Automated Fault Detection and Diagnostics for Outdoor-Air Ventilation Systems and Economizers: Methodology and Results from Field Testing

Srinivas Katipamula, Ph.D. *Member ASHRAE*

Robert G. Pratt

David P. Chassin

Z. Todd Taylor *Associate Member ASHRAE*

Krishnan Gowri, Ph.D., P.E. *Member ASHRAE*

Michael R. Brambley, Ph.D. *Member ASHRAE*

ABSTRACT

This paper describes a prototype diagnostic system that automatically detects and diagnoses problems with outdoor-air ventilation and economizer operation in commercial buildings using data available from building automation systems (BASs). The system also provides context-sensitive suggestions for correcting the problems detected. The diagnostics are based on rules derived from engineering models of proper and improper air-handler performance. These rules are implemented as a decision tree structure in software. Data collected periodically from a BAS are used to navigate the decision tree and reach conclusions regarding the operating state of the air-handling unit (AHU). Errors and uncertainty in measured data are handled through adjustable tolerance settings in the diagnostic software. Results to date indicate that meaningful results can be obtained using this approach. The diagnostic system can be implemented for either continuous or batch processing of data.

This system is currently installed on seven AHUs in two buildings. Four of the seven AHUs were found to have problems shortly after installation of the diagnostic system. The diagnostic methodology, its implementation in software, the field installations, and test results are described in this paper. The findings clearly demonstrate the potential for automated diagnostic technology to serve an important role in commercial building commissioning and operation.

INTRODUCTION

Operational problems associated with degraded equipment, failed sensors, improper installation, poor maintenance, and improperly implemented controls plague commercial buildings. Automating diagnostics for building systems and equipment promises to help remedy these problems and improve building operation by automatically and continuously detecting performance problems and bringing them to the attention of building operators.

Most problems with building systems today are detected as a result of occupant complaints or alarms provided by building automation systems (BASs). Operators often respond by checking space temperatures or adjusting set points (or thermostat settings). The root causes of operational problems are often not diagnosed, so problems recur and the operator responds again by making an adjustment. When the operator diagnoses problems more carefully by inspecting equipment, controls, or control algorithms, the process is time consuming and often based on rules of thumb built on personal experience. Many times, properly operating automatic control is overridden or turned off when it appears incorrect and possibly the cause of a problem.

Some problems do not manifest themselves in conditions that directly affect occupants in obvious ways and, as a result, go undetected. These problems may, however, affect energy costs or indoor air quality. Tools that automatically detect and diagnose these problems will help alleviate them.

Methods for automatically detecting and diagnosing faults in building systems are emerging from research and development efforts, and open software protocols such as OPC (OLE for Process Control) and standard protocols such as BACnet™[1] (ASHRAE 1995) will contribute to easier implementation by providing standard mechanisms by which

1. Building automation and control network.

Srinivas Katipamula and **Krishnan Gowri** are senior research engineers, **Robert G. Pratt** and **Michael R. Brambley** are staff scientists, **David P. Chassin** is a technical group manager, and **Z. Todd Taylor** is a senior development engineer at Pacific Northwest National Laboratory, Richland, Wash.

BACK TO PAGE ONE

diagnostic software and devices can communicate. Using these methods, practical applications of automated fault detection and diagnosis will soon emerge that assist facility staff in solving operational problems and ensuring comfortable, healthy indoor environments while reducing costs and even providing building staff greater job satisfaction.

Most of the work to date in the field of automated diagnostics has focused on development of techniques for fault detection and diagnosis (Haves et al. 1996; Lee et al. 1997; Li et al. 1997; Peitsman and Soethout 1997; Stylianou 1997) and laboratory testing (Rossi and Braun 1997). However, these technologies are beginning to move into field testing and in the next few years should begin to appear in commercially available building automation systems and software for building management.

This paper reports on one of those techniques and its initial application in field tests. This tool, known as the Outdoor-Air/Economizer (OAE) Diagnostician, monitors the performance of AHUs and automatically detects problems with outside-air control and economizer operation using sensors that are commonly installed for control purposes. It is deployed as a module of the Whole-Building Diagnostician (WBD) (Brambley et al. 1998), which is a modular diagnostic software system currently under development that will provide detection and diagnosis of selected common problems associated with the operation of heating, ventilation, and air-conditioning (HVAC) equipment and lighting in buildings.

The current prototype of the OAE Diagnostician works on constant-volume and variable-air-volume systems that do not use volume compensation (i.e., outside-air intake is a constant fraction of the supply-air flow rate). The AHUs may or may not use economizer control. For systems without economizers, the diagnostician detects only ventilation problems. For systems with economizers, it detects both ventilation and economizer operation problems.

This paper provides brief descriptions of systems for which the OAE tool provides diagnostics, the diagnostic methodology, and the software that implements the diagnostics. It then presents results from testing with simulation data and results from initial field installations.

OUTDOOR-AIR VENTILATION AND ECONOMIZER OPERATION

The OAE Diagnostician is designed to work with major types of economizer and ventilation systems. These are described here to define a consistent vocabulary and provide a context for the discussions of control modes, fault types, and diagnostic methods that follow.

Economizer Physical Description

Many commercial buildings require space cooling year-round, even during periods when outdoor temperatures are low, because of internal loads from lighting, computers, and other office equipment. An economizer enables a cooling system to utilize cool outdoor air to supply (or supplement) the required cooling when outdoor conditions are favorable to such use. By reducing or eliminating the need to mechanically cool supply air, economizers can provide significant energy/cost savings in favorable climates. An economizer system must control the use of outdoor air for cooling, maintain proper “fresh” outdoor-air ventilation for occupants, and prevent overcooling or coil freeze-up.

Economizers use controllable dampers to mix outdoor air and return air in appropriate quantities to provide supply air of the right temperature. The components necessary to achieve this—and those for which the OAE module diagnoses—include:

- *Damper System*—A system of controllable dampers is used to balance the intake of outdoor air with the exhaust of “stale” return air. The dampers are controlled to achieve supply air of the appropriate temperature.
- *Economizer Controller*—A controller is used to open/close the outdoor-air (and return- and exhaust-air) damper system, usually using one of two common control strategies, high limit or differential. The controller determines when outdoor air will be used for cooling, based on whether outdoor conditions are conducive to cooling and how much outdoor air to use. It attempts to provide appropriate cooling without inadvertently increasing heating or cooling loads by introducing outdoor air at the wrong times or in the wrong quantities. Whether outdoor conditions are considered favorable for economizing is based on either the temperature or enthalpy of the outdoor air.
- *Temperature Controller*—A temperature controller limits the temperature of the building’s supply air (or, sometimes, mixed air). It overrides the economizer controller when outdoor conditions would cause coil freezing or result in supply air that is too cold.
- *Minimum-Position Limiter*—The minimum-position limiter ensures that a minimum amount of outdoor air required for occupants is introduced to the building even when outdoor conditions are not favorable for economizing.

