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## Project 2.7 – Enabling Tools

## Task 2.7.4 – Results of Testing WBD Features under Controlled Conditions

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# Executive Summary

## Introduction

This report on Task 2.7.5 – Conduct Blind Test of WBD FDD Capabilities for Project 2.7 – Enabling Tools documents results from testing of the Outdoor-Air Economizer (OAE) and Whole Building Energy (WBE) diagnostic tools. These two diagnostic tools are part of the Whole Building Diagnostician (WBD). The objectives of this project were to test: 1) the automated diagnostic capabilities of the WBD diagnostic modules and 2) the ability of the Virtual Cybernetic Building Testbed (VCBT) to generate test data for both fault free and faulty operating states.

## Description of the WBD

The WBD is a production-prototype software package with two modules providing automated diagnostics for air-handling systems and energy use of major building systems (Brambley et al. 1998; and Katipamula et al. 1999). The data for the WBD are generally collected from a direct-digital control (DDC) system employed in the building. The WBD has two diagnostic modules: 1) Outdoor Air Economizer Diagnostician, and 2) Whole Building Energy Diagnostician.

The OAE module diagnoses whether air handlers in a building are supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outdoor air when it is appropriate to do so and whether the economizer is wasting energy by supplying excess outdoor air when it should not. Few, if any, sensors other than those used to control most economizers are required, making the tool practical in near-term markets because of its low installed cost.

The OAE diagnostician has five levels of detection sensitivity selectable by users. Increasing the detection sensitivity increases the ability to detect faults and decreases the rate of undetected faults (false negatives), while it also increases the probability of false alarms (i.e., false positives). Properly selecting the sensitivity setting is critical to achieve the desired balance between these factors. Because of differences in equipment among buildings and differences in preferences among users, each user can empirically adjust the sensitivity level to obtain the desired OAE performance.

The OAE alerts users to the presence of faults with results provided for each hour. Because of uncertainty in measurements and changing indoor and outdoor conditions, a given fault may or may not manifest continuously (during consecutive hours). In some cases, the fault may appear for a few hours and then may not appear again for several weeks or months. As a result, it is recommended that users ignore sporadic indications of operation problems and instead wait for the appearance of several sequential fault indicators or fault indicators occurring in a repetitive pattern over time (e.g., at 1 p.m. on every week day). In general, the ability and experience of the user plays a significant role in how the diagnostic tool is used.

The WBE module monitors variations in energy use at the whole-building or subsystem levels. It does this by tracking actual energy consumption and comparing it to estimated expected

consumption, which is provided by an empirical model that uses up to five independent variables including time of day, day of week, and weather conditions. The WBE automatically constructs the baseline model for estimating expected consumption using historical energy consumption data from the system being tracked and values for the relevant independent variables specified by the user. Using this baseline model, the WBE alerts the user when the actual measured consumption deviates significantly from the estimated expected consumption. The tool requires up to 9 months of data to build a model adequate for predicting an entire year of operation; however, useful results become available with about 6 weeks of data.

Both tools provide information to users in simple, graphical displays that indicate the presence or absence of faults at a glance. They also provide cost estimates of detected energy waste to provide feedback to users on the relative importance of the fault detected.

## Description of the VCBT and Simulation Environments

The VCBT is an emulation environment that combines simulations of a building and its heating, ventilation, and air-conditioning (HVAC) system with actual commercial controllers. It provides a way to conduct tests under a wide variety of controlled conditions and to compare the results of several different commercial products. Details of the VCBT design and operation are documented by Bushby et al. (2001). Emulation provides a test environment that is closer to a real building because it uses real building controllers. Like simulation, it also provides controlled and reproducible conditions. Because emulation is done in real time, it takes much longer than simulation, making it more difficult to test a broad range of faults and conditions in a limited time. The VCBT was used to generate data to test the OAE module. For this study, the VCBT was configured with one AHU for each of three floors, designated AHU-1, AHU-2, and AHU-3. AHU-1 and AHU-3 are variable air volume (VAV) systems, each with three VAV boxes. AHU-2 is a constant volume system, with three zone reheat coils.

As reported earlier, the WBE module requires 9 months of training data, as well as several days of data for each fault; the use of the VCBT (which runs in real time) as a testing environment was not possible. Instead, a pure computer simulation based on HVACSIM$^+$ (Park et al. 1986) and similar to the HVAC system and building shell simulation components of the VCBT was used. The model simulates one floor of an office building and its associated mechanical equipment. A single duct AHU supplies air to three zones. Each zone is served by a VAV terminal box. The AHU sensors, dampers, valves, coils, actuators, ducts, and fans, and the VAV box sensors, dampers, coils, and valves are represented by HVACSIM$^+$ component models. Most of the component models used were originally developed for an ASHRAE research project and documented by Haves and Norford (1997). For this study, the model was expanded to three floors, each of which is provided with an AHU and three VAV boxes. In addition, chiller and boiler component models were added to compute electricity and gas energy consumption data for the WBE module.

## Testing Process

Similar testing processes were used for both the OAE and WBE modules. The ability of these modules to detect and diagnose faults was tested as follows:

1. Specify system, controls and data requirements for the OAE module and the data requirements for the WBE module and list the potential faults that each module can detect.

2. Modify the VCBT and the HVACSIM$^+$ simulation to conform to the requirements.

3. Configure the WBD for the systems and controls selected.

4. Generate "clean" fault-free data.

5. Validate the "clean" data using the WBD and build baseline models for the WBE module.

6. Generate fault data for the selected systems for non-blind verification of data and the WBD.

7. Validate the WBD with the known fault data .

8. Generate fault data for the selected systems for blind tests of the WBD: 15 blind-test data sets for testing the OAE diagnostician and 4 data sets for blind testing the WBE diagnostician. The data sets for blind tests were developed by NIST without consultation with Battelle Staff.

9. Process the blind fault data with the WBD (by Battelle staff).

10. Evaluate the results of the blind tests.

## Results

The performance of the OAE diagnostician in the blind tests is presented in Table ES1. Results are presented for low, normal, and high sensitivity. Using the OAE at its low sensitivity setting, 8 of the 15 faults were correctly identified, no false positives were obtained, and 7 faults were not detected (false negatives). For the normal sensitivity setting, 11 of the 15 faults were correctly detected, no false positives were reported, and 4 faults were not detected. With the high sensitivity setting, 10 of the 15 faults were correctly identified, 2 false positives were reported, and 3 faults were not detected (false negatives). In each of the three cases, two of the false negatives were due to the conditions masking the faults so that even though the fault existed in the model, conditions were not appropriate for conditions (e.g., temperatures) to be affected by the presence of the faults.

The performance of the WBE diagnostician is presented in Table ES2. In three of the four blind trials, the WBE correctly identified anomalous energy use caused by a fault; with the single false negative (undetected problem) due to the small magnitude of the fault (this fault had an energy impact below the WBE reporting threshold of $1/day).

## Conclusions

Overall, both the OAE and WBE modules of the WBD performed quite well. The best performance of the OAE module was obtained with normal sensitivity, which is the normally recommend setting. More research is needed to provide specific guidance to users regarding 1) how to select the appropriate sensitivity settings and 2) how to interpret the results of the WBD.

The VCBT emulation and the HVACSIM$^+$ simulation were successful in generating data representing normal and faulty operations and provided data useful for testing automated diagnostic tools. Further use of these environments to complement field testing of FDD tools is justified.

**Table ES1 - Summary of Results for the OAE Module (SAT = supply-air temperature, MAT = mixed-air temperature, RAT – return-air temperature, OA = outdoor air, OAT = outdoor-air temperature)**

| | Sensitivity = Low | | Sensitivity = Normal | | Sensitivity = High | |
|---|---|---|---|---|---|---|
| Fault Instigated in VCBT | OAE Result (Fault / No fault) | OAE Correct? | OAE Result (Fault / No fault) | OAE Correct? | OAE Result (Fault / No fault) | OAE Correct? |
| SAT sensor drift | No fault | False negative | No fault | False negative | No fault | False negative |
| Fault Free | No fault | Correct | No fault | Correct | No fault | Correct |
| MAT sensor failure | Fault | Correct | Fault | Correct | Fault | Correct |
| Recirculation damper leakage | Fault | Correct | Fault | Correct | Fault | Correct |
| Fault free | No fault | Correct | No fault | Correct | Fault | False positive |
| RAT sensor drift | No fault | False negative[1] | No fault | False negative[1] | No fault | False negative[1] |
| OAT sensor failure | Fault | Correct | Fault | Correct | Fault | Correct |
| RAT sensor drift | No fault | False negative[1] | No fault | False negative[1] | No fault | False negative[1] |
| OA damper stuck at minimum | No fault | False negative | Fault | Correct | Fault | Correct |
| MAT sensor drift | Fault | Correct | Fault | Correct | Fault | Correct |
| Fault free | No fault | Correct | No fault | Correct | Fault | False positive |
| Recirculation damper leakage | No fault | False negative | Fault | Correct | Fault | Correct |
| SAT sensor failure | No fault | False negative | No fault | False negative | Fault | Correct |
| Economizer control logic fault | Fault | Correct | Fault | Correct | Fault | Correct |
| RAT sensor drift | No fault | False negative | Fault | Correct | Fault | Correct |

[1] The presence of the fault was masked by the conditions.

**Table ES2 - Summary of Results for the WBE module.**

| Fault Instigated in Simulation | WBE Result (Fault / No Fault) | Correct? |
|---|---|---|
| 10% increase in HVAC electricity consumption | No fault | False negative[1] |
| 15% increase in boiler gas consumption | Fault | Correct |
| Scheduling problem – same internal loads weekdays and weekends | Fault | Correct |
| Progressively developing increase in chiller electrical energy consumption | Fault | Correct |

[1] The false negative was due to the small magnitude of the fault (faults resulting in impacts of less than $1/day are below the WBE reporting threshold.

# 1 Introduction

The last decade has seen a tremendous growth and interest in the development of methodologies to detect and to diagnose performance degradation and faults in building systems (Katipamula et al. 2000). However, only a few fault detection and diagnostic (FDD) systems developed actually have been deployed in the field. Most of the development, testing and prototyping of FDD systems, with a few exceptions, has been limited to work in research laboratories and universities.

The Whole Building Diagnostician (WBD) has been one notable exception to this. It has been tested at a number of sites throughout the western U.S. In Project 2.4 of this program, it is currently being tested in three use scenarios: 1) use by the operation staff of a single, large, office building; 2) use by the staff managing a collection of office buildings; and 3) use by a heating ventilation and air-conditioning (HVAC) service provider. These field tests have been useful to verify the success of the WBD in detecting actual building operation problems and to demonstrate the value of the WBD, but because many uncontrolled variables exist in real operation, they do not provide controlled tests of the WBD. This project is intended to provide testing of the WBD under controlled conditions, while also providing an opportunity to demonstrate the value of the National Institute for Standards and Technology's (NIST's) Virtual Cybernetic Building Testbed (VCBT) and fault detection and diagnostics (FDD) test shell in testing automated diagnostic tools like the WBD.

The objectives of this project were to test: 1) the automated diagnostic capabilities of WBD diagnostic modules and 2) the ability of the VCBT and FDD test shell to generate test data for both fault free and faulty operating states. In this report, the results for testing of the WBD modules on data corresponding to faulty operation are presented. The data were generated under controlled conditions at NIST.

The WBD is a production-prototype software package with two modules providing automated diagnostics for air-handling systems and energy use of major building systems (Brambley et al. 1998; and Katipamula et al. 1999). The data for the WBD are generally collected from a direct-digital control (DDC) system employed in the building. The WBD has two diagnostic modules: 1) Outdoor Air Economizer diagnostician (OAE), and 2) Whole Building Energy Diagnostician (WBE).

The OAE module diagnoses whether air handlers in a building are supplying adequate outdoor air for the occupants it is designed to serve, by time of day and day of week. It also determines whether the economizer is providing free cooling with outdoor air whenever it is appropriate to do so and not wasting energy by supplying excess outdoor air when it should not. Few, if any, sensors other than those used to control most economizers are required, making the tool practical in near-term markets because of its low installed cost.

The WBE module monitors variations in energy use at the whole-building or subsystem levels. It does this by tracking actual consumption and comparing it to estimated expected consumption, which is modeled as a function of up to five independent variables including time of day, day of

week, and weather conditions. The WBE automatically constructs a baseline model for estimating expected consumption using historical energy consumption data from the system being tracked and values for the relevant independent variables specified by the user. Using this baseline model, the WBE alerts the user when the actual measured consumption deviates significantly from the estimated expected consumption. The tool requires up to 9 months of data to build a model adequate to predict an entire year of operation; however, useful results become available with about 6 weeks of data.

Both tools provide information to users in simple, graphical displays that indicate the presence or absence of faults at a glance. They also provide cost estimates of detected energy waste to provide feedback to users on the relative importance of the faults detected.

This document provides a summary and background on the WBD and its modules, a brief description of the plan for testing, the evaluation process and the results for the blind tests. In Section 2, the various steps in the testing process are outlined, followed by Section 3, which provides a description of the evaluation process, followed by the WBD test plan in Section 4. The data generation process in the VCBT environment is described in Section 5. The results from blind tests of the OAE on data for air-handling units (AHUs) are provided in Section 6, followed by the results from blind tests of the WBE in Section 7. The results from the diagnostic modules are summarized and compared with actual faults instigated by NIST in Section 8. The conclusions and recommendations are provided in Section 9, and a list of references is provided in Section 10.

# 2 Testing Process

The process that was used to test the diagnostic capabilities of the two WBD modules (OAE and WBE) was:

1. Battelle specified the capabilities of the WBD diagnostic modules and provided NIST with lists of possible faults for the two modules.

2. NIST made the necessary modifications to the VCBT simulation engine and the HVACSIM$^+$ (Park et al. 1986) simulation models (the latter used to generate data for the WBE module) to generate fault-free data.

3. Battelle validated the fault-free data for AHUs from NIST by processing it with the OAE module. This ensured that the OAE showed that the data being generated was as specified and that the OAE module was properly configured with the type of controls being used in the VCBT and the sensor accuracies and thresholds properly specified.

4. NIST also generated 12 months of fault-free end-use data for training the WBE module. A reference model for each end-use being monitored was built using this fault-free training data.

5. NIST then generated three data sets with known faults for non-blind tests of the OAE module. The data sets spanned periods of 1 week. These data sets were used to further calibrate the OAE configuration parameters and to ensure that the OAE was properly configured to distinguish the faults. This process also validated the ability of the VCBT to generate data for faulty operation as specified.

6. NIST also generated end-use consumption data corresponding to known faults. This data was then used for non-blind tests of the WBE module.

7. NIST then generated data corresponding to faulty operations for the two WBD modules. The faults were selected by NIST and were unknown to Battelle so that testing would be blind.

8. The data sets for faulty operations were automatically processed by Battelle using the two diagnostic modules with no knowledge of what faults, if any, were represented in the data sets, and results were sent to NIST for evaluation.

# 3 Evaluation Process

The evaluation process used to test the automated diagnostic capabilities of the two WBD modules is described in this section. The data sets representing faulty operations were generated by NIST using the VCBT/FDD test shell. These data sets were processed in an automated way similar to how a building operator or a building manager would use the tool. In addition to the automated processing, the data from AHUs were also processed using semi-automated graphical routines outside the WBD that were developed for advanced users. These graphical routines provide additional details not provided directly by the WBD.[1] The various steps of the evaluation process are:

1. First, the "faulty" data sets were processed with the WBE and OAE modules.

2. Selected AHU data sets were processed using semi-automated graphical routines.

3. The results from automated and semi-automated analysis were summarized, tabulated, and reported to NIST.

4. NIST compared the faults identified by the WBE and the OAE to the faults actually introduced.

5. If the identified faults did not match the actual, the cause of the difference was identified jointly by NIST and Battelle.

6. Finally, the ability of the two modules to detect the faults was summarized by Battelle.

[1] They also represent additional diagnostics, which could be added to the tools in the future.

# 4 WBD Test Plan

This section specifies how the team planned to verify the data from the VCBT and describes the general requirements for the test data and limitations of the two diagnostic modules.

## *4.1 VCBT Validation Plan*

One of the primary objectives of this work was to verify the capability of VCBT to generate both fault-free data and data from faulty operations. Therefore, before the OAE and the WBE modules process the simulated data from faulty operations, the data from the VCBT and the simulation models (for WBE) must be verified and validated. To a large extent, the validation can be accomplished by using graphical tools to view the raw data from the VCBT and the simulation models.

### 4.1.1 VCBT Validation Process

The process to test the ability of the VCBT to generate fault-free data and data corresponding to faulty operations was:

1. Specify system, controls and data requirements for the OAE (Battelle).

2. List the faults that the OAE can detect and diagnose (Battelle).

3. Modify the VCBT as needed to provide the measured data required for the OAE module (NIST).

4. Modify the VCBT to emulate one AHU with a constant air-volume system (NIST).

5. Pick one or more economizer-control strategies (NIST).

6. Generate “clean” fault-free data for the selected AHUs and economizer-control strategies. Preferably, the data should span all operating modes of the AHU (heating, cooling, economizing only, and economizing with cooling) (NIST).

7. Validate the “clean” data using the WBD and the OAE modules (Battelle).

8. Pick a list of faults that will be used in the blind tests (NIST).

9. Modify the VCBT to provide data corresponding to faulty operation (NIST).

10. Generate data with faulty operations for the selected systems (NIST).

11. Validate the raw data from faulty operations through the use of graphical tools (NIST and Battelle).

## *4.2 OAE Plan*

To detect and diagnose the faults with ventilation and economizer operations of an AHU, all data listed in the data requirements section are needed. In addition, the OAE must be properly configured to identify the type of AHU and the type of economizer controls employed.

### 4.2.1 Selection of Systems

As mentioned earlier, the OAE module is capable of detecting and diagnosing faults with constant-air volume (CAV) systems and variable-air volume (VAV) systems that do not meter the outdoor-air-flow rate (i.e., the intake). Therefore, for the blind tests, NIST selected three air-handling systems with one being a CAV system, and the other two VAV systems. The OAE has been designed primarily to detect and diagnose faults with constant-volume built-up systems and constant-volume packaged roof-top units. If a VAV system is selected, the outdoor-air flow must be ensured to float with the supply-air flow rate (i.e., the outdoor-air flow is not metered).

### 4.2.2 Selection of Economizer Controls

Again, as mentioned earlier, the OAE module can detect faults with almost all commonly found economizer-control strategies, such as, high-limit (dry-bulb temperature or enthalpy), or differential (dry-bulb temperature or enthalpy). For the test, NIST picked one air handler with high-limit dry-bulb-temperature control, and the other two systems with differential enthalpy economizer control strategies.

### 4.2.3 Generation of Fault-Free Data for the OAE Module

First, NIST generated “clean” fault-free data for all AHUs selected. The data was to preferably span all operating modes (heating, cooling, economizing only, economizing and cooling). The “clean” data without faults was processed using the OAE; this enabled verification of the configuration parameters, the dead bands, the sensitivities set in the OAE, and enabled ensuring that the data from the VCBT/FDD test shell was as expected. Once the “clean” data from the AHUs was validated using the OAE, the OAE was ready to accept the faulty data for the blind tests.

### 4.2.4 Generation of Faulty Data for the OAE Module

The OAE module can detect and diagnose a number of faults with ventilation and economizer operations of an AHU. Because blind tests with a number of different faults were created for testing the OAE’s detection and diagnostic capabilities, the data from the blind tests were stored in separate databases, each database representing a single (fault-free or faulty) blind test. As mentioned earlier, some faults take several hours, days and sometimes even months to manifest themselves. Therefore, faulty operation was to persist for the entire period of data collection for each blind test. The length of faulty operation was to be sufficiently long for the fault to manifest.

If an AHU has simultaneous multiple faults (i.e., more than one fault at a time), the OAE module will detect a problem, but may not be able to diagnose the causes of more than one fault simultaneously. Therefore, it was preferable not to have simultaneous multiple faults for the majority of the blind tests; this limitation was already known.

### 4.2.5 OAE Testing Process

The ability of the OAE to detect and diagnose faults was tested as follows:

11. Specify system, controls and data requirements for the OAE (Battelle).

12. List the potential faults that the OAE can detect and diagnose (Battelle).

13. Modify the VCBT to provide the measured data required for the OAE module (NIST).

14. Implement modifications to the VCBT so that one of the AHUs emulated is a CAV system (NIST).

15. Pick one or more economizer control strategies (preferably one of them based on high-limit dry-bulb temperature) (NIST).

16. Configure the WBD for the systems and controls selected (Battelle).

17. Generate "clean" fault-free data for the selected AHUs and economizer-control strategies. Preferably, the data should span all operating modes of the AHU (heating, cooling, economizing only, and economizing with cooling) (NIST).

18. Validate the "clean" data using the WBD and the OAE modules (Battelle).

19. Pick a list of faults to be used in the blind test (NIST).

20. Modify the VCBT to provide the "faulty data" (NIST).

21. Generate fault data for the selected systems (NIST).

22. Process the fault data with the OAE (Battelle).

23. Evaluate the results (Battelle/NIST).

## *4.3 WBE Test Plan*

Unlike the OAE module, the WBE operates independently of the details of the building systems and control strategies. The WBE can detect abnormal energy end-use consumption cause by improper or faulty operations, and more than one fault can cause the abnormal energy consumption. The current version of the WBE is limited to monitoring four end-uses at a time. As the VCBT is an emulator, it generates data in real time. Given this limitation, it would take a significant amount of time for the VCBT to generate the necessary training data (6 to 9 months) for the WBE. Therefore, it was decided that the test data (both training and "faulty data") would be generated using an HVACSIM$^{+}$ simulation (based on the simulation models used in the VCBT without the emulation elements).

### 4.3.1 Generation of Fault-Free Data for the WBE Module

First, NIST generated "clean" fault-free data for all energy end-uses selected. The data covered 12 months, so that it spanned all operating modes (heating, cooling, economizing only, and economizing with cooling). The "clean" data without faults was processed using the WBE; this enabled verification of the configuration parameters and the sensitivity settings of the WBE, and also ensured that the data from the simulation models were as expected. In addition, the "clean" data was used by the WBE to empirically develop the baseline reference models. Once the fault-free data for each end-use was validated and baseline models developed, the WBE was ready to accept "faulty data" for the blind tests.

