Commercial Building Performance Evaluation System for HVAC Diagnostics and Commissioning

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A hardware and computer software system for diagnostics and commissioning and impact evaluation of HVAC and lighting systems in commercial buildings has been developed. The hardware and software form a system referred to as the Commercial Building Performance Evaluation System (CBPES). The system provides a structured method for comprehensive monitoring and performance evaluation to systematically identify problems with commercial HVAC equipment. This paper discusses the development of the CBPES software and the application of the CBPES to HVAC system diagnostics.

The CBPES software runs under the Windows environment and is designed to prepare an instrumentation plan based on the type of HVAC equipment being diagnosed, initialize a suite of portable battery-powered dataloggers to collect data specified by the software, download the data directly for analysis, and assist the user during the analysis phase to diagnose the condition of the HVAC system.

Results from the application of the Commercial Building Performance Evaluation System to several commercial buildings are presented.

Introduction

Significant amounts of energy are wasted each year in commercial buildings due to inefficient operation of heating, cooling, and ventilation (HVAC) equipment. Computer simulations performed by the authors of typical problems indicate that increased energy consumption ranging from 10% to 35% is not uncommon due to what appear to be minor adjustments to equipment and controls. Many of these problems contribute to increased HVAC system electrical demand coincident with the utility system's peak demand. Increased levels of demand on the order of 0.5 to 1.5 watts per square foot are common in some climates. Often, routine maintenance procedures do not recognize or correct these problems, and may, in some cases, cause them.

The need exists for comprehensive monitoring and performance evaluation procedures to systematically identify problems with commercial HVAC equipment. The potential exists for reducing traditional monitoring costs using centralized data loggers by one-fifth. This potential can be met by reducing the time required for planning, instrumentation installation and removal, data analysis, and reporting. The approach discussed in this paper to reduce labor requirements is to automate many of these activities by developing a hardware and software system called the Commercial Building Performance Evaluation System (CBPES).

Another goal of the CBPES is to provide a consistent method for performing diagnostics of HVAC systems. With this system, HVAC monitoring and the presentation of the results will be consistent from project to project, even if different individuals or agencies are responsible for the monitoring and data analysis.

Approach to Structured Diagnostics

Since each HVAC system is somewhat different, the methods used to diagnose the performance of HVAC systems must be flexible enough to accommodate variations in system configuration, yet structured enough to ensure that the data and diagnostic procedures will sufficiently indicate any problems within the operation of the HVAC system. The approach that has been used in the software development is to provide a method for a user to describe the HVAC system as a set of functional building blocks. Figure 1 shows how a typical Variable Air Volume (VAV) HVAC system would redescribed in this software. First, the heating and cooling plants are described. Next, the air distribution system is described and linked to the heating and cooling plants. Finally, the zones that will be monitored are described and linked to the air distribution system serving each zone. It is not necessary to monitor all zones within the building. Describing the HVAC system in this manner sets up dependencies between each generic component that are useful during the diagnostic phase.

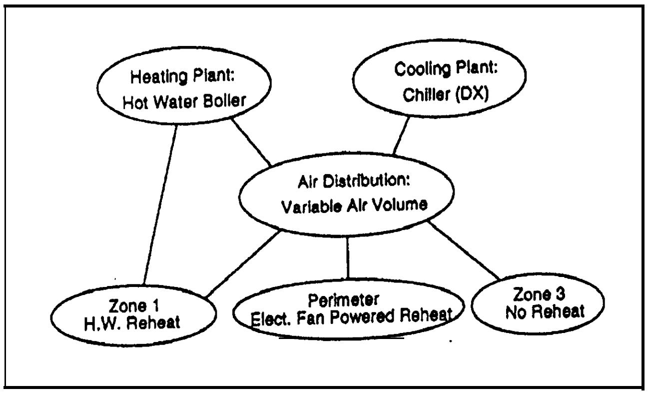

Figure 1. Block Diagram of HVAC System Description in CBPES

After the HVAC system is described, the software determines the set of Diagnostic Performance Plots that will best show the HVAC system performance for diagnostic purposes. Diagnostic Performance Plots display system performance data in several ways. Plotting system performance data as a function of time is an example of one kind of Diagnostic Performance Plot. Another example is an X-Y plot of system performance data, such as supply air temperature, versus ambient temperature. These plots can be used to investigate many aspects of HVAC system performance, including temperature reset schedules, time clock schedule, night-time temperature setbacks, etc. The CBPES software determines the most appropriate plots for the HVAC system being diagnosed and then develops an instrumentation plan to collect the required data.