Economizer Types

There are two major types of economizers, integrated and nonintegrated. An integrated economizer, as its name implies, is fully integrated with the mechanical cooling system such that it can either provide all of the building’s cooling requirements if outdoor conditions allow or it can supplement the mechanical cooling when outdoor conditions are not sufficiently favorable to handle the entire cooling load. An economizer often has the ability to throttle outdoor-air intake rates between minimum and maximum levels.

Conversely, the operation of a nonintegrated economizer is mutually exclusive with the mechanical cooling system. If outdoor conditions are not sufficiently favorable to allow 100% economizing, no economizing is used. A two-stage

BACK TO PAGE ONE

thermostat often controls a nonintegrated economizer. The first stage opens the economizer; the second stage locks out the economizer and turns on the mechanical cooling.

Economizer Control Strategies

The control strategies used by economizers from different vendors vary widely and are often proprietary. However, most economizers use one of the common strategies described below. The OAE diagnostic tool supports diagnostics of these generic strategies.

- *High-Limit Control*—This strategy bases the decision of whether and how much to economize on a single, often fixed, outdoor-air set point (the "high limit"). If the outdoor-air condition (either temperature or enthalpy) is below the set point, outdoor air is used for cooling. If the outdoor condition is above the high limit, the economizer is turned off (i.e., outdoor-air intake is reduced to the minimum).
- *Differential Control*—This strategy bases the decision of whether and how much to economize on a comparison of the outdoor-air condition (either temperature or enthalpy) with that of the return air. Provided the outdoor conditions are more favorable to cooling than the return-air conditions, outdoor air is used for cooling. This approach works especially well for an integrated economizer because it always ensures the most favorable air enters the cooling coil.

DIAGNOSTIC METHOD

Faults Detected

As with any mechanical system, faults can occur that diminish or eliminate an economizer's usefulness. However, unlike the primary (mechanical) cooling system, a failure of the economizer may go completely unnoticed. Any failure, for example, that prevents outdoor air from being used for cooling when outdoor conditions are favorable may go unnoticed because the mechanical cooling system will pick up the load and occupants will suffer no discomfort. Similarly, a failure that results in too much outdoor air may not be apparent in a reheat system. Reheating will ensure that the air supplied to the space is at a comfortable temperature. In both of these examples, however, the system would be using more energy (and costing more to operate) than necessary.

The OAE Diagnostician is designed to monitor conditions of the system not normally experienced by occupants and alert the building operator when there is evidence of a failure. The common types of outdoor-air ventilation and economizer problems handled by the module include outdoor-air dampers that are stuck, failures of temperature and humidity sensors, economizer and ventilation controller failures, supply-air controller problems, and airflow restrictions that cause unanticipated changes in overall system circulation. The diagnostician also performs some self-diagnosis to identify errors introduced by users in setup and configuration of the software.

Diagnostic Approach

The OAE Diagnostician uses a logic tree to discern the operational "state" of outdoor-air ventilation and economizer systems at each point in time for which measured data are available.

The tool uses rules derived from engineering models of proper and improper air-handler performance to diagnose operating conditions. The rules are implemented in a decision tree structure in software. The diagnostician uses periodically measured conditions (temperature or enthalpy) of the various airflow streams, measured outdoor conditions, and status information to navigate the decision tree and reach conclusions regarding the operating state of the AHU. At each point in the tree, a rule is evaluated based on the data, and the result determines which branch the diagnosis will follow. A conclusion is reached regarding the operational state of the AHU when the end of a branch is reached.

Many of the states correspond to normal operation and are dubbed "OK states." For example, one OK state is described as "ventilation and economizer OK; the economizer is correctly operating (fully open), and ventilation is more than adequate." Other states correspond to something operationally wrong with the system and are referred to as "problem states." An example problem state might be described as "economizer should not be off; cooling energy is being wasted because the economizer is not operating; it should be fully open to utilize cool outside air; ventilation is adequate." Other states (both OK and problem) may be tagged as incomplete diagnoses if the measured information is insufficient.

Each problem state known by the OAE module has an associated list of possible failures that could have caused the state; these are identified as possible causes. In the example above, a stuck outdoor-air damper, an economizer controller failure, or perhaps a misconfigured setup could cause the economizer to be off. Thus, at each metered time period, a list of possible causes is generated.

An overview of the logic tree used to identify operational states and to build the lists of possible failures is illustrated in Figure 1. The boxes represent major subprocesses necessary to determine the operating state of the air handler; diamonds represent tests (decisions), and ovals represent end states and contain brief descriptions of OK and problem states. Only selected end states are shown in this overview.

Data Requirements

The OAE Diagnostician uses two primary types of data—measured and setup. The measured data include information on mixed-air, return-air, and outdoor-air temperatures (and enthalpies for enthalpy-controlled economizers), supply fan on/off status, and heating/cooling on/off status. These data are typically available from BASs at semi-regular intervals (typically hourly, half-hourly, etc.). Alternatively, measured data