### 4.3.2 Generation of Data for Faulty Operation for the WBE Tests

The WBE module can detect a number of faults with energy end-uses. Unlike the blind test data for the OAE module, all data for blind tests of the WBE were stored in a single database, because the reference models were common to all faults.

As mentioned earlier, the WBE processes hourly data, but generates the Energy Consumption Indexes (ECIs) at daily intervals. Therefore, unless the faults or deviations in the energy consumption occur over several hours within a day, the WBE may not detect them (depending on the magnitude of the energy impacts of those faults and the sensitivity setting of the WBE). A fault with gradual degradation in performance or gradual increase or decrease in energy end-use was created.

### 4.3.3 WBE Testing Process

The process to test the ability of the simulation models to generate fault-free data and "faulty data" and the ability of the WBE to detect faults was accomplished as follows:

1. Specify data requirements for the WBE (Battelle).

2. List the potential faults the WBE can detect (Battelle).

3. Modify the HVACSIM$^+$ simulation to provide the measured data required for the WBE module (NIST).

4. Configure the WBD to the systems selected (Battelle).

5. Generate twelve months of "clean" fault-free data for the selected end-uses. Preferably, the data was to span all operating modes of the AHU (heating, cooling, economizing only, and economizing with cooling).

6. Validate the "clean" data using the WBD and also build baseline models for the selected end-uses (Battelle).

7. Pick a list of faults that will be used in the blind tests (NIST).

8. Modify the simulation to provide the data corresponding to faulty behavior (NIST).

9. Generate data with faulty operation for the selected end-uses (NIST).

10. Process the data for faulty operation with the WBE (Battelle).

11. Evaluate the results (Battelle/NIST).

# 5 Data Generation

## 5.1 Data Generation for the OAE Module

The Virtual Cybernetic Building Testbed (VCBT) is an emulation environment that combines simulations of a building and its HVAC system with the actual commercial controllers. It provides a way to conduct tests under a wide variety of carefully controlled conditions and to compare the results of several different commercial products. Details of the VCBT design and operation are documented by Bushby et al. (2001). Emulation provides a test environment that is closer to a real building because it uses real building controllers but, like simulation, it also provides carefully controlled and reproducible conditions. Because emulation is done in real time, it takes much longer than simulation, making it more difficult to test a broad range of faults and conditions in a limited time.

For this study, the VCBT was configured with one AHU for each of the three floors, designated AHU-1, AHU-2, and AHU-3. AHU-1 and AHU-3 are VAV systems, each with three VAV boxes. AHU-2 is a constant volume system, with three zone reheat coils.

## 5.2 Control Strategies AHU-1

### 5.2.1 Fan Control

The supply-air fan speed is controlled to maintain the supply-air pressure at a fixed supply-air pressure set point. The return-air fan speed is controlled to maintain a constant difference between the supply- and return-air flow rates.

### 5.2.2 Temperature Control

AHU-1 uses a single proportional integral (PI) control loop to determine a temperature control signal to maintain the supply-air temperature at a fixed supply-air temperature set point. Depending on the magnitude of the signal, it is mapped to one of three outputs, which control the heating coil, cooling coil, or mixing-box dampers. Logical interlocks set the position of the other two outputs appropriately depending on which one is active. For example, if the heating coil valve is active, the cooling coil valve will be fully closed and the mixing-box damper will be set to the minimum position (which depends on the occupancy status). The outdoor-air and the return-air enthalpies are compared to determine whether to enable or disable economizer operation.

## 5.3 Control Strategies AHU-2

### 5.3.1 Fan Control

AHU-2 is a constant volume system, so the supply-air fan and return-air fan both operate at fixed speeds.

### 5.3.2 Temperature Control

AHU-2 uses a single PI control loop to determine a temperature control signal to maintain the supply-air temperature at a fixed supply-air temperature set point. Depending on the magnitude of the signal, it is mapped to one of three outputs, which control the heating coil, cooling coil, or mixing-box dampers. Logical interlocks set the position of the other two outputs appropriately depending on which one is active. For example, if the heating coil valve is active, the cooling coil valve will be fully closed and the mixing-box damper will be set to the minimum position (which depends on the occupancy status). The outdoor-air temperature is compared to a fixed changeover temperature to determine whether to enable or disable economizer operation.

## *5.4 Control Strategies AHU -3*

### 5.4.1 Fan Control

The supply-air fan speed is controlled to maintain the supply-air pressure at a fixed supply-air pressure set point. The return-air fan speed is controlled to maintain a constant difference between the supply-air and return-air flow rates.

### 5.4.2 Temperature Control

AHU-3 uses a separate PI control loop for each of three outputs which control the supply-air temperature: the heating coil, cooling coil, and mixing-box dampers. The heating coil and cooling coil outputs are controlled to maintain supply-air temperature at a fixed supply-air temperature set point. The mixing box dampers are controlled by comparing the outside-air and the return-air enthalpies. If the return-air enthalpy is greater than the outdoor-air enthalpy, the mixing-box damper control loop maintains mixed-air temperature at its set point (also fixed). Interlocks, dead bands, and time delays are incorporated to prevent undesirable simultaneous heating, cooling, and economizing.

## *5.5 Normal Operation*

Data from a 3-week fault-free emulation using swing season (October) weather data are presented to highlight normal operation.

Figure 1 and show temperature and control signal data, respectively from AHU-2 on day 4 of the 21-day emulation. During the early part of the day, the outdoor-air temperature (green, Figure 1) is low, as is the outdoor-air enthalpy (not shown). At this time, the economizer (green, Figure 2) is fully open, bringing in 100 % outdoor air. As the day progresses, the outdoor-air temperature and enthalpy increase, so that at some point the condition is no longer favorable for economizing. When this happens, the economizer goes from fully open to 20 % open (the minimum position for ventilation). Throughout the day, the cooling coil (blue, Figure 3) modulates to maintain the supply-air temperature (light blue, Figure 1) at the supply-air temperature set point (dark blue, Figure 1).

Figure 3 show temperature and control signal data, respectively, from AHU-2 on day 8 of the 21 day emulation. During the early part of the day, the outdoor-air temperature (green, Figure 3) is low, as is the outdoor-air enthalpy (not shown). At this time, the economizer (green, Figure 4) modulates to maintain the supply-air temperature (light blue, Figure 3) at the supply-air temperature set point (dark blue, Figure 3). As the day progresses, the outdoor-air temperature

and enthalpy increase, so that the economizer must open further and further to maintain the supply-air temperature at the set point. At some point, the economizer saturates at the fully open position, and the cooling coil (blue, Figure 4) opens and modulates to maintain the supply-air temperature at the set point.

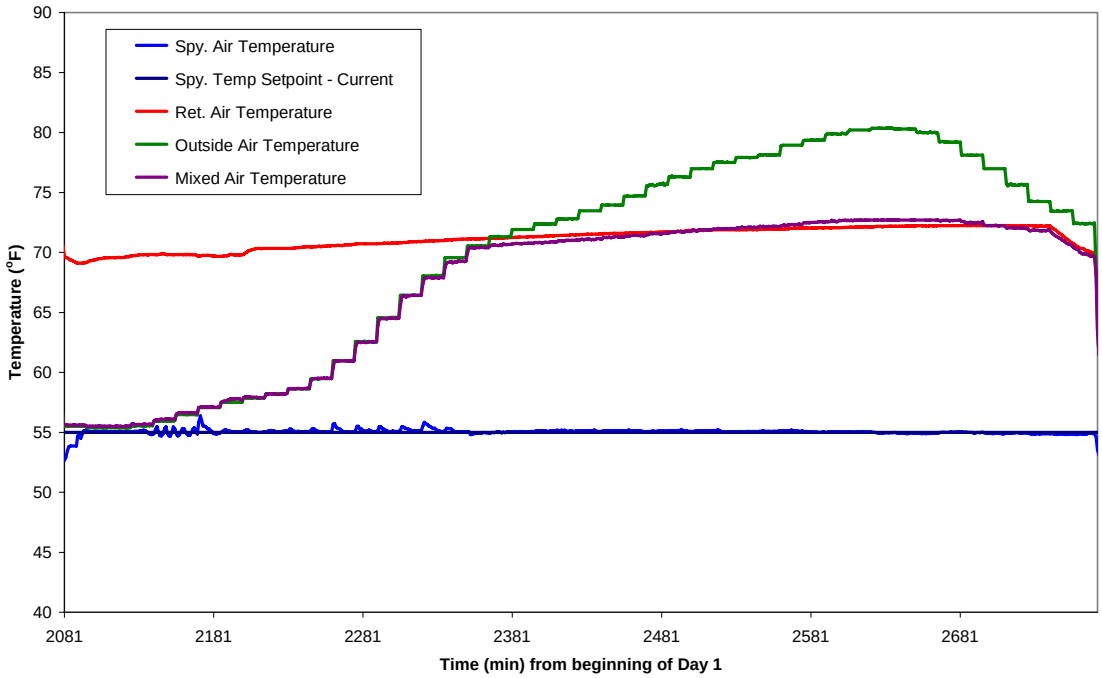



**Figure 1 – VCBT AHU-2 Temperatures Representing Normal Operations (Swing Season Day 4)**

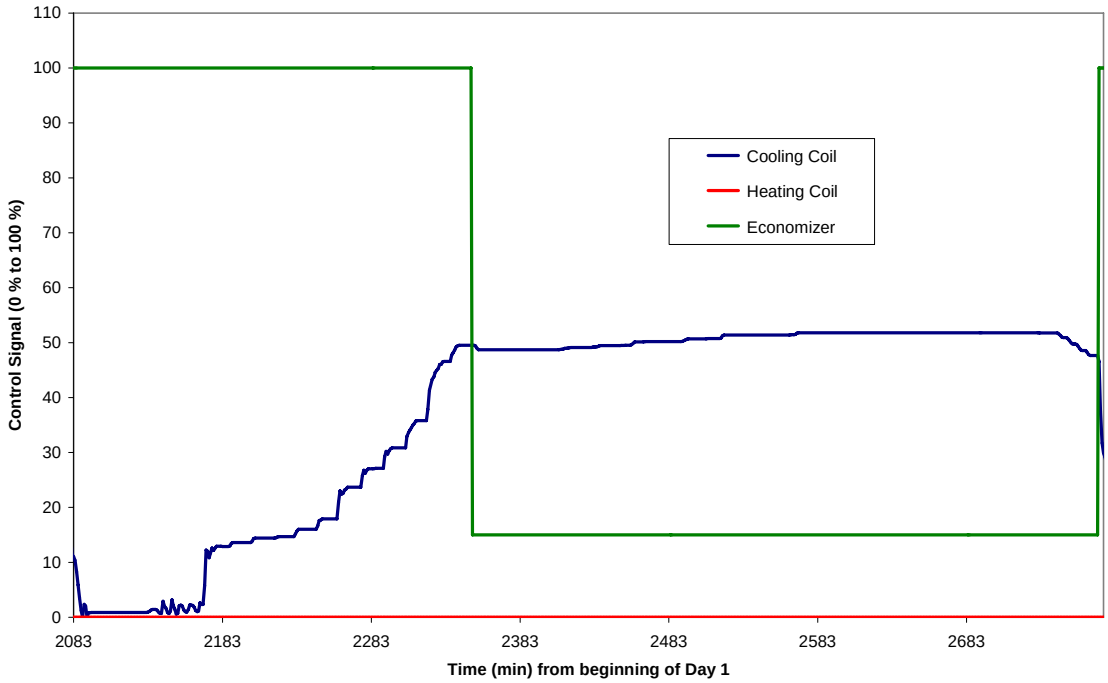



**Figure 2 – VCBT AHU-2 Control Signals Representing Normal Operations (Swing Season Day 4)**

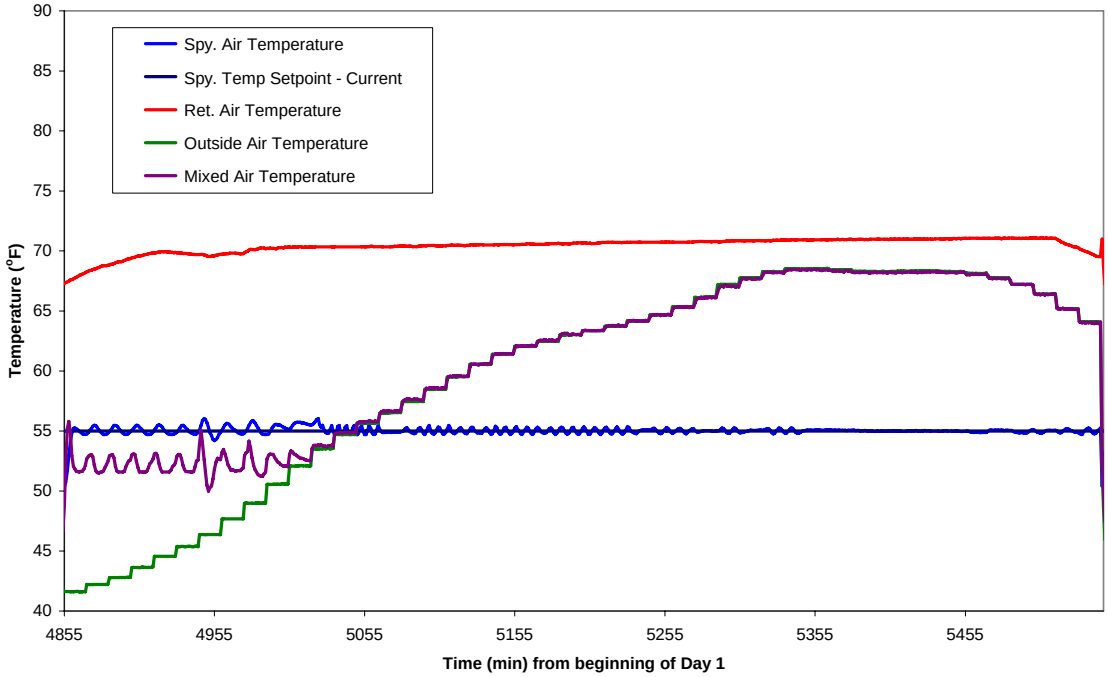



**Figure 3 – VCBT AHU-2 Temperatures Representing Normal Operations (Swing Season Day 8)**

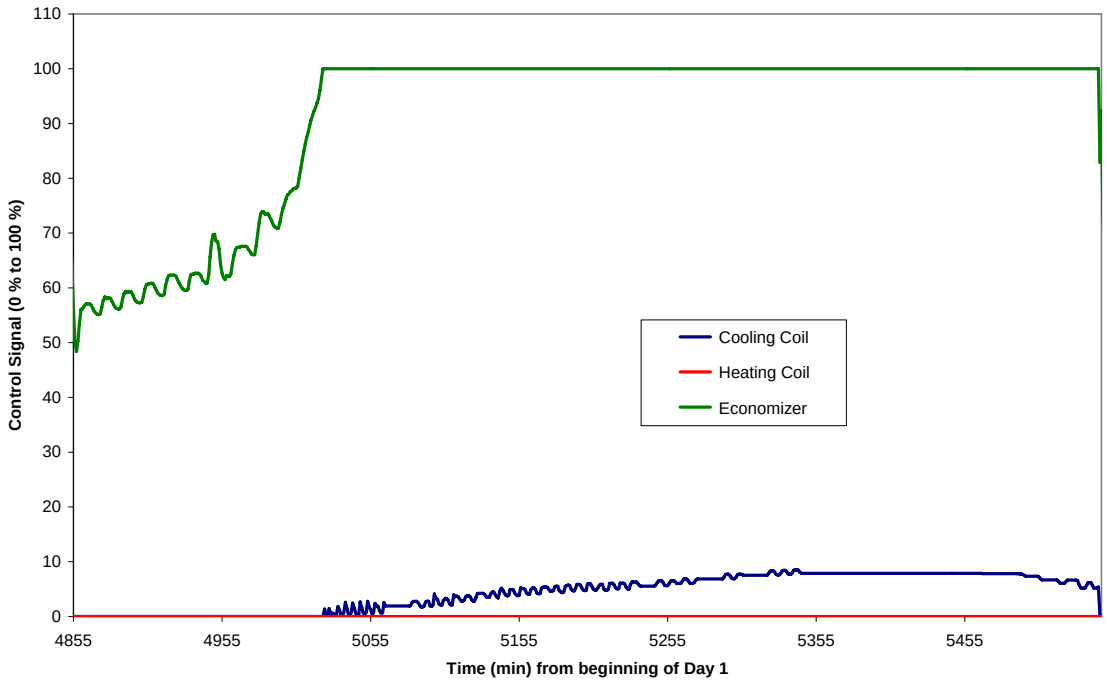



**Figure 4 – VCBT AHU-2 Control Signal Representing Normal Operation (Swing Season Day 8)**

## *5.6 Faulty Operation*

The following faults were included in the blind tests of the OAE module.

### 5.6.1 Supply Air Temperature Sensor Drift

This fault is introduced as a sensor offset beginning at 0 ºF and increasing linearly over a three week emulation period to +7 ºF. The positive sensor drift means that the measured supply-air temperature is greater than the actual supply-air temperature by the amount of the offset.

Figure 5 and Figure 6 show AHU-1 data from the occupied portion of 1 day during the emulation of this fault. On this particular day, the outdoor-air temperature (green, Figure 5) and humidity (not shown) are low enough to permit economizing, so the mixing box dampers (green, Figure 6) are modulated to maintain the supply-air temperature (light blue, Figure 5) at its set point (dark blue, Figure 5). The effects of this fault are easily observed on this day, as the cooling coil (blue, Figure 6) and heating coil (red, Figure 6) are closed. Under these conditions, the supply and mixed-air temperatures should be equal (with a small difference caused by the temperature rise across the supply fan), but in fact the supply-air temperature (light blue, Figure 5) is nearly 4 $^{o}$C less than the mixed-air temperature (purple, Figure 5). Because the AHU controller maintains the supply-air temperature at the supply-air temperature set point (dark blue, Figure 5), the fault causes an increase in actual supply-air temperature.

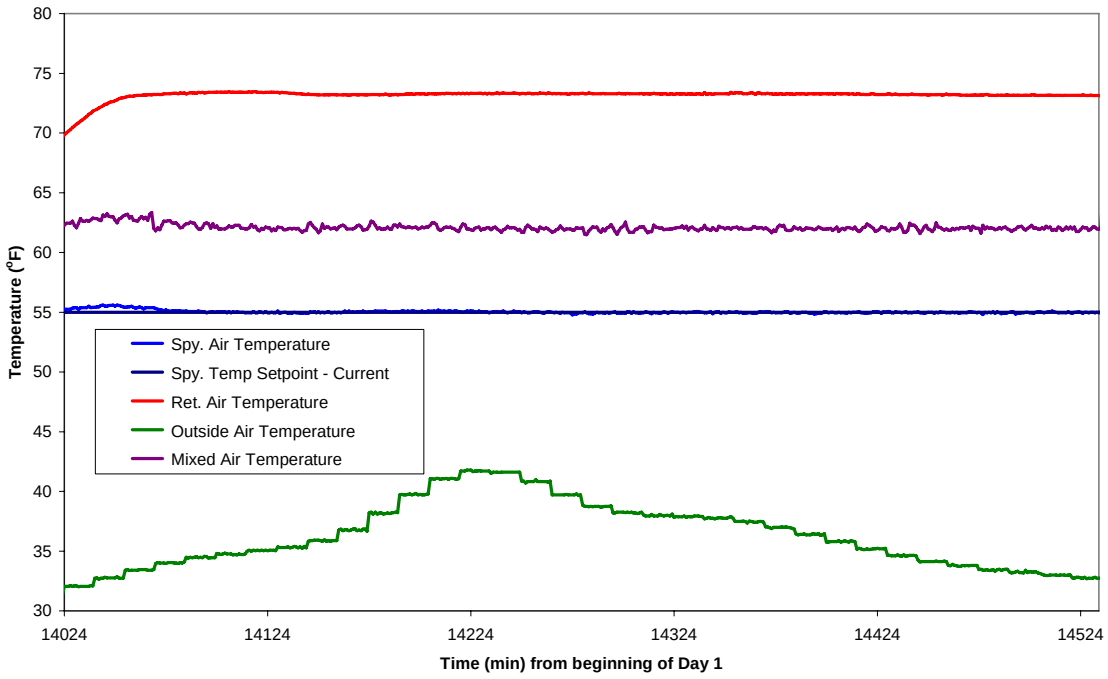



**Figure 5 – VCBT AHU-1 Temperatures for Supply-Air Temperature Sensor Drift Fault (Heating Season Day 21)**

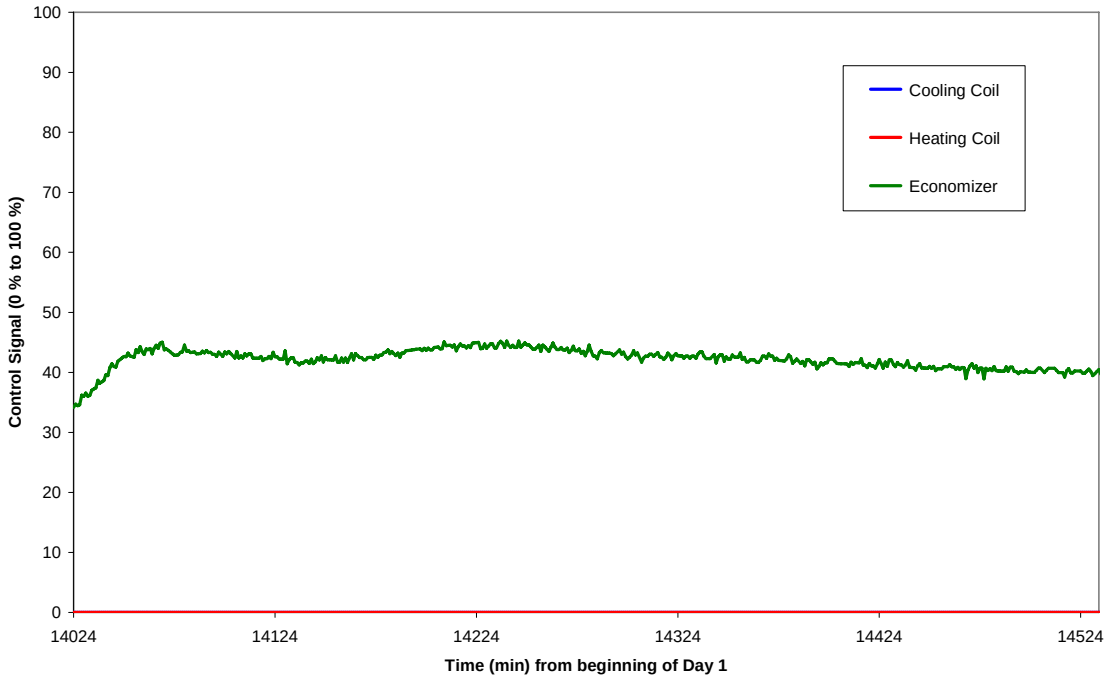



**Figure 6 – VCBT AHU-1 Control Signals for Supply-Air Temperature Sensor Drift Fault (Heating Season Day 21)**

### 5.6.2 Mixed-Air Temperature Sensor Drift

This fault is introduced as a sensor offset beginning at 0 ºF and increasing linearly over a 3 week emulation period to +7 ºF. The positive sensor drift means that the measured mixed-air temperature is greater than the actual mixed-air temperature by the amount of the offset.

