for 8 possible metrics.	Compares subject fan to (filtered) database to compare performance.
System Temperature Analysis (STA_Tool)	AHU airside temperature monitoring	Time series tool to ascertain airside performance problems.
Start	Enter schedule and economizer assumptions	
Enter Data	Import system temperatures logger data	
Summary	Summary parameters & statistics	
MAT-OAT chart	Economizer performance chart	Find OSA fraction from analysis of economizer operation.
SAT-OAT chart	SAT performance plot	Identify SAT trends, control problems.
SAT,RAT – TOD Chart	SAT, RAT versus time of day plot	
MAT, OAT – TOD Chart	MAT, OAT versus time of day plot	

Tool/tabs	**Description**	**Comments**
SAT, OAT, MAT, RAT Time Chart	All airside temperatures trend plot	
Fan Power Analysis (FPA_Tool)	Power monitoring	Accepts time series power data
Start	Enter motor and HVAC data	
Enter data	Import power, OAT logger data	
Summary	Summary statistics	
LF Histogram	Histogram of load factor for occupied and unoccupied hours	Shows fan power load profile
LF - OAT Chart	Load factor versus OAT	Shows sensitivity to OAT
LF - TOD Chart	Load factor versus time of day	
Power – Time Chart	Power trend with schedules	
Static Pressure Analysis (DSP_Tool)	Fan discharge static pressure	Accepts duct static pressure (near the fan) time series data.
Start	Enter schedule and duct static setpoint	
Enter Data	Import static pressure, OAT logger data	
Summary	Summary statistics	
DSP-OAT chart	Discharge static pressure versus OAT	
DSP – TOD Chart	Discharge static pressure versus time of day	
DSP – Time Chart	Discharge static pressure trend log	
Motor Efficiency (ME_Tool)	Motor efficiency analysis	Single point analysis to evaluate motor efficiency
Start/summary	Enter nameplate and measured data for maximum operating point	Displays motor operating efficiency based on a comparison of measured and nameplate data.
Motor HP tabs	Charts of efficiency versus load factor for motors 2-100 HP, standard & premium, ODP and TEFC	Used as reference data to support efficiency analysis.
Zone Air Temperature Analysis Tool (ZAT_Tool)	Analyze zone temperatures for up to 4 zones	Provides a way to determine if zone conditions are being met.
Start	Enter schedule and setpoint data	
Enter Data	Import zone temperature and OAT logger data	

Tool/tabs	**Description**	**Comments**
Summary	Summary statistics for 4 zones	
ZAT - OAT Chart	Zone(s) temperature versus OAT plot	
ZAT – TOD Chart	Zone(s) temperature versus time of day plot	
ZAT Time Chart	Zone(s) temperature trends	
Reheat Analysis Tool (RHT_Tool)	Analyze over/under airing for CAV systems	For CAV systems to determine over and under airing.
▪ Start	Enter schedules and zone set point data	
▪ Enter Data	Import temperature logger data	
▪ Summary	Zone temperature and HW delta T summary statistics	
▪ ZAT , HWDT - OAT Chart	ZAT and HW deltaT versus OAT plot	
▪ HWST, HWRT – OAT Chart	HWST, HWRT versus OAT plot	
▪ HWST, HWDT – TOD Chart	HWST, HWDT versus time of day plot	
▪ ZAT Time Chart	Zone, outside, reheat temperature logs	
Field data sheets	Field data sheets to assist data collection	Summarizes AHU data for handy reference.
▪ **Data collection**	Data collection and summary information sheet	
▪ Pitot traverse	Pitot traverse calculation sheet	

Appendix II: Field study of Novell

SYSTEM DESCRIPTION

The Novell campus project focuses on Building D, primarily an office space for high technology design and project management (there is no lab space). Construction finished in late 1999 and full occupancy began immediately. The Novell building has three stories and a penthouse with conditioned floor space of 105,000 ft^2. The penthouse contains boilers and two centrifugal water-cooled chillers, rated at 250 tons each, to serve a single air-handling unit.

The air-handling unit consists of a plenum mixing room with two unhoused (plug) fans, Loren Cook 660-CPL-A, 66 in. diameter fans with a design rating of 79,860 cfm and 4 in. FSP. The fans pressurize the plenum, to which the ductwork is directly connected. This design saves space by eliminating the fan housing and ductwork transition to the fan discharge. The supply is split into two shafts that serve floor loop ducts which in turn supply the VAV boxes. The return is not ducted and there are no return fans. There are relief fans to assist with controlling building pressurization. Economizer dampers (outside and return air) are modulated to take advantage of favorable ambient conditions.

The BMS control system operates the air-handlers 24-hours per day; however, the office core zones operate typically from 4 AM to 10 PM. A local zone controller functions independently but receives set point adjustments from the BMS to control the terminal VAV boxes. Each zone is controlled to maintain a maximum heating and minimum cooling set point during the occupancy period. These set points are manually adjustable by specific terminal box from the host computer, but are generally 70°F heating and 74°F cooling.

The economy cycle system (outdoor, return, and exhaust fans) is interlocked to provide 100% outside air when the outside air temperature (OAT) is cooler than return air temperature (RAT). The economizer OAT low limit is 55°F and the high limit is 70°F. When the OAT exceeds the RAT, the outside air damper closes to a minimum damper position.

MONITORING

Both supply fans SF1 and SF2 were studied. Data used for the fan performance analysis came from both the BMS and the SBW installed data acquisition system (DAS); a total of 61 points were logged, only a few of which were used for this study. Airflow was measured using the pitot static tube based airflow monitoring station (AFMS) installed by SBW in the inlet of the fans. Fan static pressure (FSP) was measured by a differential pressure transducer with sample points in the fan discharge and inlet mixing plenums. Speed was derived from BMS monitored data of the variable frequency drive (VFD), and power was measured with power meters on the bus side of the VFD. We calibrated the AFMS stations using the constant injection tracer gas (CITG) method for measuring airflow as presented in Appendix V. The average error found for all three buildings studied was –17%.

DATA ANALYSIS

Two sets of data were derived from the logged data sets as supplied by SBW. As in the other field studies described in this report, we determined the maximum operating point by analyzing data logs for airflow, FSP, speed, and power for selected warm days. For the diagnostic tools we selected two weeks of warm weather data out of the same base data set (the maximum currently accommodated by the diagnostics tools).

Tool data set selection and analysis

The selection and analysis was complicated by several problems with the data, including missing records for various data points (e.g., large portions of the speed records were missing), and lack of calibration of some sensors. Long periods of stable operation in warm weather with complete data records were difficult to find. For example, inspection of the data set revealed significant oscillations in fan operation sometimes when only one fan was running, as shown in Figure I-1. The limited available speed data indicates that these were the result of control instability. (These oscillations were not obvious from any of the tools used, but they may have been if we used the Static Pressure Analysis Tool.) In addition to the oscillations, significant scatter in the data is generated as the fans are cycled for lead/lag operation and during the transitions when a fan starts or stops. Cycling of the fans in response to demand also limits the range of speeds experienced. Finally, we decided to use portions of two separate weeks to construct a two-week set; 7/8 to 7/16 and 7/26 to 7/31.

Although one fan always operates at night, inspection of the data revealed what appears to be a daily occupancy schedule of 5:30 AM to 8:30 PM. At these times the lag fan is enabled or disabled, respectively. Analysis of the data (secondary chilled water flows) suggests that the chiller is locked out at 60-63°F outside air temperature (OAT). Calibration of the fan drives made with a handheld tachometer revealed an error in the speed data reported in the base data set; this error was corrected for our analysis. Likewise, handheld comparisons for mixed air temperature (MAT) and OAT revealed an offset in OAT of about +5°F (i.e., sensor reading low).

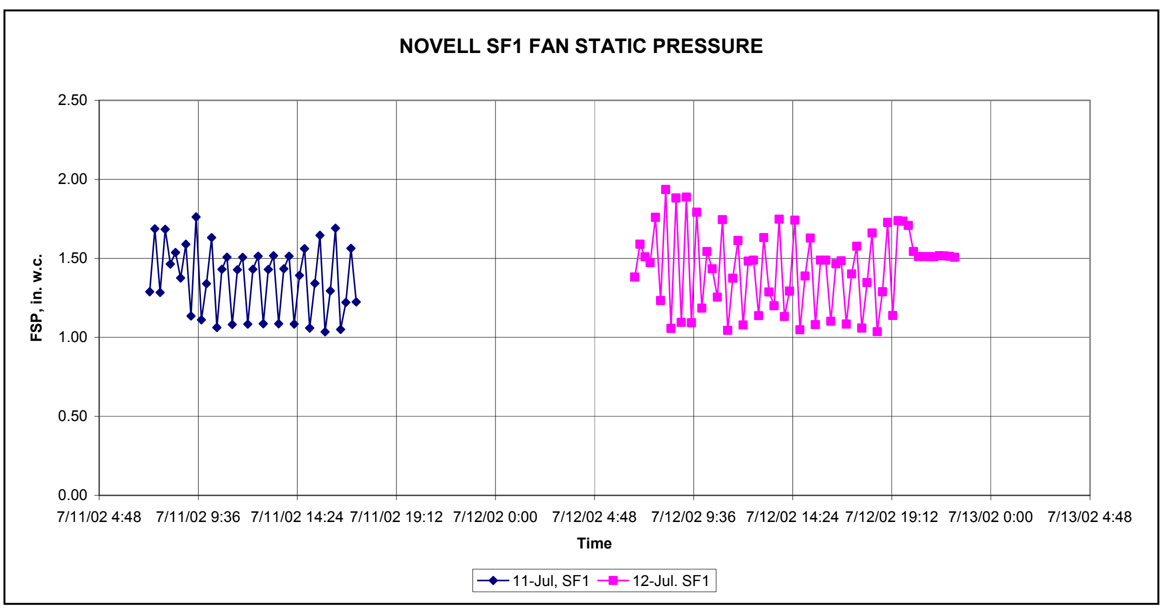

Figure I-1: SF1 static pressure oscillations

Maximum Operating Point

Using a modification of the original protocol, we determined the maximum operating point by first plotting FSP versus airflow for high load conditions. Regressions on this data produces a *system* operating curve (i.e., the states that the fan assumes to meet system demands) which can be used to extrapolated to higher load conditions. Similar charts are made for speed and power vs. airflow. Once these curves are obtained they can be used to extrapolate to the maximum operating point for the monitoring period. As noted in the body of this report, these regressions can also be used to extrapolate to the design speed to find the equivalent operating point to compare to the design intent. (See Apply Tools section for further discussion.) For these charts the airflow was corrected by -17% per the tracer gas calibration results (see Appendix IV). The data set used for this analysis was derived from the complete set for July through September 2002. The data was filtered to select only those records where both fans were operating on warm days (since these are representative of peak operating conditions) and to remove obvious transient and oscillating conditions (e.g., when a fan was cycled off or on). As shown by the fan operating curves in Figure I-2, SF2 operates at a somewhat greater volume than SF1. Sometimes this behavior is switched, the fans rarely seem to operate at the same volume despite running at the same speed. This behavior may be a result of operation in an unstable region of the fan curves due to oversizing and/or greater than expected system resistance. Plug fans have a fan (flow vs. FSP curve) characteristic similar to forward curve fans where the FSP curve flattens in the "do not select" region.

Note also that the performance over the measured range is not consistent for all periods of operation. Figure I-2 shows two distinct system curves for two different periods for SF2. It is unclear as to why, when two fans are operating in parallel that the system resistance seems to vary for an individual fan. For the lower system curve (triangle data points) for SF2 the maximum operating condition for the monitoring period was 33,000 cfm at 2.3 in. w.c. FSP. Extrapolation to the equivalent design point could not be done for this system due to limited speed data in the BMS dataset (partly due to the fact that the fans operate over a narrow speed range because a staging strategy is used to control static pressure).

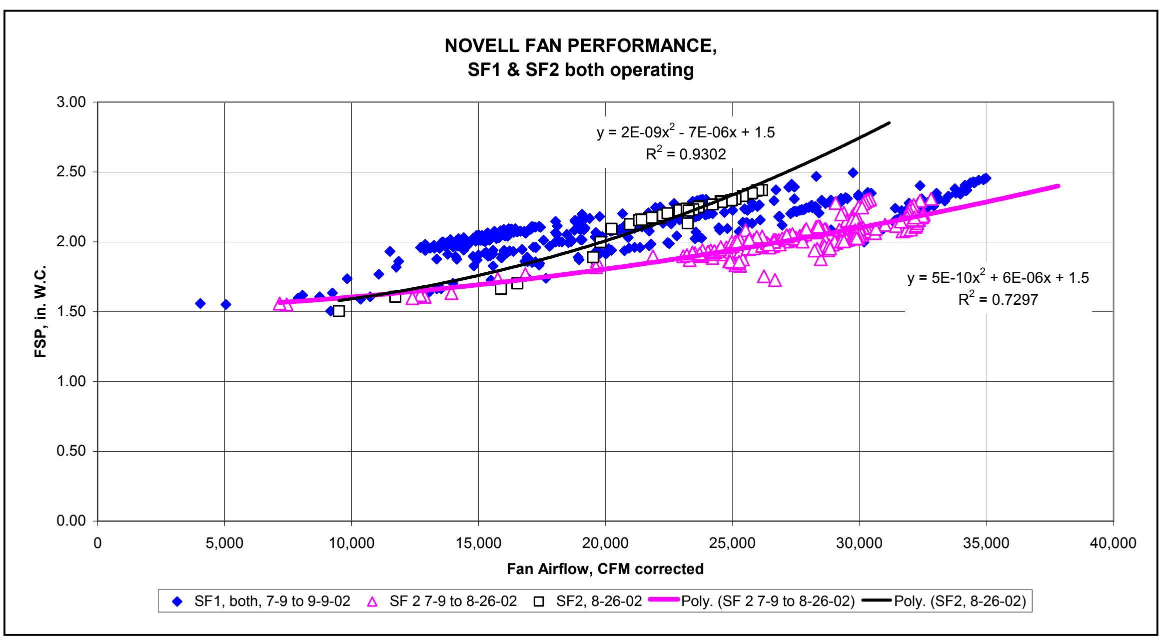

Figure I-2: Novell Maximum operating point analysis

APPLY TOOLS

The standardized tools used for this analysis are:

- System Analysis (STA_Tool)
- Fan Analysis/benchmarking (FA_BM_Tool)
- Fan Power Analysis (FPA_Tool), and
- Motor Efficiency (ME_Tool)

The results from the first three of these are discussed and shown by the figures below. To keep this report concise, only results for tools that were used to draw significant conclusions are included. We refer the interested reader to Webster [Webster 1999] for a complete description of all the tools and their associated data visualization charts. This report also includes a compete description of the error analysis the results of which are shown in the measurement error column in Table I-1.

Fan Analysis/Benchmarking Tool (FA/BM_Tool)

Table I-1 shows the original summary page of the FA_BM_Tool where the field measured maximum operating point is extrapolated to the design speed using fan laws and is compared to design. As noted in the body of this report (Objective #3 of outcomes section) this is technically incorrect and the equivalent design speed point should be used instead. However, since this data could not be derived from the logged dataset, this correction could not be made.

Table I-1 shows the results of the comparison of the maximum operating point to the original design point of 79,860 cfm and 4.0 in. w.c. This table indicates that as measured, the fan operates at an efficiency of 42%. Using the catalogue data for these fans it was found that when both fans are running they operate mostly in the “do not select” region of the fan curves. However, the catalogue efficiency does not decrease significantly due to this design operating point difference. Assuming there are no gross errors in measurements, this suggests that there may be other problems with the fans that are causing a drop in efficiency, such as system effect. (See Discussion section in body of report.)

Figure I-3 is included for illustrative purposes to show a typical benchmarking result for these fans when compared to other fans in the database (only two others at this point). Efficiency ratio is one of eight possible comparison metrics that can be selected with this tool.