Description of Structured Diagnostics System

The major components of the CBPES are portable, battery-powered, microprocessor based data loggers, software to structure the use of the system as well as perform portions of the data analysis, and a user's manual. The system relies upon measurements of physical parameters and energy consumption taken in a building over a 2-week period to diagnose problems in the HVAC system. The system is unique in a number of respects, as explained below:

Standardization

The procedures used to perform the diagnostics and commissioning are completely standardized. With proper training, they will be implemented in exactly the same way regardless of who performs them. This standardization eliminates the uncertainties associated with different people having different skill levels performing the procedures. The standardization is accomplished by using computer software to direct all aspects of the procedures, including defining the data requirements, establishing the performance monitoring plan, verifying the set-up of the data acquisition equipment, analyzing the data, and specifying reporting formats for results.

Modular Organization

The system is organized in hardware and software modules. The system was structured this way for two reasons. The first is flexibility. The user is able to define the characteristics of the HVAC equipment component by component in the software, allowing many combinations of equipment to be analyzed. The second is expandability. It allows new types of systems and equipment to be easily added to the software and to the manual. The capabilities can be easily extended as the needs to handle other types of systems are identified.

Wireless Hardware

Small, 4-channel, battery-powered, microprocessor controlled data loggers are dispersed throughout a building to collect the data needed by the system. The data loggers communicate with the software for initial programming and for data transfer via the computer's serial port. For data collection, they are disconnected from the computer and operate on battery power. They each have their own clock and form a distributed wireless data acquisition network. At the completion of data collection, the loggers are retrieved and reconnected to the computer for downloading their data.

The main advantage of using small battery-powered data loggers is that they can be placed very close to the points where the measurements are to be taken, even placing the data loggers within the equipment being monitored, if appropriate. Flexibility in placement of the data loggers significantly reduces installation costs.

Using the HVAC Diagnostics and Commissioning System

The procedure for performing HVAC diagnostics using CBPES is described in the following paragraphs.

Pre-test Data Gathering

The first step in the diagnostic process is to gather information about the HVAC system design, such as the type and size of the air distribution, heating and cooling systems, the types of terminal equipment in the conditioned areas, and the control schedules and sequences used to operate the building. If plans are available, they can be used as a source of information. Often, however, some information may not be available, such as building schedules or equipment sizing and must be gathered during a site visit, either before or during installation of the monitoring equipment.

Often, the occupants of the building can describe the conditions they encounter in their work spaces. In these cases, a questionnaire can be administrated to the occupants to quantify their knowledge of the comfort in their office spaces. These results can be used to determine if there are zones within the building that require special attention. The results of the questionnaires will provide an indication of comfort levels during occupied hours, but will not provide any information about the operation of the HVAC system during unoccupied hours.

Enter Information into CBPES Software to Develop Instrumentation Plan

After the system information has been gathered, it is entered into the software. The CBPES software uses this information to determine what data are required to diagnose the performance of the HVAC system, as previously described. After determining what measurements are required, the software will develop the instrumentation plan. The software develops the instrumentation plan assuming that 4-channel battery powered data loggers will be used, and distributes the instrumentation onto the loggers, grouping sensors onto loggers that are monitoring parameters in specific locations. For example, sensors that are monitoring the condition of the supply air will be placed on a data logger that is dedicated to the supply air location. Sensors that are measuring fan current will be placed on separate data loggers for each fan. This technique ensures that minimal amounts of instrumentation cable are required to install the monitoring package. Typically, about 10 four-channel data loggers are required to monitor a variable air volume (VAV) HVAC system.