Figure 7 and Figure 8 show AHU-3 data from the occupied portion of 1 day during the emulation of this fault. On this particular day, the outdoor-air temperature (green, Figure 7) and humidity (not shown) are high enough to prohibit economizing, so the mixing-box dampers (green, Figure 8) are aligned to bring in the minimum amount of outdoor-air needed for ventilation. The actual mixed-air temperature is between the return-air and outdoor-air temperatures, because it is the result of blending the outdoor-air and return-air streams. However, because of the sensor drift, the measured mixed-air temperature is below the return-air temperature by approximately 5.4 °F.

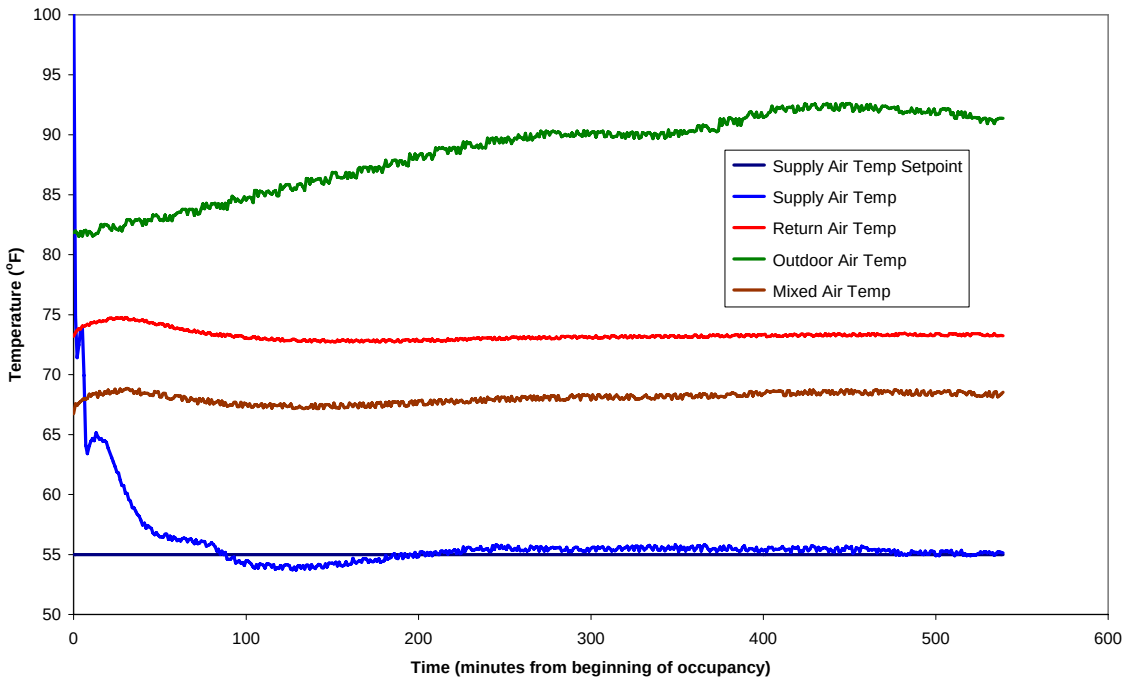



**Figure 7 – VCBT AHU-3 Temperatures for Mixed-Air Temperature Sensor Drift Fault (Cooling Season Data)**

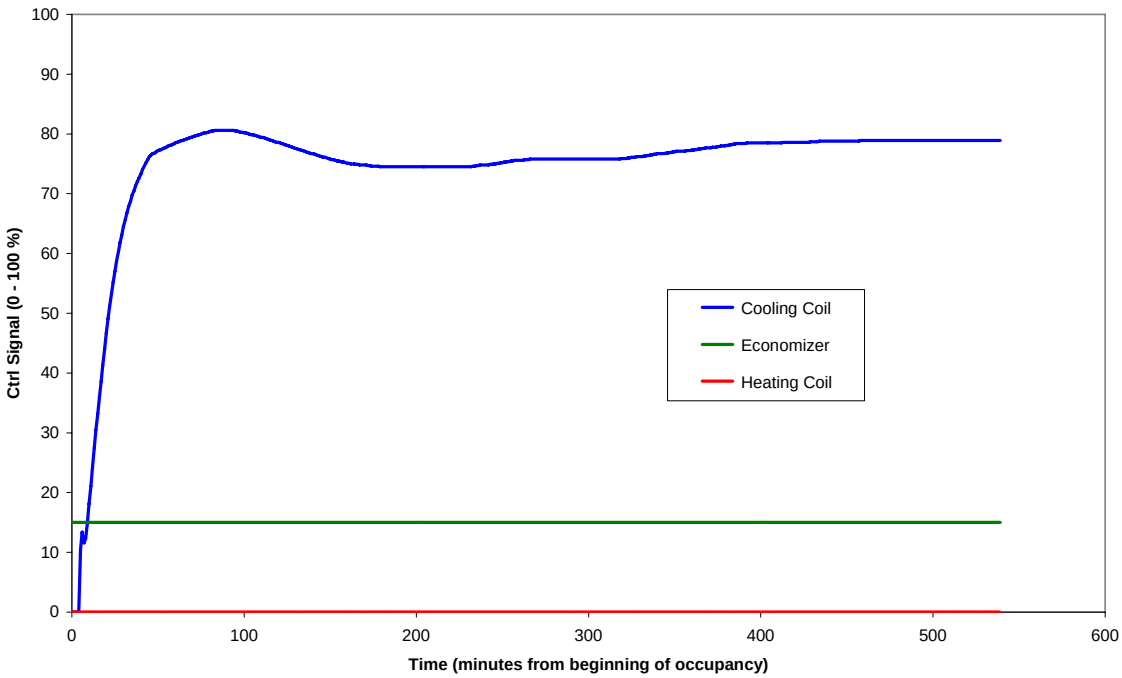



**Figure 8 – VCBT AHU-3 Control Signals for Mixed-Air Temperature Sensor Drift Fault (Cooling Season Data)**

### 5.6.3 Return Air Temperature Sensor Drift

This fault is introduced as a sensor offset beginning at 0 ºF and increasing linearly over a 3 week emulation period to +7 ºF. The positive sensor drift means that the measured return-air temperature is greater than the actual return-air temperature by the amount of the offset.

Figure 9 and Figure 10 show AHU-3 data from the occupied portion of 1 day during the emulation of this fault. On this particular day, the outdoor-air temperature (green, Figure 9) and humidity (not shown) are high enough to prohibit economizing, so the mixing-box dampers (green, Figure 10) are aligned to bring in the minimum amount of outdoor air needed for ventilation. The mixed-air temperature is between the actual return-air and outdoor-air temperatures, because it is the result of blending the outdoor-air and return-air streams. However, because of the sensor drift, the mixed-air temperature is below the measured return-air temperature by approximately 5.8 °F.

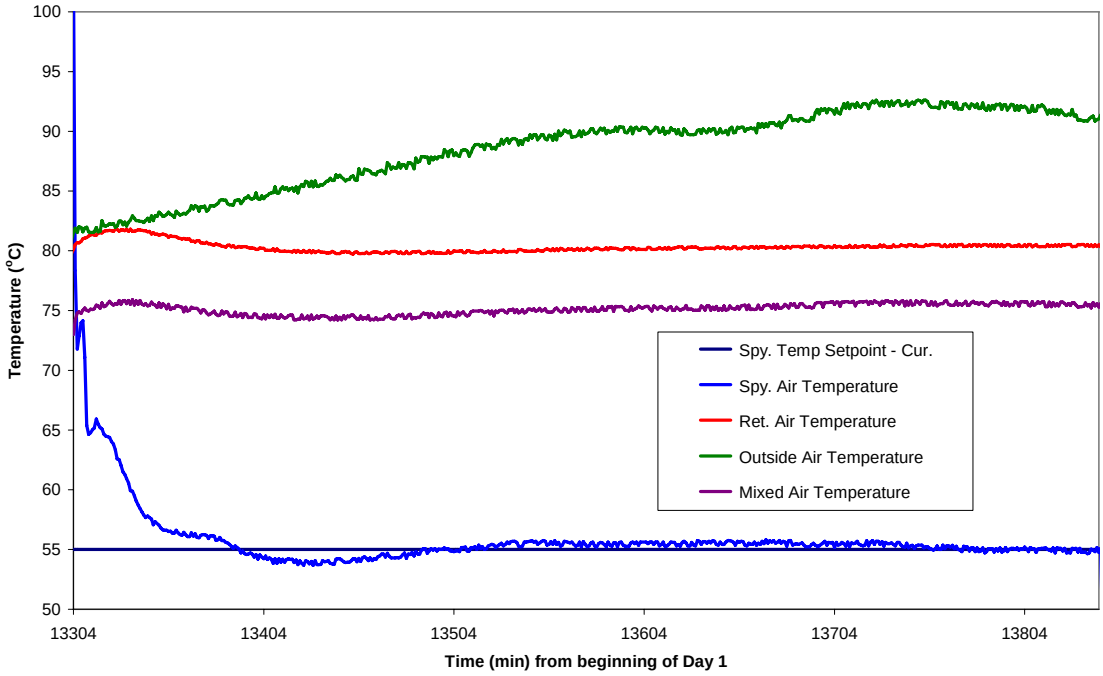



**Figure 9 – VCBT AHU-3 Temperatures for Return-Air Temperature Sensor Drift Fault (Cooling Season Day 21)**

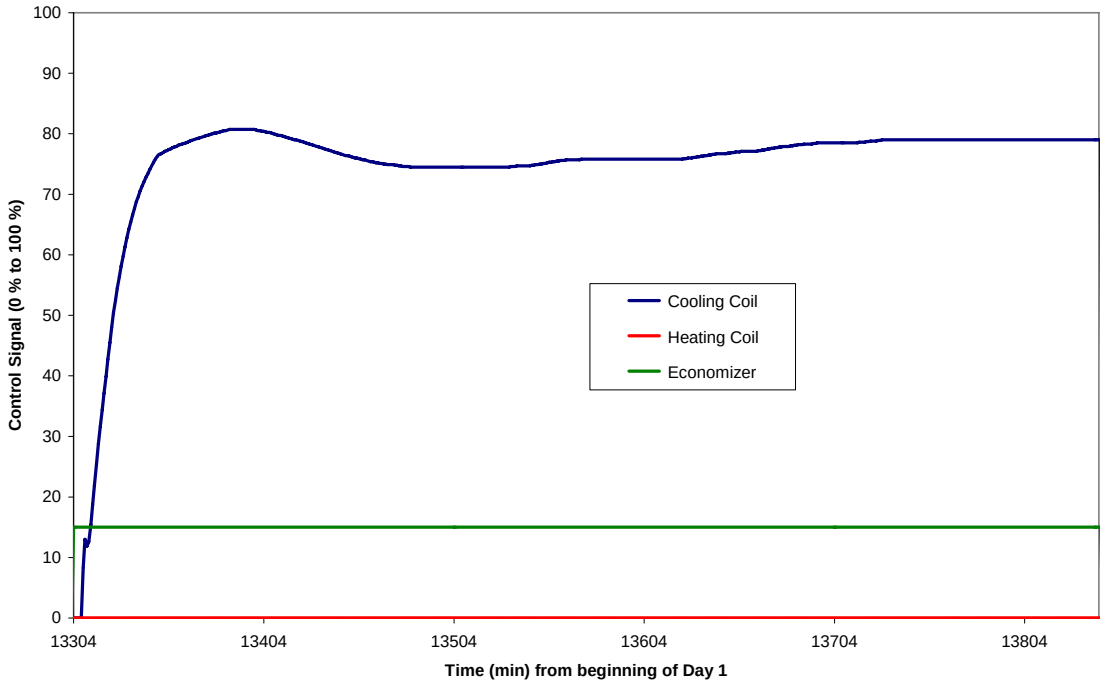



**Figure 10 – VCBT AHU-3 Control Signal for Return-Air Temperature Sensor Drift Fault (Cooling Season Day 21)**

### 5.6.4 Supply-Air Temperature Sensor Failure

This fault was introduced by sending a 10 VDC (volts direct current) signal to the terminal leads on the AHU-1 controller on which the supply-air temperature sensor was connected. This is a 0 to 10 VDC analog input calibrated to a range of 0 °F to 150 °F, so the 10 VDC signal is scaled to a supply-air temperature of 150 °F.

When this fault is introduced, the controller reads a supply-air temperature (light blue, Figure 11) of 150 °F, which is well above the supply-air temperature set point (dark blue, Figure 11) of 55 °F. The temperature control PID (proportional integral differential) loop in the AHU controller responds by opening the cooling coil valve (blue, Figure 12) until it saturates.

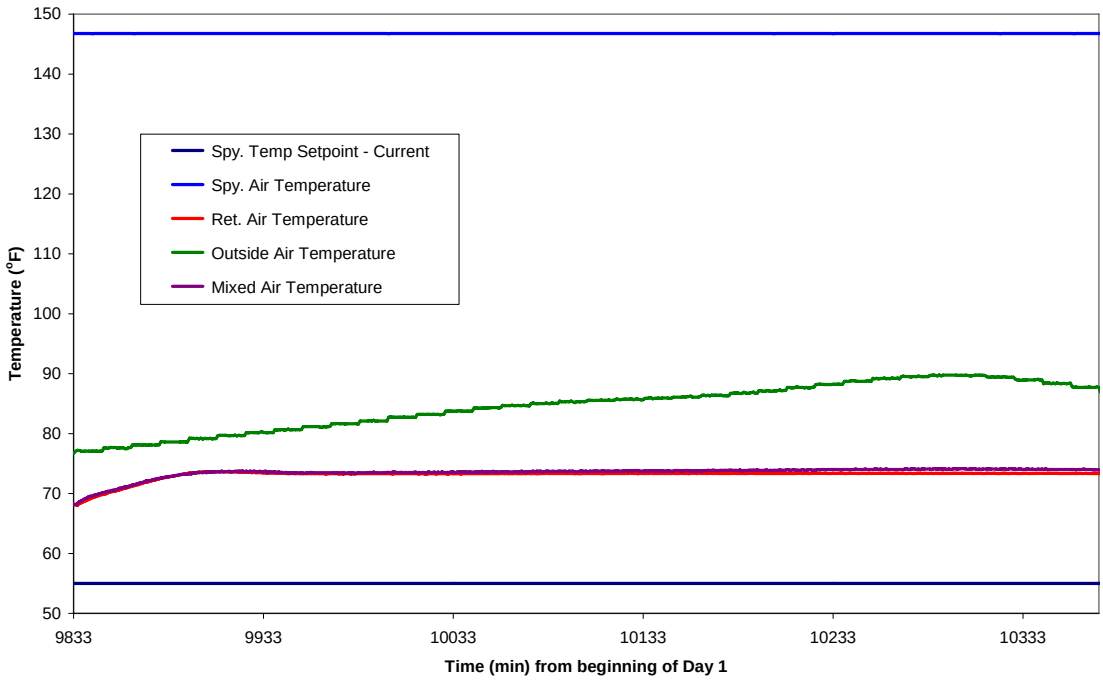



**Figure 11 – VCBT AHU-1 Temperatures for Supply-Air Temperature Sensor Failure Fault (Cooling Season Day 15)**

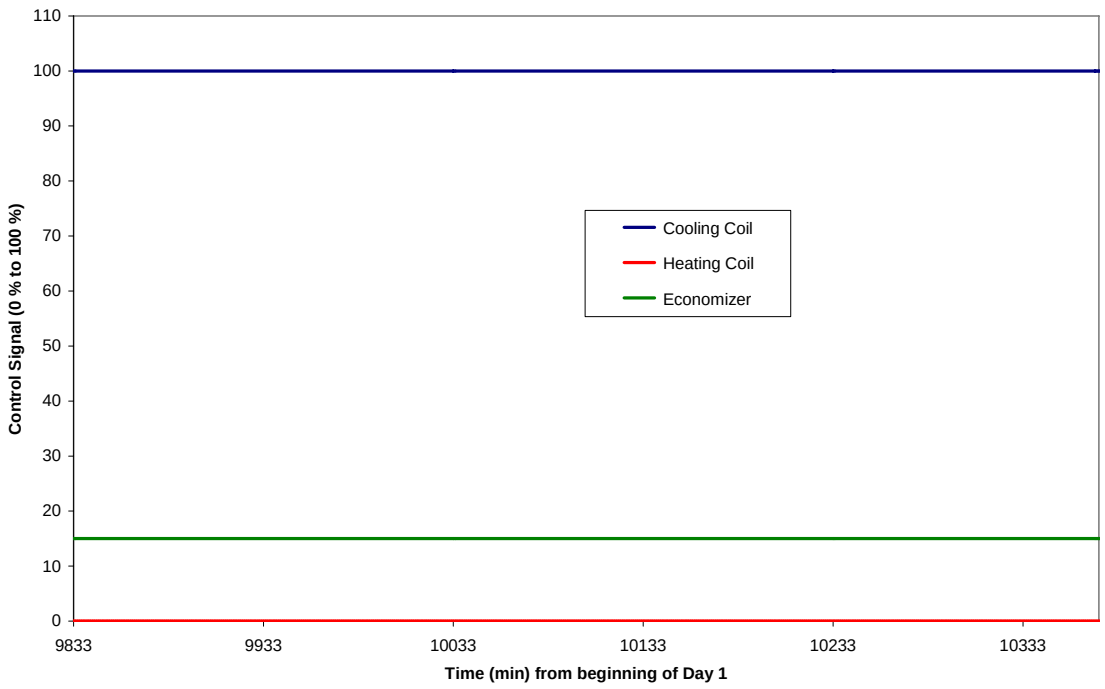



**Figure 12 – VCBT AHU-1 Control Signals for Supply-Air Temperature Sensor Fault (Cooling Season Day 15)**

### 5.6.5 Mixed-Air Temperature Sensor Failure

This fault was introduced by subtracting a large offset from the actual mixed-air temperature and sending the 0 to 10 VDC signal to the terminals on the AHU-3 controller on which the mixed-air temperature sensor was connected. In this case, the fault is introduced during heating season, when the economizer dampers blend the outdoor air and return air to maintain the mixed-air temperature at its set point. When this fault is introduced, the controller reads a very low mixed-air temperature (green, Figure 13), causing the mixed-air temperature control PID loop to respond by closing the economizer dampers (green, Figure 14) to the minimum position. The heating coil valve (red, Figure 14) and cooling coil valve (blue, Figure 14) temperature control PID loops both use supply-air temperature (light blue, Figure 13) as the controlled value, so both valves stay closed.

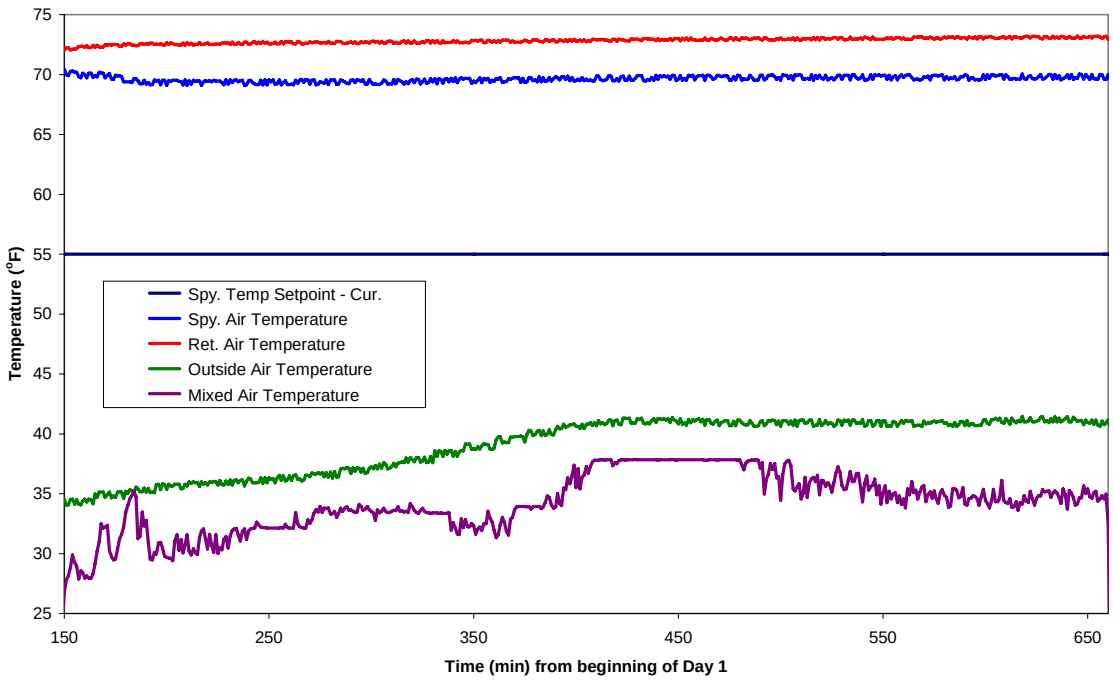



**Figure 13 – VCBT AHU-1 Temperatures for Mixed-Air Temperature Sensor Failure (Cooling Season Day 21)**

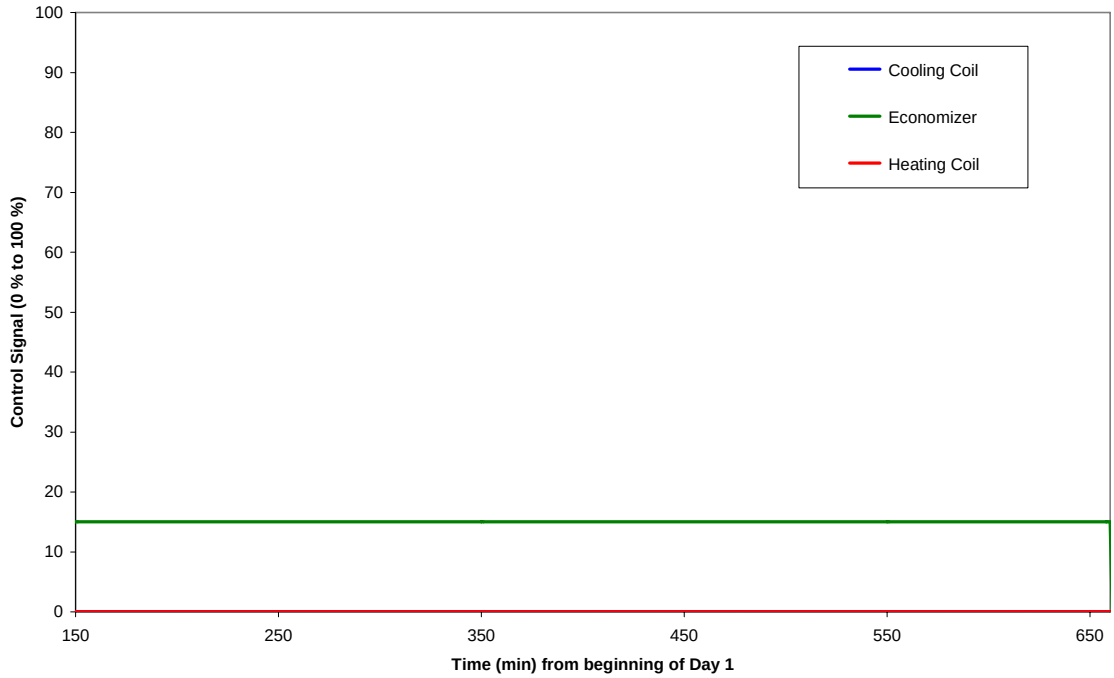



**Figure 14 – VCBT AHU-3 Control Signals for Mixed-Air Temperature Sensor Fault (Heating Season Day 1). Both the heating and cooling controls signals are zero for the entire time period.**

### 5.6.6 Outdoor-Air Temperature Sensor Failure

This fault was introduced by disconnecting the leads to the terminals on the AHU-1 controller on which the outdoor-air temperature sensor was connected. This is a 0 to 10 VDC analog input calibrated to a range of 20 °F to 120 °F, so with the leads disconnected, the controller reads 0 VDC, which is scaled to an outdoor-air temperature of 20 °F.