Table I-1: Novell Summary (FA_BM_tool)

CIEE Fan Project

Fan Analysis & Benchmarking Tool: Summary Page

Select Subject Fan:	**Function:**	**Control:**	**Design:**
Novell, SF1,2 (LC 660 CPL-A)	Supply	VAV	SWSI
	Size:	**Type:**	**Configuration:**
	Over 45"	Backward Curved	Plug

FAN SUMMARY INFORMATION	**Design Data**	**Field Measured Data**	**Corrected to Design Speed**	**Measurement Error (+/-)**
Fan Power (KW)	64.33	20.12	79.87	2.77
Volumetric Flow (CFM)	79,860	33,000	52,250	2,613
Fan Static Pressure (In. W.C.)	4.00	2.20	5.52	0.28
Fan Speed (RPM)	665	420	665	-
Specific Fan Power (Watt/CFM)	0.81	0.61	1.53	0.08
Flow Density (CFM/SF)	1.52	0.63	1.00	0.05
Fan Total Efficiency	58%	42%	42%	3.3%

QUICK ANALYSIS:
MEASURED VS. DESIGN DATA

Measured Fan Power:	**Lower than Design**		
Measured Fan Speed:	**Slower than Design**		
Measured Fan Operating Point:	**Different:**	Lower Volume	Lower Pressure
Corrected Fan Opearting Point:	**Different:**	Lower Volume	Higher Pressure
Measured Fan Efficiency:	**Less Efficient than Design**		

Fan Efficiency Ratio	0.73

Ratio of measured fan efficiency to reference (design) fan efficiency

MOTOR SUMMARY INFORMATION	**Namplate Data**	**Field Measured Data**
Motor Output (HP)	75	
Motor Speed (RPM)	1775	1176
Motor Current (Amps)	82.00	0.00
Motor Voltage (Volts)	460	0
Motor Power Factor	0%	0%
Motor Efficiency	94.0%	90.8%
Motor Input (KW)*	59.52	25.00
Motor Load Factor:		42.0%

**If Motor Current = 0, Motor Input (KW) calculated from Motor Output and Motor Efficiency*

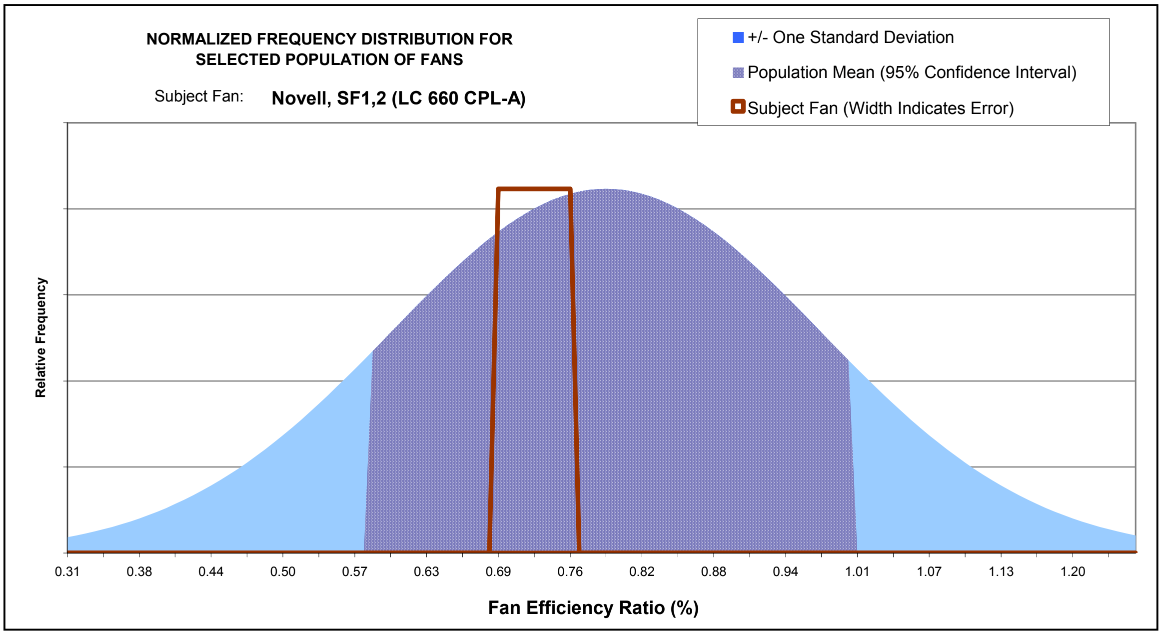

Figure I-3: Novell Benchmarking example, fan efficiency ratio (FA_BM_tool)

System Analysis Tool (STA_Tool)

Selected results from the SA_Tool are shown in Figures I-4 and I-5. Figure I-4 shows economizer performance. Note that when the economizer is open the mixed air temperature (MAT) is about 5°F greater than OAT as shown in Figure I-4. This is consistent with a single point calibration made at the site. It appears that the OAT sensor is out of calibration. This also explains why there is no apparent difference in the trend below 60°F since the economizer will end up being fully open because the actual OAT is greater than that read by the control system while it tries to modulate to control to 60°F SAT. Also, note that the 40% outside air fraction shown will also be in error; when the chart is corrected for the 5°F offset (not shown) in OAT, a value of 30% is obtained. This indicates the importance of accurately calibrated sensors and highlights how installed short-term data loggers may yield more reliable results.

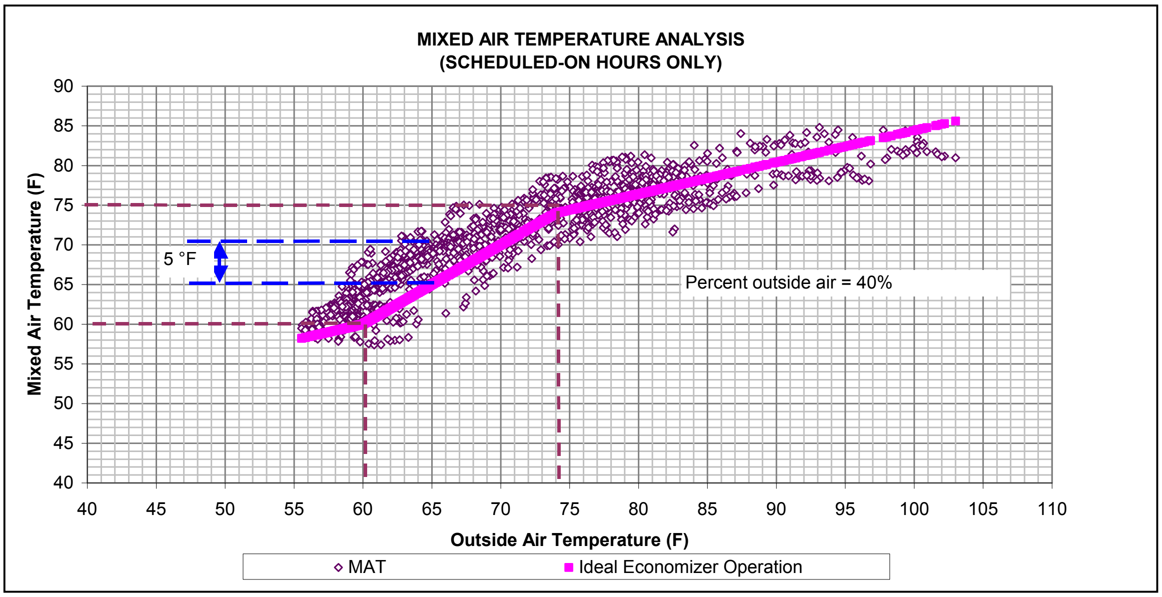

Figure I-4: Novell economizer performance (STA_tool)

Figure I-5 shows the SAT versus OAT, which confirms a constant setting of 60°F without reset. The large scatter below about 63°F results from the economizer operation when the chiller is locked out as explained previously.

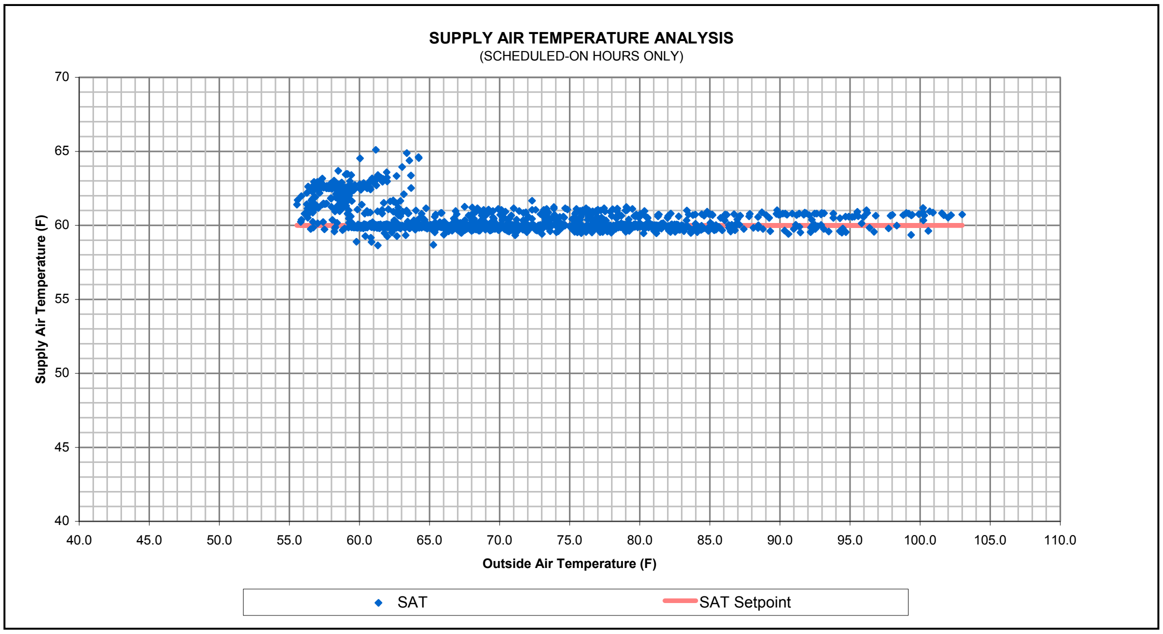

Figure I-5: Novell SAT temperature performance (STA_tool)

Fan Power Analysis Tool (FPA_Tool)

Since the fans for the Novell system are cycled, combined power for SF1 and SF2 were used in most of the analysis. Also, since this tool relates to building load for some displays, the OAT was corrected by +5°F to account for the sensor offset. For this tool the scheduled on hours were assumed to be the weekday hours between 5:30 AM and 8:30 PM.

The load factor is the measured fan motor input power divided by the nameplate rating of the motor. It indicates the degree of turn down for both the motor and fan. The distribution shows the degree of modulation and thus shows when modulation is not operating correctly or the fans are oversized (low load factors). Comparing scheduled hours to off hours provides and indication of off-hours energy use; this is more explicitly shown in Table I-2.

Table I-2: Novell FPA_tool summary, SF1 + SF2

CIEE Fan Project

Fan Power Analysis Tool

Summary of Logged Data

Data Collection Parameters	Scheduled On Hours	Scheduled Off Hours	All Measured Hours	
Data log start time:			7/8/2002 12:15	
Data log end time:			7/31/2002 23:45	
Logging Interval:			25.2	minutes
Total Measured Hours:			563.22	Hrs
Operating Hours:*	253.68	309.54	563.22	Hrs
Operating Hrs. as % of Total Hrs:	45.0%	55.0%	100.0%	
Projected Operating Hrs/Yr:	3,946	4,814	8,760	Hrs/Yr

** Hours with Power > 0.1 KW*

Motor Input Power	Scheduled On Hours	Scheduled Off Hours	All Measured Hours	
Minimum Power Demand	13.96	10.61	10.61	KW
Average Power Demand	33.83	14.09	22.98	KW
Maximum Power Demand	50.86	15.27	50.86	KW
Standard Deviation	7.62	0.49	11.08	KW
Projected KWH/Yr.	133,465	67,827	201,292	KWH/Yr

Operating Load Factor (% of Full Load Motor Power)	Scheduled On Hours	Scheduled Off Hours	All Measured Hours
Minimum Load Factor	12%	9%	9%
Average Load Factor	28%	12%	19%
Maximum Load Factor	43%	13%	43%
Standard Deviation	6%	0%	9%

Outside Air Temperature	Scheduled On Hours	Scheduled Off Hours	All Measured Hours	
Minimum OAT	56.7	55.8	55.8	F
Average OAT	79.7	68.4	73.5	F
Maximum OAT	108.0	88.0	108.0	F
Standard Deviation	11.1	7.8	11.0	F

Figure I-6 clearly shows the large number of hours where fans are operating at low load factors (but not necessarily low efficiencies; see above). This is true even for the occupied part of weekdays. However, this is primarily due the fact that only one fan is operated for much of the time as shown by comparing Figure I-6 with Figure I-7. This causes the chart to indicate a substantial number of hours at low load factors due to operating at low loads at night. However, the distribution is broader and more even than for two fans yielding a better representation of the performance. Table I-2 shows that off-hours operation accounts for about 33% of the estimated total annual fan consumption. Figure I-8 shows the load factor versus OAT which shows only a slight sensitivity to OAT, indicating an internally load dominated building. Figure I-9 shows the daily profile for load factor and again indicates the low load factor for occupied hours and the pervasive off-hours power use at low load factor, which would be expected when night time loads are serviced.

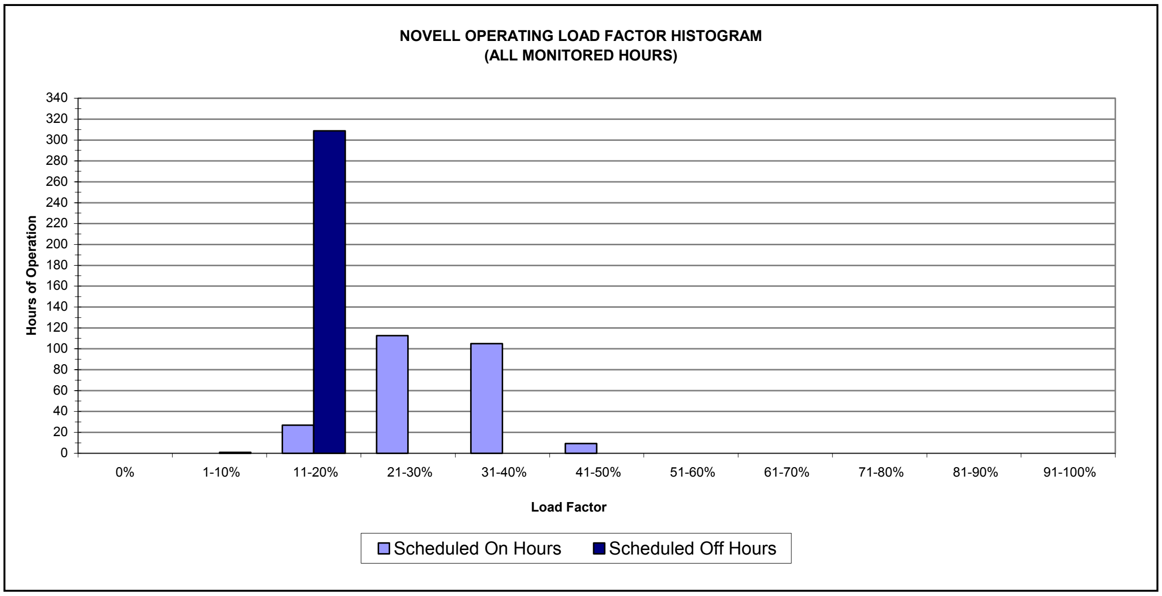

Figure I-6: Novell load factor histogram for both SF1 + SF2 (FPA_tool)