After the instrumentation plan is developed, the user can edit the plan, moving sensors between data loggers or adding additional sensors, if required. One case where additional sensors may be necessary is at the mixed air location, where the air temperature is usually stratified and multiple sensors or an averaging temperature sensor is required.

Next, the data loggers are initialized. The initialization process configures the channels of each data logger for the type of sensor that will be connected to the logger, sets the start, stop, sample and storage interval, and resets the internal clock of all of the data loggers so that they are all time-synchronized. After the data loggers are initialized, they are deployed in the building for a 2-week period to collect data.

Install Data Loggers and Instrumentation

Because small battery-powered data loggers are used, installation can be accomplished relatively quickly. In each of the buildings that are discussed in Case Studies, the complete installation, including configuration of the data loggers, took less than 8 hours. There are very few limitations on where the data loggers can be placed. Where possible, the loggers can be placed directly in the airstream. In these cases, no holes need to be drilled in ductwork. In the zones, if a suspended ceiling is present, the loggers can be placed in the ceiling plenum. This reduces the impact of instrumentation on the building occupants. The key to fast installation is flexibility in placing loggers.

Retrieve Data Loggers and Download into CBPES Software

After the monitoring period is completed, the data loggers are retrieved and the data are downloaded into the computer using the CBPES software. The software will recognize each data logger, and will place the data into the proper files for analysis. The software performs the calculations required to analyze the performance of the HVAC system. These calculations include heat flows, airflows, economizer performance data, etc.

As in the installation of the data loggers and instrumentation, the retrieval and download procedure is accomplished relatively quickly. The time required to retrieve the data loggers and instrumentation and download the data into the computer for each building discussed in Case Studies was between 2 and 4 hours. Since the installation was non-intrusive, essentially no repair work was required to return the building to its previous condition.

Perform Diagnostic Analysis

The data are presented to the user in graphical form for analysis. Interactive filters are available for the user to examine the data in more detail. Often, data are valid only under certain conditions. For example, supply air temperatures are valid only if the air is flowing. Also, operation during occupied periods versus unoccupied periods is different, and should be viewed separately. It is important to be able to easily turn on and off filters to enable the user to quickly view the data of interest. This capability is built into the CBPES software.

The time required to perform the diagnostic analysis on each building presented in Case Studies was between 16 and 24 hours for each building. As CBPES becomes more fully developed, this time could be reduced by automating the actual diagnostic process.

Building Monitoring Issues

As has been stressed in the development of this system, reducing the cost of data collection is a very important component for the success and implementation of this system. Therefore, the cost of installing instrumentation must also meet this requirement. There is a tradeoff, however, between the accuracy and the cost of measurements. Very accurate measurements usually require a more costly installation procedure. For example, accurate in-situ airflow measurements require a multi-point flow station. Installing a flow station for short-term monitoring is prohibitively expensive, and is not justified. Single point air velocity measurements are not adequate for calculating the total volumetric flowrate in a duct unless the measurement is taken several duct diameters downstream of any changes in direction or diameter. This condition is rarely encountered in an actual design. However, absolute accuracy is not always necessary for HVAC diagnostics. Often, surrogate measurements are sufficiently accurate. For example, air velocity can be a surrogate for air flow if the desired result is to determine how much the air flow is modulating during normal operation, rather than to calculate the actual airflow produced by a fan. Similarly, current can often be a surrogate for electrical power if the power factor is sufficiently stable or well characterized.

Case Studies

As part of the CBPES development, field tests of the hardware and software were performed for each of the electric utilities participating in the development of the system. The buildings selected for the initial field tests were not considered “broken” buildings, so no problems were identified prior to the tests. The tests were not performed as a result of occupant complaints. All of the monitoring discussed here was performed during the heating season.