When this fault is introduced, the controller reads an outdoor-air temperature of 20 °F. The logic in the controller calculates outdoor-air enthalpy based on outdoor-air temperature and outdoor-air humidity, so the erroneously low reading of outdoor-air temperature will result in an erroneously low calculated value of outdoor-air enthalpy. The AHU-1 controller compares the calculated value of outdoor-air enthalpy to return-air enthalpy (calculated in a similar fashion based on return-air temperature and return-air humidity) and enables economizer operation if the outdoor-air enthalpy is less than the return-air enthalpy. The erroneously low calculated value of outdoor-air enthalpy will cause the controller to enable economizer operation, even if such operation is inappropriate.

Because the actual outdoor-air temperature is greater than the supply-air temperature set point, the mixing box dampers (green, Figure 15) will saturate at the 100 % outdoor air position, and the AHU controller will modulate the cooling coil valve (blue, Figure 16) to maintain the supply-air temperature at its set point. The heating coil valve (red, Figure 16) is closed.

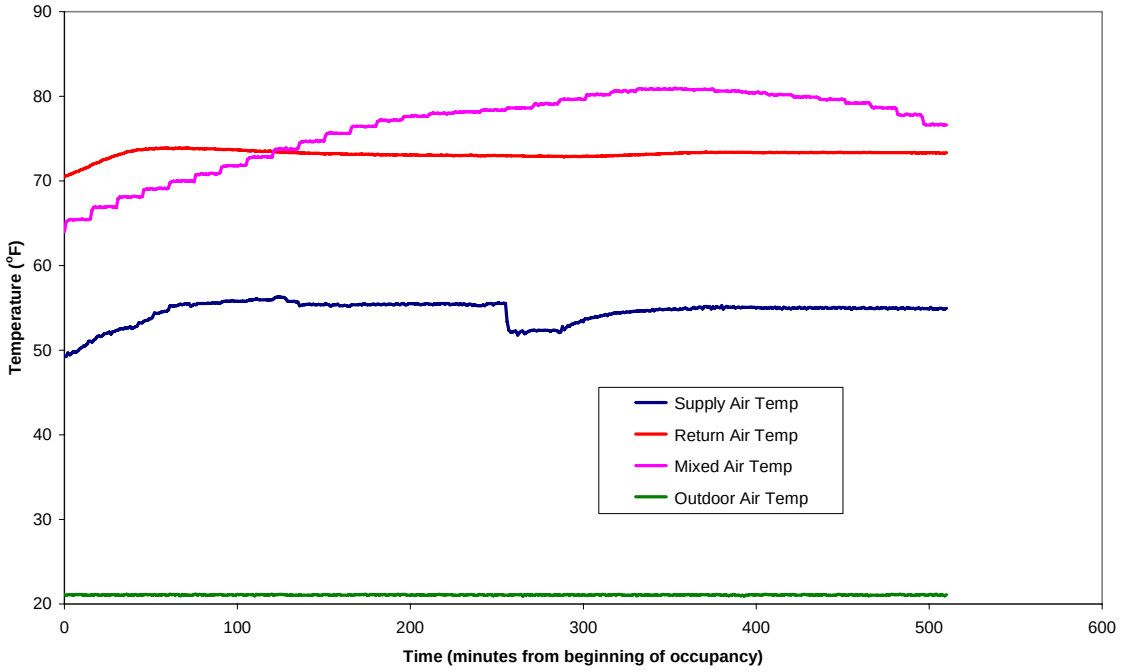



**Figure 15 – VCBT AHU-3 Temperatures for Outdoor-Air Temperature Sensor Fault (Swing Season Data)**

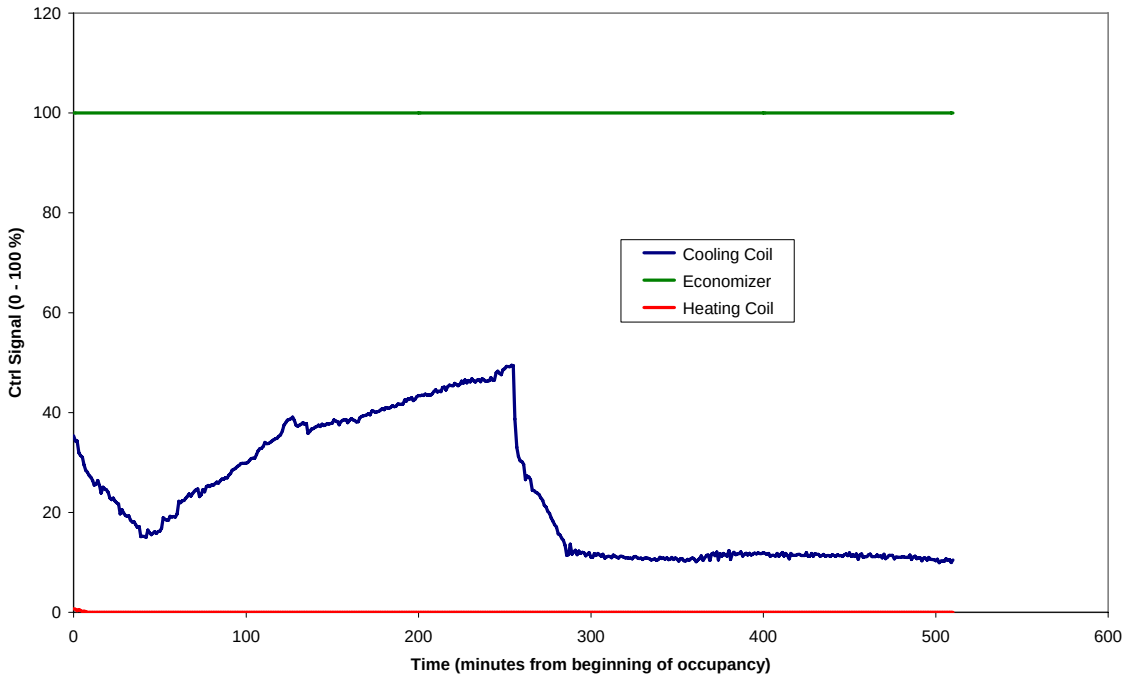



**Figure 16 – VCBT AHU-3 Control Signals for Outdoor-Air Temperature Sensor Fault (Swing Season Data)**

### 5.6.7 Recirculation Damper Leakage

When this fault is introduced, the AHU controller calculates the desired position of the damper and sets the damper control signal normally. If the damper control signal is less than 40 %, the damper position is set to the 40 % open position within the emulation. During emulation of this fault, the outdoor-air and exhaust-air dampers follow normal operation.

On this particular day, the outdoor-air temperature (green, Figure 17) and humidity (not shown) are low enough to permit economizing, and the mixing box dampers (green, Figure 18) saturate at 100 % open and the cooling coil valve (blue, Figure 18) is modulated to maintain the supply-air temperature (light blue, Figure 17) at its set point (dark blue, Figure 18). Under these conditions, the recirculation damper would normally be set to 0 % open (fully closed), but because of the leakage fault, some recirculation flow occurs. The qualitative effect of the leaking recirculation damper can be seen by comparing the mixed-air temperature (brown, Figure 17) to the return (red, Figure 17) and outdoor-air temperatures. If the dampers were aligned correctly, the mixed-air temperature should be very close to the outdoor-air temperature, but it is actually somewhere between the return-air temperature and the outdoor-air temperature, because of the return-air leaking through the recirculation damper.

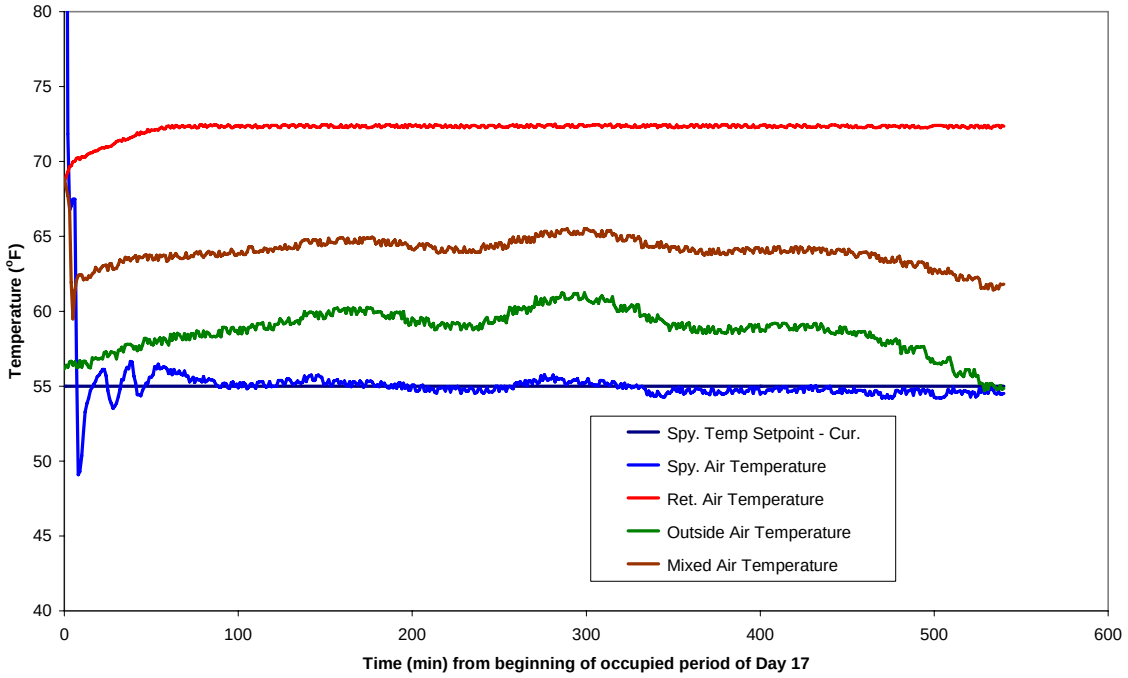



**Figure 17 – VCBT AHU-3 Temperatures for Recirculation-Air (return-air) Damper Leakage Fault (Swing Season Day 17)**

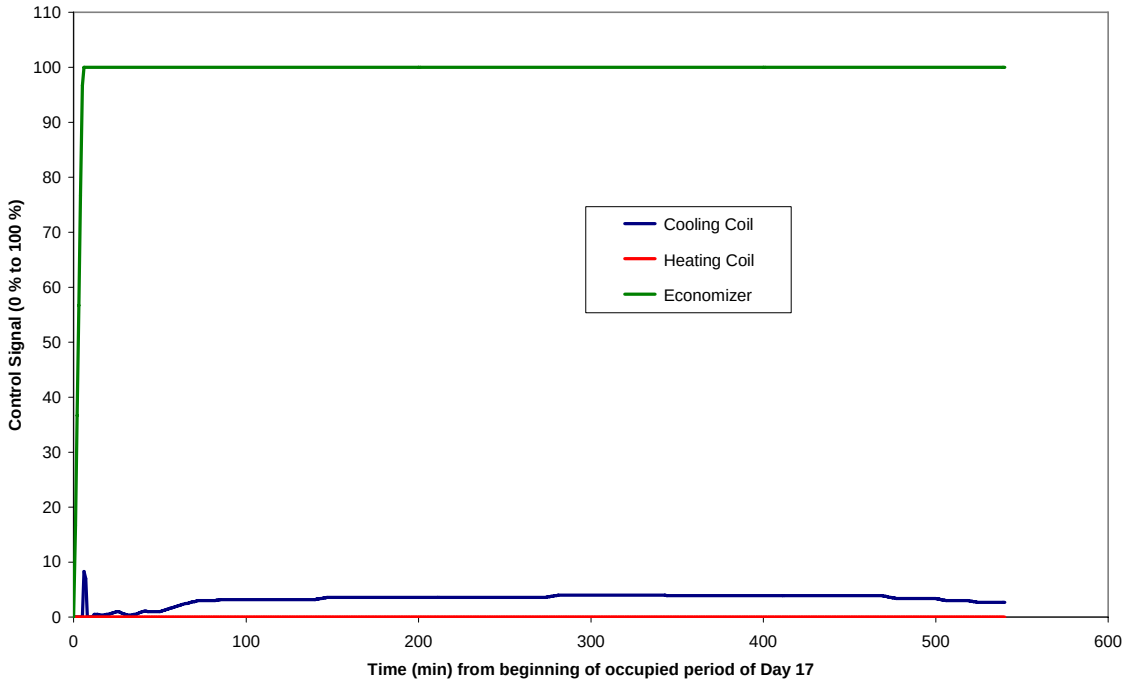



**Figure 18 – VCBT AHU-3 Control Signals for Recirculation-Air (return-air) Damper Leakage Fault (Swing Season Day 17)**

### 5.6.8 Stuck Outdoor-Air Damper

When this fault is introduced, the emulation overrides the outdoor-air damper control signal from the AHU and sets the position of the outdoor-air damper to the minimum position for ventilation (15 % open). During emulation of this fault, the outdoor-air and exhaust-air dampers follow normal operation.

On this particular day, the outdoor-air temperature (green, Figure 19) and humidity (not shown) are low enough to permit economizing, and the mixing box dampers (green, Figure 20) saturate at 100 % open and the cooling coil valve (blue, Figure 20) is modulated to maintain the supply-air temperature (light blue, Figure 19) at its set point (dark blue, Figure 19). Because of the fault, the actual percentage of outdoor air is much less than the 100 % indicated by the damper control signal. This can be seen qualitatively by comparing the mixed-air temperature (purple, Figure 19) to the return (red, Figure 20) and outdoor-air temperatures. If the outdoor-air damper were set as intended, the mixed-air temperature would be the same as the outdoor-air temperature, but it is actually somewhere between the outdoor-air temperature and the return-air temperature.

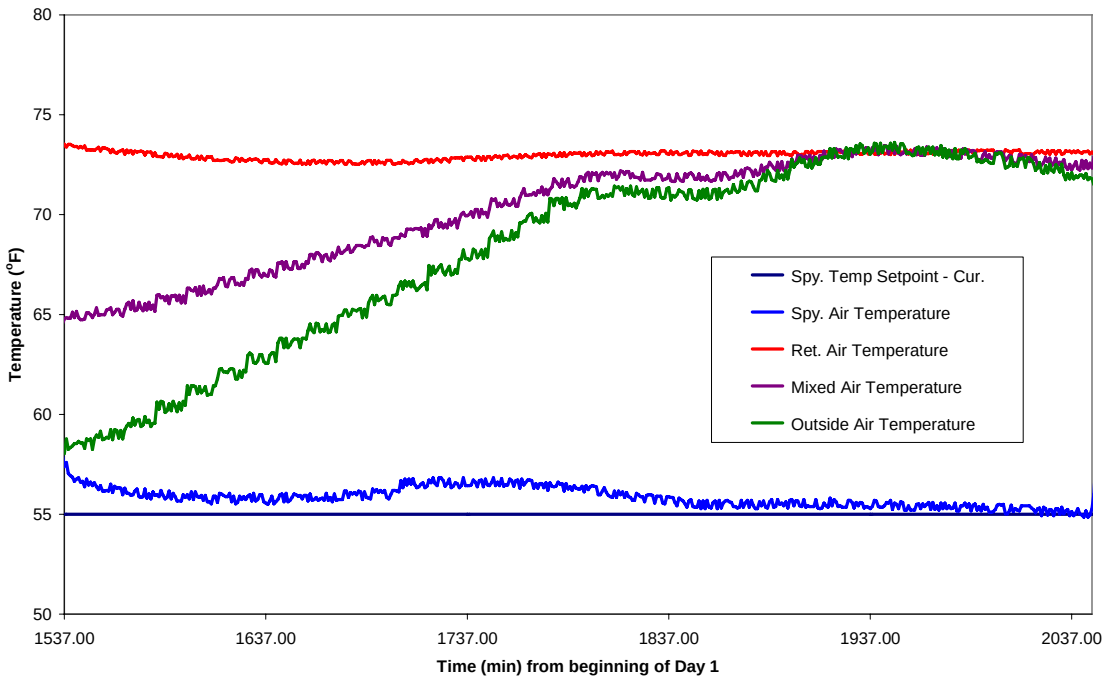



**Figure 19 – VCBT AHU-3 Temperatures for Stuck Outdoor-Air Damper Fault (Swing Season Day 3)**

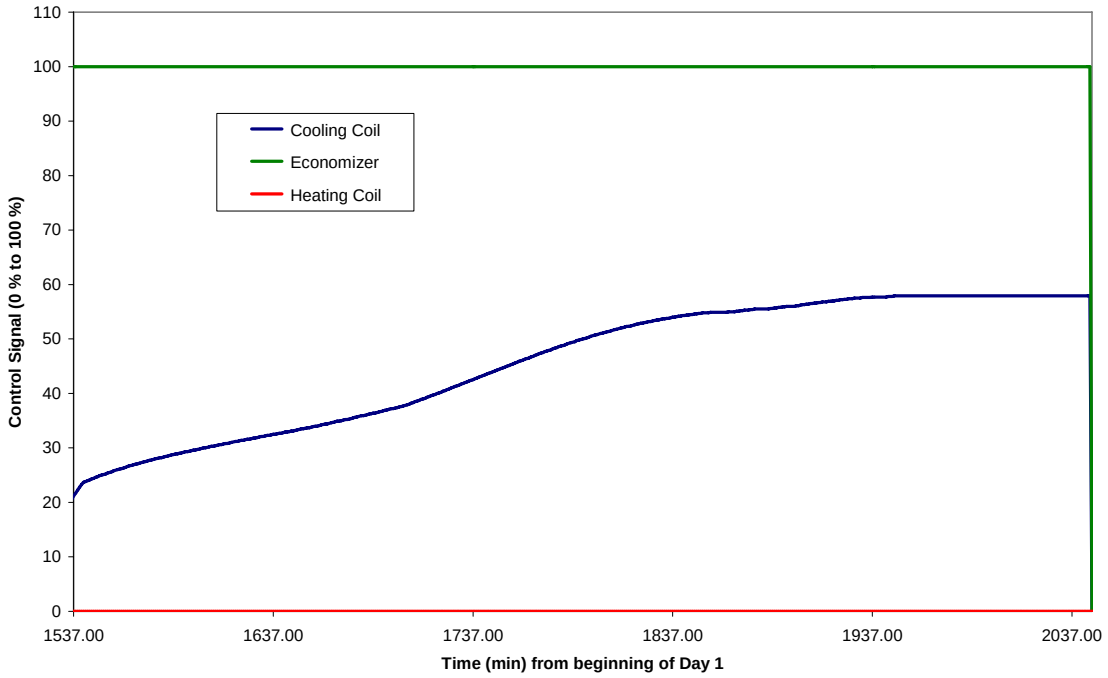



**Figure 20 – VCBT AHU-3 Control Signals for Stuck Outdoor-Air Damper Fault (Swing Season Day 3)**

### 5.6.9 Economizer Control Logic Fault

When this fault is introduced, the logic used to select economizer or minimum ventilation operation is reversed. The AHU-2 controller compares the outdoor-air temperature to a fixed changeover temperature, 72 °F, to determine whether to enable or disable economizer operation. Normally, economizer operation is disabled if the outdoor-air temperature is greater than the changeover temperature and enabled if the outdoor-air temperature is less than the changeover temperature, subject to a specified deadband, 2.0 °F. When the economizer fault is implemented, this relationship is reversed: economizer operation is enabled if the outdoor-air temperature is greater than the changeover temperature and disabled if the outdoor-air temperature is less than the changeover temperature, still subject to the specified deadband.