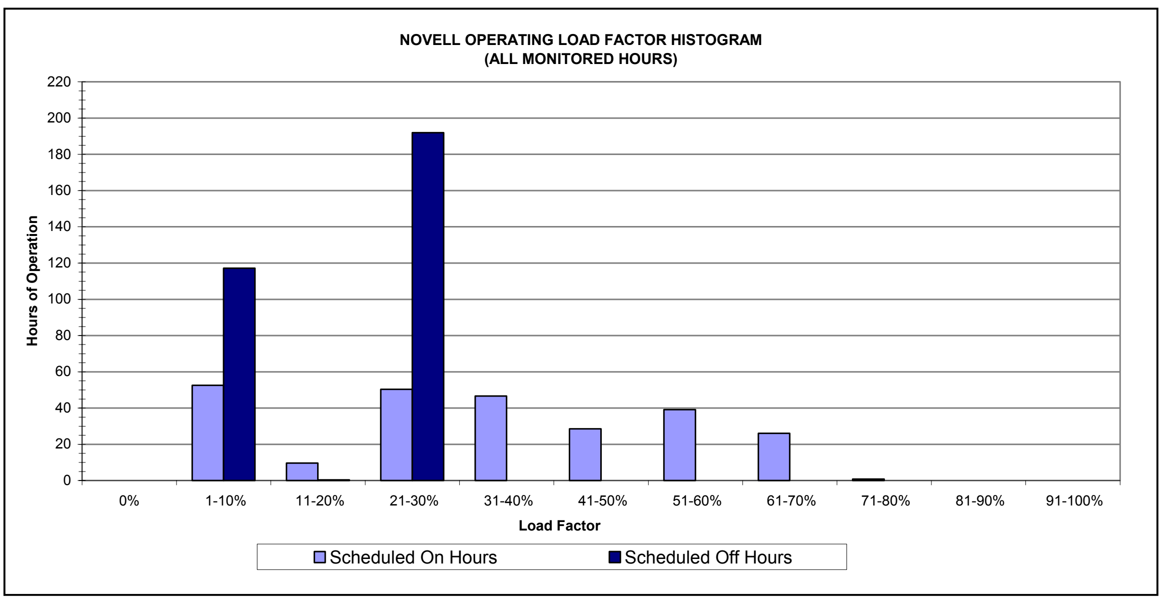

Figure I-7: Novell load factor histogram for SF1 (FPA_tool)

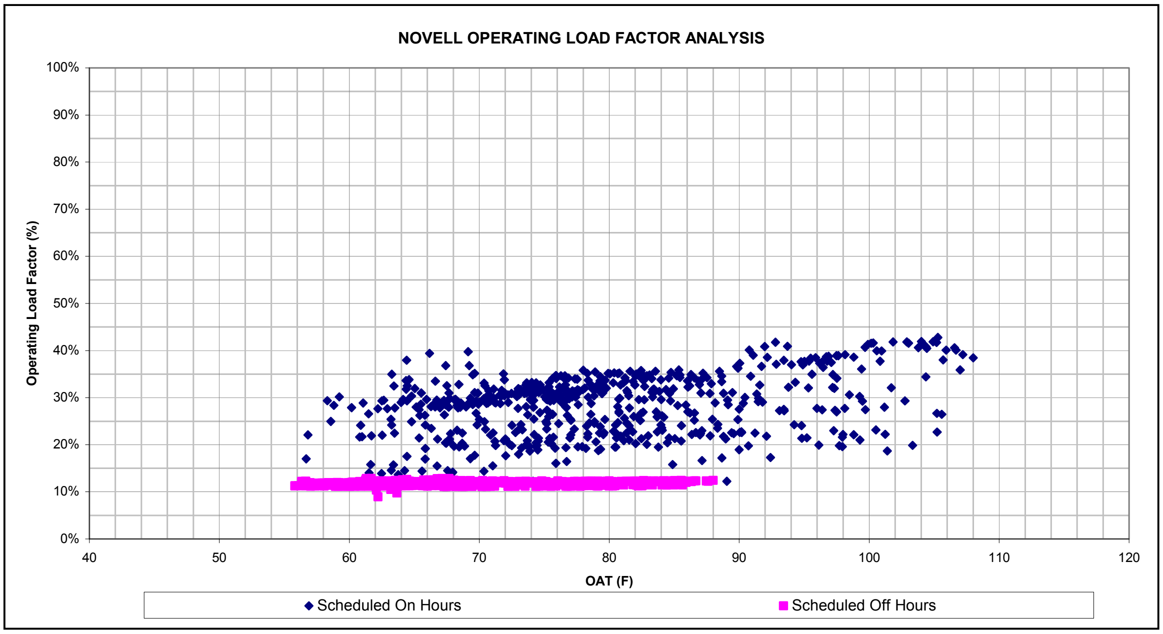

Figure I-8: Novell load factor vs OAT (FPA_tool)

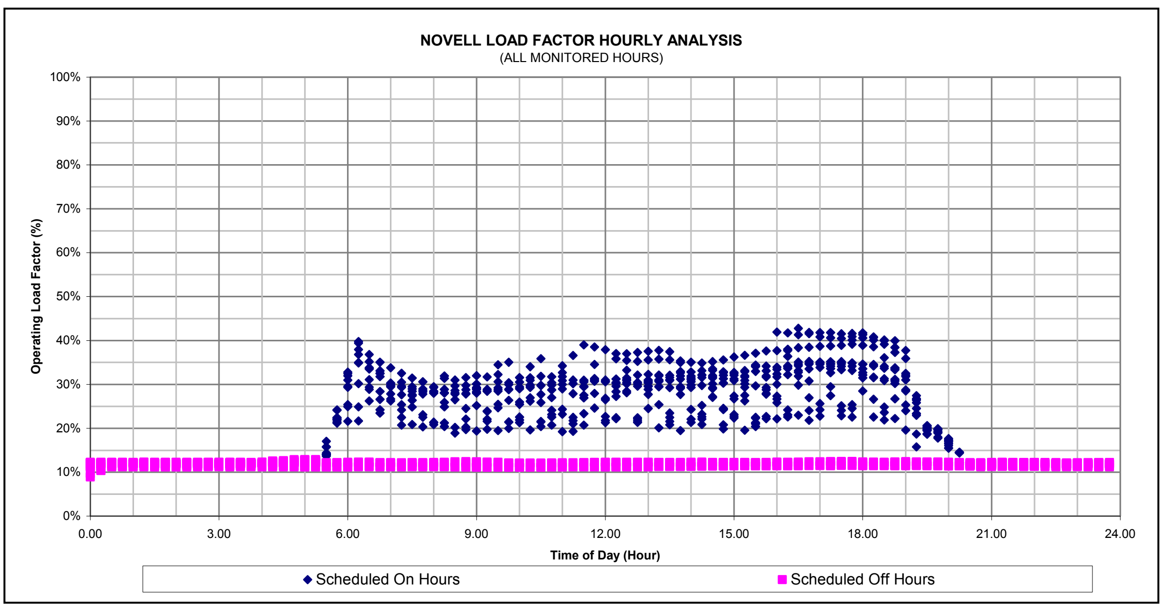

Figure I-9: Novell daily load factor profile (FPA_tool)

SUMMARY OF FINDINGS

Economizer. The economizer appears to be operating correctly but there appears to be a problem during modulation at low outside temperatures due to poor calibration of the outside air sensor. The estimated outside air fraction of 30% seems reasonable, although it could possibly be lowered since there is a large number of full open economizer operation in this climate.

Motor/drive efficiency. Drive and fan motors are operating correctly at relatively high efficiency during peak load conditions. Efficiencies are estimated to be motor, 90.8%; belt drive, 94.1%; VFD, 94%.

Fan performance. The fans are oversized compared to the maximum load conditions experienced during testing. Although system resistance is greater, the airflow requirements are much less than design. Theoretically this alone only reduces efficiency by about 5%. However, the data indicates that fan operating static efficiency is about 42%, ~30% less than design. While an explanation was not obvious, it may have to do with restrictions on the inlet due to the back draft dampers, and/or the unstable and transient manner that the system operates, (i.e, oscillations when a single fan is running, operating in a potentially unstable region when both fans are operating, and frequent cycling of fans off and on). Fan cycling is an additional method of volume control that overall results in the fans operating over a narrow speed range.

Appendix III: Field study of Broadway

SYSTEM DESCRIPTION

The Oakland Administration Building Project consists of two separate buildings that were constructed under a single design/build contract: the Dalziel Building and the Broadway Building, the subject of this study. The Broadway building, also known as the Wilson building, consists of a new construction portion and an historic preservation portion. Construction was completed in spring 1998 and occupancy began in the summer of 1998. The Broadway building has eight stories including 24-hour computer rooms. The floor area excluding the retail space is 172,762 ft^2. The main HVAC system is central variable-air-volume with hot water reheat. A single chilled water plant in Dalziel, which consists of two 500-ton chillers, serves the main air handlers in both buildings. Each building has its own hot water boilers. Broadway also has an air-cooled chiller (ACH-1), which serves three computer room AC units.

There are two AHUs each with their own supply and return fans that are configured to operate in parallel. Each AHU's airflow is split at discharge, with one duct providing supply air to the older section of the building, and the other duct providing air to the newer section. There are two supply air shafts for each section of the building. In the older part, there are single-ended ducts with VAV boxes, and no interconnections between supply air shafts. For the new area on the lower floors, the trunk ducts are looped so that the supply shafts from each fan are effectively interconnected.

The control system is a Staefa BMS with a central workstation in the Dalziel building. The supply fans are equipped with VFDs and two pressure sensors, one for each shaft of each AHU. These are averaged together pneumatically providing one input to the control sensor. Although supply-return fan tracking is specified to operate with an airflow offset, it appears that fan tracking is based on a speed offset.

According to the building operations personnel, the SAT is reset based on OSA temperature. This schedule is constructed to never supply air below about 62°F. The operating engineer reported that he saves energy using this reset strategy and that any supply air temperature below 62°F would be too cool for occupants. At 62°F OSA temperature the chiller is locked out.

A small section of the OSA dampers have an independent control actuator and an airflow station presumably to provide minimum OSA during economizer operation; however, these dampers did not appear to operate independent of the main dampers. There is also a propeller fan that may be used for OSA control but it is not clear how or if it works.

DATA ACQUISITION AND ANALYSIS

Supply fan SF2 was used for this study. Data used for the fan performance analysis came from both the BMS and data loggers we deployed. The loggers were used to collect FSP using a differential pressure transducer connected to a manifold that averaged the fan discharge pressure at four locations relative to inlet pressure measured in the fan room. Fan power was logged using current transducers that were calibrated against a power meter. Airflow was measured using existing pitot static tube based airflow monitoring stations (AFMS) mounted in the inlet of the fans. We calibrated these stations using the constant injection tracer gas (CITG) technique as described in Appendix IV. Fan speed readings were also taken with a handheld tachometer and calibrated with the VFD speed percentage output shown on the VFD console in the fan room. During our site visit on July 17, 2002 we discovered that a switch on the AMFS interface box was off which prevented sending the airflow signal to the BMS. Thus no data before July 17, 2002 was available for our analyses.

As with the other data sets described in this report, data from the BMS was difficult to obtain and work with due to the limited accessibility, unorthodox file structures used, and missing data records for some points. Since a number of teams were using these data sets, they were processed by multiple parties, which included re-sampling to a 5-minute time step. Ultimately these BMS files were merged with the logger data, time synchronized, changed back to a 15-minute sample time, and filtered for transient conditions and missing data to provide a dataset for the system curve determination. Another subset of the dataset was extracted from the MS Access database and output in an Excel format for a two-week period to use for the tools. This last step resulted in a truncation of the data values for unexplained reasons.

The final data sets were corrected for airflow (-17% as indicated in Appendix IV), %VFD signal to fan speed, and power (based on calibrated current to power readings). The system curve was derived from data recorded over the period August 12 to September 12, 2002 and the tools data set covered the period August 28 to September 11, 2002.

Maximum Operating Point

We tried two methods to determine the max operating point: (1) we increased the SAT to simulate the design maximum operating condition, and (2) we used the corrected logged airflow and FSP to develop the system operating curve as described in Objective #3 of the Outcomes section of the body of this report. Method 1 proved to be too cumbersome and was abandoned in favor of the system curve method described in the body of the this report. Figures II-1 and II-2 show results from this analysis. From these regressions the maximum operating point for the monitoring period was determined to be 55,000 cfm; other associated data are shown in Table II-1.

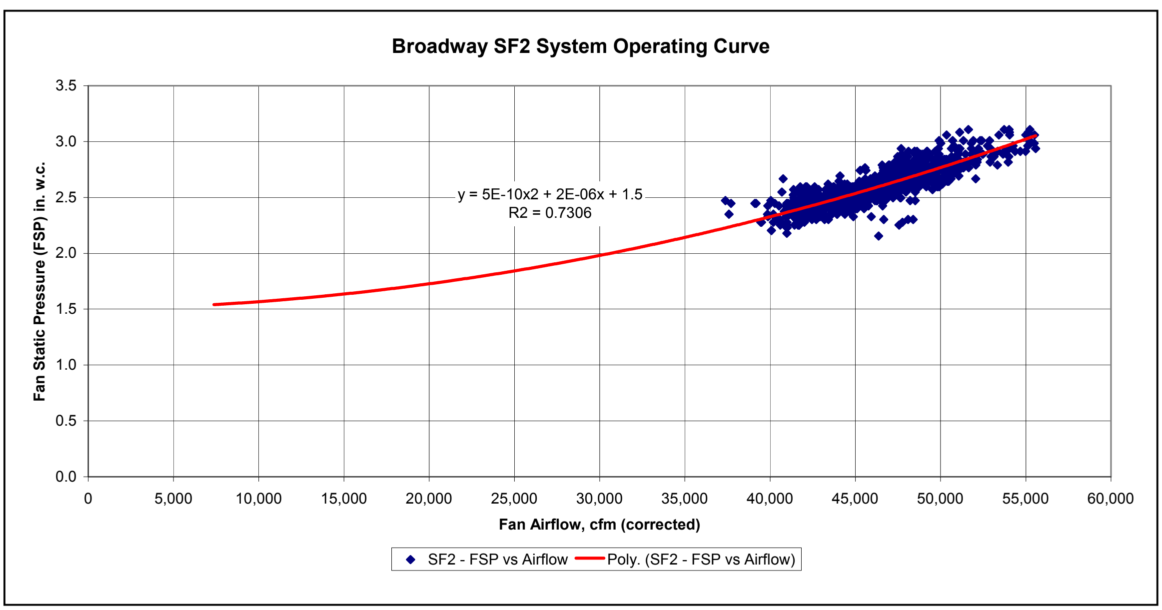

Figure II-1: Broadway system operating curve for SF2

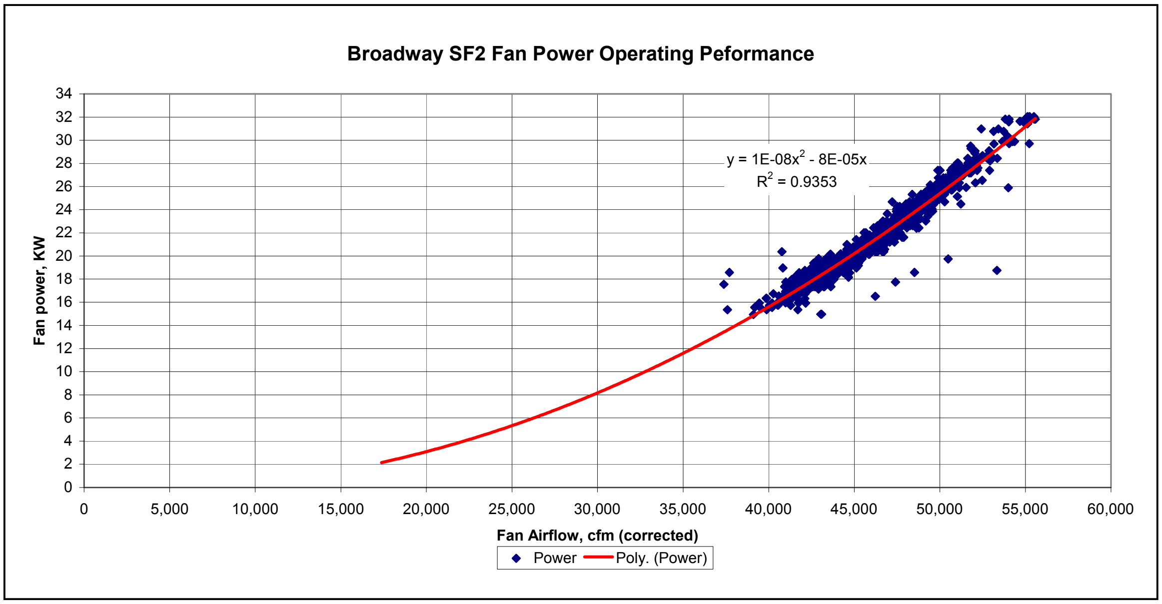

Figure II-2: Broadway operating power curve for SF2

APPLY TOOLS

Fan Analysis/Benchmarking Tool (FA_BM_Tool)

Table II-1 and Figures II-3 and II-4 show the results of the single point tests based on the maximum monitored operating point determined as described above. Since the maximum monitored operating speed was virtually the same as the design speed, this point is the same as the equivalent design point that is determined by extrapolation of the system curve as described in Outcome Objective #3 in the body of this report.