Building 1 is relatively new construction, being occupied for less than a year. The floor area of Building 1 is approximately 14,000 square feet on 3 levels. It has a rooftop VAV system with a hot water boiler and mechanical chiller in the basement. The boiler and chiller are shared between the new construction and an older building. Heat is supplied to the perimeter zones using hot water baseboard heat.

Building 2 has been occupied for approximately 2 years, and has had extensive monitoring. This building was chosen as a test bed for CBPES because its operation has been fairly well characterized. The floor area of Building 2 is approximately 250,000 square feet on 3 levels, but only the northern third was monitored. It has a rooftop VAV system with a DX chiller and fan powered electric reheat VAV boxes in the perimeter zones. Heat can also be supplied at night by a gas fired furnace located after the supply fans.

Building 3 has been occupied for about 10 years. It is much larger than the other building, being a 32-story high rise. The floor area of the building is approximately 720,000 square feet. Monitoring was limited to zones on one floor and one half of the total HVAC system. Heat is supplied to the perimeter zones using electric radiant panels.

Monitoring results that show how CBPES is applied to HVAC system diagnostics are presented in the following sections.

Zone Temperatures

The zone temperatures for occupied and unoccupied days are presented in Figures 2 and 3. The zone temperature should be within the comfort setpoints during occupied periods, and go to setback positions during unoccupied periods. Building 1 shows proper temperature control during the occupied periods (Figure 2), but during the night when the building is unoccupied, there is no temperature set back. Although the supply fan is off during the unoccupied hours, heat is being supplied by the hydronic baseboards. There is opportunity for savings in Building 1 by checking the setback schedule for zone temperatures.

Building 2 has a zone temperature setback, as shown in Figure 3. Overnight, the zone temperature drops, since no heat is being added to the zones. Notice the temperature rise at 5 a.m. when the gas fired furnace supplies heat to the building. This is considered normal operation.