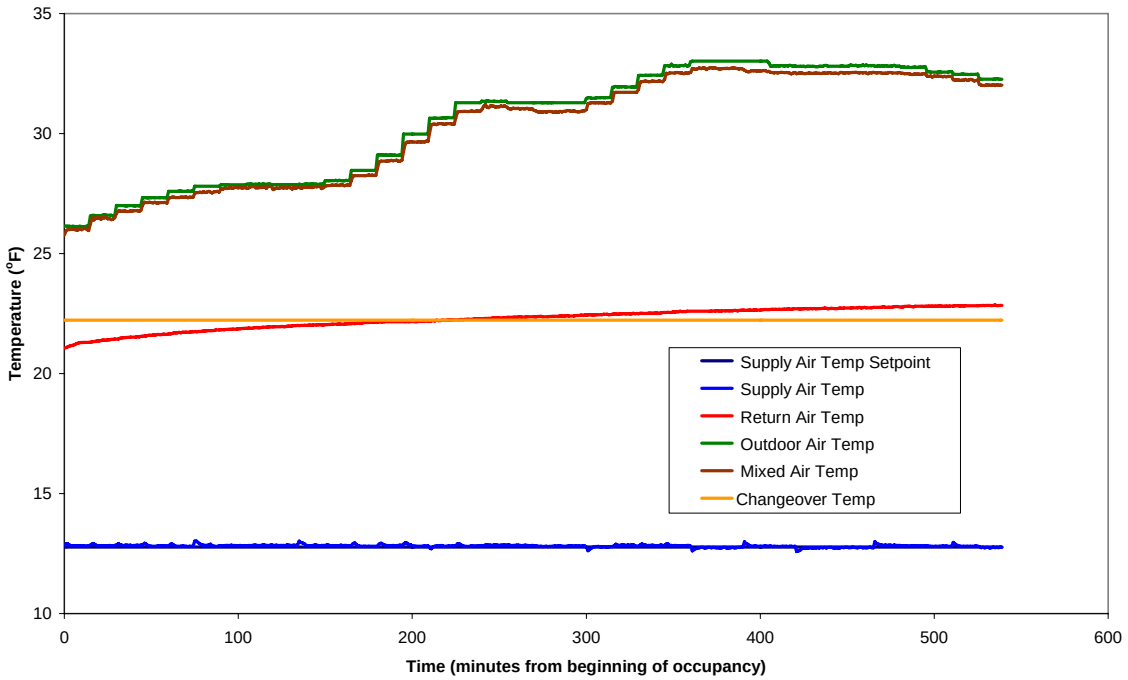



**Figure 21 – VCBT AHU-2 Temperatures for Economizer Control Logic Fault (Cooling Season Data)**

Figure 20 and Figure 21 show data from AHU-2 from the occupied portion of 1 day during the emulation of this fault. On this particular day, the outdoor-air temperature (green, Figure 20) ranges from 79 °F to 91 °F, which is greater than the changeover temperature (orange, Figure 20) by more than the deadband as is typically the case for cooling season. If AHU-2 was operating without any faults, these conditions would cause the AHU controller to disable the economizer and align the mixing box dampers to bring in the minimum amount of outdoor air needed for ventilation. Because of the control logic fault, the mixing box dampers (green, Figure 21) are actually aligned to bring in 100% outdoor air. Qualitatively, this can be seen by comparing the mixed-air temperature (brown, Figure 21) to the return (red, Figure 21) and outdoor-air temperatures (green, Figure 21). If the dampers were aligned for minimum outdoor-air, the mixed-air temperature would be very close to the return-air temperature, but actually the mixed-air temperature is nearly identical to the outdoor-air temperature, because the fault in the AHU control logic has positioned the dampers to bring in 100% outdoor air.

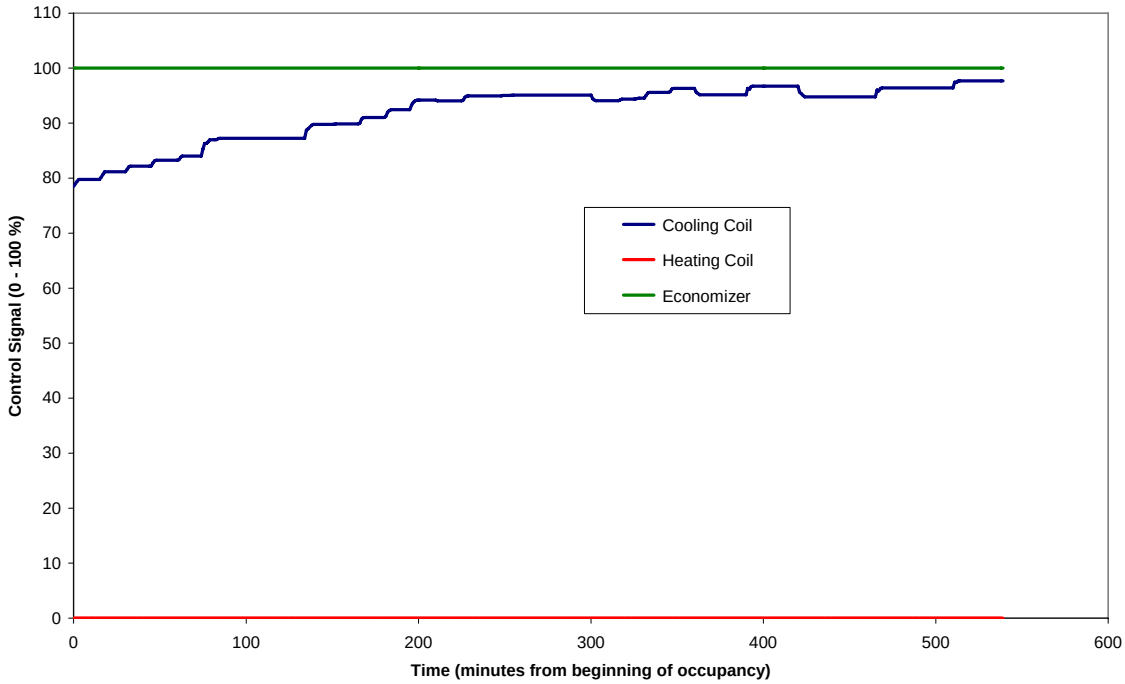



**Figure 22 – VCBT AHU-2 Control Signals for Economizer Control Logic Fault (Cooling Season Data)**

## *5.7 Data Generation for the WBE Module*

The WBE module requires 9 months of training data, as well as several months of data for each fault; the use of the VCBT (which runs in real time) as a testing environment was not possible. Instead, a pure computer-simulation based on HVACSIM$^+$ was used, similar to the HVAC system and building shell simulation components of the VCBT.

The model simulates one floor of an office building and its associated mechanical equipment. A single duct AHU supplies air to three zones. Each zone is served by a variable-air-volume (VAV) terminal box. The AHU dampers, valves, coils, actuators, ducts, and fans, and the VAV box dampers, coils, and valves are represented by HVACSIM$^+$ component models. In addition, all sensors are represented by HVACSIM$^+$ component models. Most of component models used were originally developed for an ASHRAE research project and documented by Haves and Norford (1997).

For this study, the model was expanded to three floors, each of which is provided with an AHU and three VAV boxes as described above. In addition, chiller and boiler component models were added to compute electricity and gas energy consumption data for the WBE module.

## *5.8 Control Strategies*

### 5.8.1 VAV Box

A pressure dependent VAV box control strategy is used. Two zone temperature set points, a heating set point (HSP) and a cooling set point (CSP), are defined (CSP > HSP). When the zone

temperature is between the two set points, the VAV box damper is set at its minimum position for ventilation and the VAV box reheat coil valve is closed. If the zone temperature rises above the CSP, the damper is opened proportionally. If the zone temperature falls below the CSP, the reheat coil valve is opened proportionally.

### 5.8.2 AHU Fan Control

The supply-air fan speed is controlled to maintain the supply-air pressure at a fixed supply-air pressure set point. The return-air fan speed is controlled to maintain a constant difference between the supply-air and return-air flow rates.

### 5.8.3 AHU Temperature Control

A single PI control loop is used to determine a temperature control signal to maintain the supply-air temperature at a fixed supply-air temperature set point. Depending on the magnitude of the signal, it is mapped to one of three outputs which control the heating coil, cooling coil, or mixing-box dampers. For example, if the heating coil valve is active, the cooling coil valve will be fully closed and the mixing box damper will be set to the minimum position (which depends on the occupancy status). The outdoor-air and the return-air enthalpies are compared to determine whether to enable or disable economizer operation.

### 5.8.4 Boiler

The boiler control strategy is similar to that described by Kohonen et al. (1993). The boiler is turned on the whole year, because the reheat coils need the hot water to maintain the zone temperatures at or near the zone-air temperature set points. A fossil-fuel-fired hot water boiler is used. The boiler employs an on-off control scheme. The boiler on-times and off-times are determined based upon demand.

### 5.8.5 Chiller

The chiller control strategy is similar to that described by Wang (1992). The chiller is turned on from April 21 until October 31. The chiller operation implements a proportional control scheme, in which the evaporator outlet water temperature is maintained at its set point by varying the capacity of the chiller.

## *5.9 WBE Normal Operation*

Data from a one year fault free emulation are presented to highlight normal operation. Figure 23 and Figure 24 show electricity and gas consumption data respectively. The lighting and equipment electrical load (dark blue, Figure 23) and the HVAC electrical load (yellow, Figure 23) vary between occupied and occupied values, however, the daily load profiles are constant throughout the year. The chiller (purple, Figure 23) consumes electrical energy during the late spring, summer, and early fall months, with the consumption trend following the outdoor conditions, with some lag. The boiler gas consumption (blue, Figure 24) is greatest during the winter months, falling off as the outdoor conditions moderate. There is still a residual level of gas consumption during nominally cooling conditions, for morning warm-up or when the cooling load is small and the cooling effect of the VAV boxes' minimum air flow rate causes the zone temperature to drop below the cooling set point.

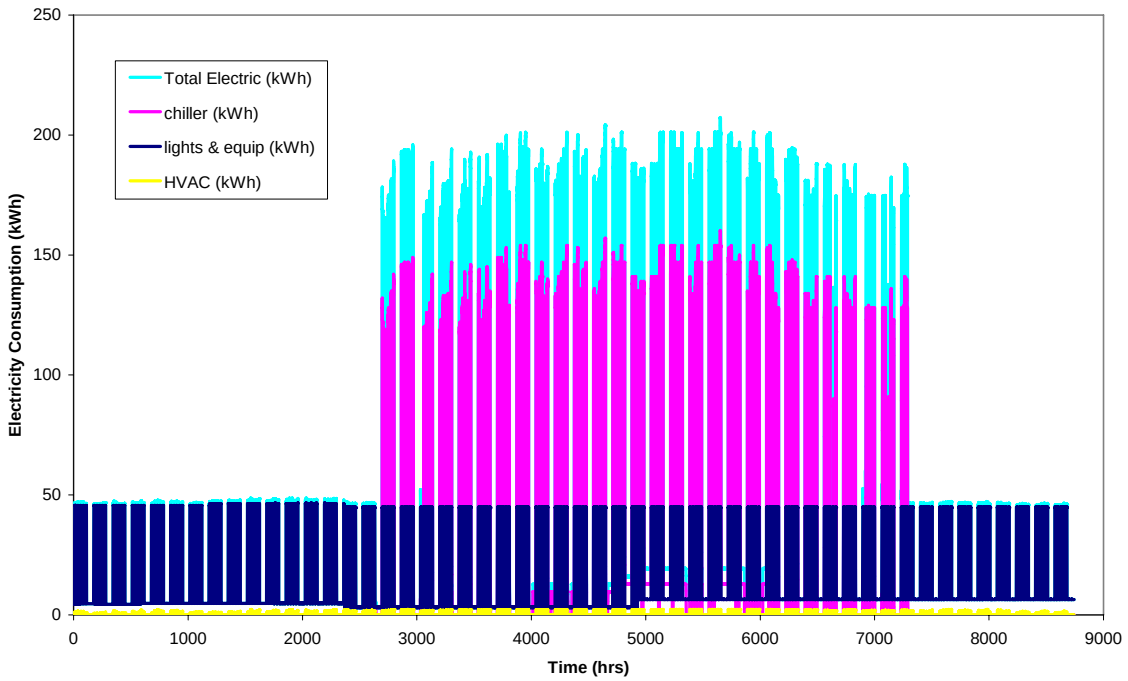



**Figure 23 – Simulated End-Use Electricity Consumption for Normal Operation**

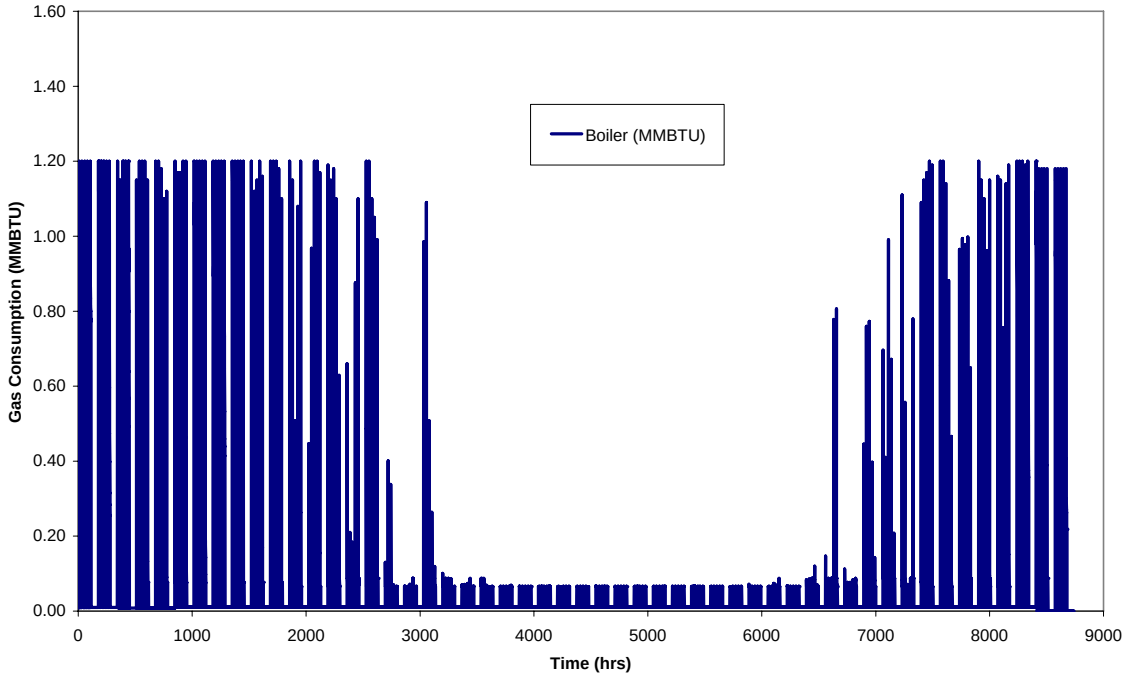



**Figure 24 – Simulated End-Use Gas Consumption for Normal Operation**

## *5.10 WBE Faulty Operation*

The following faults were included in the blind tests of the WBE module.

## 5.11 Increase in HVAC Electrical Energy Consumption

This fault is implemented by increasing the HVAC electrical energy consumption by 10 % during the period the fault is instigated, as illustrated in Figure 25 (fault-free) and Figure 26 (10 % increase in HVAC electrical energy consumption).

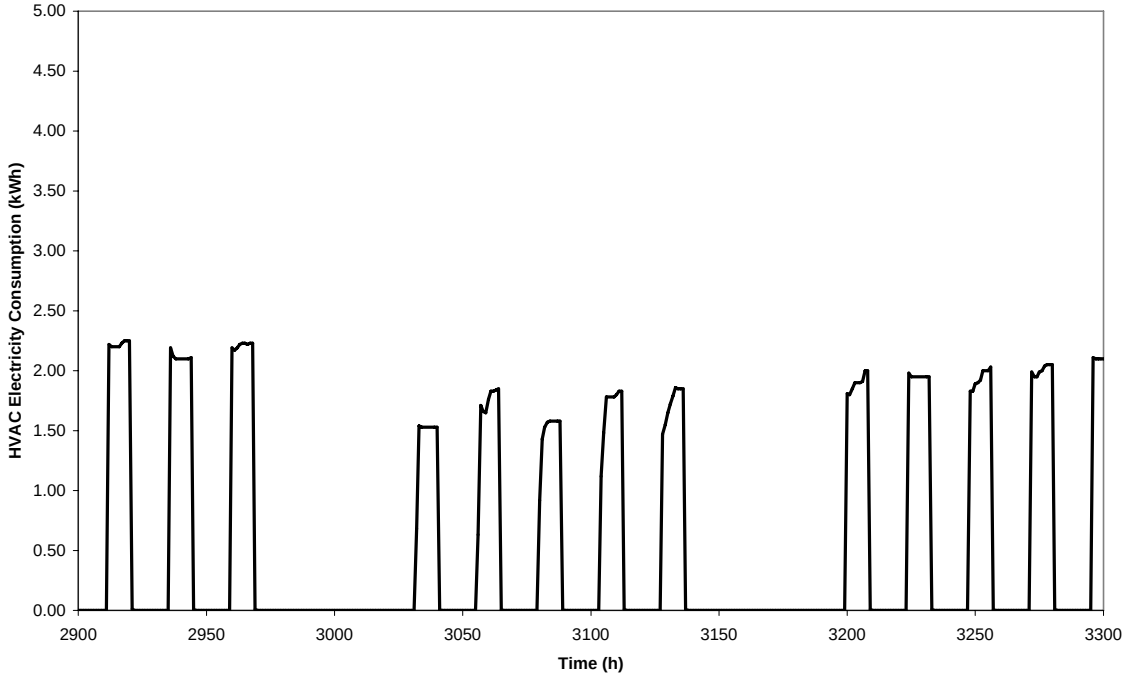



**Figure 25 – Simulated HVAC Electricity Consumption for Normal Operation**

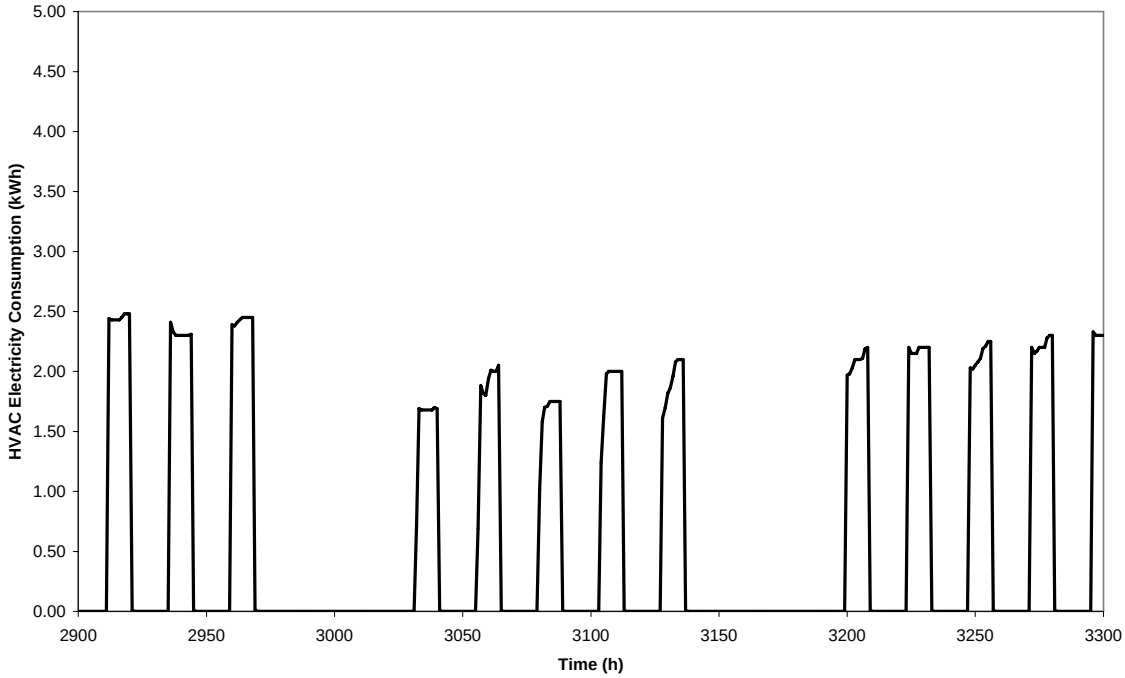



**Figure 26 – Simulated HVAC Electricity Consumption with "Faulty" Operation**

## 5.12 Increase in Boiler Gas Consumption

This fault is implemented by increasing the boiler gas consumption by 15 % during the period the fault is instigated, as illustrated in Figure 27 (fault-free) and Figure 28 (15 % increase in boiler gas consumption).