Table II-1: Fan performance summary

CIEE Fan Project

Fan Analysis & Benchmarking Tool: Summary Page

Select Subject Fan:	**Function:**	**Control:**	**Design:**
Broadway, SF2 (Trane CAFD60)	Supply	VAV	DWDI
	Size:	**Type:**	**Configuration:**
	Over 45"	Backward Curved	Shrouded

FAN SUMMARY INFORMATION	**Design Data**	**Field Measured Data**	**Corrected to Design Speed**	**Measurement Error (+/-)**
Fan Power (KW)	67.07	25.63	25.28	0.88
Volumetric Flow (CFM)	90,000	55,000	54,750	2,738
Fan Static Pressure (In. W.C.)	5.00	3.12	3.09	0.15
Fan Speed (RPM)	657	660	657	-
Specific Fan Power (Watt/CFM)	0.75	0.47	0.46	0.02
Flow Density (CFM/SF)	2.09	1.28	1.27	0.06
Fan Total Efficiency	79%	79%	79%	6.2%

QUICK ANALYSIS:
MEASURED VS. DESIGN DATA

Measured Fan Power:	**Lower than Design**		
Measured Fan Speed:	**Equivalent to Design**		
Measured Fan Operating Point:	**Different:**	Lower Volume	Lower Pressure
Corrected Fan Opearting Point:	**Different:**	Lower Volume	Lower Pressure
Measured Fan Efficiency:	**Equivalent to Design**		

Fan Efficiency Ratio	1.00

Ratio of measured fan efficiency to reference (design) fan efficiency

MOTOR SUMMARY INFORMATION	**Namplate Data**	**Field Measured Data**
Motor Output (HP)	100	
Motor Speed (RPM)	1770	1800
Motor Current (Amps)	119.00	0.00
Motor Voltage (Volts)	460	0
Motor Power Factor	0%	0%
Motor Efficiency	93.6%	90.2%
Motor Input (KW)*	79.70	32.00
Motor Load Factor:		40.2%

**If Motor Current = 0, Motor Input (KW) calculated from Motor Output and Motor Efficiency*

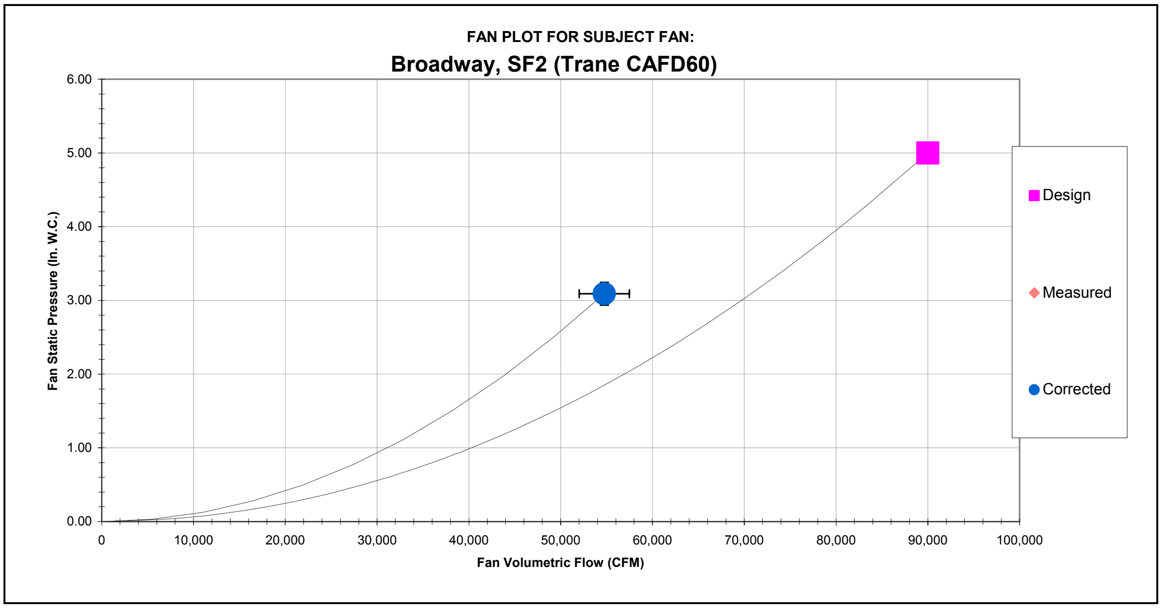

Figure II-3: Broadway fan operating point comparison for SF2 (measured point is behind corrected point)

Figures II-3 and II-4 indicate that the system resistance is somewhat greater than design but the output (airflow and FSP) is significantly less than design (when compared at design speed). However, these results are contradictory because we would expect this reduced output to be accompanied by a reduction in fan efficiency; fan efficiency is still 79% based on our measurements. Although system effect factors may be less of an impact than in the other systems studied, the outlet configuration was still not ideal so we would expect some impact on output and fan efficiency. Extensive review of the data and calibration procedures provided no explanation of this contradictory result. However, we suspect that the power readings might be faulty for some reason (e.g., wrong conversion factors for CTs etc.) but there was no opportunity to investigate this further.

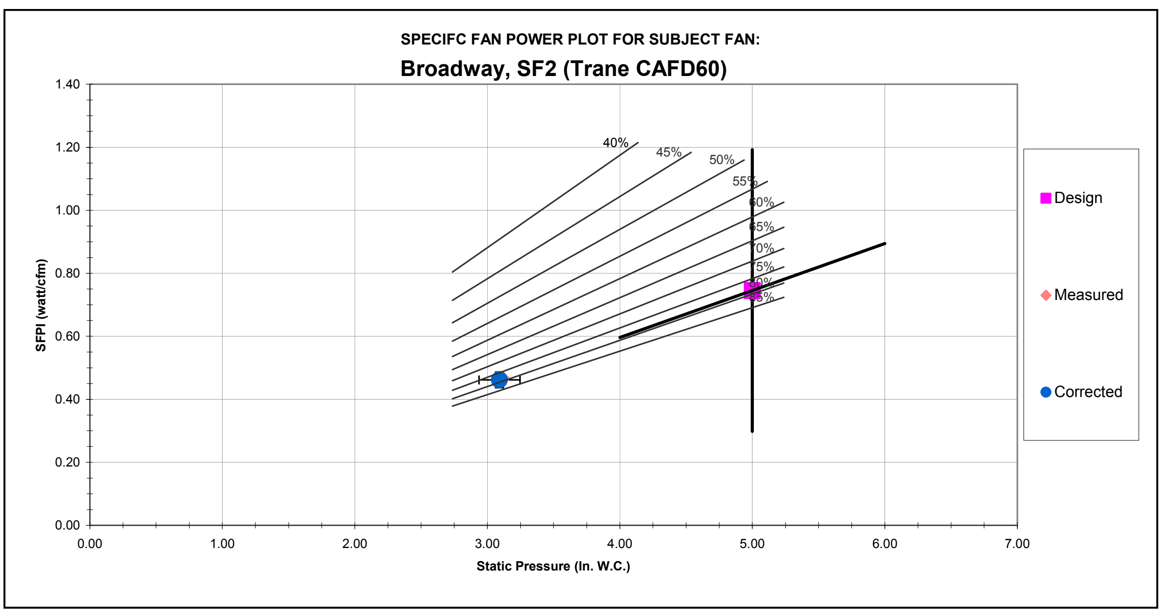

Figure II-4: Broadway specific fan power for SF2 (measured point is behind measured point)

System Analysis Tool (STA_Tool)

Selected results from the SA_Tool are shown in Figures II-5 and II-6. In Figure II-5, which shows economizer performance, the data points for mixed air temperature (MAT) generally track the ideal economizer operation line and this represents normal economizer operation; however, there is a tendency for high MAT when the OAT is below about 68°F. This operation indicates there might be leakage by the mixed air damper that allows warmer return air to continue to mix with the outside air thus producing mixed air temperatures that are too warm and thus potentially adding to the cooling load during partial mechanical cooling periods. It was observed that the main damper sections are misaligned during actuation and OSA dampers seemed to hunt when near the changeover point while controlling SAT to the (reset) value of 63°F. Mixed air dampers also were not moving in unison with the OSA dampers. Other researchers from Lawrence Berkeley National Laboratory reported that this is due to delay problems with the BMS control algorithms due to the heavy demands of data trending.

It is recommended to calibrate the sensors and to verify proper operation of the mixed air damper during the economizer cycle, and to reduce trending requirements.

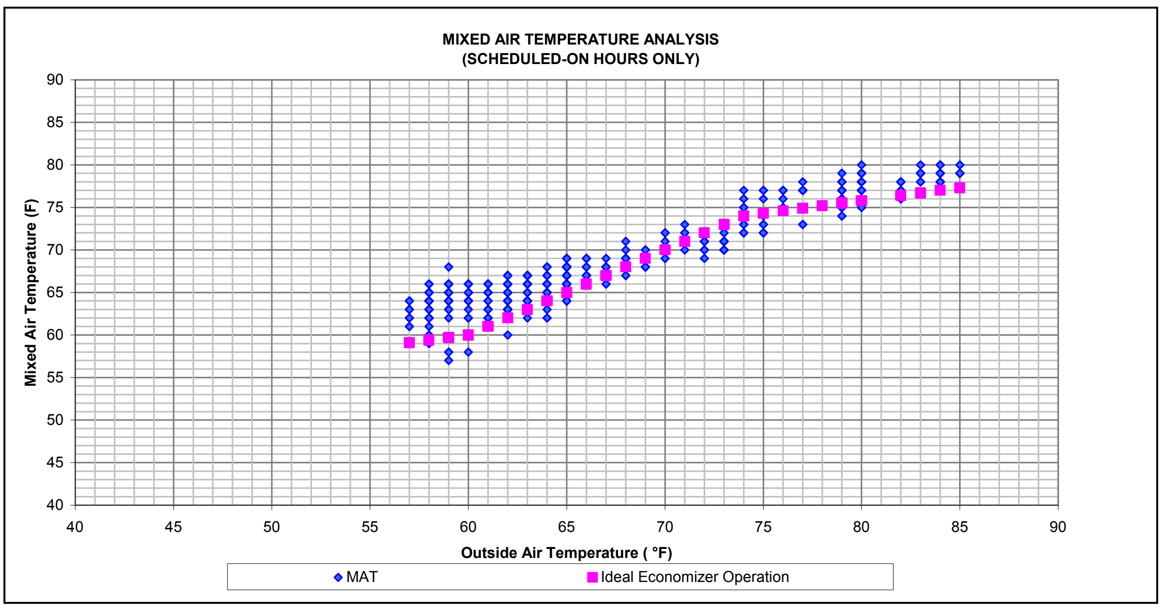

Figure II-5: Broadway economizer performance (STA_tool)

Figure II-6 shows the SAT versus OAT, which indicates an average operating temperature that varies around 65°F. Recall that the data used for these charts has been truncated to two significant figures so the true variation is masked. Therefore, it is not clear if the reset is working properly or not. However, the fact that the SAT rises to about 65°F suggests that the system is using more airflow than required to meet load under some conditions. Supply air reset strategies normally result in increased overall energy use because fan energy is less efficient than chiller energy.

As discussed previously, the building engineer prefers to maintain a relatively high SAT because he believes people are more comfortable and that he can save energy by implementing a reset strategy that minimizes chiller use. In this case the data shows that the SAT is always greater than the 62°F minimum specified. These issues along with calibration of all the sensors involved should be investigated further to optimize operation of the system

Figure II-5 shows that the economizer operates at an estimated 40% outside air fraction. This is a relatively high value especially for a climate like the Bay Area where during much of the operating hours the economizer is open 100% [1], which offsets the need to operate at high load conditions at high outside air fractions. Readjusting the economizer minimum position could save energy.

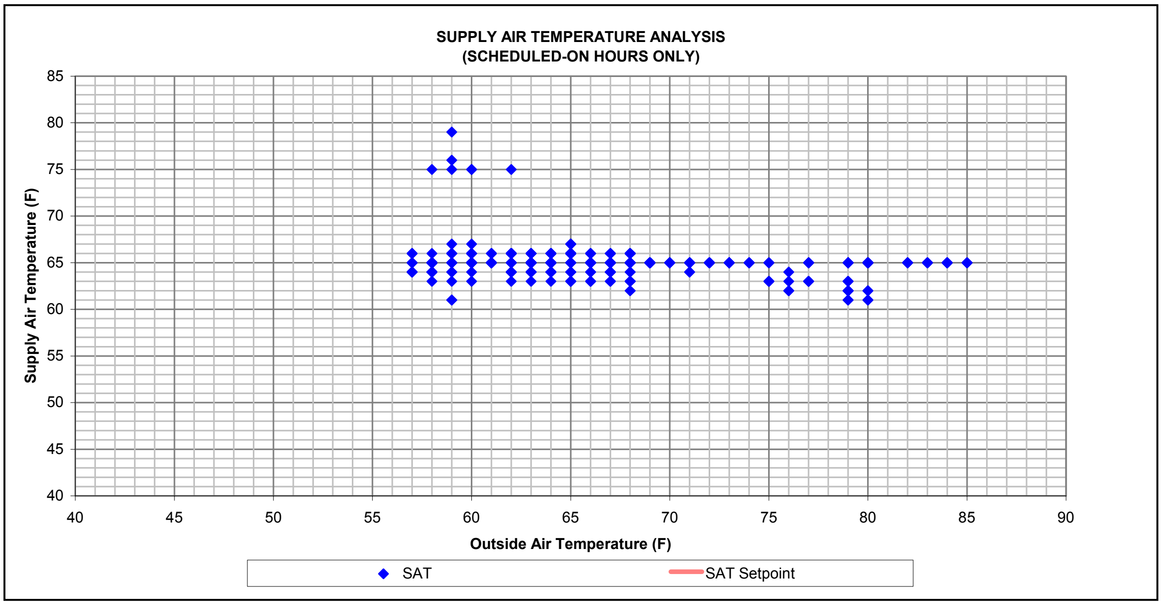

Figure II-6: Broadway SAT temperature performance (STA_tool)

Fan Power Analysis Tool (FPA_Tool)

Recall that Broadway's West AHU which houses supply fan SF2 is operated in parallel to the same fan model SF1 in the East AHU. This study focused on SF2 for the analysis. For this tool the scheduled on-hours were assumed to be the weekday hours between 7:00 AM and 6:30 PM.