BACK TO PAGE ONE

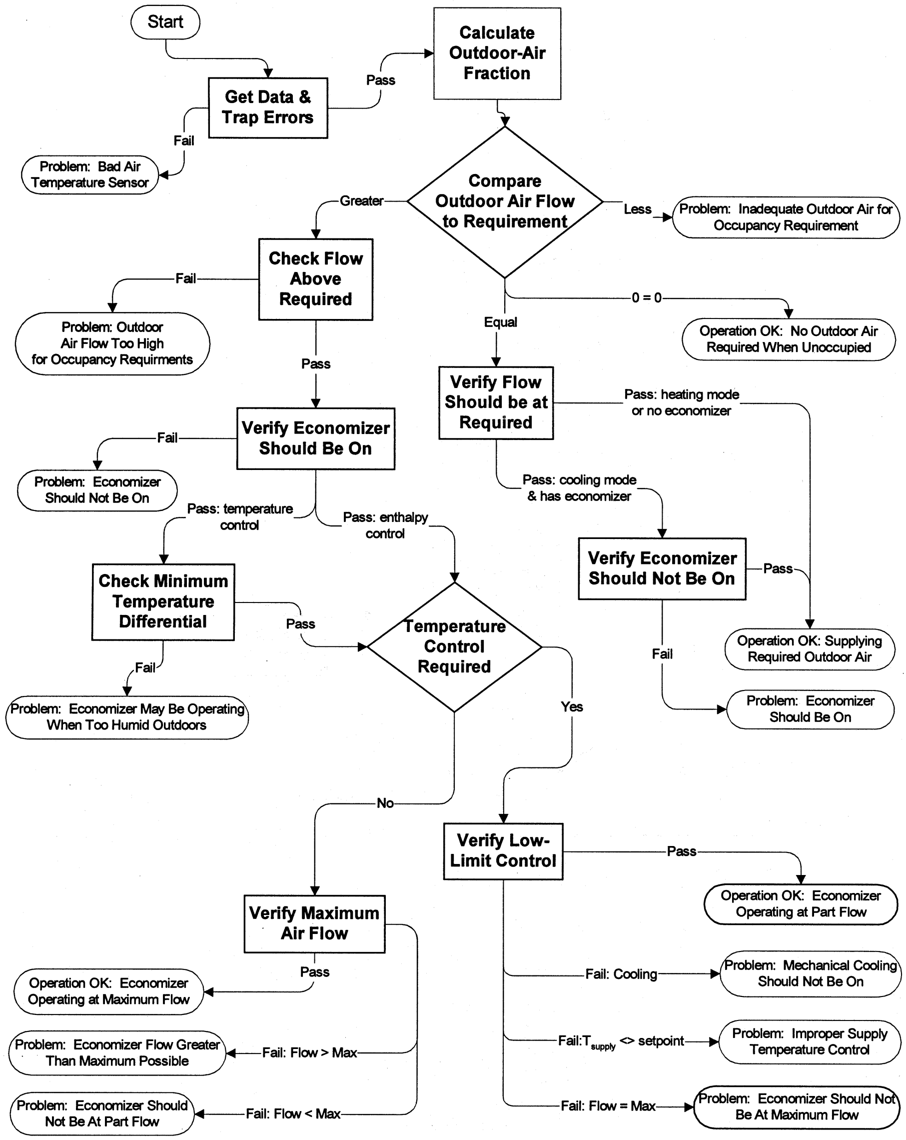

Figure 1 *Overview of the diagnostic logic tree, showing key operating states.*

could be collected using custom metering and data collection systems, or the diagnostician could be used to process an existing database containing the required data. The setup data, obtained by querying the user (building operator or installer), includes information describing the type of economizer, its control strategies and set points, and building occupancy (and hence, ventilation) schedules.

DIAGNOSTIC SOFTWARE

Software Architecture

The OAE Diagnostician is implemented as a module of the Whole-Building Diagnostician (WBD). The WBD is a modular diagnostic software system (see Figure 2) that provides detection and diagnosis of common problems associated with HVAC equipment and lighting in buildings. Modules within the WBD will provide specific collections of these diagnostic functions. The OAE, as one of those modules, monitors, detects, and diagnoses problems with outdoor-air ventilation and economizer operation.

The WBD is implemented on a desktop computer. The diagnostic modules use a central database and share a common graphical user interface. Typically, the user interacts with the WBD to start analysis or to view results of diagnoses. Data are stored in the database by an external process. The data may originate directly from a BAS or other data acquisition system or may already be stored in another database. Diagnostic modules access the central database to obtain configuration data and measured data to be analyzed and to store the diagnostic results. Diagnostic modules can process (i.e., analyze) the information as it is stored or batch-process time-series data or entire databases. The user may schedule processing at regu-

BACK TO PAGE ONE

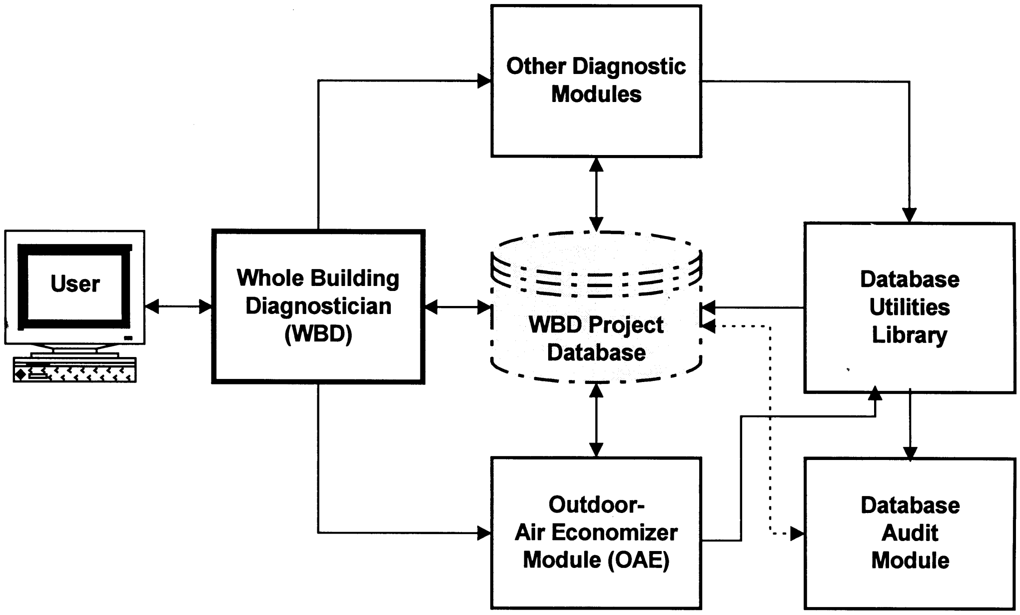

Figure 2 Whole building diagnostician—software architecture.

lar intervals (e.g., hourly or daily) or may manually initiate processing by a diagnostician. Once a diagnostic module completes its processing, results are stored in the database. They can be retrieved by the user at any time through the WBD, which retrieves the diagnostic results and displays them graphically for the user.

A run-time library of database utility functions is available to all diagnostic modules for database creation, message logging, and other database operations. In addition, a database audit module is available to check the consistency and completeness of a database before any task is undertaken. All WBD modules are implemented in Visual C++, and the database is implemented using ODBC (object database connectivity).

Data Management

The project database is central to the operation of the WBD. All modules interact through the database using the structured query language (SQL) for database transactions. Figure 3 shows the component hierarchy with which all WBD building data are represented. The highest level in the hierarchy is a building. A building may have many plants; each plant may have several air-handling units, and each air-handling unit may serve multiple zones. This hierarchy allows maintenance of independent data tables for components and provides the ability to traverse the hierarchy to resolve relationships during data retrieval.

The project database contains several data tables implemented using a relational model. Each data table represents a building component and contains data specific to (1) configuration, (2) schedules, (3) metered data, or (4) intermediate

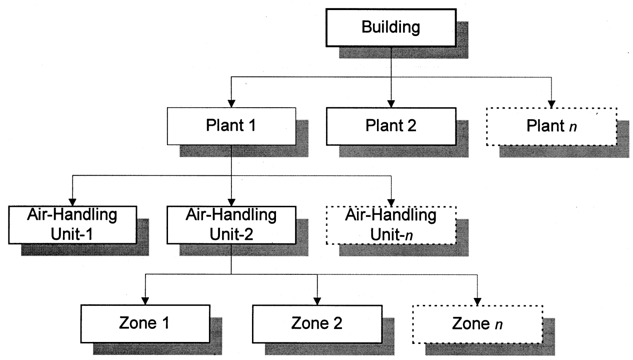

Figure 3 *Database hierarchy and relationships among building components.*

calculations. Two other sets of data tables are used to control analysis and store the diagnostic results.

Automation of Data Collection and Processing

The system architecture makes possible development of automated monitoring systems that can run diagnostics of specified equipment on a regular basis by a specific diagnostic module. To automate the diagnostics, a separate monitoring program module is run to bypass the graphical user interface. This program allows automated collection and processing of data. As a result, the open architecture and modularized nature of the WBD provides abundant opportunities for implementing automated monitoring and diagnosis.