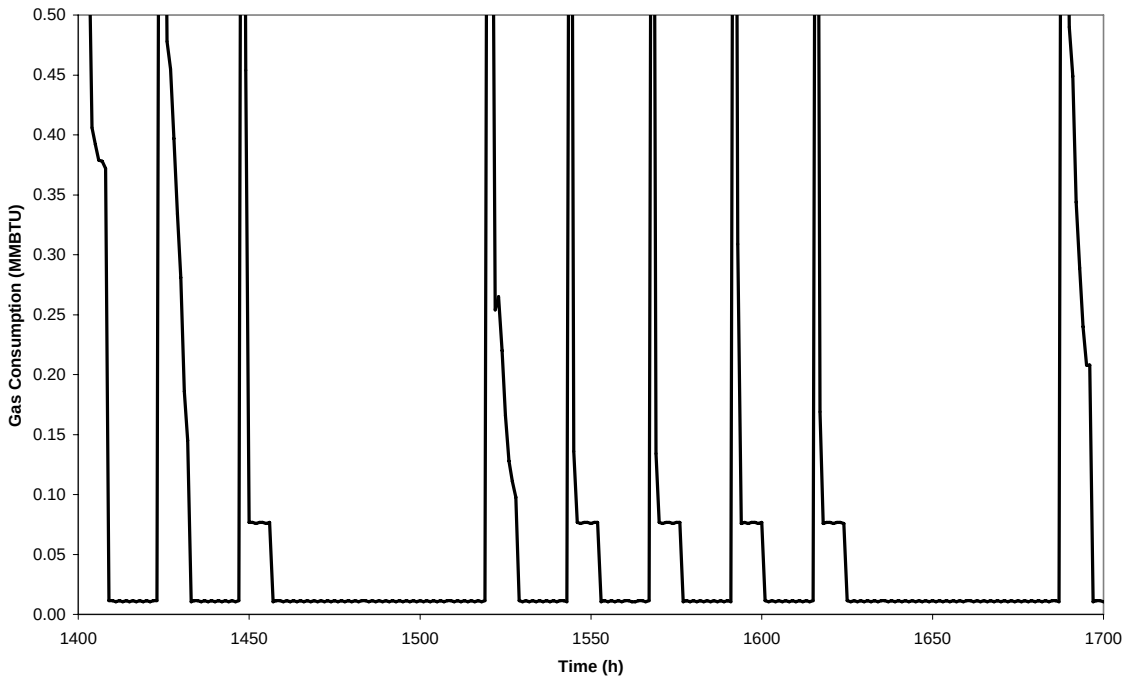



**Figure 27 – Simulated Fault-Free Boiler Gas Consumption**

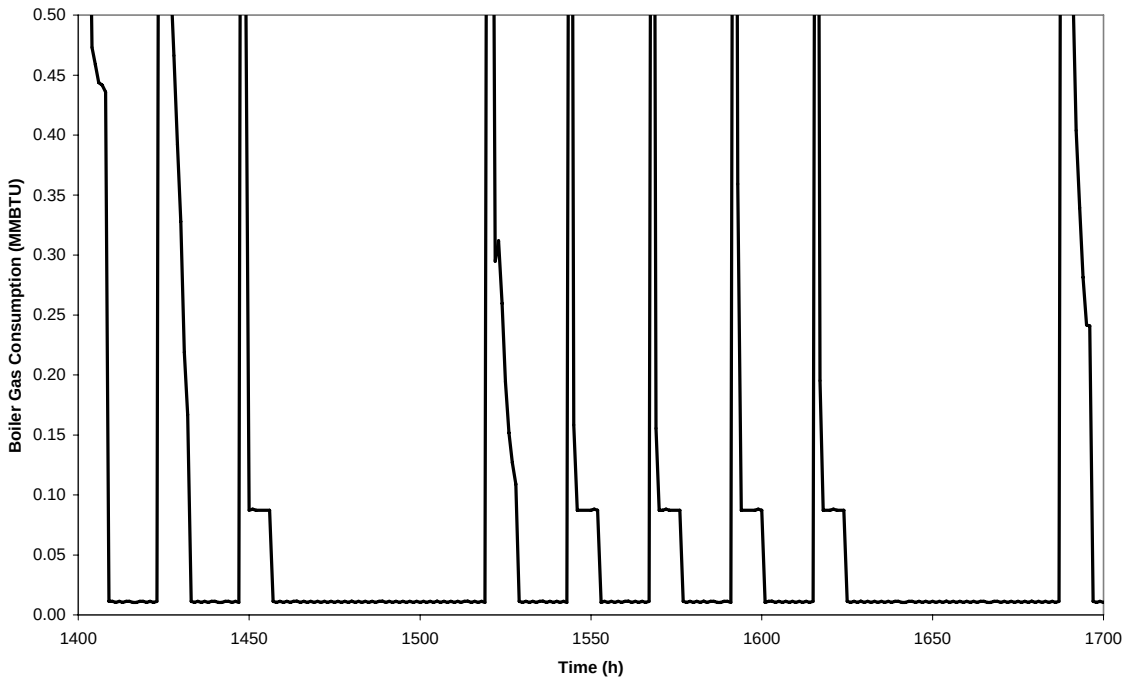



**Figure 28 – Simulated Boiler Gas Consumption Representing "Faulty" Operations**

## *5.13 Scheduling Problem*

This fault is implemented by removing the scheduling related to reduced loads on weekends as opposed to weekdays, as illustrated in Figure 29 (fault-free) and Figure 30 (15 % scheduling problem).

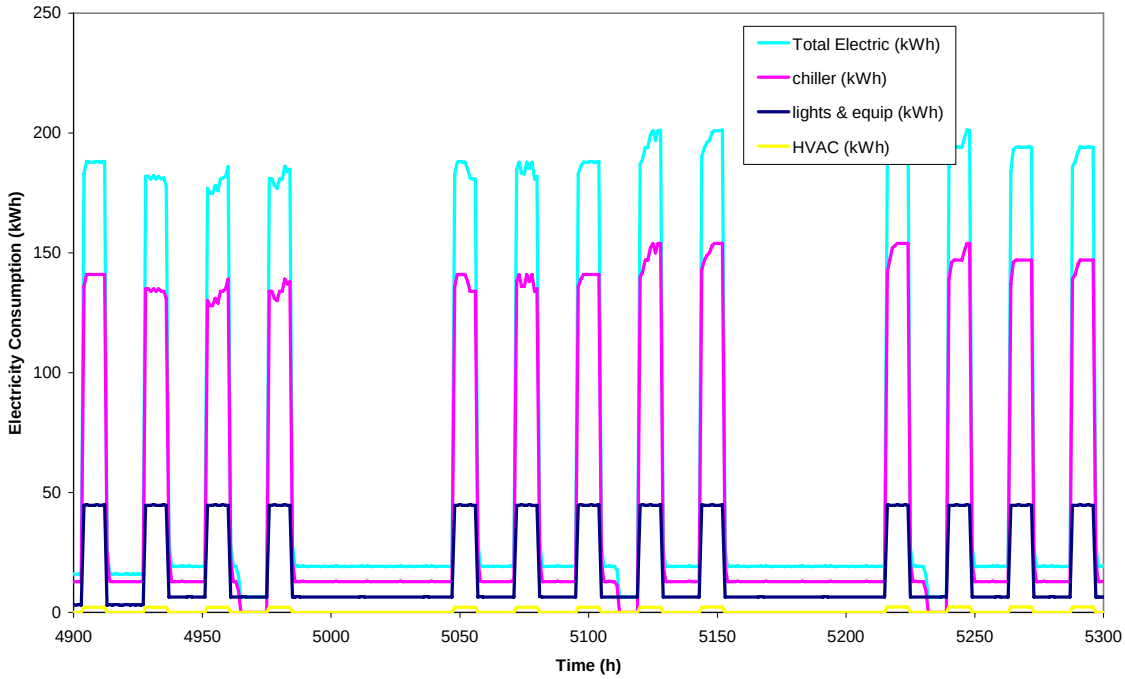



**Figure 29 – Simulated Fault-Free Electricity Consumption**

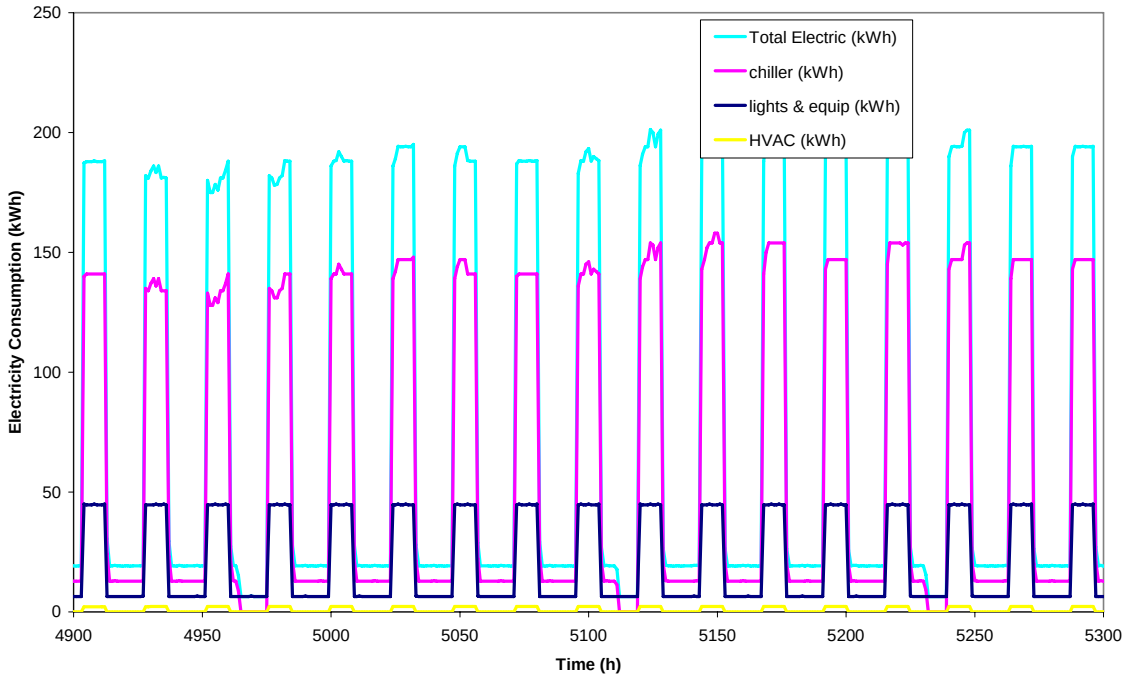



**Figure 30 – Simulated Scheduling Problem for Electricity Consumption**

## *5.14 Progressively Developing Increase in Chiller Electrical Energy Consumption*

This fault is implemented by increasing the chiller electrical energy consumption linearly from 0 % to 25 % during the period the fault is instigated, as illustrated in Figure 31 (0 % to 25 % increase in chiller electrical energy consumption).

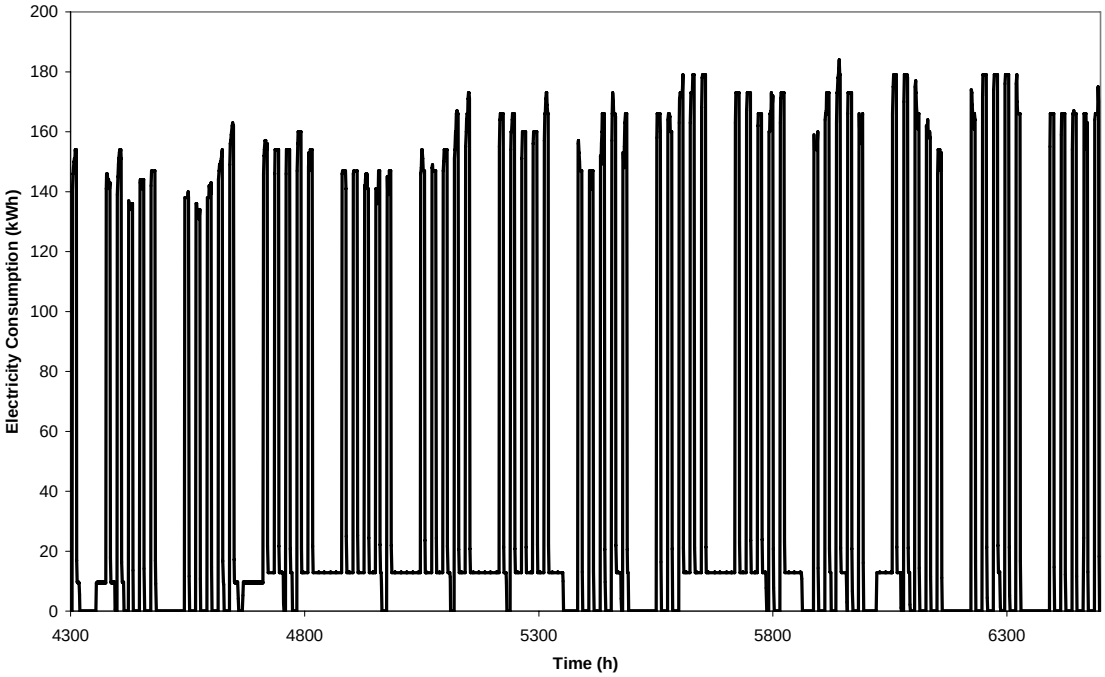



**Figure 31 – Simulated Progressively Developing Chiller Fault**

# 6 OAE Results

The results from automated processing of data sets with fault-free operation, operation with known faults, and operation with unknown faults (blind test) are presented in this section. All data sets with the exception of those with known faults have at least 3 weeks of data. The three data sets with known faults only have 1 week of data.

The OAE uses a rule-based methodology, which relies on comparison tests between variables to traverse a decision tree. These comparison tests account for random noise and measurement uncertainty to ensure reasonable levels of confidence in the decisions.

In the OAE module, tolerances are predefined for each measured and static input variable to account for the uncertainty in measured values[2]. The tolerances are propagated through all calculations and tests. For example, to test if the outdoor-air temperature is greater than the return-air temperature, not only should the outdoor-air temperature value be greater than the return-air temperature, it should be greater than the return-air temperature plus the uncertainty of the difference between the two measured values to minimize the probability that the true outdoor-air temperature is less than or equal to the return-air temperature. Similarly, the uncertainty associated with other algebraic combinations of measured variables and tests are evaluated using standard formulas for the propagation of errors in calculations (see, for example, Croarken and Tobias 2002). The tolerances assigned to each variable account for the actual uncertainty in the measured values including measurement uncertainty (or accuracy) specified by the sensor manufacturer. For example, a typical commercial-grade temperature sensor is accurate to about $\pm 0.5^{o}$F to $\pm 1^{o}$F.

The OAE diagnostician has five levels of detection sensitivity selectable by users. Increasing the detection sensitivity increases the ability to detect faults and decreases the rate of undetected faults (false negatives) while it also increases the probability of false alarms (i.e., false positives). Properly selecting the sensitivity setting is critical to achieve the desired balance between these factors. This presents a tradeoff to the user, who must subjectively judge which sensitivity setting is best, based on experience with the tool. Because noise and bias are unique to each specific combination of sensor and data acquisition equipment installed on an HVAC system and the environment in which it operates, selection of proper setting may vary from building to building or even between HVAC units in the same building. In general, we recommend setting the sensitivity at the middle of the sensitivity range (i.e., the normal setting). Initially, when data are processed with normal sensitivity setting and the AHU operation is found to be fault free, the user might choose to increase the sensitivity to see whether any faults are detected. Similarly, if experience shows that the OAE detects faults with little energy or operational impact, the user might opt to decrease the sensitivity so the OAE only reports faults with significant impacts. Because of differences in equipment among buildings and differences in preferences among users, we recommend that each user empirically adjust the sensitivity level to obtain the desired OAE performance.

[2] Actually, although the OAE method, in principle, provides for adjusting tolerances individually, in the OAE software, all tolerances are adjusted simultaneously by the user selecting a sensitivity level for the tool. This approach is used to simplify user interaction with the tool.

## 6.1 OAE Diagnostic Approach

The OAE uses color in its display to alert users to the presence of faults with a result provided for each hour. Each color designates a different category of fault (and the absence of faults). In addition to providing easily seen indicators of faults, it also provides more complete descriptions of detected faults and for each fault a list of possible causes and suggested actions to correct the faulty operation. Because of uncertainly in measurements and ever changing indoor and outdoor conditions, the fault may or may not manifest continuously or during consecutive hours. In some cases, the fault may appear for a few hours and then may not appear again for several weeks or months (see, for example, Figure 55 for Test Z3-SS-F5C). As a result, it is difficult to devise a systematic process to help guide users in every situation. We provide users with general guidance on use of the OAE, but have not yet developed a catalog of specific situations. The ability and experience of the user plays a significant role in how the diagnostic tool is used.

## 6.2 Naming Convention for the Data Sets

The naming convention used to name data sets has the form Z1-CS-F10. The first part represents the virtual zone in the VCBT environment, for example, Z1 is used to denote zone 1 of the VCBT environment. The second part of the data set name identifies the part of the weather data used in the simulation. For this part, "CS" represents cooling season, "HS" represents heating season, and "SS" represents swing season (i.e., spring or fall). The third part is a number for the blind test, which is assigned by NIST.

## 6.3 OAE Results from Normal Operation

In this section, the OAE results for fault-free AHU operation are described. Using the VCBT simulation/emulation environment, NIST generated nine fault-free data sets, which represented normal AHU operation, three each for cooling, heating and swing seasons. The VCBT environment has three zones with each zone having an AHU. Two AHUs use enthalpy based differential controls for economizer operation, while the third uses differential dry-bulb controls. All three AHUs operate between 8 a.m. to 5 p.m., 7 days a week. After configuring the OAE diagnostician with proper control strategies and schedules, the nine fault-free data sets were processed.

The OAE diagnostician found no systematic errors with any of the nine fault-free data sets; however, it reported a few random errors. The 9 data sets have 6 to 8 days of data; all data sets are labeled as starting on the same day (February 1, 2001), although they represent different seasons (for convenience).

Diagnostic results for AHU-1, which serves virtual zone 1 in the VCBT, are shown in Figure 32. Six days of heating-season weather data were used in simulation of normal operation for AHU-1. As seen in Figure 32, all cells during occupied times are "white," indicating that the AHU operation is fault free. Diagnostic results for AHU-2, which serves virtual zone 2 in the VCBT, are shown in Figure 33. Seven days of cooling season data are used in the simulation of normal operation for AHU-2. In this case, there are several "gray" cells and a single "red" cell. When indoor and outdoor conditions are nearly equal or if certain data are missing, the OAE can not perform diagnosis for that hour and it assigns gray to the corresponding cell. In this case, none of the data were missing, but the mixed and indoor conditions were nearly equal, as shown in Figure 34. Although the weather data was from cooling season, there were several hours with

temperatures around 75°F. Diagnostic results for AHU-3, which serves virtual zone 3 in the VCBT, are shown in Figure 35. Six days of swing-season weather data was used in simulation of normal operation for AHU-3. In this case, there are several "gray" cells and a single "red" cell. The red cells that appeared in Figure 33 and Figure 35 appear to be random.

As seen from the representative results (fault-free) shown in Figure 32, Figure 33, and Figure 35, the simulation of normal operation is fault-free, with a few exceptions. This confirms that 1) the VCBT environment has generated fault-free data as specified, 2) the user specified inputs including the sensor accuracies are set properly in the OAE module, and 3) the economizer controls and operating schedules for each of the three AHUs are correctly set.