The load factor is the measured fan motor input power divided by the nameplate rating of the motor. It indicates the degree of turn down for both the motor and fan. The distribution shows the degree of modulation and thus shows when modulation is not operating correctly or the fans and/or motors are oversized (low load factors). Comparing scheduled hours to off-hours provides and indication of off-hours energy use; this is more explicitly shown in Table II-2.

[1] Even during the summer, some days will have part of the day operating with 100% economizer providing all fresh air.

Table II-2: Broadway FPA_tool summary, SF2

CIEE Fan Project

Fan Power Analysis Tool

Summary of Logged Data

Data Collection Parameters	Scheduled On Hours	Scheduled Off-Hours	All Measured Hours	
Data log start time:			8/28/2002 0:12	
Data log end time:			9/11/2002 23:57	
Logging Interval:			15.0	minutes
Total Measured Hours:			360.00	Hrs
Operating Hours:*	211.00	125.25	360.00	Hrs
Operating Hrs. as % of Total Hrs:	58.6%	34.8%	100.0%	
Projected Operating Hrs/Yr:	5,134	3,048	8,760	Hrs/Yr

** Hours with Power > 0.1 KW*

Motor Input Power	Scheduled On Hours	Scheduled Off-Hours	All Measured Hours	
Minimum Power Demand	0.00	0.00	0.00	KW
Average Power Demand	8.94	0.15	5.66	KW
Maximum Power Demand	31.85	26.11	31.85	KW
Standard Deviation	10.84	1.86	9.65	KW
Projected KWH/Yr.	45,880	451	46,331	KWH/Yr

Operating Load Factor (% of Full Load Motor Power)	Scheduled On Hours	Scheduled Off-Hours	All Measured Hours
Minimum Load Factor	0%	0%	0%
Average Load Factor	9%	0%	6%
Maximum Load Factor	34%	28%	34%
Standard Deviation	11%	2%	10%

Outside Air Temperature	Scheduled On Hours	Scheduled Off-Hours	All Measured Hours	
Minimum OAT	57.0	58.0	55.0	F
Average OAT	65.7	62.6	64.3	F
Maximum OAT	85.0	78.0	85.0	F
Standard Deviation	6.9	4.2	6.1	F

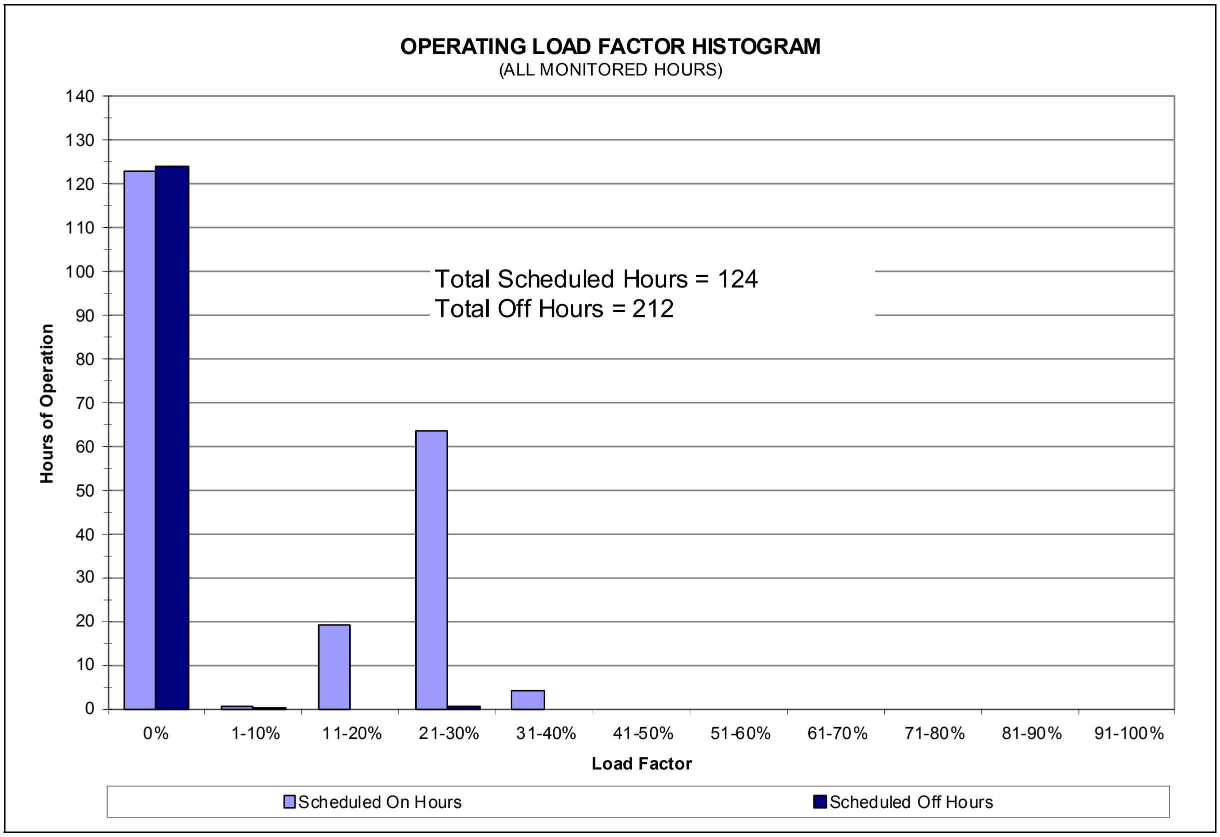

Figure II-7: Broadway load factor histogram for SF2 (FPA_tool)

Figure II-7 clearly shows the large number of hours where SF2 is operating at low load factors although turndown occurs over an expected range. These results could be skewed by a suspected error in the power readings.

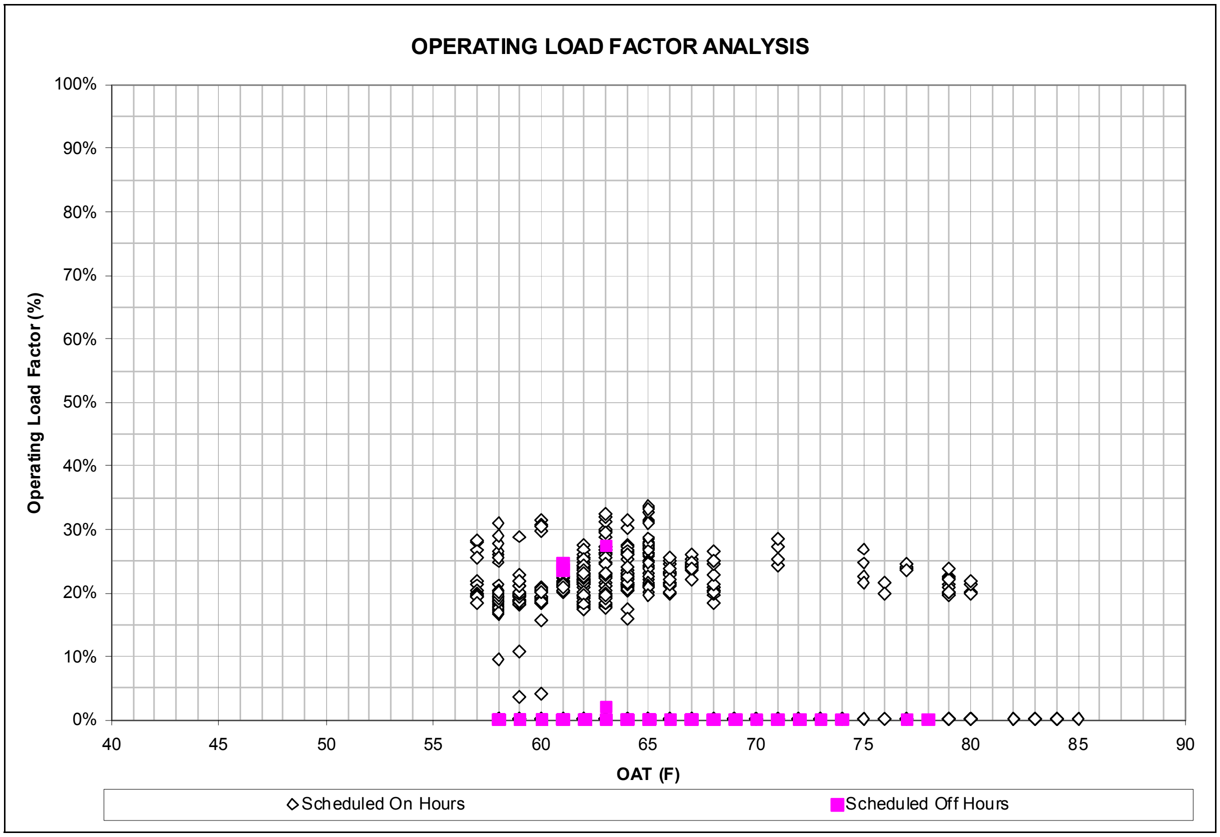

Figure II-8: Broadway SF2 load factor vs OAT (FPA_tool)

Figure II-8 shows the load factor versus OAT where there appears to be little sensitivity to OAT, indicating an internally load dominated building.

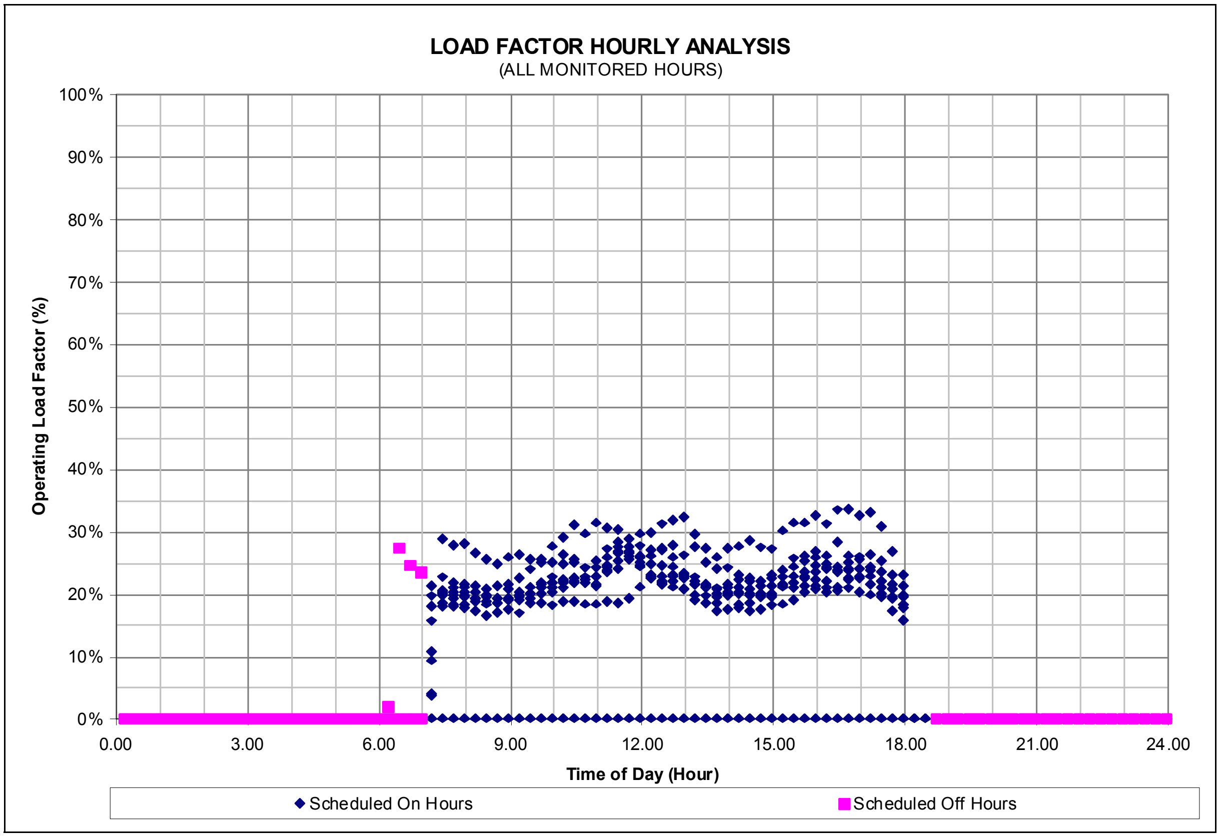

Figure II-9: Broadway daily load factor profile (FPA_tool)

Figure II-9 shows the daily profile for load factor and again indicates the low load factor for occupied hours.

SUMMARY OF FINDINGS

Economizer and airside operation. The economizer appears to be operating correctly but the STA_Tool analysis indicates that the mixed air dampers may be faulty. Also, the minimum position may be greater than necessary for this climate. It is recommended to verify proper operation of the mixed air damper during the economizer cycle and to readjust minimum position to reduce cooling energy during hot weather.

The SAT rises to about 65°F at low outside air temperatures, but the degree of reset is unclear due to problems with the granularity of the dataset used. It is recommended that the SAT sensor be calibrated and the impact of the chosen reset strategy be analyzed for its energy impact. Furthermore, the impact of reset on meeting load should be evaluated by tracking critical zone temperatures, possibly by using the Zone Air Temperature Analysis Tool.

Motor/drive efficiency. Assuming the measured fan power is correct (i.e., there is some doubt about this as discussed previously) the motor load factor at the maximum operating condition is about 40%, which results in an in-situ motor efficiency of about 90% as calculated by the ME_Tool. The drive belts were in good condition so the drive efficiency was assumed to be 94%. The VFD efficiency was assumed to be 95% since the maximum operating speed was close to maximum.

Fan performance. The fans appear oversized compared to the maximum load conditions experienced during testing. Although system resistance is somewhat greater, the airflow requirements are about 60% of design rating. The results of the performance analysis of SF2 were contradictory in that the output was low but computed fan efficiency was no different than design. Although erroneous power measurements are conjectured as the cause of this discrepancy, we could not confirm it before work terminated on this project.

Appendix IV: Field study of Mission Towers

SYSTEM DESCRIPTION

The Misson Towers building is one of two identical office towers located in San Jose, California. It is a twelve-story building with a gross square footage of 307,000 ft^2. Design occupancy is 750 but 1050 people are reported to be assigned to the building, with 30% out on average. The mechanical system is housed in two penthouses on top of the building. A VAV system consists of reheat VAV boxes supplied by a looped duct system on each floor which is supplied by shafts on opposite ends of the building. Each AHU consists of two double inlet, 49 in. airfoil centrifugal fans (Loren Cook 490 CA DWDI) driven by 100 Hp variable speed motors. The fans are connected to the shafts with a Y at the fan discharge and the Y is succeeded by a large elbow that enters the shaft. Design specifications call for 70,000 cfm at 5.0 in. fan static pressure (FSP) at 813 rpm.

The HVAC system operates weekdays and a half-day on Saturday. Each AHU system includes an outside air economizer using a dry bulb economizer control strategy. Propeller relief fans control return air to maintain building pressurization.

MONITORING

For this study only SF1 was studied in detail; we assumed that performance of SF2 would be similar. Data used for the fan performance analysis came from both the BMS and a data acquisition system (DAS) installed by SBW; we installed no additional loggers. Airflow was measured using the pitot static tube based airflow monitoring station (AFMS) installed by SBW in the inlet of the fans. Fan static pressure (FSP) was obtained by a differential pressure measurement between the fan discharge (an average of four locations on the perimeter of the discharge flange) and the fan inlet (in the fan room). Speed was derived from BMS monitoring of the variable frequency drive (VFD), and power was likewise measured with power meters on the bus side of the VFD. We calibrated the AFMS stations using the constant injection tracer gas (CITG) method for measuring airflow as described in Appendix IV. The average error found for all three buildings studied was –17% and this correction was applied to the Mission airflow readings.

Table III-1 shows differential pressure measurements taken at the fan discharge flange with a digital manometer. Note the uniformity of readings, which indicates a relatively uniform flow field.