Basic OAE Functionality

The current prototype of the OAE Diagnostician detects about 25 different basic operational problems using the methodology described earlier. The user interface uses color coding to alert the building operator when problems occur and then provides assistance in identifying the causes of the problems and in correcting them. (For this paper, we have changed the colors of the cells to patterns in order to distinguish between different states of operation.) Figure 4, for example, shows a representative OAE Diagnostician window. Each cell in the diagram represents an hour. The color of the cell (patterns in this paper) indicates the type of state. Green cells (with small dot pattern) identify OK states, for which no problems were detected. Other colors (other than the small dot pattern) represent problem states. "Clicking" the computer mouse on any colored cell brings up the specific detailed diagnostic results for that hour.

Figure 5 shows pop-up windows providing a description of a problem, an "explanation" of the diagnostic logic (list of

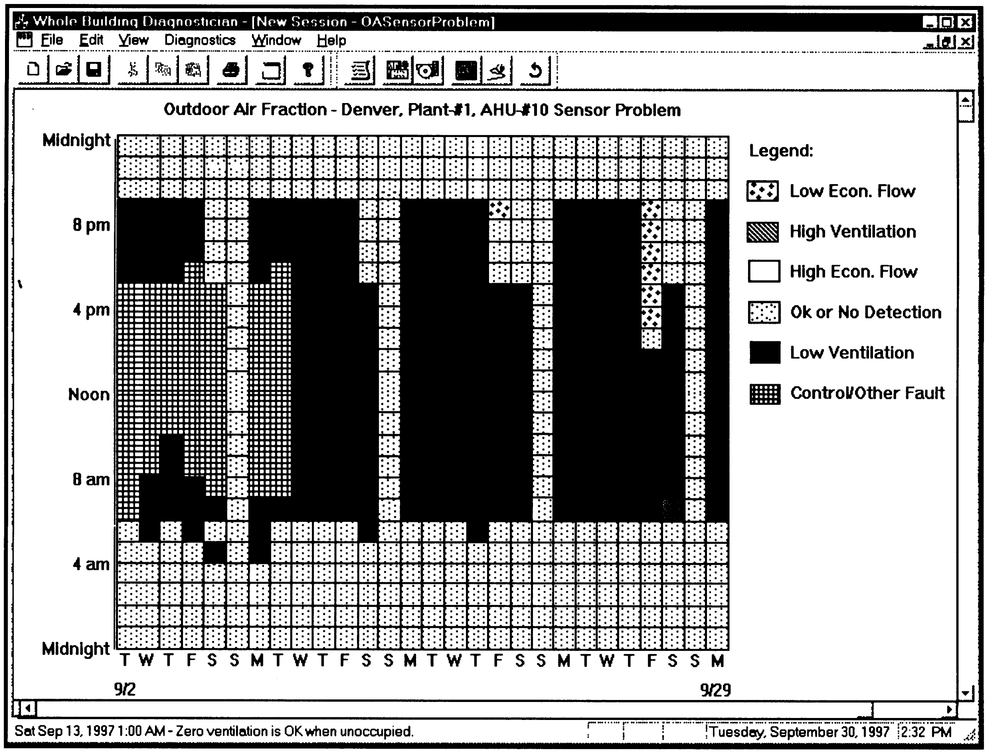

Figure 4 *Diagnostic results showing proper (small dot pattern) and faulty operation (other than the small dot pattern) for a data set having a faulty outdoor-air sensor.*

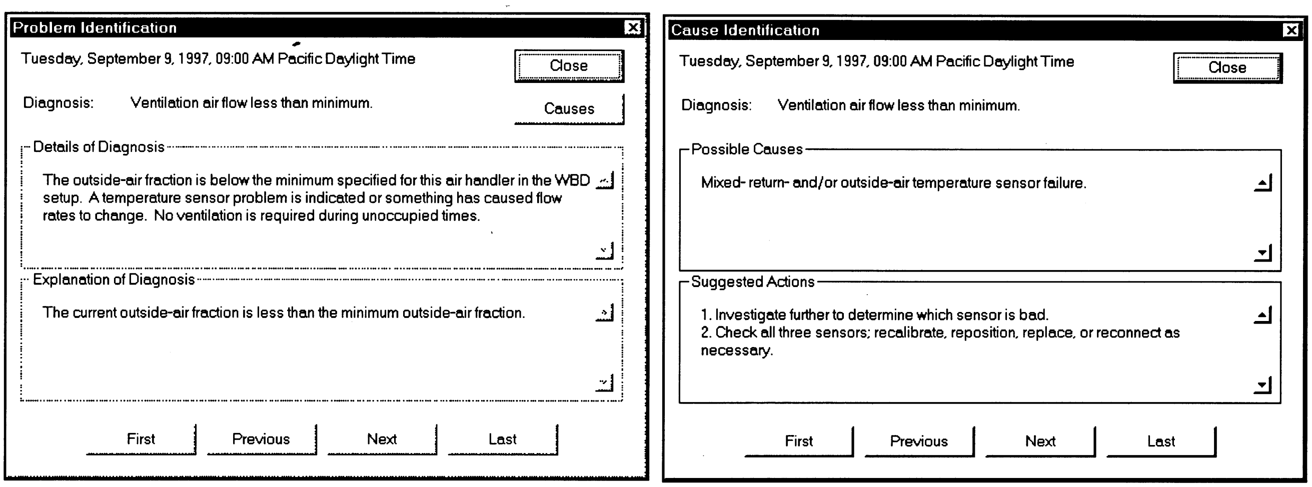

Figure 5 *Screen on the left shows the details of the diagnosis and a description of how the diagnosis was obtained; the screen on the right shows a possible cause for the problem identified and suggested actions to correct the problem.*

BACK TO PAGE ONE

conditions that led to this diagnosis), a potential cause, and suggested actions to correct that cause. The second window with causes and suggested corrective actions is revealed by clicking on the “Causes” button in the other (first) window. If other potential causes exist, they can be revealed by clicking on the “Next” button (second).

The OAE Diagnostician alerts building operators to problems in air handlers and assists them in identifying specific causes that they can investigate further or correct. Without this assistance, many of these problems go undetected and uncorrected.

TESTING AGAINST SIMULATIONS

Although field testing is ultimately required, simulations provide an effective way of generating data that would be more costly to generate in a laboratory or field test. The results are also valuable for illustrating the success of the diagnostician in detecting operational problems and their underlying causes.

The general approach involved generating sets of data by simulation, where each set corresponds to an air handler with a specific underlying fault. These data sets were then processed by the OAE Diagnostician to determine whether it detected problems and identified the correct cause (i.e., underlying problem).

Simulated Data Sets

Test data sets were generated using DOE-2 (LBNL 1989) hourly simulation software. Each data set was generated for a common problem associated with economizers in the field. In some cases, the results from DOE-2 were post-processed to produce the desired fault condition (CEC 1991).