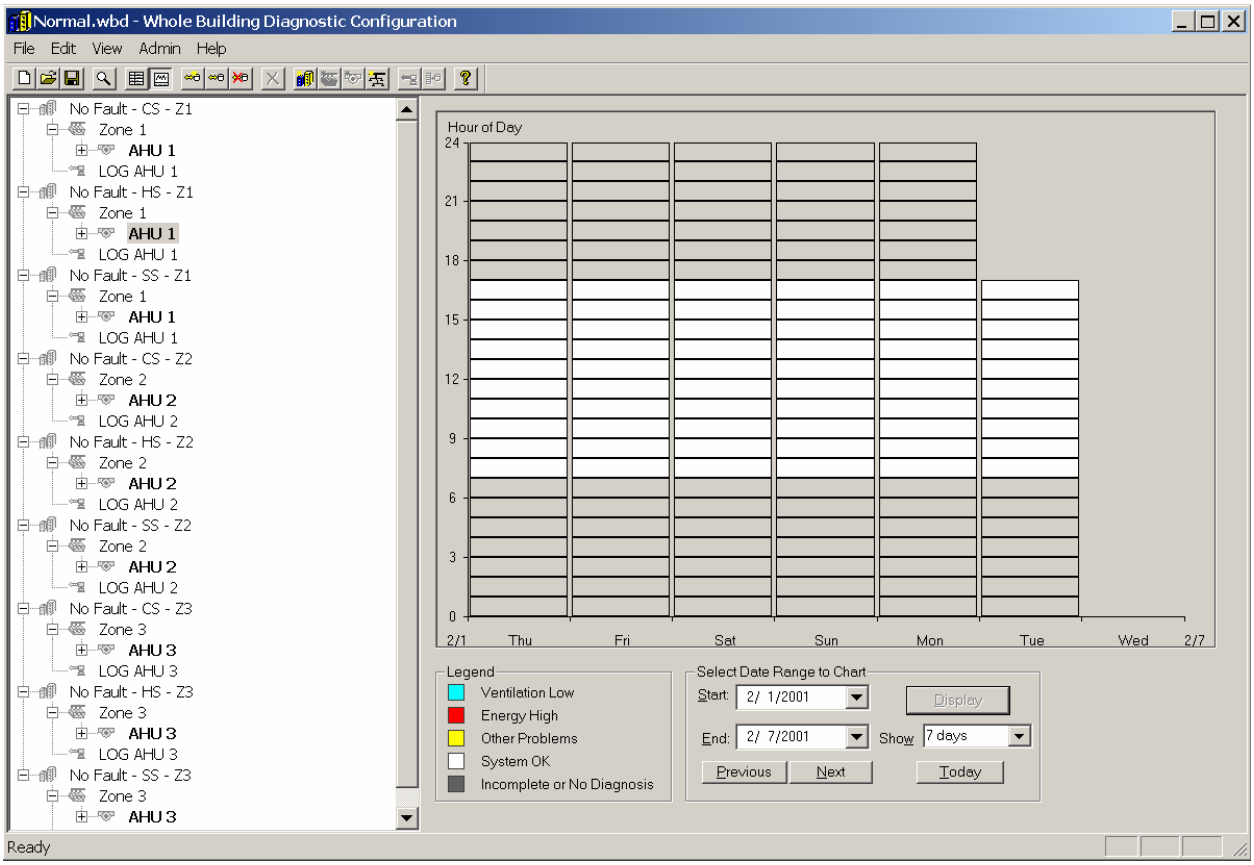



**Figure 32 – OAE Diagnostic Results for AHU-1 with Fault-Free Data from the Heating Season (Z1-HS-FX)**

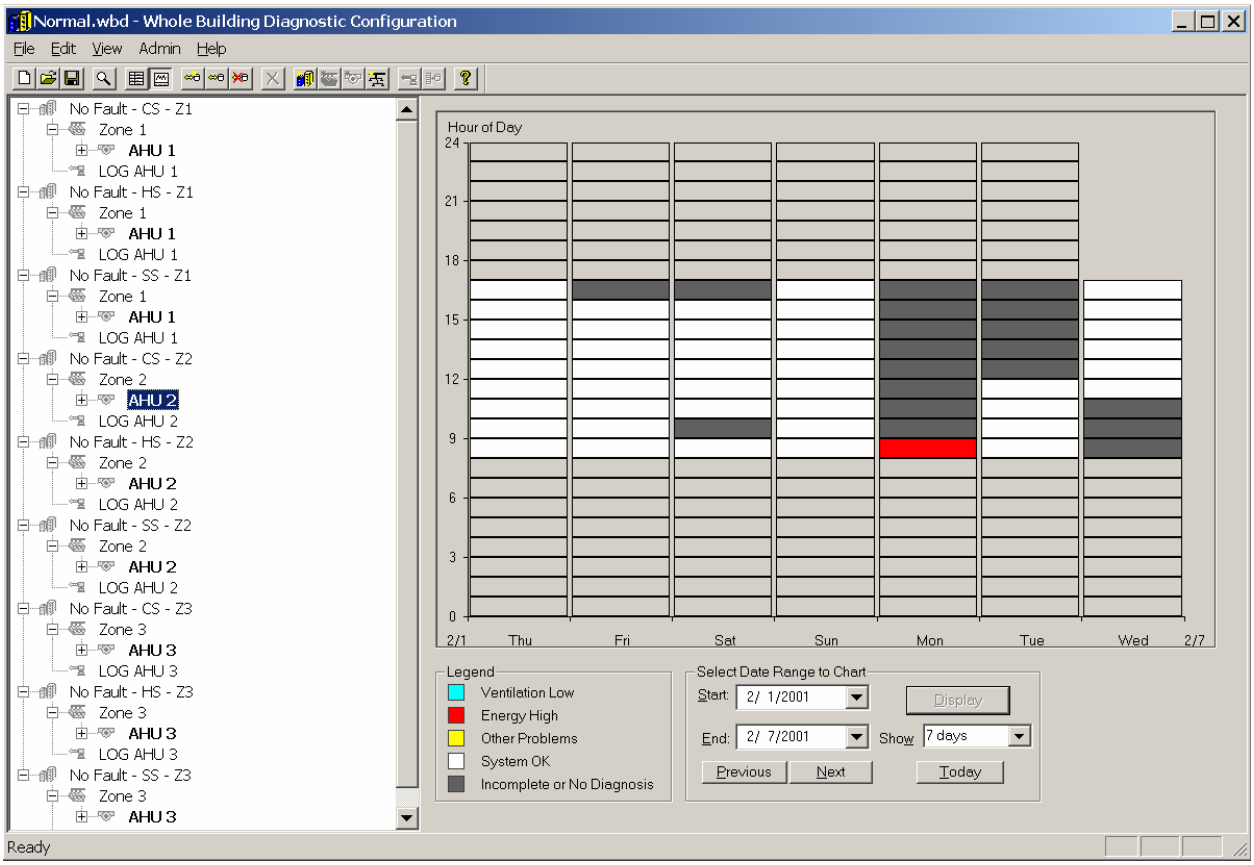



**Figure 33 – OAE Diagnostic Results for AHU-2 with Fault-Free Data from the Cooling Season (Z2-CS-FX)**

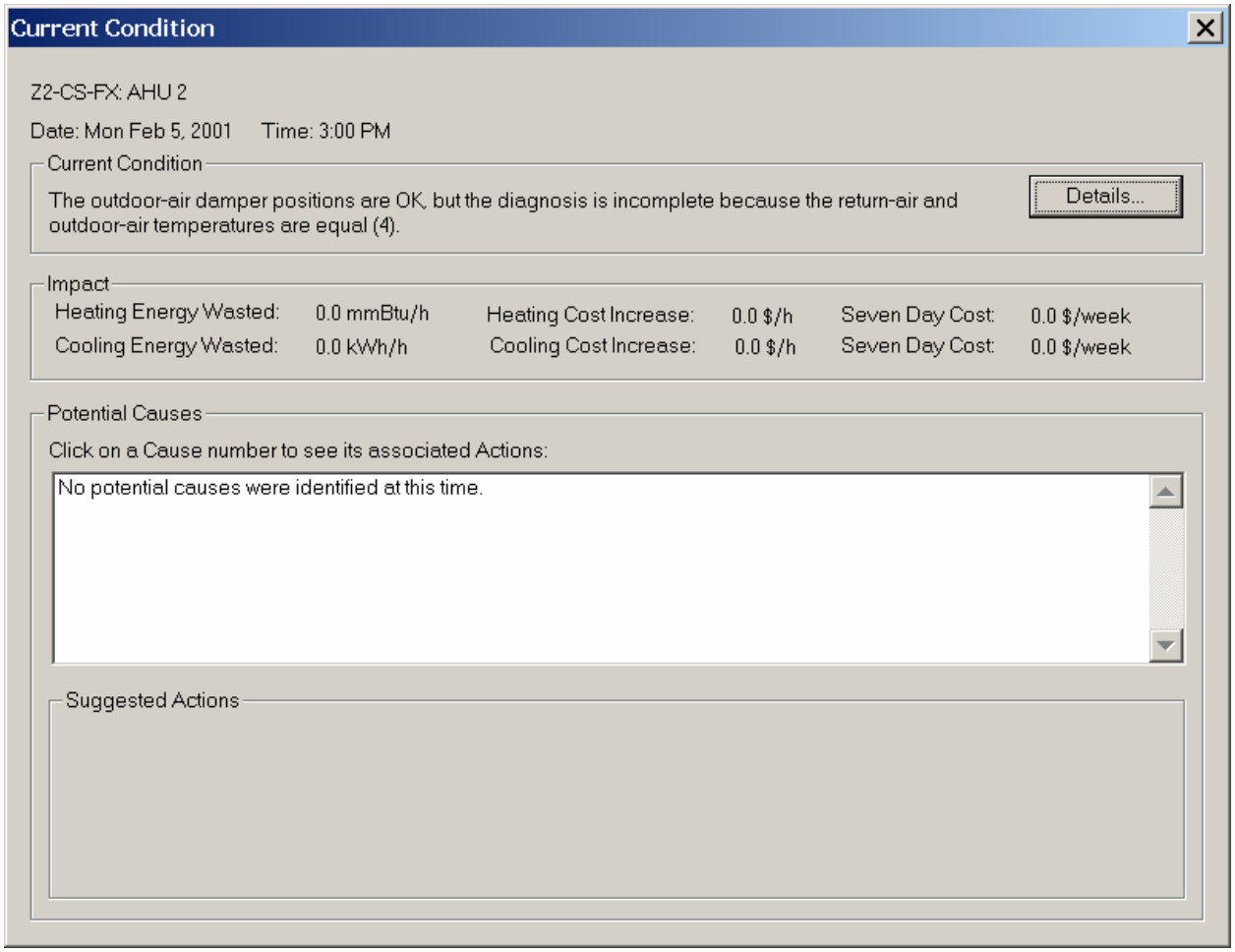



**Figure 34 – Current Conditions Dialogue that shows Conditions for 3:00 p.m. on February 5, 2001 (Z2-CS-FX)**

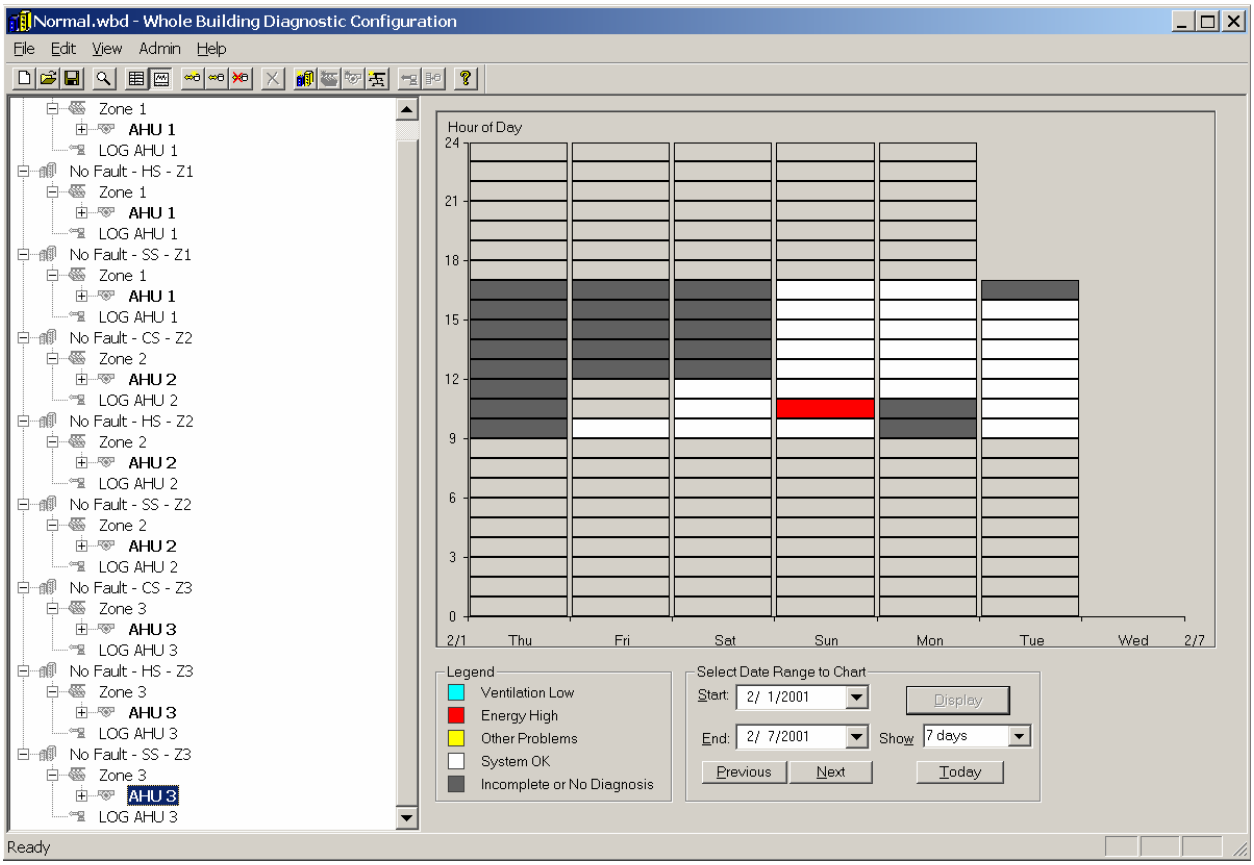



**Figure 35 – OAE Diagnostic Results for AHU-3 with Fault-Free Data from the Swing Season (Z3-SS-FX)**

## *6.4 OAE Results for Non-Blind Tests*

After validating the configuration of the AHUs and the ability of the VCBT to generate fault-free data, the next step was to confirm the capability of the VCBT to generate "faulty data" that represents improper AHU operation. Using the VCBT environment, NIST generated three data sets with known faults for non-blind tests. Each of the "faulty data" sets was 1 week long and represented the cooling season. The three faults simulated were: 1) return-air damper stuck in a fully-closed position, 2) faulty economizer control logic, and 3) mixed-air temperature sensor drift. All data sets are labeled as starting on February 14, 2001 (for convenience), although the weather data used in the simulation represents the cooling season.

### 6.4.1 Return-Air Damper Stuck Fully Closed (Z1-CS-F10)

The data set named Z1-CS-F10 was created using cooling season weather data and represents an AHU operation with the return-air damper stuck in a fully closed position. The OAE diagnostic results for this data set are shown in Figure 36. The fault was instigated by overriding the control signal to return-air damper motor to make it remain in the closed position irrespective of the controller's damper command signal. When the return-air damper is stuck fully closed, only outdoor air is used. In general, this is not a problem when outdoor conditions are favorable for economizing. When the conditions are not favorable for economizing, however, the outdoor-air damper will be aligned at the minimum position. Under these conditions, more than the

minimum outdoor-air is drawn through the outdoor-air dampers because the return-air dampers are closed. This is faulty operation, and the OAE should recognize this as such. However, the diagnostic results shown in Figure 36 indicate otherwise, where all cells are white indicating no faults were found.

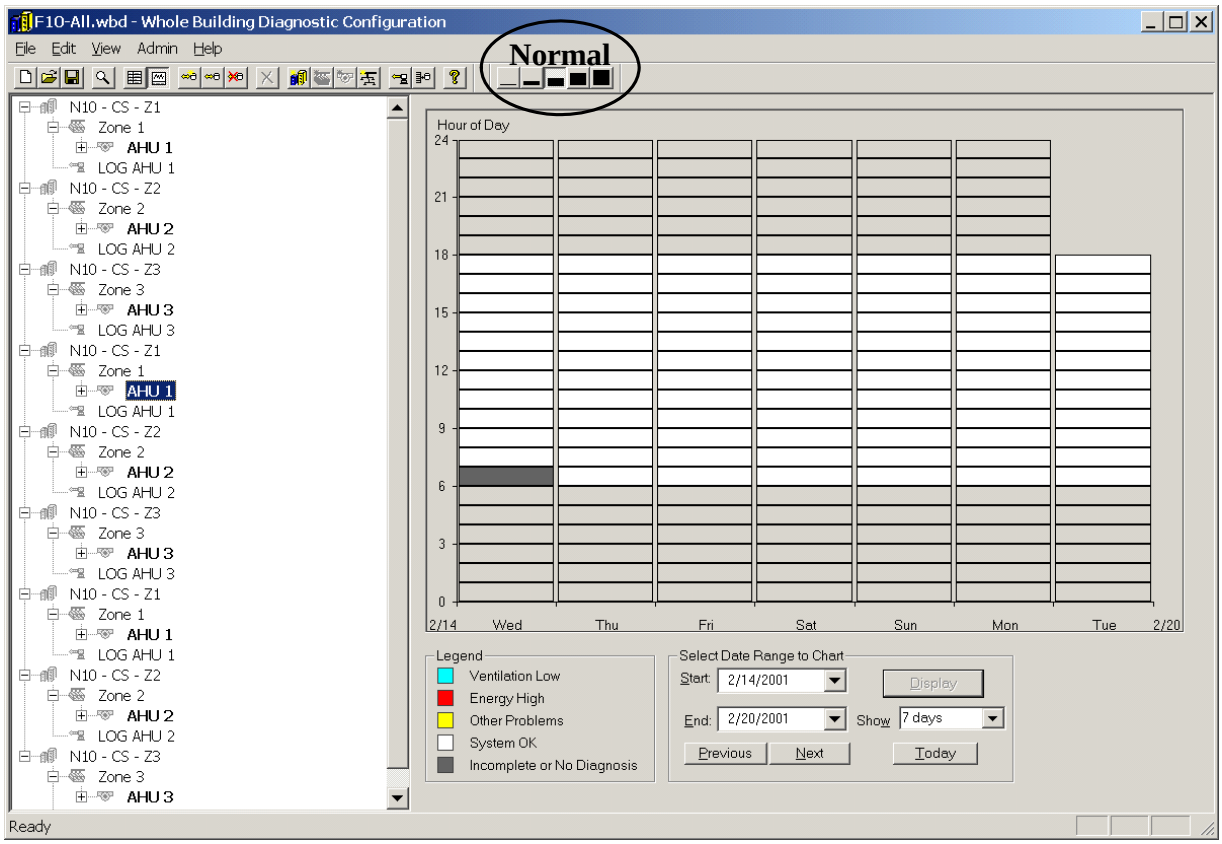



**Figure 36 – OAE Diagnostic Results for AHU-1 with the Return-Air Damper Stuck in a Fully Closed Position for the Normal OAE Sensitivity Setting (data set Z1-CS-F10)**

As noted in the previous section, the OAE has five levels of sensitivity. By default the OAE module is set at normal sensitivity (level 3), which is a mid-level sensitivity. The diagnostic results shown in Figure 36 were generated using normal sensitivity. To increase fault detection sensitivity, the sensitivity level was increased to High (level 5) and the data reprocessed
(

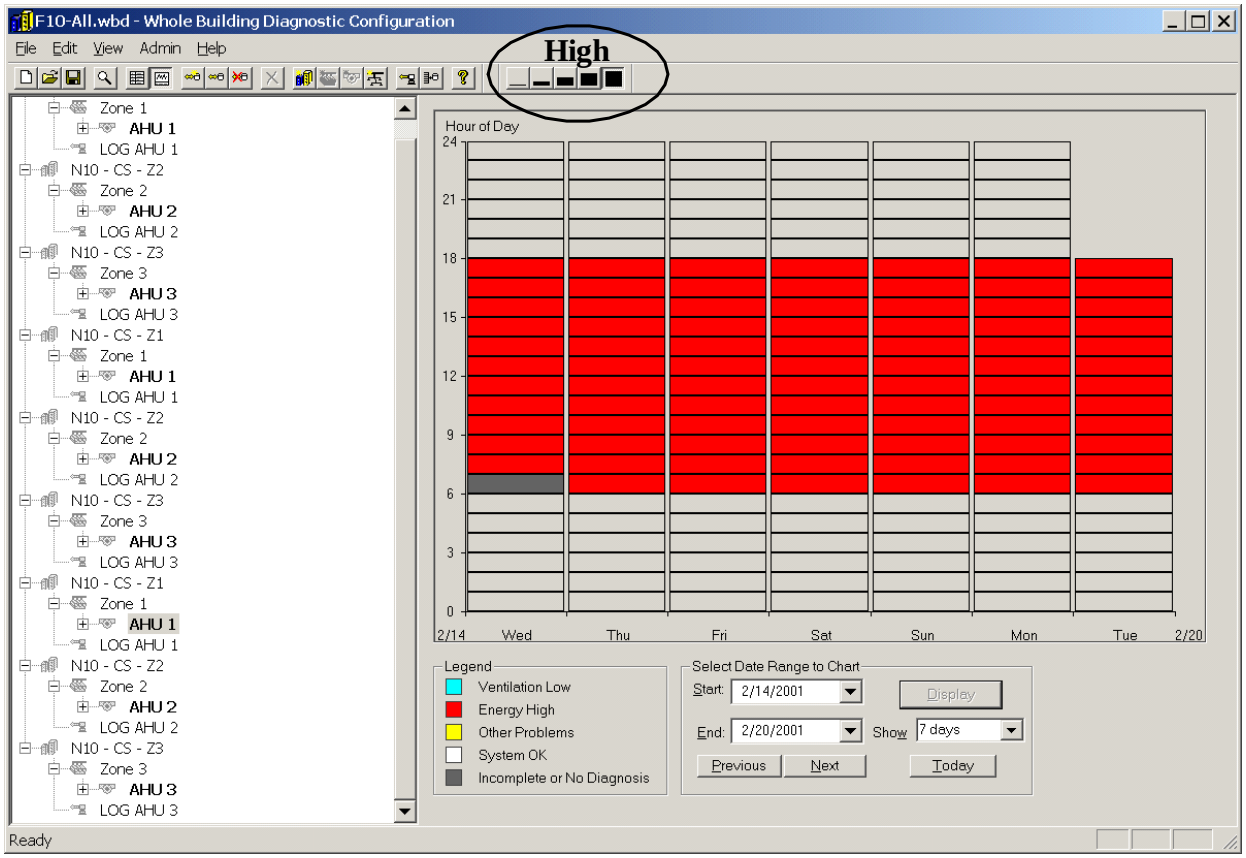



Figure 37)[3]. With the increased sensitivity, all cells (with the exception of one) during the occupied period are red, indicating higher than expected energy consumption. This finding is consistent with the fault induced. By clicking on a red cell, the current conditions, a list of potential causes, and suggested solutions can be obtained. Figure 38 shows the Current Conditions dialogue for February 20, 2001, at 4:00 p.m. The current condition as reported by the OAE is that the damper position signal is "OK" but the outdoor-air flow is too high, consistent with the fault instigated in the VCBT environment. Browsing through several other red cells reveals the same problem. The lists of possible causes do not explicitly indicate a problem with return-air damper. They do, however, point to the damper system failure. In addition, the detailed information clearly indicates the exact problem as shown in Figure 39.

[3] Note that increasing the fault-detection sensitivity creates a potential to increase the number of false alarms.

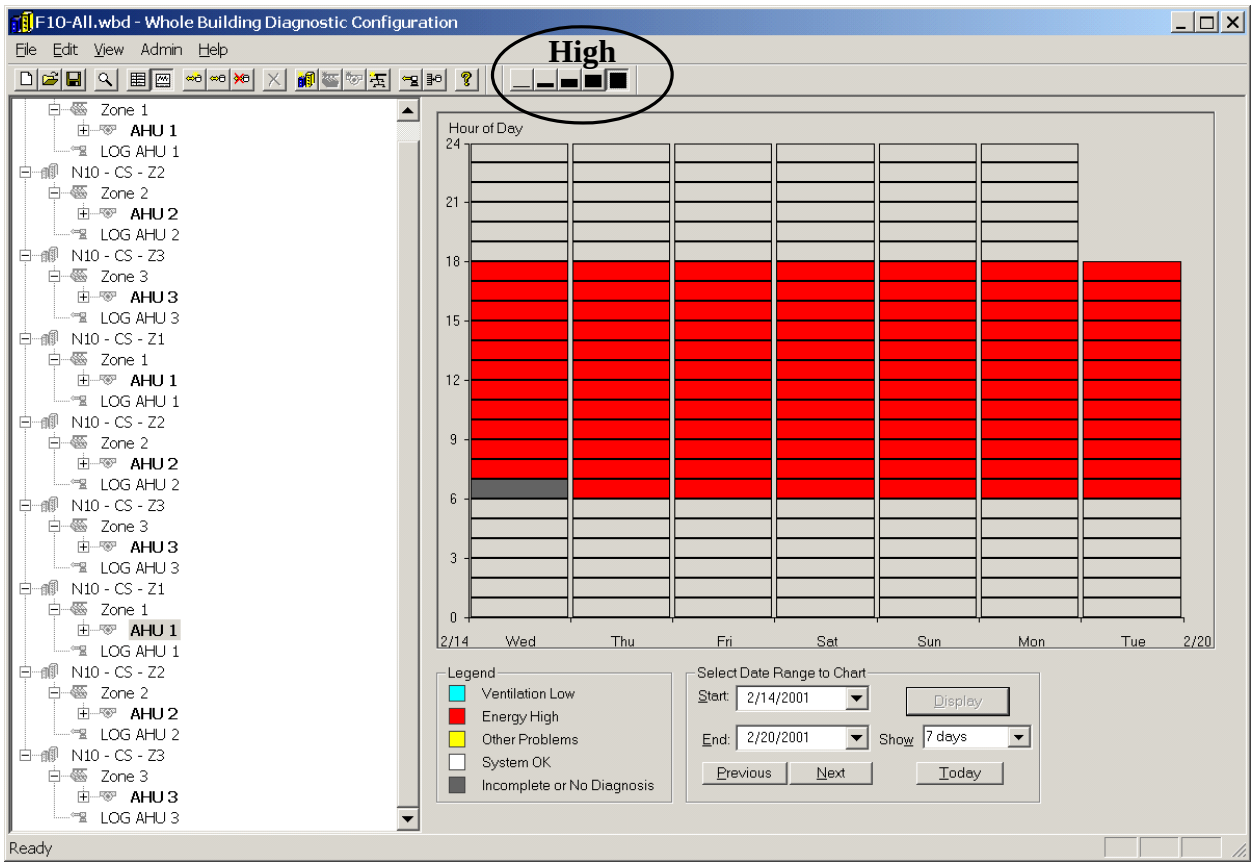



**Figure 37 – OAE Diagnostic Results for AHU-1 with the Return-Air Damper Stuck in a Fully Closed Position for the High OAE Sensitivity Setting (data set Z1-CS-F10)**