Table III-1: Fan static pressure measurements (facing discharge duct), inches w.c.

FSP1 left	FSP2 Top	FSP3 Right	FSP4 Bottom	Average/SD
2.7	2.68	2.75	2.79	2.73/1.8%

Drive belts were inspected and found to be in good condition; the other drive components showed no obvious problems so standard drive efficiency is an acceptable assumption.

DATA ANALYSIS

Two sets of data were derived from the logged data sets supplied by SBW for the period of March to September 2002. As in the other field studies described in this report, we determined the maximum operating point by analyzing data logs for airflow, FSP, speed, and power for selected warm days. For the diagnostic tools we selected two weeks of warm weather data out of the same base data set (the maximum currently accommodated by the diagnostics tools).

Tool data set selection and analysis

As with the other data sets described in this report, the fan data records from the monitored data sets were either missing data (e.g., speed), reported erroneous values (e.g., one of the MAT sensors), and some points were obviously out of calibration. Measurements made with a hand held tachometer revealed that the sheave ratio used for scaling by the BMS was in error by about 21%. These corrections were applied to the data as part of our data reduction process. Due to these factors and difficulties gaining access to the data sets, we found the logistics and manipulation of the data sets tedious and time consuming. Interviews with the operators also revealed that a number of maintenance and repair activities were being accomplished during the monitoring period. For example, the fan room door was broken for a (unknown) period of time possibly causing air to periodically recirculate between return and supply. To the best of our knowledge it was repaired some time in June 2002. The interviews also confirmed that setpoints were not changed during the period of study.

Analysis of the data confirmed that the HVAC schedule was 6 AM to 6 PM weekdays, 7 AM to 12 noon on Saturdays, and off on Sundays. Extensive analysis of the data for the period of 5/29/02 to 8/31/02 showed three important trends:

- After 6/18/02 SF2 operated at a fixed speed of 762 rpm (corrected). This apparently resulted from faulty signal processing by the BMS (or output from the VFD).
- As shown by Figure III-1, the operating curves for SF1 are markedly different before and after 6/18/02 due to the constant speed operation of SF2.
- The fan performance was significantly different between operation with economizer open and closed.

We filtered the data set for daytime operation and closed economizer to determine the operating curve and the maximum operating point for SF1. For the tools data set we used a subset of the data before 6/18 (5/29 – 6/11/02) that was relatively intact and filtered to remove transient conditions.

Maximum Operating Point

Using the procedure described in Objective #3 of the outcomes section of the body of this report, the maximum operating point for the monitoring period was determined to be 50,000 cfm from Figure III-1. Other parameters associated with this point are shown in Table III-2. Figures III-2 and III-3 show other charts used for determining the monitoring period maximum operating point.

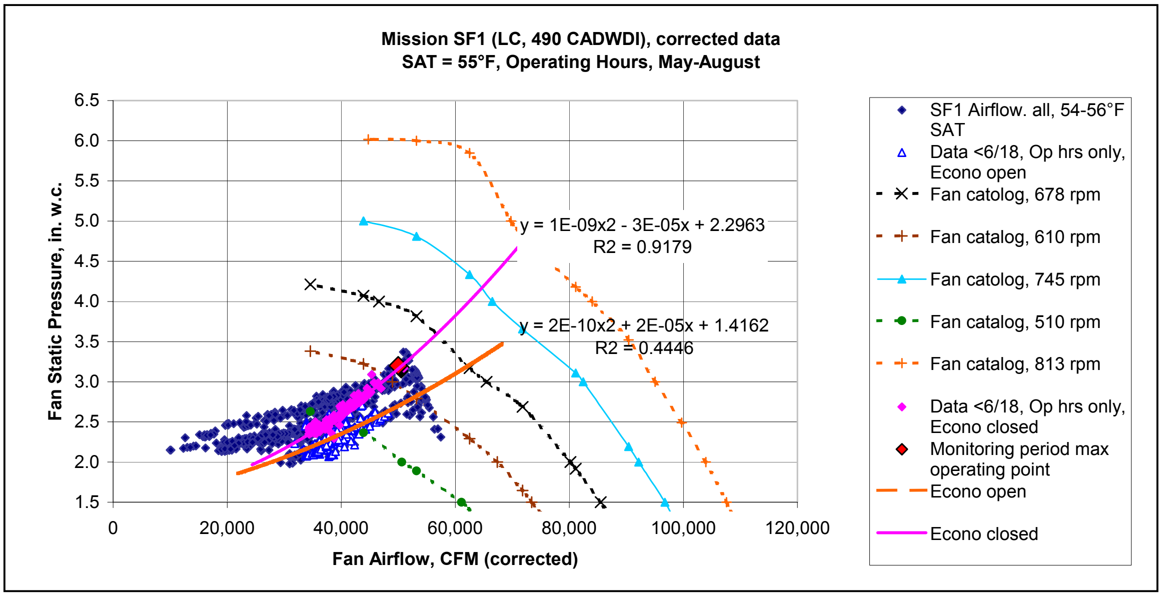

Figure III-1: Mission measured system operating trends and catalog fan curves for SF1

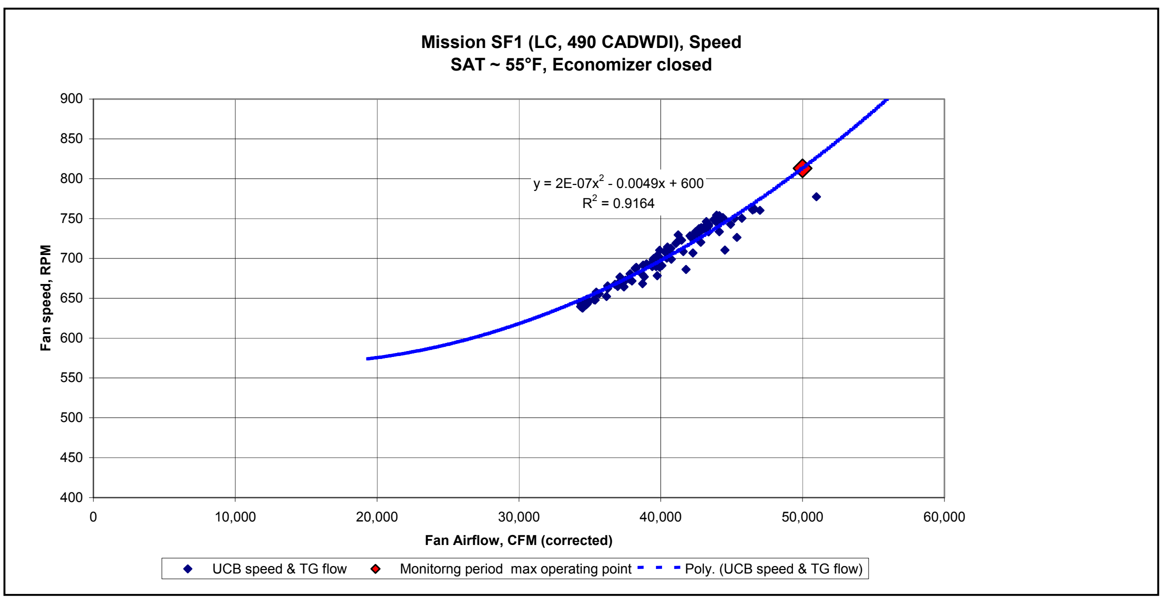

Figure III-2: Mission system operating speed trend for SF1

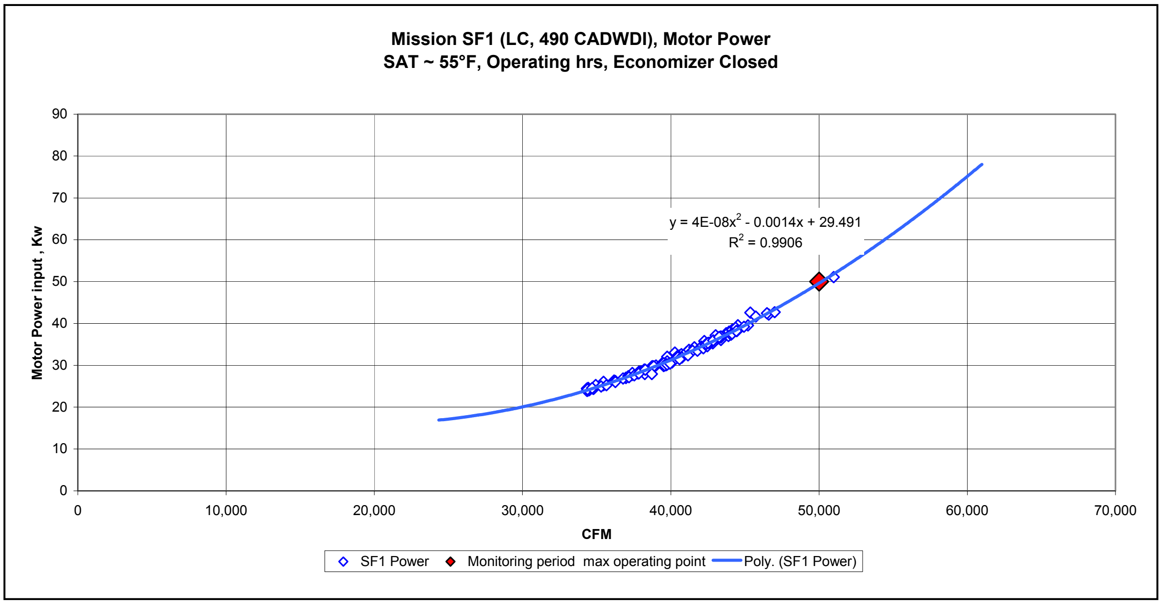

Figure III-3: Mission system operating power trend for SF1

APPLY TOOLS

Table III-2 and Figures III-4 and III-5 show the results of the single point tests based on the maximum operating point determined as described above. These figures and Figure III-1 show the significant discrepancy between catalog ratings and measured data. Figure III-1 shows catalog curves showing fan performance significantly higher for the same fan speeds measured during the monitoring period.

Table III-2: Mission Towers maximum operating point summary (From FA_BM_Tool)

CIEE Fan Project

Fan Analysis & Benchmarking Tool: Summary Page

Select Subject Fan:	**Function:**	**Control:**	**Design:**
Mission, SF1,2 (LC 490 CPA)	Supply	VAV	DWDI
	Size:	**Type:**	**Configuration:**
	Over 45"	Backward Curved	Shrouded

FAN SUMMARY INFORMATION	**Design Data**	**Field Measured Data**	**Corrected to Design Speed**	**Measurement Error (+/-)**
Fan Power (KW)	56.02	40.28	39.69	1.38
Volumetric Flow (CFM)	70,000	50,000	49,755	2,488
Fan Static Pressure (In. W.C.)	5.00	3.20	3.17	0.16
Fan Speed (RPM)	813	817	813	-
Specific Fan Power (Watt/CFM)	0.80	0.81	0.80	0.04
Flow Density (CFM/SF)	0.91	0.65	0.65	0.03
Fan Total Efficiency	73%	47%	47%	3.7%

QUICK ANALYSIS:
MEASURED VS. DESIGN DATA

Measured Fan Power:	**Lower than Design**		
Measured Fan Speed:	**Equivalent to Design**		
Measured Fan Operating Point:	**Different:**	Lower Volume	Lower Pressure
Corrected Fan Opearting Point:	**Different:**	Lower Volume	Lower Pressure
Measured Fan Efficiency:	**Less Efficient than Design**		

Fan Efficiency Ratio	0.64

Ratio of measured fan efficiency to reference (design) fan efficiency

MOTOR SUMMARY INFORMATION	**Namplate Data**	**Field Measured Data**
Motor Output (HP)	100	
Motor Speed (RPM)	1780	1763
Motor Current (Amps)	112.00	0.00
Motor Voltage (Volts)	460	0
Motor Power Factor	0%	0%
Motor Efficiency	92.6%	92.6%
Motor Input (KW)*	80.56	49.00
Motor Load Factor:		60.8%

**If Motor Current = 0, Motor Input (KW) calculated from Motor Output and Motor Efficiency*

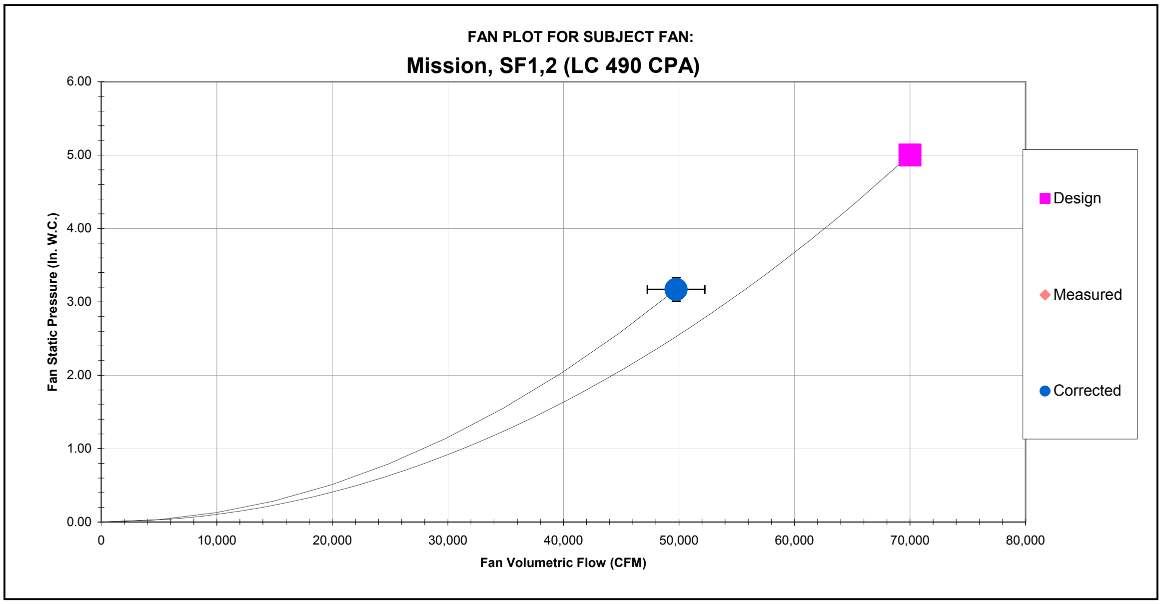

Figure III-4: Mission fan operating point comparison

Figure III-4 shows a comparison between design and maximum operating conditions and that there is little difference in system resistance between the design and actual operation, but airflow demand is about 25% less.

The maximum operating point can be compared in another way as illustrated in Figure III-5. This figure shows the performance as a function of static pressure and the specific fan power (SFPI). As described in Webster [Webster 1999], four quadrants are defined by the heavy lines shown in the figure. When the operating point falls in the upper left quadrant as shown, energy can be saved by determining the cause of low efficiency and correcting it, if economically feasible. It is obvious from this and other analyses below that these fans are operating significantly below their design efficiency, about 64% of rated efficiency. Analysis of fan fan performance under VAV control (see Figure 1 and associated discussion in body of report) shows that, theoretically, the fan efficiency difference between these two operating conditions should be small, which suggests that there may be a problem with the fan that if corrected may yield savings in fan energy.