The simulated test building is a three-story,15-zone, prototype building (Friedrich and Messinger 1995). Annual simulations were performed for Denver TMY[2] weather data and an economizer with a differential dry-bulb temperature-based controller. The outputs from the simulation include hourly values of: dry-bulb temperatures of outdoor air, return air, mixed air, and supply air; supply fan on/off status; air-handler operational mode (cooling or heating); and mechanical cooling on/off status. In addition to these time-series data, there are several one-time setup data requirements to configure the OAE Diagnostician (see “Data Requirements” section).

Although more than 25 problem states are defined in the OAE algorithm, only a few common fault states (problems) were tested with annual hourly simulated data sets:

- Bad sensor(s) (outdoor-air sensor biased to read 10°F higher)
- Outdoor-air damper stuck fully closed
- Outdoor-air damper stuck fully open
- Outdoor-air damper stuck at required ventilation position
- Outdoor-air damper stuck between fully closed and fully open.

Diagnostic Results with Simulation Test Data

Figure 4 shows an OAE Diagnostician window with the results generated using the data set with a bad outdoor-air sensor (first data set). The x-axis represents the day and the y-axis identifies the hour of the day from midnight to midnight. The details of the diagnosis obtained by clicking on the purple cell (shown with crosshatch pattern) for 9 a.m. Tuesday, September 9, are shown in Figure 5, along with the identified cause and suggested corrective actions. The diagnostician came to this conclusion because the outdoor-air fraction is less than the minimum (when the outdoor-air dampers are completely closed).

In some cases, the diagnostician can isolate a single cause of the fault. In most cases, even a single fault, depending on outdoor and operating conditions, can manifest itself in different ways. When this occurs, the building operation and maintenance staff must distinguish among the causes by reasoning about the diagnostic results for different times or inspecting the AHU. The number of unique non-green colors (other than the small dot pattern) displayed on the screen will depend on the type of fault and also on outdoor and operating conditions.

For the first test data set, where the outdoor-air sensor is biased to read 10°F higher, the diagnostician exhibits at least three nongreen colors (problem states, other than the small dot pattern, see Figure 4). The details for two of the problem states, explanations on how the fault state was arrived at, possible causes for the economizer to be in that state, and suggested corrective actions are tabulated in Table 1. For some outdoor and operating conditions, the sensor fault is not apparent; therefore, the cells during that period are green (small dot pattern) (for example, hours when the true outside-air condition is not favorable for economizing). The cells are brown (crosshatch pattern) when the second law is violated (i.e., when the mixed-air temperature is either less than or greater than both the return- and outdoor-air temperatures). The cells are purple (crosshatch pattern) when the true outdoor-air conditions are favorable for economizing but, because of the bias, the economizer is not economizing.

The third problem state (not shown in Table 1) is indicated by orange cells (diagonal pattern) (Figure 4.) If the air handler is in the heating mode and there is no economizer lockout, the economizer will open the outdoor-air dampers because of the bias in the outdoor-air sensor. This problem state has several potential causes: failure of the outdoor-air damper system to fully close; outdoor-air damper system stuck at a position above the minimum required for ventilation; outdoor-air damper system fully open; configuration/setup problem; or outdoor-air, mixed-air, or return-air temperature sensor prob-

2. A typical meteorological year (TMY) is a data set of hourly values of solar radiation and meteorological elements for a one-year period. It consists of months selected from individual years and concatenated to form a complete year.

BACK TO PAGE ONE

TABLE 1
Detailed Diagnostic Results for Two of the Three Non-Green Colored Cells (Other Than Small Dot Pattern) From the First Test Data Set (Bad Outdoor-Air Temperature Sensor Problem)

Current State	Detailed Diagnosis	Explanation	Possible Causes	Suggested Actions
Ventilation air flow less than minimum (Crosshatch Pattern)	The outside-air fraction is below the minimum specified for this air handler in the WBD setup. A temperature sensor problem is indicated, or something has caused flow rates to change. No ventilation is required during unoccupied times.	The current outside-air fraction is less than the minimum outside-air fraction.	Mixed-, return-, and/or outside-air temperature sensor failure.	Investigate further to determine which sensor is bad. Check all three sensors; recalibrate, reposition, replace, or reconnect as necessary.
Temperature sensor problem (Crosshatch Pattern)	A temperature sensor problem is indicated because the mixed-air temperature cannot be significantly lower than both the return-air temperature and the outside-air temperature. If this problem persists or is frequent, ventilation and economizer controls are operating incorrectly and are likely to be misdiagnosed until the sensor problem is fixed.	The mixed-air temperature is less than the outside-air temperature and the return-air temperature.	Mixed-, return-, and/or outside-air temperature sensor failure.	Investigate further to determine which sensor is bad. Check all three sensors; recalibrate, reposition, replace, or reconnect as necessary.

lem. The diagnostician also provides suggested actions to correct each of the potential causes, but it cannot isolate the specific cause of the problem under these conditions.

Although the diagnostician reported three different problem states, there is only one underlying cause. However, the actual cause may be identified by examination of the results across problem states. A close inspection of the list of potential causes for the three problem states shows a failed return-, mixed-, or outdoor-air temperature sensor as the cause common to all three states. The current version of the OAE Diagnostician alerts staff to the problem and directs them to the most likely causes, but the staff must still distinguish between these causes by further analysis (as shown here) or inspection. A problem that might have gone undetected is found, and repair efforts are targeted to the most likely causes. Time is saved, but some additional sleuthing by an operator is

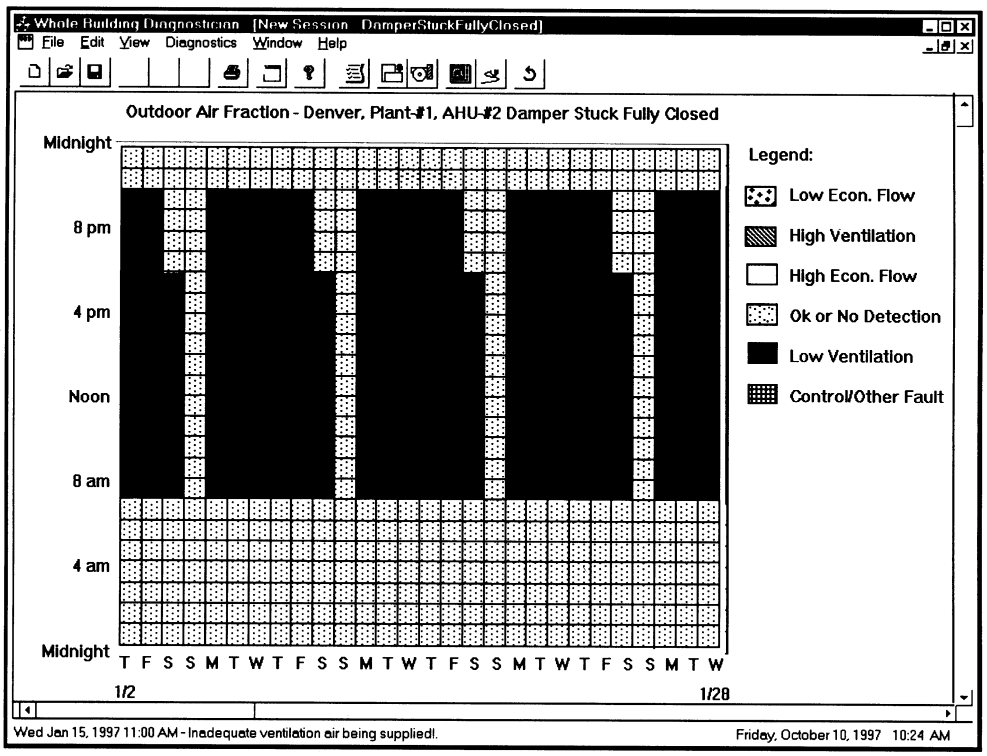

Figure 6 *Diagnostic results showing proper (small dot patterns) and faulty operation (patterns) for a data set with an outdoor-air damper stuck fully closed.*