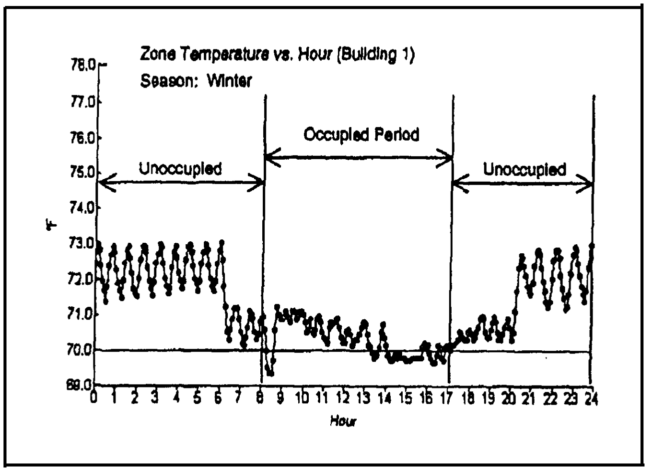

Figure 2. Zone Temperature vs. Hour for Building 1

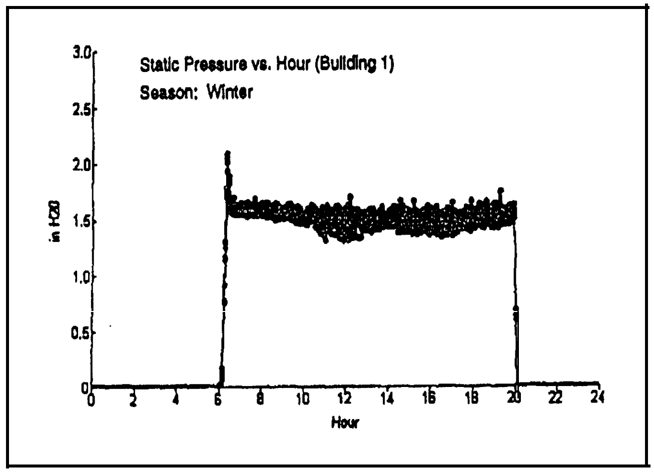

Figure 4. Static Pressure vs. Hour for Building 1

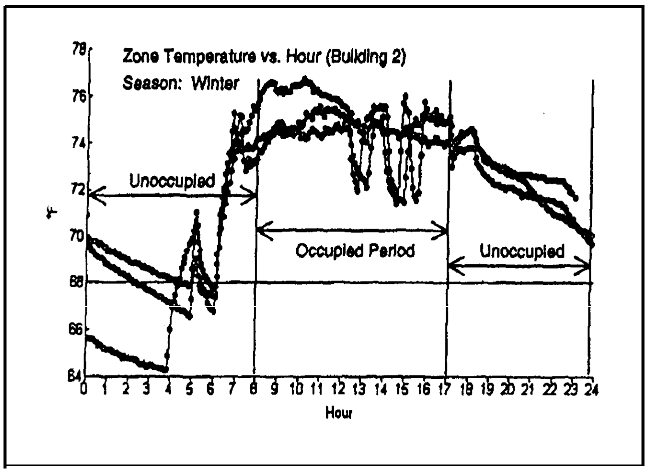

Figure 3. Zone Temperature vs. Hour for Building 2

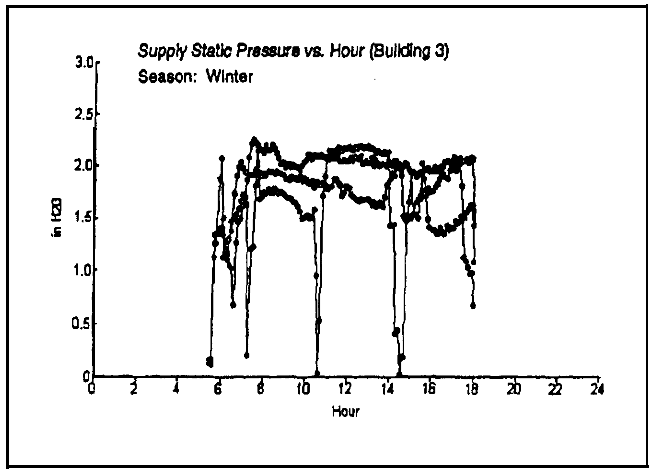

Figure 5. Static Pressure vs. Hour for Building 3

Static Pressure Control

For a VAV system, constant static pressure in the supply duct is required for proper operation of the zone VAV boxes. Static pressure versus hour for Building 1 is shown in Figure 4. Building 1 has relatively constant static pressure control. Also, the system on and off times are clearly visible when the static pressure drops to zero. This plot shows the proper static pressure control.

Static pressure versus hour for Building 3 during a 3-day period is shown in Figure 5. Compared to the relatively constant static pressure shown in Figure 4, there is poor control of static pressure. Insight into this control problem is gained by examining static pressure versus supply airflow, shown in Figure 6. Variation in static pressure is visible in this plot as two groups of data, each group corresponding to either two or three supply fans being operated. The vaneaxial supply fans used in Building 3 are designed to modulate to provide variable flow, but little modulation is evident in this data. Supply airflow and static pressure appear to be controlled entirely by adding

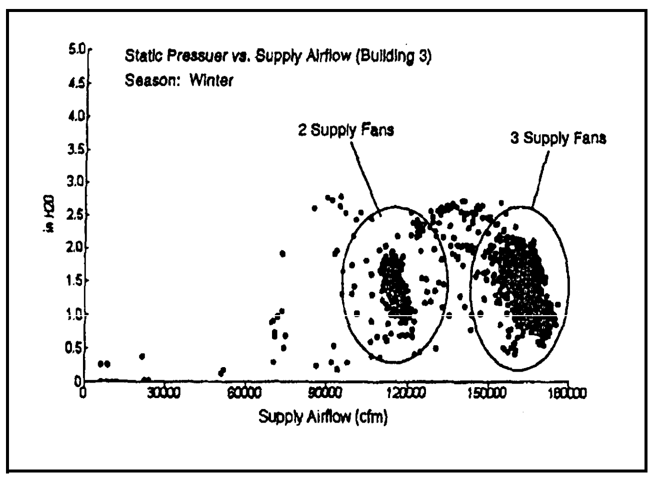

Figure 6. Static Pressure vs. Supply Airflow for Building 3

and reducing the number of supply fans used. In a VAV system, there should be little variation in static pressure as the flowrate changes, as shown in Figure 7 for Building 2.