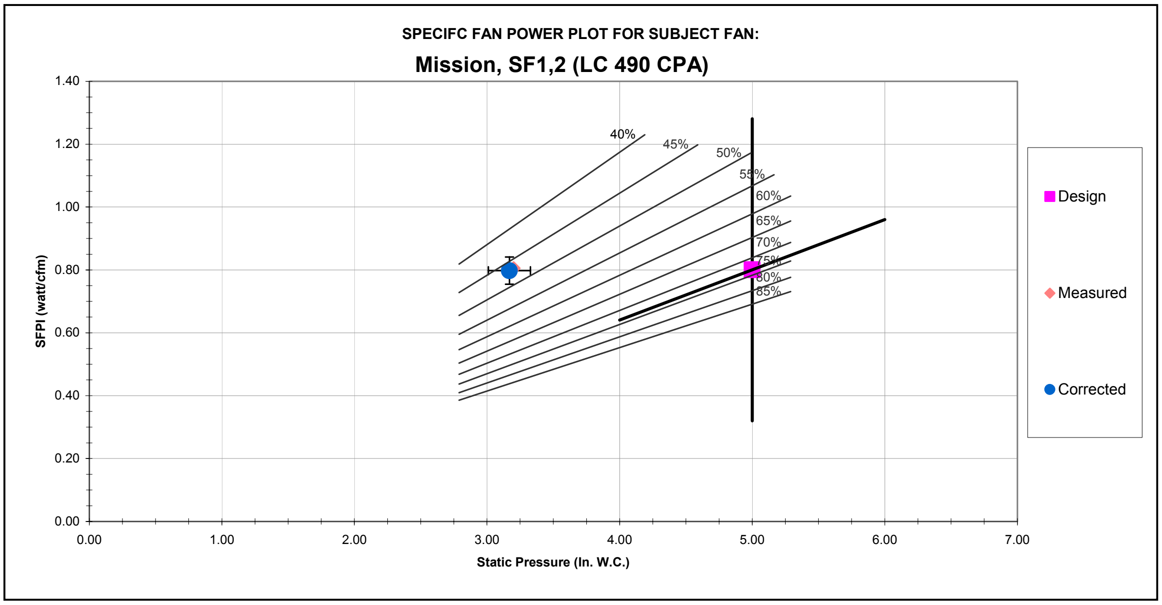

Figure III-5: Mission specific fan power comparison

System Temperature Analysis Tool (STA_Tool)

Selected results from the STA_Tool are shown in Figures III-6 to III-8. Figure III-6 shows economizer performance with large scatter in the 100% open range. In Figure III-6 the body of the data lies below the ideal economizer line. Since the MAT sensors our upstream of the coil the MAT should never be below OAT. There is no plausible explanation for this other than a problem with sensor calibration. In this case the MAT sensors (4) were measured by the DAS and the SAT and OAT were derived from the BMS logs which may contribute to the mismatch. Figure III-6 shows the estimated outside air fraction to be 40%, however when corrected for an assumed OAT sensor calibration error of –5°F as shown in Figure III-7, it could be as high as 50%.

Figure III-7 also indicates that MAT increases relative to OAT as OAT increases. This could be caused by leakage through the return air damper, which might be influenced by how the relief fans are operating at higher loads.

Figure III-8 shows a significant amount of scatter for the SAT; it is too scattered to be the result of a reset schedule. A more detail inspection of the data suggested that the SAT set point (either by reset or minimum setting) is different on weekends than weekdays, which would add scatter to the data. It is also possible that there is a problem with SAT controls and/or that the chiller is being cycled off for some reason allowing the SAT drift upward. Further analysis of this issue is seems warranted.

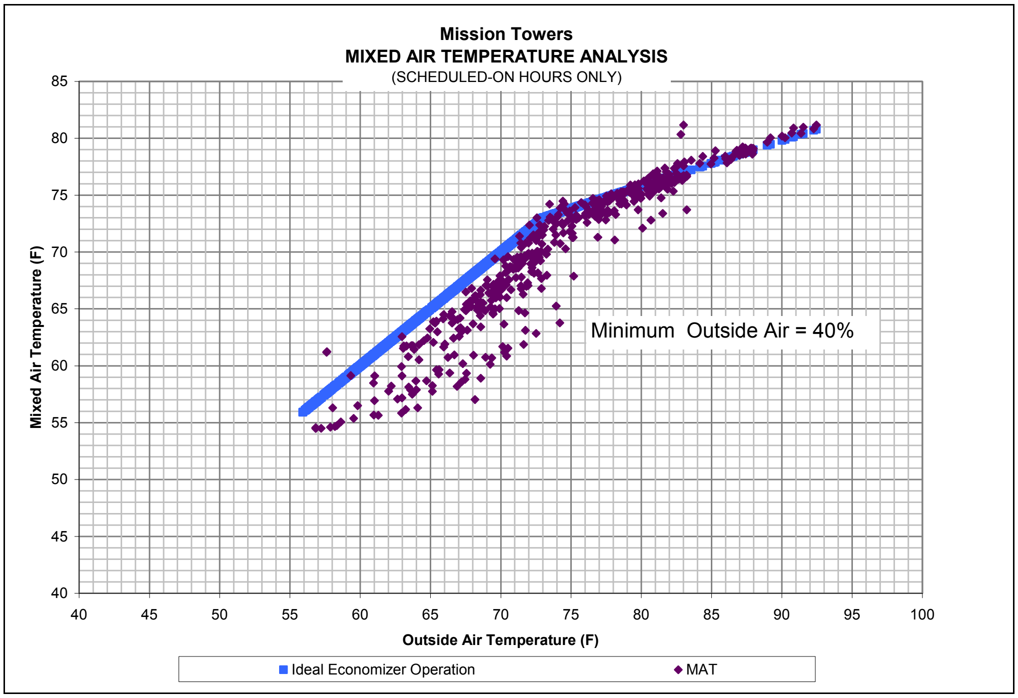

Figure III-6: Mission economizer performance (STA_tool)

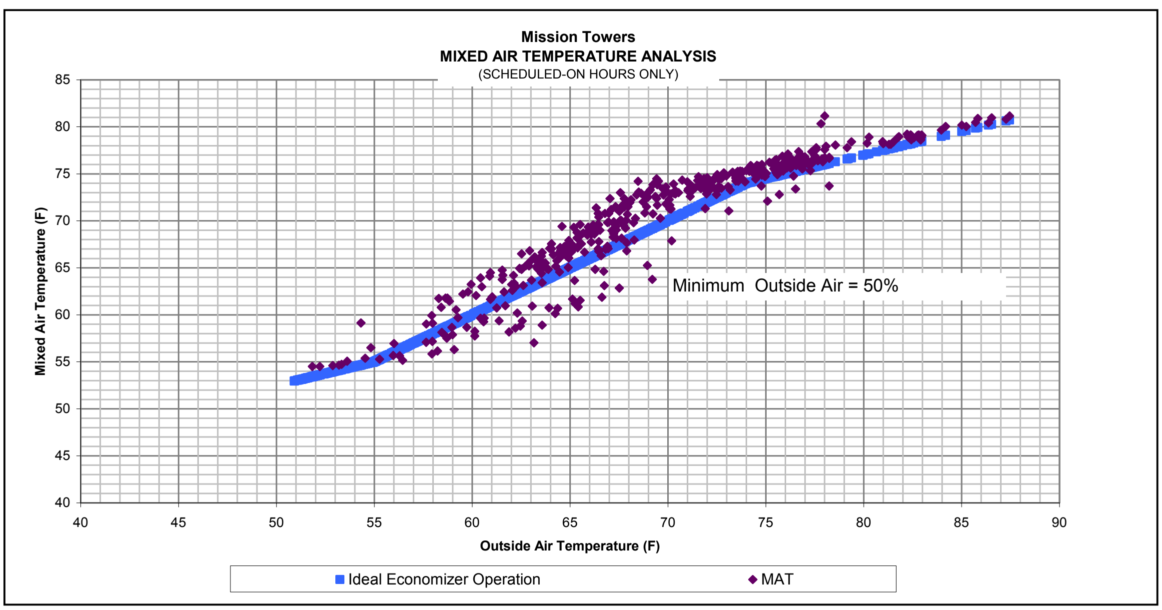

Figure III-7: Mission economizer performance with OAT corrected by –5°F.

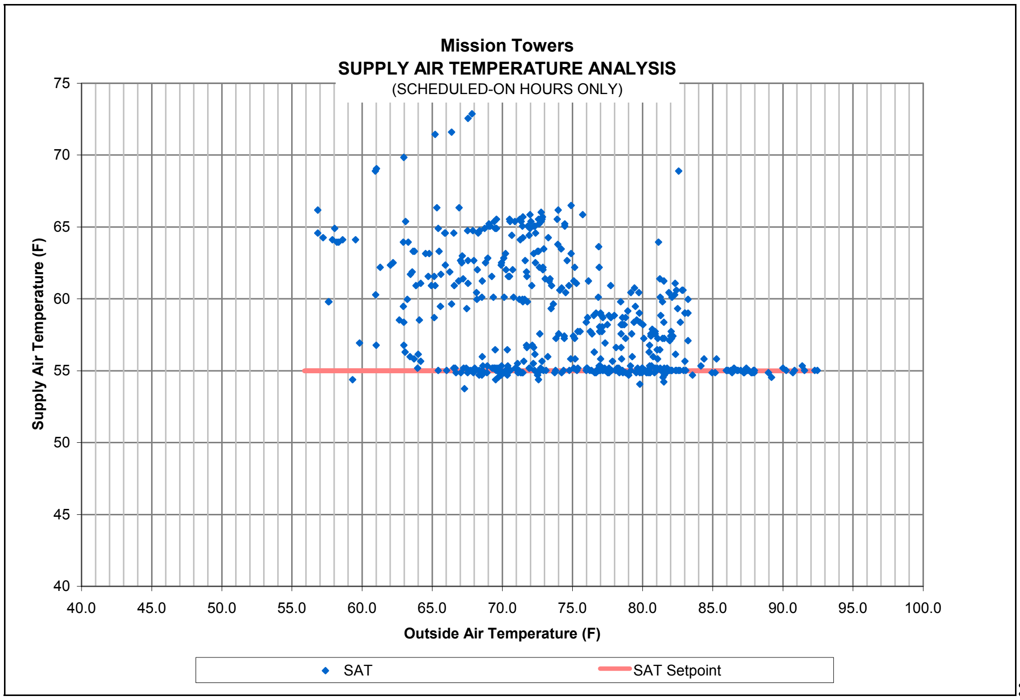

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Figure III-8: Mission SAT temperature performance (STA_tool)

FAN POWER ANALYSIS

The load factor is the measured fan motor input power divided by the nameplate rating of the motor. It indicates the degree of turn down for the combination of motor and fan. The distribution shows the degree of modulation; problem with it tend to skew the distribution. Comparing scheduled hours to off hours provides an indication of off-hours energy use which can identify unknown off-hours operation that could lead to impacts on overall energy use; this is more explicitly shown by Figure III-10.

The fans for the Mission system operate together on a nominal schedule of 8:00 AM to 6:00 PM during the weekdays, 7:30 AM to 12 noon on Saturday, off on Sunday so the combined power for SF1 and SF2 was used in the power analysis tool. Figure III-9 shows a histogram of fan power usage. This chart indicates a uniform profile at relatively high load factors, which is typical for VAV systems in summer. This corroborates that the system turns down in response to load in a normal manner. Note, however, that the system operated some time during non-scheduled hours, most likely due to occupant override.

Figure III-11 shows the load factor as a function of OAT. There is virtually no directionality to the data indicating that the loads are predominately internally generated.

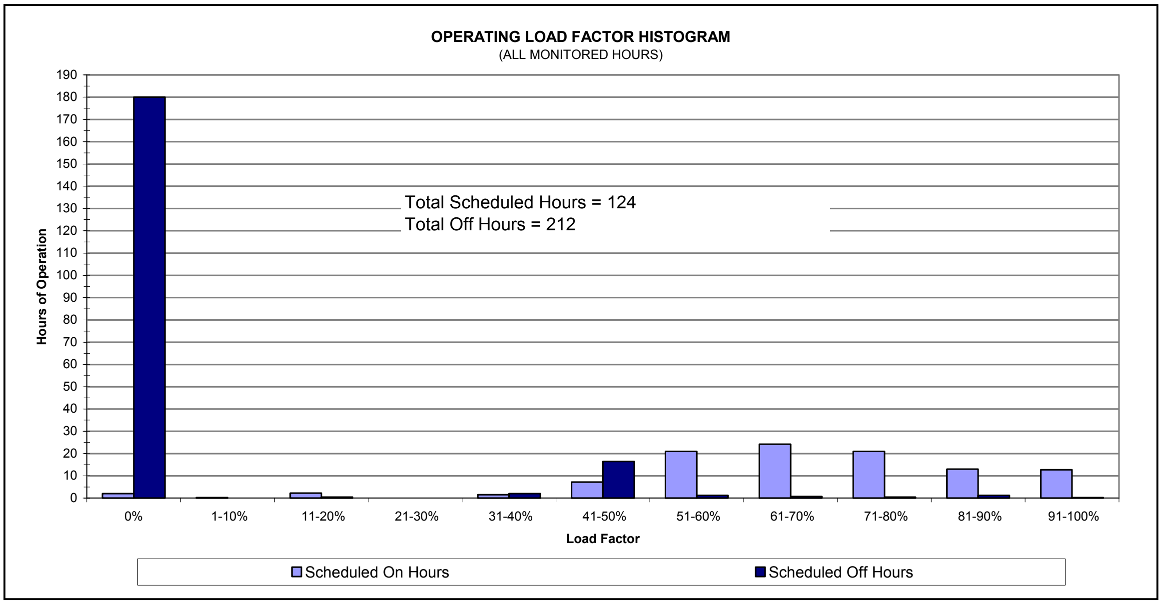

Figure III-9: Mission load factor histogram for both SF1 and SF2 (FPA_tool)

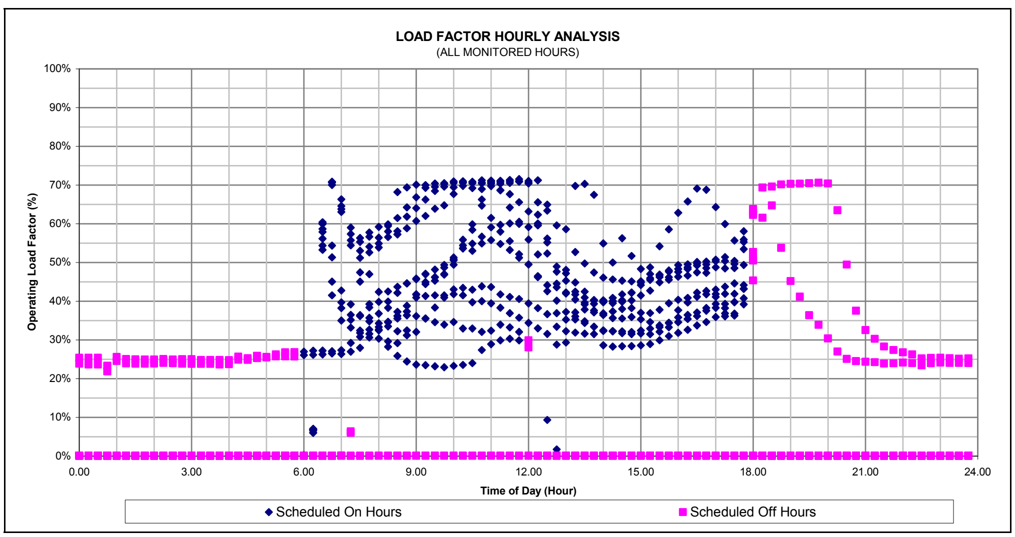

Figure III-10: Mission load factor time of day (FPA_tool)

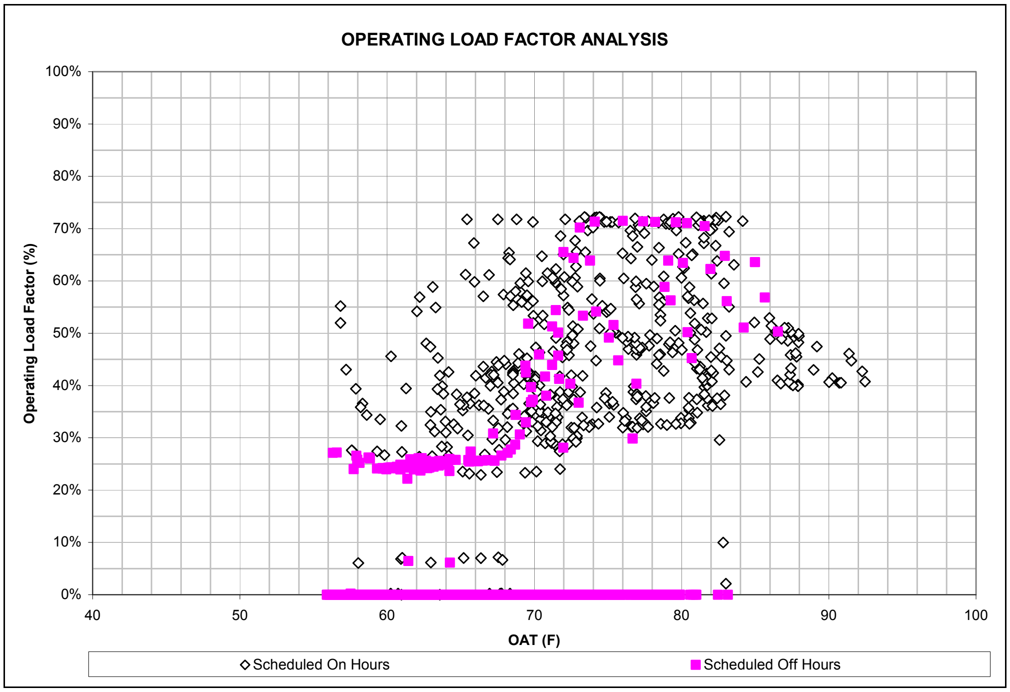

Figure III-11: Fan Power Analysis Tool: Load factor vs OAT

SUMMARY OF FINDINGS

Economizer. The economizer appears to be operating basically as intended but the economizer and SAT data suggests that there may be problems with sensor calibration, return damper leakage (and/or relief fan operation), or controls. Also, the outside air fraction appears to be greater than necessary for the Bay Area climate.