still required. The next version of the OAE Diagnostician will isolate the cause of a problem to the one most likely, providing even greater benefits.

The second data set was generated by simulating an air handler with the outdoor-air damper stuck fully closed. The results from processing this data set with the diagnostician are shown in Figure 6. In this case, the diagnostician reported only one problem state (blue cells, fully shaded pattern): inadequate ventilation air being supplied (for times when the AHU was ON). It also reported several possible causes including: blockage in the outdoor-air intake duct; damper system stuck below the required ventilation level or fully closed; configuration/setup error; or mixed-air, return-air, or outdoor-air temperature sensor error. In this case, because the diagnostician only reported one problem state, the possible cause cannot be reduced further using only the results from the diagnostician. So the operator may need to investigate all the possible causes listed.

The third data set was generated by simulating an air-handling unit with an outdoor-air damper stuck fully open. The diagnostic results showed two problems states, depending on whether the air handler was in heating or cooling mode: (1) too much ventilation during heating mode and (2) economizer should not be operating. Both states shared one common possible cause, the damper stuck fully open. The results from the remaining two test data sets also confirmed that the diagnostician was generating correct results.

FIELD TEST RESULTS

The OAE Diagnostician has also been installed in two buildings for initial field testing. Field testing provides opportunities to investigate unanticipated practical problems and to test usefulness in practice. Although the results obtained are preliminary, they suggest that the OAE Diagnostician will provide significant benefits. Descriptions of the two test buildings, their HVAC systems, and diagnostic results follow.

Test Buildings and Systems

The OAE Diagnostician is presently installed and operating on seven air-handling units in two buildings. The first is the newly constructed and occupied the U.S. Department of Energy (DOE) William R. Wiley Environmental Molecular Sciences Laboratory (EMSL) in Richland, Washington. The 200,000 ft^2 (18,580 m^2) building houses laboratories, offices, conference rooms, and computer facilities. A commercial BAS provides monitoring and control of the facility using 3,421 sensor points. This building is more highly instrumented than most commercial buildings of similar size, but the data used by the diagnostician are commonly found in buildings with BASs. The diagnostician currently monitors three AHUs in this building. All AHUs are of 20 ton (70 kW) or greater cooling capacity.

The second building is the Technology Management Center (TMC), also located in Richland. This 72,700 ft^2 (6754 m^2) office building constructed in 1973 has four central AHUs with economizers. A commercial BAS provides monitoring and control of the facility using 420 sensor points. The diagnostician monitors all four AHUs in this building.

All air handlers use high-limit temperature controllers to control the economizer operation. The supply temperature is reset based on the average zone temperature, and the econo-

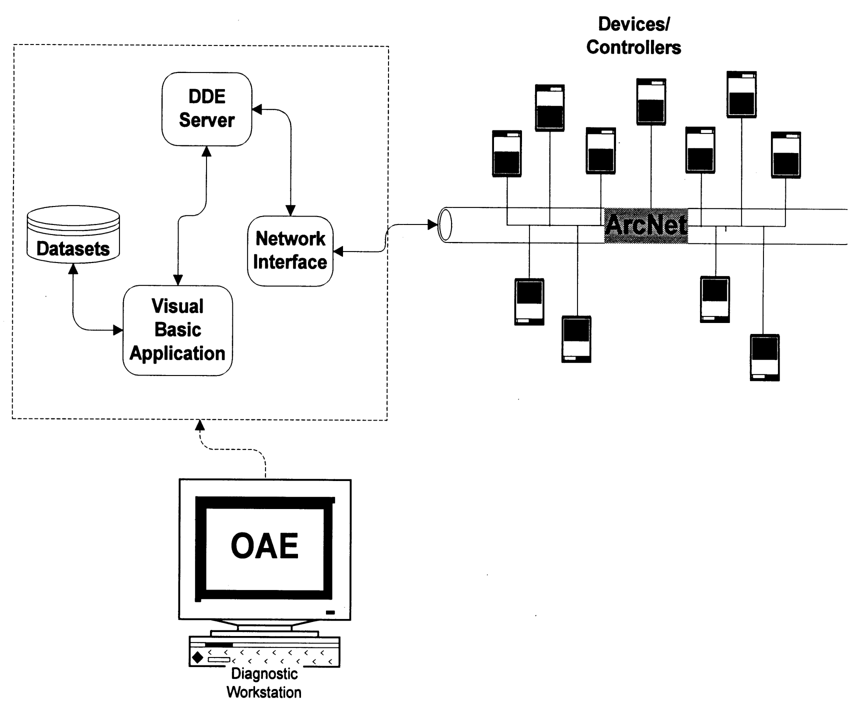

Figure 7 *Data pipeline.*

mizer is controlled to limit the supply temperature when the outdoor temperature is colder than the supply-air temperature set point.

Data Pipeline

For each AHU, data are recorded hourly from BAS sensors for outside-air, return-air, mixed-air, and supply-air temperatures and status of the supply fan, the hot-water valve, and the chilled-water valve. No sensors were installed specifically for the diagnostician; all of these data points are used by the BAS for control purposes. The data are automatically transferred each hour from the BAS to the diagnostician's database using a dynamic data exchange (DDE) connection.

A schematic diagram of the "data pipeline" is shown in Figure 7. A Visual Basic application (VBA) running in the background initiates a DDE conversation between the DDE server, provided by the BAS manufacturer, and the diagnostician's database to update the diagnostician's database periodically (at the beginning of each hour). It uses predefined relationships to map data from the sensors from each of the air handlers into the database. The OAE Diagnostician then periodically processes the new data, producing diagnostic results that can be viewed with the user interface.

Results

Of the seven air handlers monitored, four were found to have problems shortly after initial processing of data. The problems found included sensor problems, return-air dampers not closing fully when outdoor-air dampers were fully open, and a chilled-water controller problem. All problems have been confirmed by inspection of the AHUs.