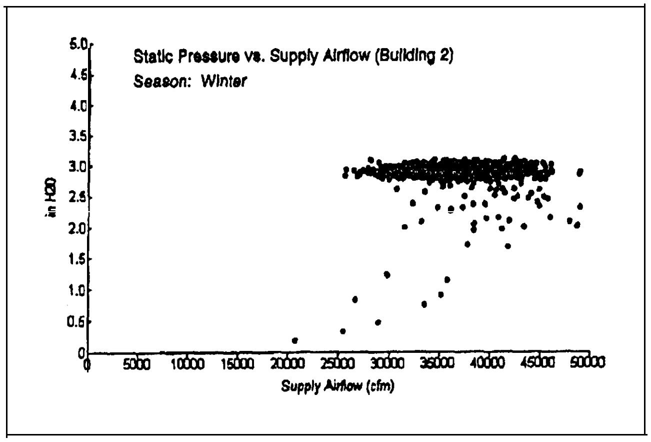

Figure 7. Static Pressure vs. Supply Airflow for Building 2

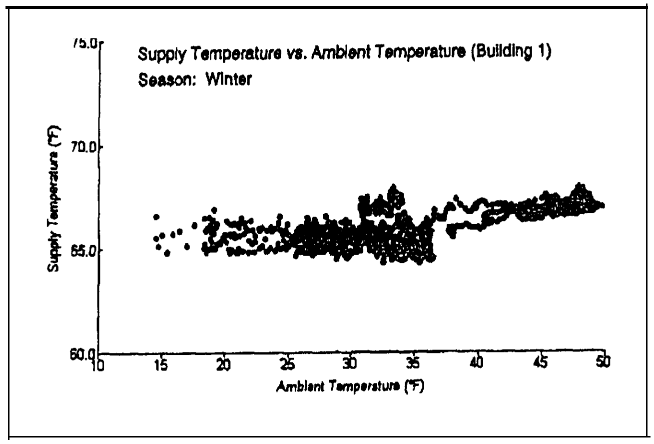

Figure 8. Supply Air Temperature vs. Ambient Temperature for Building 1

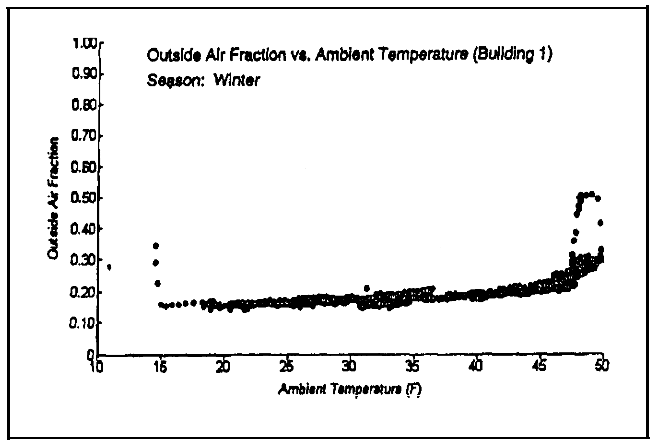

Figure 9. Outside Air Fraction vs. Ambient Temperature for Building 1

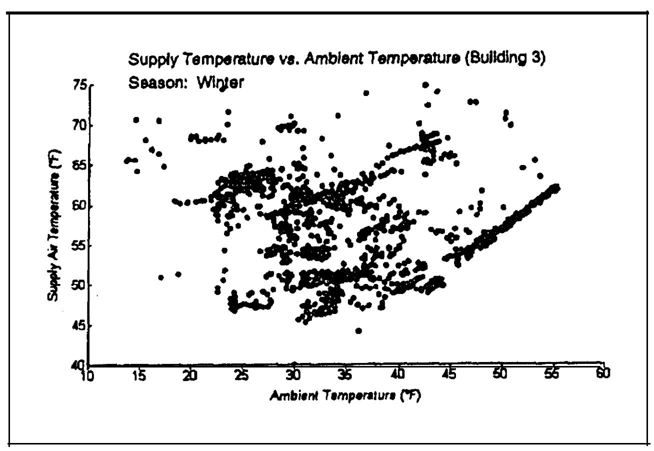

Figure 10. Supply Air Temperature vs. Ambient Temperature for Building 3

Supply Air Temperature Control

Since the monitoring was performed during the heating season, the supply air temperature was controlled by outside air damper control and in the case of Building 1, by using the hot water coil installed in the rooftop unit. The chillers were inactive during the entire monitoring period. Figure 8 shows the supply temperature versus ambient temperature for Building 1. The supply air temperature control for Building 1 is within the specification for the supply air temperature, but appears to be rising with ambient temperature. The zones are being maintained within comfort levels so for the period being monitored, the system may be operating properly. However, rising supply temperature could be an indication of improper economizer operation. The outside air fraction as a function of ambient temperature is shown in Figure 9. The outside air fraction does not change appreciably with ambient temperature. Monitoring during the cooling season would determine if there is a problem with the economizer.

The supply air temperature control for Building 3 is shown in Figure 10. There is significant variation in supply air temperature. The outside air fraction is shown in Figure 11. Generally, the economizer is providing increasing amounts of outside air as the ambient temperature increases, but there is a lot of variation below 40°F ambient temperature.

Conclusions