Motor/drive efficiency. Although results from the ME_Tool are not shown, the drive and fan motors are operating correctly at relatively high efficiency during peak load conditions. Efficiencies are estimated to be motor 92%; belt drive 94.1%; VFD 94%.

Fan performance. From the monitored data it appears that the fans are appropriately sized; i.e., motor load factors ~80% with a wide range of turndown and a uniform distribution. Little energy is used for off-hours operation.

However, the measured efficiency is 47%, with a fan efficiency ratio (actual efficiency/design efficiency) of 64%. There were no obvious outward signs of why this might be the case, but further investigation is warranted given the opportunity for energy savings. System effects could be implicated in causing this type of decrease. The low efficiency is most likely the cause of the low airflow and FSP for the fan was operating virtually at design speed at the peak conditions for the monitored period.

The most obvious problem discovered was the lack of modulation of SF2 after 6/18/02 due to a faulty signaling at the VFD.

Appendix V: Airflow measurements

AIRFLOW STATIONS

All thee sites studied used the same brand of airflow monitoring station (AFMS). The product literature indicates that the expected error in measurements using these devices is +/- 3%. However, no indication is given how different inlet geometries might affect this error. Contact with the manufacturer revealed that this error figure was derived from one set of tests on a single fan system in 1984. Further investigation revealed that a TAB contractor calibrated the Mission Towers AFMS. The contractor indicated that the calibration was derived from the fan curves with measured speed and FSP due to the difficulty in making a pitot traverse. He indicated that the error was on the order of a few percent and that this offset was used to adjust the readings in the EMCS. He also stated that in his experience, errors of up to 20% have been found in other buildings using these AFMS's. Given the lack of robust data from the manufacturer, uncertainty of the one calibrations, and the need for accurate airflow measurements to support the protocols, it was decided to calibrate these devices using constant injection tracer gas (CITG) techniques. [Carter, 1998]

TRACER GAS MEASUREMENT PROCEDURES

Procedures:

In these procedures we used a gas analyzer with an infrared detector, tuned to measure sulfur hexafluoride (SF_6) in near real time (Wilks Miran 101). For the injection we used a flow controller connected to high quality retail irrigation soaker hose (lower quality hose proved to perform erratically) that was attached to the fan inlet(s) in a circular pattern. We measured the background levels before and after each test. Two separate injection ports were used for fans with double inlet. The injection was adjusted to a range whereby the maximum airflow rate would produce concentration above the minimum range of the detector.

In these techniques, mixing downstream of the fan is very important, so concentration traverses were made at a suitable point down stream of the fan. This allowed us to average the results (on a concentration basis) to evaluate uniformity and calculate an average concentration.

RESULTS

Broadway

The supply ducts are split at fan discharge, which required the measurements to be taken in both ducts. In this case we adjusted the injection on each side of the double width fan to ensure that the concentrations in the two ducts were the same. In each duct so it was apparent that good mixing occurred prior to the measurement position (several feet from discharge). Inlet concentrations were not measured; we assumed very little mixing of return and OSA with outside air dampers fully open.

Although return fan measurements were taken, the data was not considered acceptable due to large variability most likely due to lack of mixing since the measurements were taken in the discharge opening.

Novell

The fans for this system are plug fans with backdraft dampers on the inlets. We could not assume that the inlet concentrations were negligible since the backdraft dampers leaked significantly. Therefore, inlet conditions were measured before and after each discharge measurement. The detector was located in a room where SF_6 concentrations increased during the tests, but this did not appear to affect the results. However, somehow dust was aspirated into the detector, which caused a zero shift. The dust scatters the IR source, which causes the detector to falsely read a concentration. We assume that when a sample is drawn into the chamber that the zero shift of 0.2 vdc appears as an offset that applies to both inlet and discharge readings alike, thus the difference between inlet and discharge concentrations should be accurate.

Although complicated by the zero shift problems, these measurements allowed us to learn some interesting things:

Recirculation: Tracer recirculation occurs by two paths, return air damper leakage and backdraft damper leakage. At the start of testing the mixed air reading (assumed to be before the offset occurred) was 0.85 ppm at high airflow. At the end of the test with injection stopped the reading was 0.22 ppm (i.e., 1.49 ppm-1.27 ppm offset). This indicates that the return damper leakage was 0.22 ppm and the backdraft leakage, 0.63 ppm. Given these results, it is unlikely that the zero shift occurred much before the end of the testing because the readings should have been in the range of 2 ppm if this were the case; for all tests they were approximately 1.3 ppm.

Mission Towers

This system, one of two AHUs that supply loop ducts on the floors, consists of dual fans, which are Y connected into a common supply duct. The Y is close to a 90° elbow at the top of the supply shaft, which is housed in the return airshaft. This configuration made it virtually impossible to perform a pitot traverse. Despite the extra precautions that were exercised to preclude difficulties experienced at other sites (e.g., the detector was placed in the outside air stream, measurements were taken in three locations – OSA, MA, RA plenums, better injection tubing was used), a number of problems occurred that required measurements to be repeated:

- The VFD of one fan was found not to be tracking for static pressure control; thus the high airflow readings were made in manual control with both fans operating at the same speed.
- One SF_6 bottle ran out of gas
- The SF_6 regulator output decreased below that required to maintain the proper injection rate.
- A hose broke loose which dumped gas into the inlet plenum.

Recirculation was avoided because the exhaust fan airflow was greater than outside airflow. Monitoring of the AFMS output (at the Synergistic data loggers) revealed that the operating points were stable during the test run. This occurred because the total system airflow was maintained by the second AHU when we manually decreased speed on the subject system. Due to the problems outlined above only two speed points were completed.

SUMMARY AND CONCLUSIONS

Results from these tests are summarized in Figure IV-1. Since all fans measured were manufactured by Loren Cook and had similar inlet designs, it is likely that the results would be similar for each site. This is indicated in the results summarized in Figure IV-1. A linear curve fit of the data is shown and has an R^2 of 0.82. Using this fit as the correction to the AFMS readings results in an average error of –17.8%. We used the standard error of the regression to represent the uncertainty (at 95% confidence) in these measurements; Figure IV-1 shows that the uncertainly varies over the range of 15-35% over the range of measurements made. All AFMS data for each site were corrected using the linear equation shown in Figure IV-1.

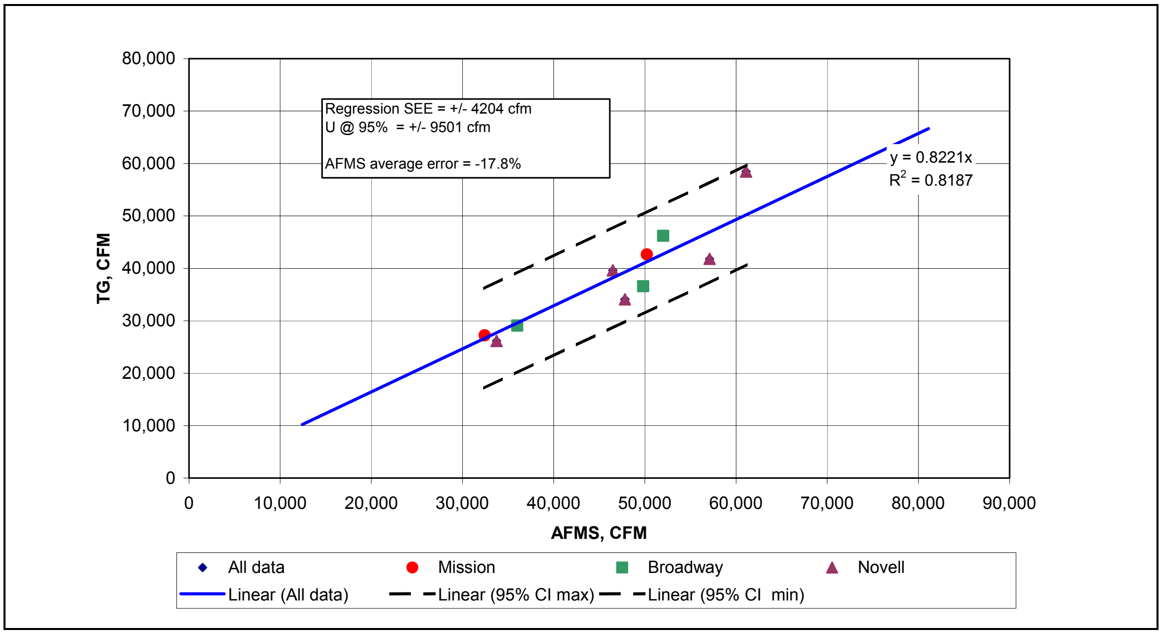

Figure IV-1: Airflow measurement results summary

Appendix VI: Potential of protocols

To determine a realistic potential for energy and cost savings derived from the application of these protocols to the California building stock we used the latest building stock characterization data [Modera, 1999] and made the following assumptions.

- Four building types (large office, schools, hospitals, hotel/motel) are the most likely to have built-up fan systems.
- Energy costs of $0.07/Kwh not considering demand charges.
- Estimated site energy savings based on previous work reported in Reference [Carter, 1998]
- Annual savings are discounted for various factors as shown in Table V-1 based on engineering judgment.
- The percentage penetrations of VAV vs. CAV systems shown in Table V-3 based on discussions with various practitioners who reported that the number of CAV systems has declined in recent years due to VAV retrofit activities.
- 1994 projected building stock escalated by 2% per year to 2002 for 6 years but assumes no significant growth in last year (2002).
- Percentage of floor space likely to be served by built-up systems based on the CBECS [EIA, 1997] for buildings over 100 k ft^2 and on distribution of central systems in California from LBL's characterization study [Modera, 1999]

CONCLUSIONS

Supporting data are contained in Tables V-2 to V-4 and results from the analysis are shown in Table V-1. This table shows an ultimate potential of saving about 18% of total fan/pump energy consumption for the four building types (3.4% for all buildings) if these protocols were applied to all possible built-up systems (i.e., 100% penetration). This represents approximately 6.4% of the HVAC energy use for these four building types in aggregate (1.2% of all buildings). This analysis shows that office buildings represent the largest potential for these protocols

Table V-1: Estimated potential of fan performance protocols in California

							Large Office	**Hospitals**	**Schools/ Colleges**	**Hotel/ Motel**	
Floorspace, M ft^2 [Modera, 1999]							1,190	307	757	327	
% Possible (% >100k SF x % Central system) (Table V-4)							16%	30%	10%	3%	
Detected Problem	**Estimated Savings (1)**	**Estimated Savings (1)**	**Problem applicability (2)**	**Probability of occurrence (3)**	**Probability fixed if found (4)**	**Assumed Penetration (5)**	**Savings (6)**	**Savings (6)**	**Saving (6)**	**Savings (6)**	**Total Site Energy & Cost**
	$\$/ft^2/yr$	$.Kwh/ft^2f/yr$	%	%	%	%	*$M*	*$M*	*$M*	*$M*	$M savings GWh/yr
Run Hours	0.036	0.514	100%	50%	95%	100%	46.8	22.6	19.3	2.5	
Dirty Filters/coils	0.0285	0.407	100%	35%	90%	100%	24.6	11.8	10.1	1.3	
Low VAV Turndown	0.0535	0.764	50%	50%	30%	100%	11.0	5.3	4.5	0.6	
System Effect	0.042	0.600	100%	75%	2%	100%	1.7	0.8	0.7	0.1	
CAV/VAV retrofit	0.08	1.143	35%	50%	35%	100%	13.4	6.5	5.5	0.7	
Over/Under Air	0.042	0.600	35%	50%	60%	100%	12.1	5.8	5.0	0.6	
Hi Duct Static	0.0255	0.364	50%	35%	35%	100%	4.3	2.1	1.8	0.2	
Inefficient motor	0.0155	0.221	100%	35%	35%	100%	5.2	2.5	2.1	0.3	
Loose belts	0.034	0.486	100%	40%	75%	100%	27.9	13.5	11.5	1.5	
Wrong SAT (CAV)	0.025	0.357	35%	15%	75%	100%	2.7	1.3	1.1	0.1	
Fan wheel change	0.1	1.429	100%	10%	5%	100%	1.4	0.7	0.6	0.1	
$M/yr							**$10.6**	**$5.1**	**$ 4.4**	**$0.6**	**$20.6**
GWh/yr							**151.0**	**72.8**	**62.3**	**8.0**	**294.1**
% Total fan/pumps energy consumption [Modera, 1999]							36%	8%	8%	4%	
Total consumption, central systems fans/pumps, GWh (Table V-2 & [Modera, 1999])							1,180	221	186	35	**1,622**
							% fan/pump energy savings				**18%**
							% HVAC energy savings				**6.4%**

Notes to Table V-1:
(1) Estimated savings from Reference [ph II rpt]
(2) Percentage of total central systems that a given problem is applicable to; i.e., VAV problems would only be applicable to the number of VAV systems in the stock (see Table V-3).
(3) Estimated frequency of occurrence of a given problem
(4) Probability that a problem will be fixed if detected; assumes that only those problems that are easy or least costly will be fixed.
(5) Assumed penetration of use of protocols/tools; 100% provides maximum potential.
(6) Estimated savings derived from % possible floor area and cumulative probabilities associated with each problem based on $0.07 Kwh

Table V-2: California HVAC energy consumption

Total Energy Use	GWh	% HVAC	% Bldg
Heating	2,068	9%	2%
Cooling	13,583	56%	16%
Fans/pumps	8,626	36%	10%
Total HVAC	*24,277*	*100%*	*29%*
Other	58,555		71%
Total Bldg	82,832		100%

Table V-3: System type penetration in existing Californian building stock

System type	Estimated Penetration
CAV	35%
VAV	50%
Other	15%
Total	100%

Table V-4: Distribution of central systems in selected types of California buildings

Buildings Floor Area, by PBA	< 100K	> 100K	>100K, %	Calif Central systems, %
Office	7100	5219	42%	38%
Health care	108	1655	94%	32%
Schools	5192	3278	39%	27%
Lodging	1996	895	31%	10%