Figure 8 shows the results for AHU-01 at the TMC. This AHU operates continuously (24 hours per day). The diagnostician predominantly detected a single problem state (shown by red cells, large dot pattern) and reported that cooling energy was being wasted because the economizer was operating partly closed even when the outside-air conditions were favorable for economizing. The possible causes reported by the diagnostician for this problem state include damper system failure, temperature sensor failure, some obstruction in the outdoor-air intake duct, and an increase in supply-air flow rate without a corresponding increase in outdoor-air flow rate. In addition to this failure state, the diagnostician occasionally reported that the supply-air temperature was higher than the supply-air set point (shown by purple cells, crosshatch pattern). Most of these problem states occurred either early in morning or late at night. The only possible cause for this second problem state is the failure of the supply-air controller to activate cooling.

Because there are no common possible causes for both of the indicated problem states, two problems exist with this AHU. Inspection of the AHU revealed that the return-air damper was not closing completely when the economizer called for 100% outside air. The diagnostician provided this as

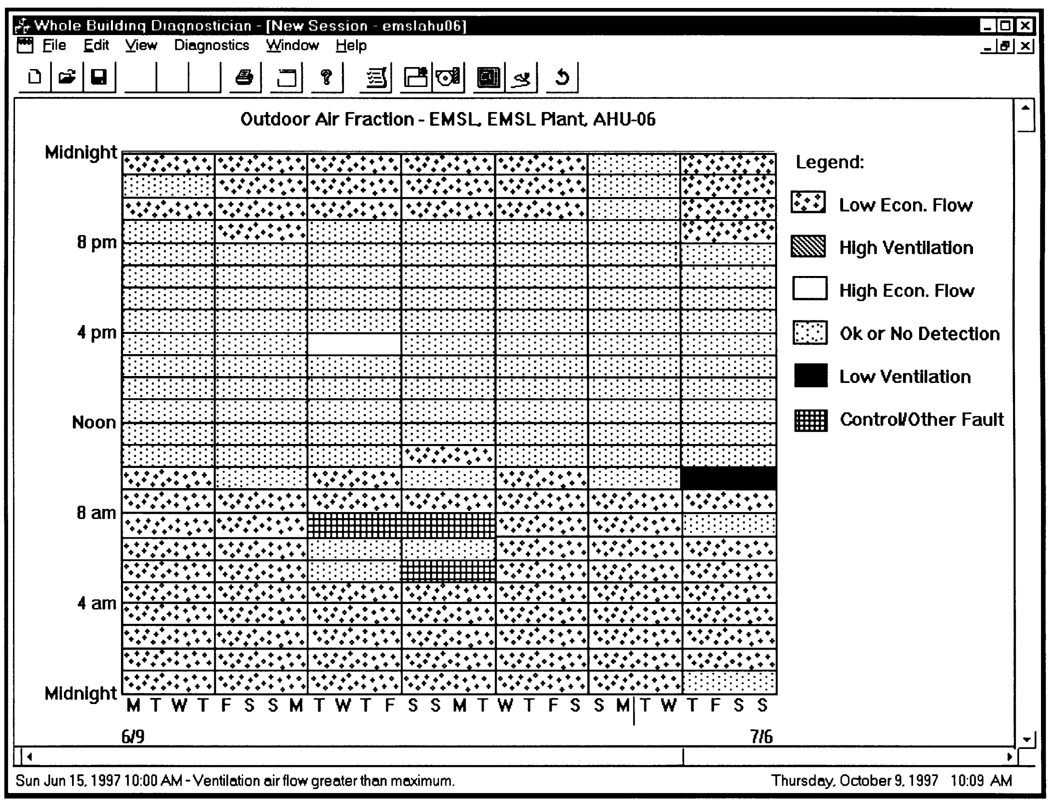

Figure 8 *Diagnostic results for AHU-01 at technology management center.*

BACK TO PAGE ONE

one of the suggested causes (the first problem). The second problem (supply-air controller failure to activate cooling) occurs infrequently when the outdoor temperature is lower than the supply set point. The building operators are evaluating possible solutions for both problems.

Figure 8 also graphically illustrates that the diagnostic results depend on outside and operating conditions. These conditions determine the mode in which the AHU operates and, therefore, whether a problem can be observed or not. For example, when the outside-air condition is not favorable for economizing, the damper problem is not apparent and the cells are green (small dot pattern). On Wednesday, August 27, the diagnostician identifies (shown by red cells, large dot pattern) that the economizer should not be at part flow from midnight to 10 a.m. At 11 a.m., the cells are green (small dot pattern), when conditions are such that a problem is not apparent. The underlying cause, which is the leaky damper described above, has not changed, but the apparent problem that the diagnostician identifies has changed because outside-air conditions and occupancy changed. The underlying problem was one of several identified as possible by the diagnostician. By observing the diagnostic results over several hours, the operator can infer the most likely cause of the problem. The ability to automatically consider trends to refine the diagnosis, as done manually for this problem, is currently under development.

Figure 9 shows results for AHU-06 in the EMSL building, which operates continuously, 24 hours per day. The diagnostician detected an operational problem with the AHU, which was manifested in three different forms depending on outdoor and operating conditions. Examination of the potential causes listed for all three states showed a failed return-, mixed-, or outdoor-air temperature sensor as a common potential cause.

Inspection of the AHU and its sensors revealed that a problem with the outside-air temperature sensor did indeed exist. Rather than a failure of the sensor itself, however, the location and installation of the sensor caused it to read incorrect air temperatures. It was located in a non-aspirated tube with the top of the tube sealed and mounted in a corner under an overhang. This arrangement did not allow the air to circulate adequately. When the walls adjacent to the tube were heated by sunlight, the sensor indicated a temperature closer to the wall temperature than the air temperature. Because each AHU in this building has its own outside-air temperature sensor, this problem can be corrected by simply mapping one of the other outside-air temperature sensors to this variable in the BAS.

The results for AHU-02 at TMC showed that the economizer and the ventilation system were working properly, but the supply-air controller was not controlling the supply-air temperature properly. This problem is identical to the problem experienced by the AHU-01 at TMC. The building operators are investigating the problem.