This paper describes an organized process for systematically performing diagnostics on HVAC equipment. The systematic approach embodies the fundamental engineering needed to conduct this activity on a variety of HVAC system components. Because the system contains this engineering "knowledge," because the hardware is designed to interface with the software, and because the hardware can be easily installed, the time and cost to perform HVAC diagnostics are reduced. The total time required to perform HVAC diagnostics for each building was less than 40 hours for an engineer or skilled technician.

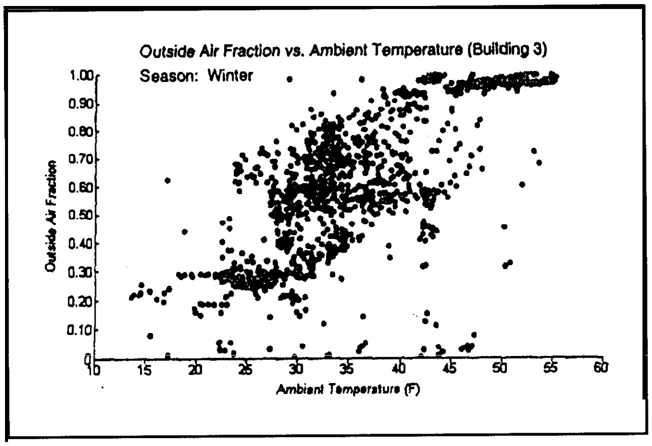

Figure 11. Outside Air Fraction vs. Ambient Temperature for Building 3

The capabilities of this system have applications for utility companies in demand side management programs and customer service programs. This system creates the capability for utilities to offer value-added services to their customers. A great deal of insight into the operation of a customer's building can be achieved in a short period of time.

Although none of the buildings being monitored were suspected of having problems, operational problems in two out of three buildings were identified using the CBPES. None of the problems that were identified were obvious to the occupants.

The data presented for Building 3 shows poor stability in the building controls. The fans are not operating as they were designed to operate, and the economizer is not maintaining a consistent supply temperature. Viewing the flow and static pressure data for Building 3 in multiple plots helped to isolate the static pressure control problem to the current control of the supply fans.

Building 1 had no zone temperature night-time setback. The lack of a temperature setback in Building 1 was apparent only during the unoccupied periods. This problem didn't affect comfort and wouldn't be noticed by the occupants, but would impact energy costs.

Acknowledgments

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