Finally, the results from AHU-03 at TMC showed predominately two problem states: (1) the economizer should

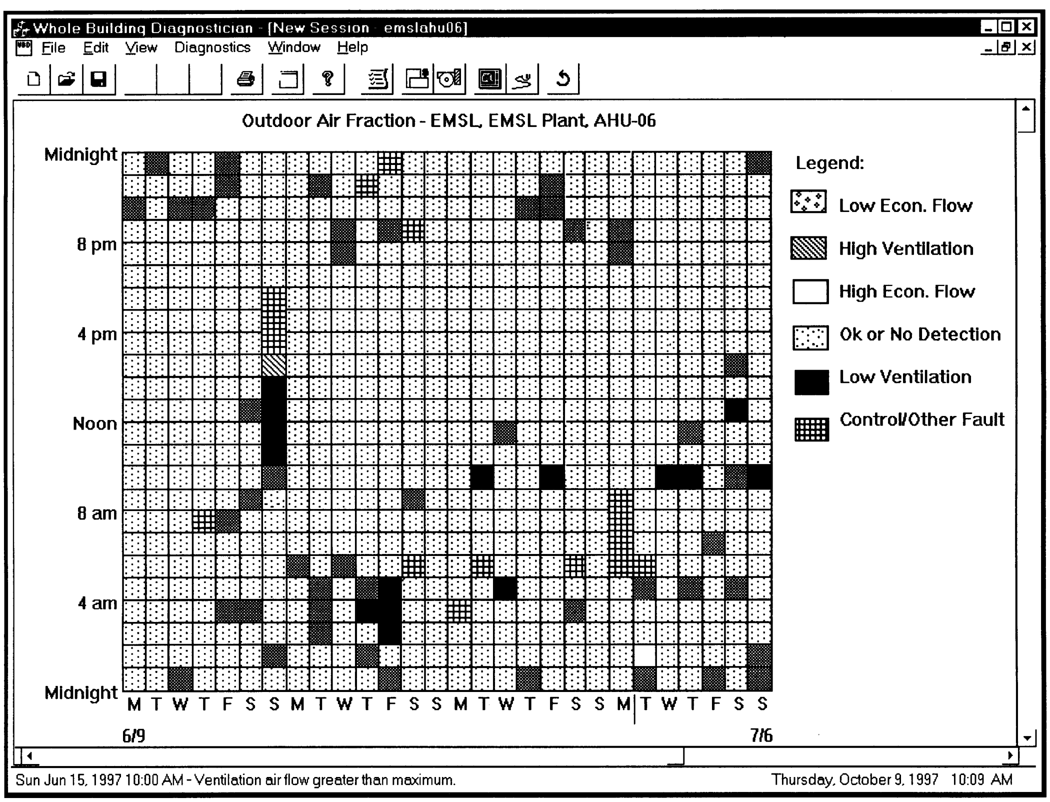

Figure 9 *Diagnostic results for AHU-06 at the EMSL building.*

BACK TO PAGE ONE

not be at part flow, and (2) the economizer should not be OFF. In addition to these two states, a few hours existed when the diagnostician reported a temperature sensor failure (detected by a second-law violation). Further investigation (review of raw data) and inspection of the AHU revealed that the mixed-air temperature sensor was the problem sensor[3].

DISCUSSION AND CONCLUSIONS

The OAE Diagnostician has proven effective in identifying outdoor-air ventilation and economizer operation problems in air-handling units during initial field testing. Furthermore, the small sample of air handlers monitored have confirmed our suspicion and that of many building operators (CEC 1991) that many economizers do not work as intended. The field test results confirm the suspicion—four of the first seven AHUs monitored had some type of problem. The results also indicate that automated diagnostic technology promises to help identify and eliminate these common problems.

The current version of the OAE Diagnostician is a prototype intended to demonstrate the potential for this technology and provide a methodology that ultimately can be deployed in different ways. For example, the OAE Diagnostician could serve as a tool to support commissioning, routine building operation, or equipment servicing. During commissioning, the diagnostician could help ensure that air handlers are installed and operating properly. It would process data and identify problems, which would be eliminated as part of the commissioning process. To extend its application to support routine building operation, control system installers or manufacturers could deploy the OAE Diagnostician as an embedded part of a control system, BAS, or supervisory software. In this form, the diagnostician would provide on-demand support to building operators or facility managers. Operations staff could access diagnostic results as often as desired to support operation of their facilities. By monitoring air-handler performance and diagnosing problems continuously, the diagnostician would ensure that equipment is maintained and operated properly, providing the equivalent of continuous commissioning. If used at a central location by a manager of several properties or a campus, the diagnostician could process data from several different buildings. This would reduce the frequency of site visits, improve operation and maintenance of air handlers, and lower operating costs.

Future developmental work will focus on improving the ability of this diagnostician to isolate the cause of problems and direct the building operator to the proper corrective actions, as well as extending automated diagnostics to other applications. In addition to isolating the cause, the future version will also highlight the energy and cost impacts due to improper outdoor air controls or economizer operation. The OAE Diagnostician represents only one application of automated diagnostics to building equipment and systems. In the future, automated diagnostic tools could be used to detect and diagnose problems with many components and systems—boilers, chillers, variable-air-volume boxes, thermal energy storage systems—to name only a few. Some of these applications will require more sophisticated diagnostic methods than used by the OAE Diagnostician. Others may employ the rule-based approach used for this diagnostician. Deployment of automated diagnostics will help improve building operation, bringing improved comfort and air quality, longer equipment life, and lower costs.

[3] All AHUs tested measure the mixed-air temperature across the cross-section of the mixed-air duct and average the value. Therefore, the problem is not caused by stratification, but by using a bad sensor data for averaging.

ACKNOWLEDGMENTS

The work described in this paper was sponsored by the Office of Building Technology, State and Community Programs of the U.S. Department of Energy as part of the Building Systems Program at Pacific Northwest National Laboratory. The Laboratory is operated for the U.S. Department of Energy by Battelle Memorial Institute under contract DE-AC06-76RLO 1830. The authors would also like to thank their colleagues at the Honeywell Technology Center and the University of Colorado, who worked on development of other diagnostic tools as part of the same DOE project, for their insightful comments as reviewers during development of the OAE diagnostic tool.

REFERENCES

ASHRAE. 1995. *ANSI/ASHRAE Standard 135-1995, BACnet™—A data communication protocol for building automation and control networks.* Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

Brambley, M., R. Pratt, D.P. Chassin, and S. Katipamula. 1998. Automated diagnostics for outdoor air ventilation and economizers. *ASHRAE Journal* 40(10).

CEC. 1991. Nonresidential standards confidence & sensitivity analysis. Building and Appliance Efficiency Office, California Energy Commission, Sacramento.

Friedrich, M., and M.T. Messinger. 1995. Method to assess the gross annual savings potential of energy conservation technologies used in commercial buildings. *ASHRAE Transactions* 101(1): 444-453.

Haves, P., T.I. Salisbury, and J.A. Wright. 1996. Condition monitoring in HVAC subsystems using first-principle models. *ASHRAE Transactions* 102(1): 519-539.

LBNL. 1989. *DOE-2 engineering manual, Version 2.1E.* LBL-8688. Energy and Environment Division, Building Energy Simulation Group, Lawrence Berkeley National Laboratory, University of California, Berkeley.

Lee, W.Y., J.M. House, and D.R. Shin. 1997. Fault diagnosis and temperature sensor recovery for an air-handling unit. *ASHRAE Transactions* 103(1): 621-633.

Li, X., J-C. Visier; and H. Vaezi-Nejad. 1997. A neural network prototype for fault detection and diagnosis of heating systems. *ASHRAE Transactions* 103(1): 634-643.

Peitsman, H.C., and L.L. Soethout. 1997. ARX models and real-time model-based diagnosis. *ASHRAE Transactions* 103(1): 657-671.

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

Stylianou, M. 1997. Application of classification functions to chiller fault detection and diagnosis. *ASHRAE Transactions* 103(1): 645-656.