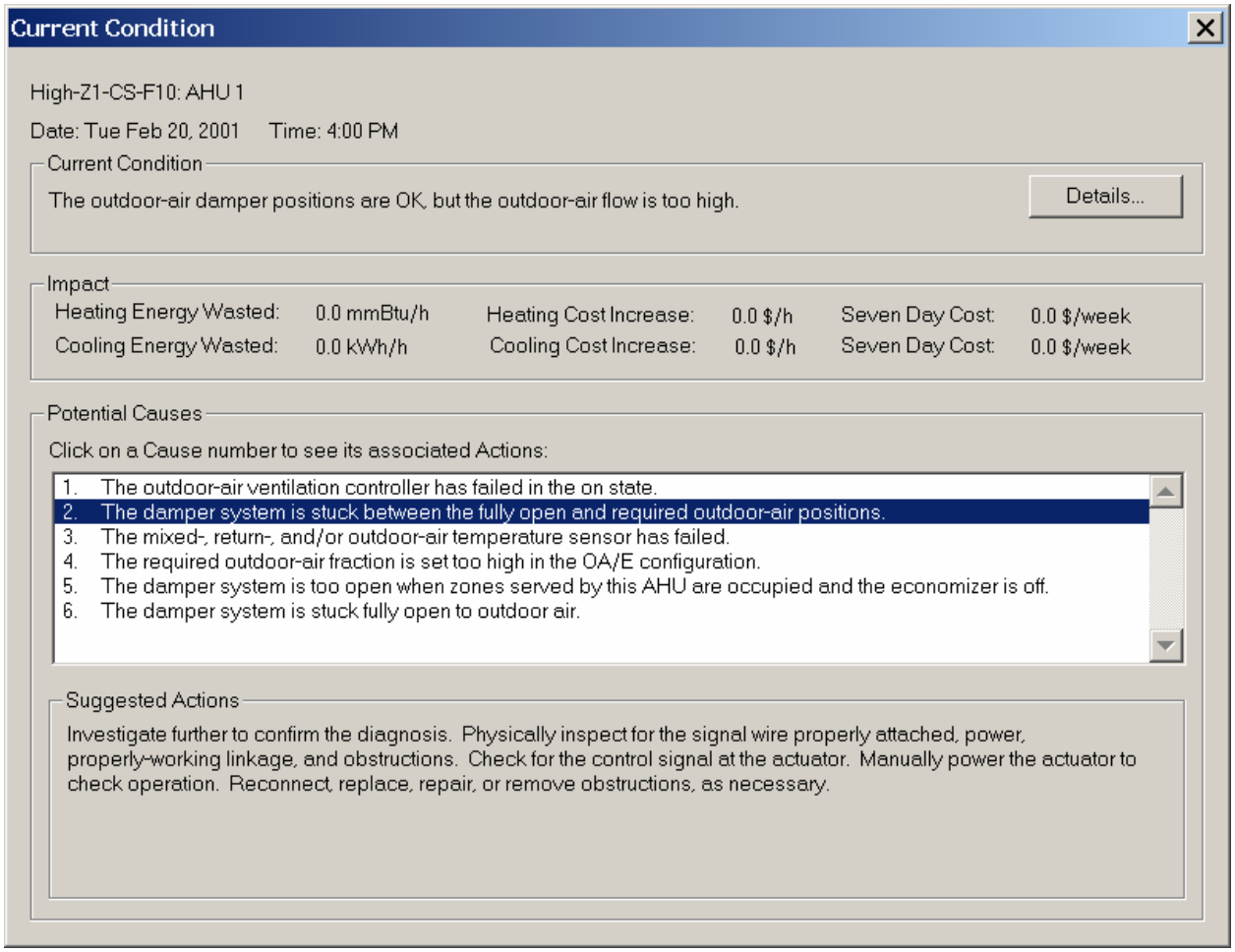



**Figure 38 – Current Conditions Dialogue for AHU-1 on February 20, 2001, at 4:00 p.m. with the Return-Air Damper Stuck Fully Closed (data set Z1-CS-F10)**

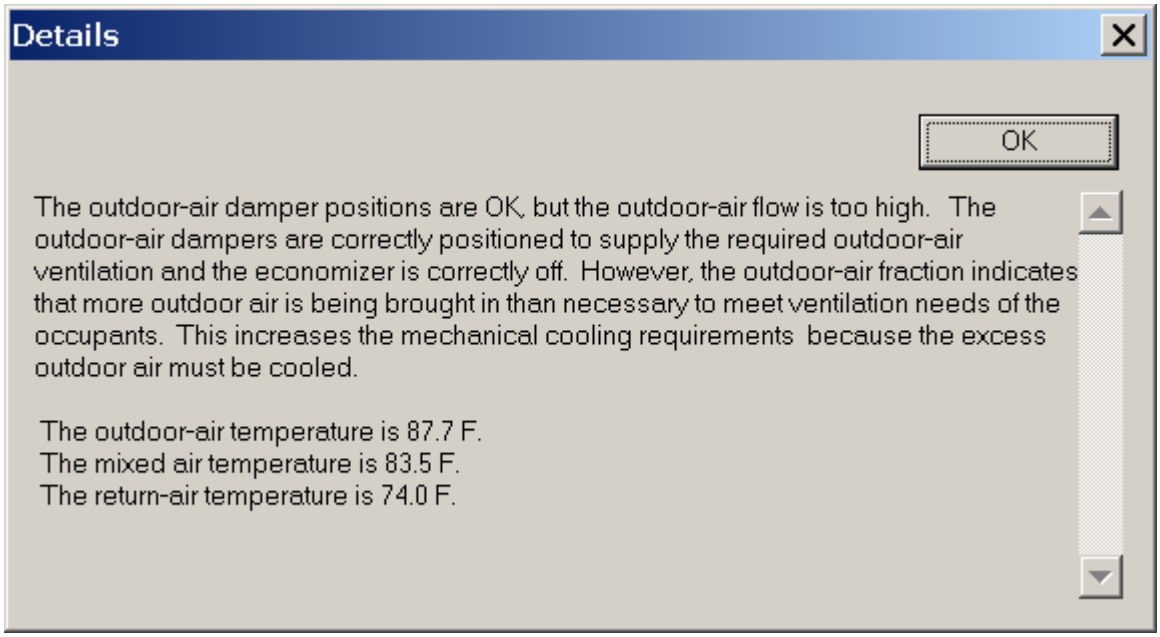



**Figure 39 – Details Dialogue for AHU-1 on February 20, 2001, at 4:00 p.m. with the Return-Air Damper Stuck Fully Closed (data set Z1-CS-F10)**

### 6.4.2 Faulty Economizer Control Logic (Z2-CS-F10)

The data set named Z2-CS-F10 was created using cooling season weather data and represents an AHU operation with faulty economizer control logic. The OAE diagnostic results for the Z2-CS-F10 data set are shown in Figure 40. This fault was introduced by reversing the logic used to decide whether the economizer or the minimum ventilation operation should become active. The supply-air temperature controller will still maintain the supply-air temperature set point under this condition. When the economizer logic is overridden to open the outdoor-air dampers more than the minimum when the conditions are not favorable for economizing, a fault occurs. Under these conditions, more outdoor air is drawn into the AHU, increasing the mechanical cooling requirements. This fault, unlike the previous one, was identified with the Normal sensitivity setting for the OAE.

Figure 41 shows the Current Conditions dialogue for February 20, 2001, at 4:00 p.m. The current condition, as reported by the OAE, is that the economizer should be off, but it is operating. This is consistent with the fault instigated in the VCBT environment. Several other red cells indicate the same problem. The fifth item in the list of potential causes corresponds to the instigated fault. Also, the detailed information clearly indicates the exact problem, as shown in Figure 42.

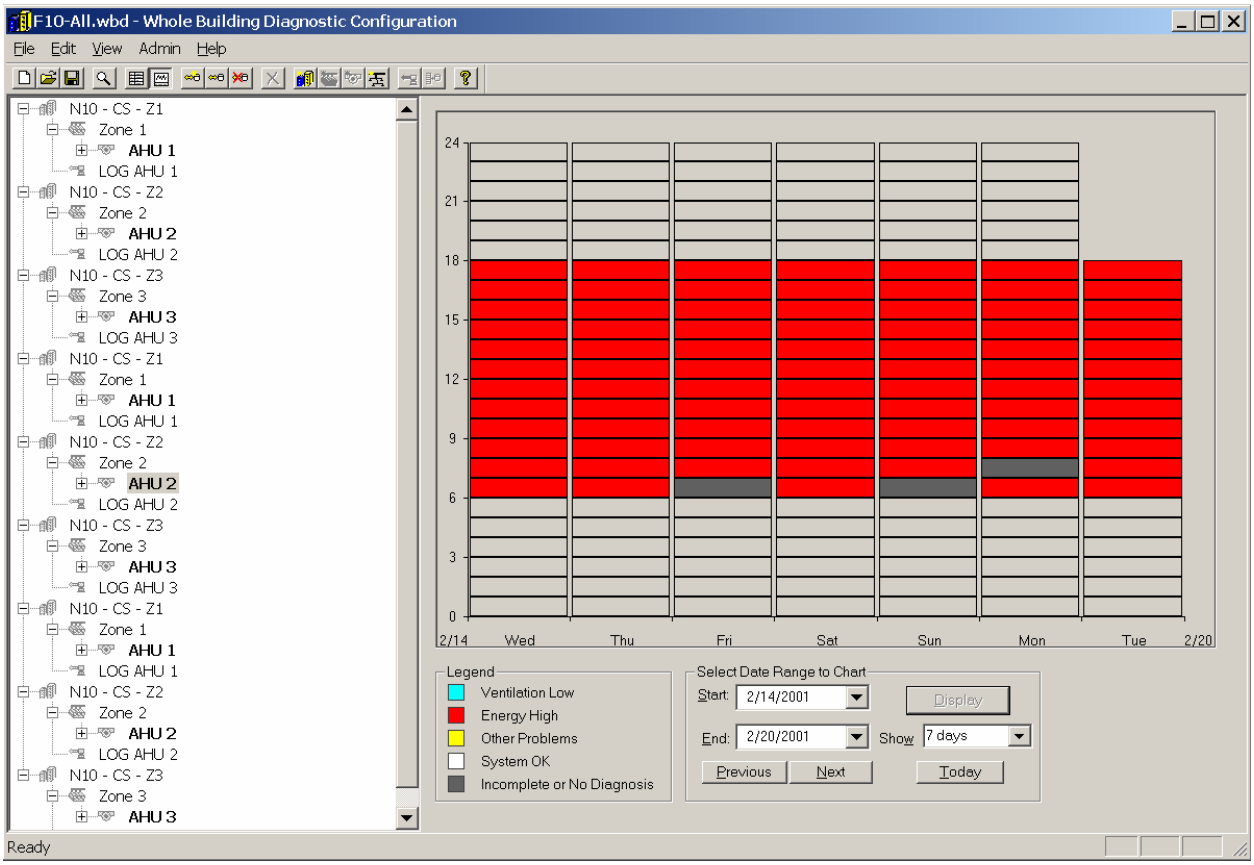



**Figure 40 – OAE Diagnostic Results for AHU-2 with Faulty Economizer Control Logic for the Normal OAE Sensitivity Setting (data set Z2-CS-F10)**

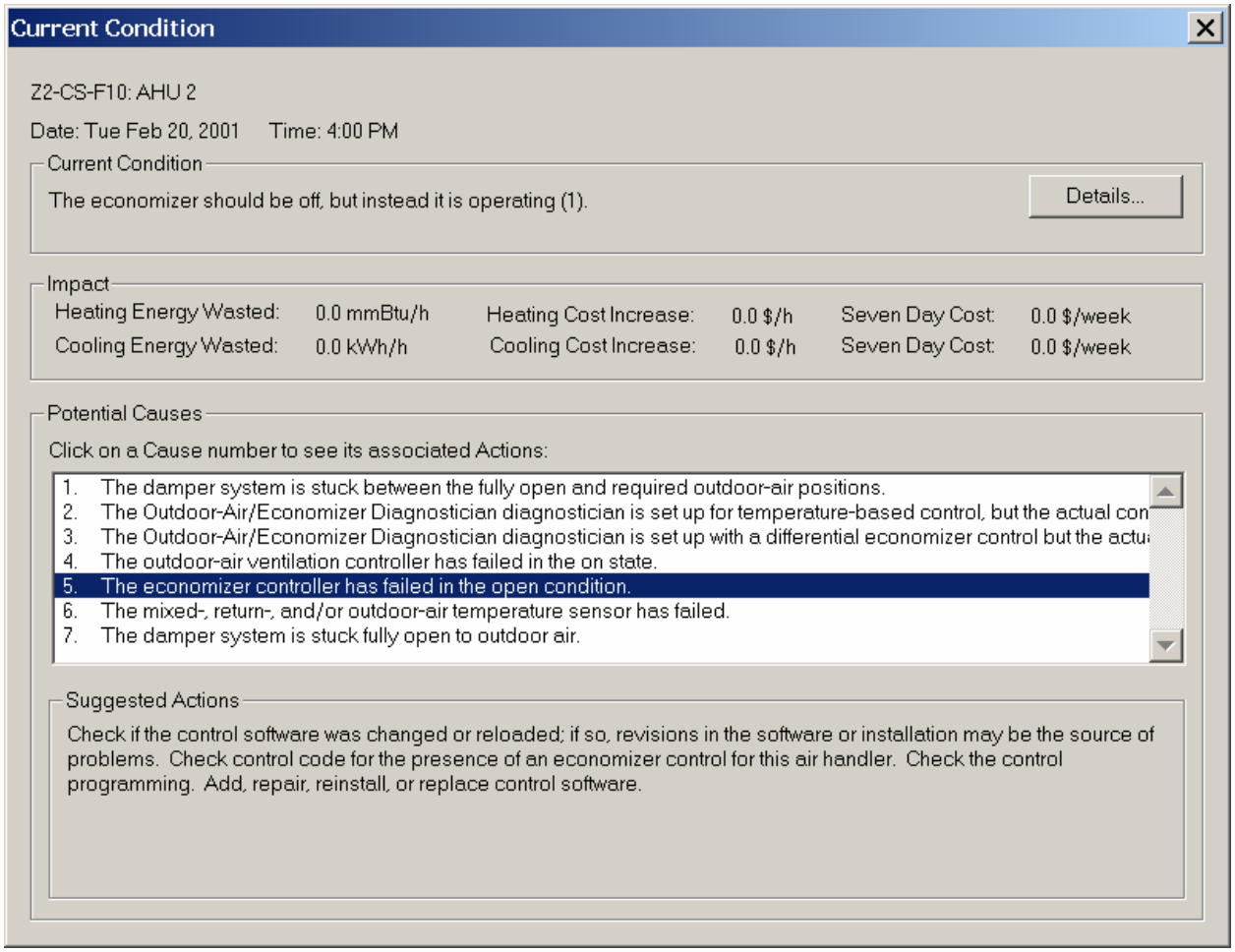



**Figure 41 – Current Conditions Dialogue for AHU-2 on February 20, 2001, at 4:00 p.m. with the Return-Air Damper Stuck Fully Closed (data set Z2-CS-F10)**

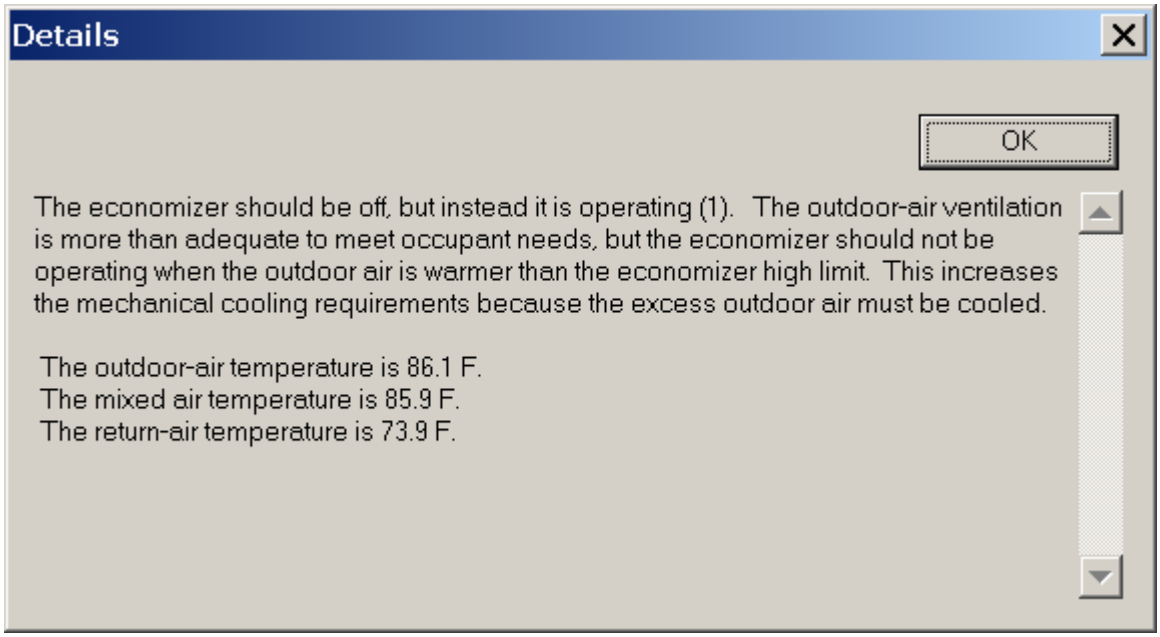



**Figure 42 – Details Dialogue for AHU-2 on February 20, 2001, at 4:00 p.m. with the Return-Air Damper Stuck Fully Closed (data set Z2-CS-F10)**

### 6.4.3 Drift in Mixed-Air Temperature Sensor (Z3-CS-F10)

The data set named Z3-CS-F10 was created using cooling season weather data and represents AHU operation with a faulty outdoor-air temperature sensor. The mixed-air temperature sensor drift was introduced as a sensor offset for a range of 0 to 7ºF, applied linearly over a 1-week emulation period.

The OAE diagnostics results for the Z3-CS-F10 data set are shown in Figure 43. The OAE diagnostician identified the fault immediately even with the Normal sensitivity setting. Figure 44 shows Current Conditions dialogue for February 20, 2001, at 4:00 p.m. The current condition as reported by the OAE is that a temperature sensor problem exists. This is consistent with the fault instigated in the VCBT environment. Browsing through several other cells also revealed the same problem. The single item in the list of potential causes corresponds to the instigated fault. Also, the detailed information clearly indicates the exact problem, as shown in Figure 45. Although the OAE identified a problem with a temperature sensor, it cannot distinguish which of the three sensors is faulty (mixed-, return- or outdoor-air temperature).

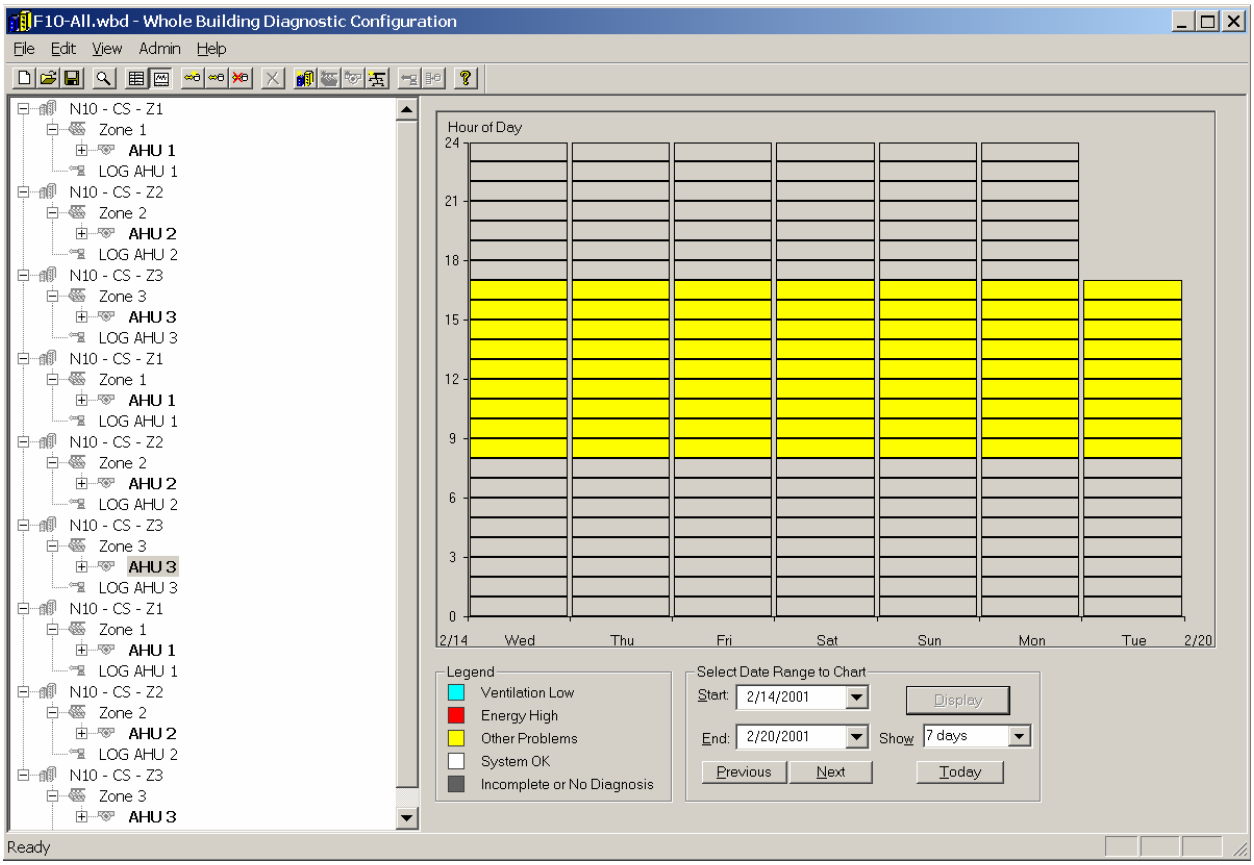



**Figure 43 – OAE Diagnostic Results for AHU-3 with a Mixed-Air Temperature Sensor Problem for the Normal OAE Sensitivity Setting (data set Z3-CS-F10)**

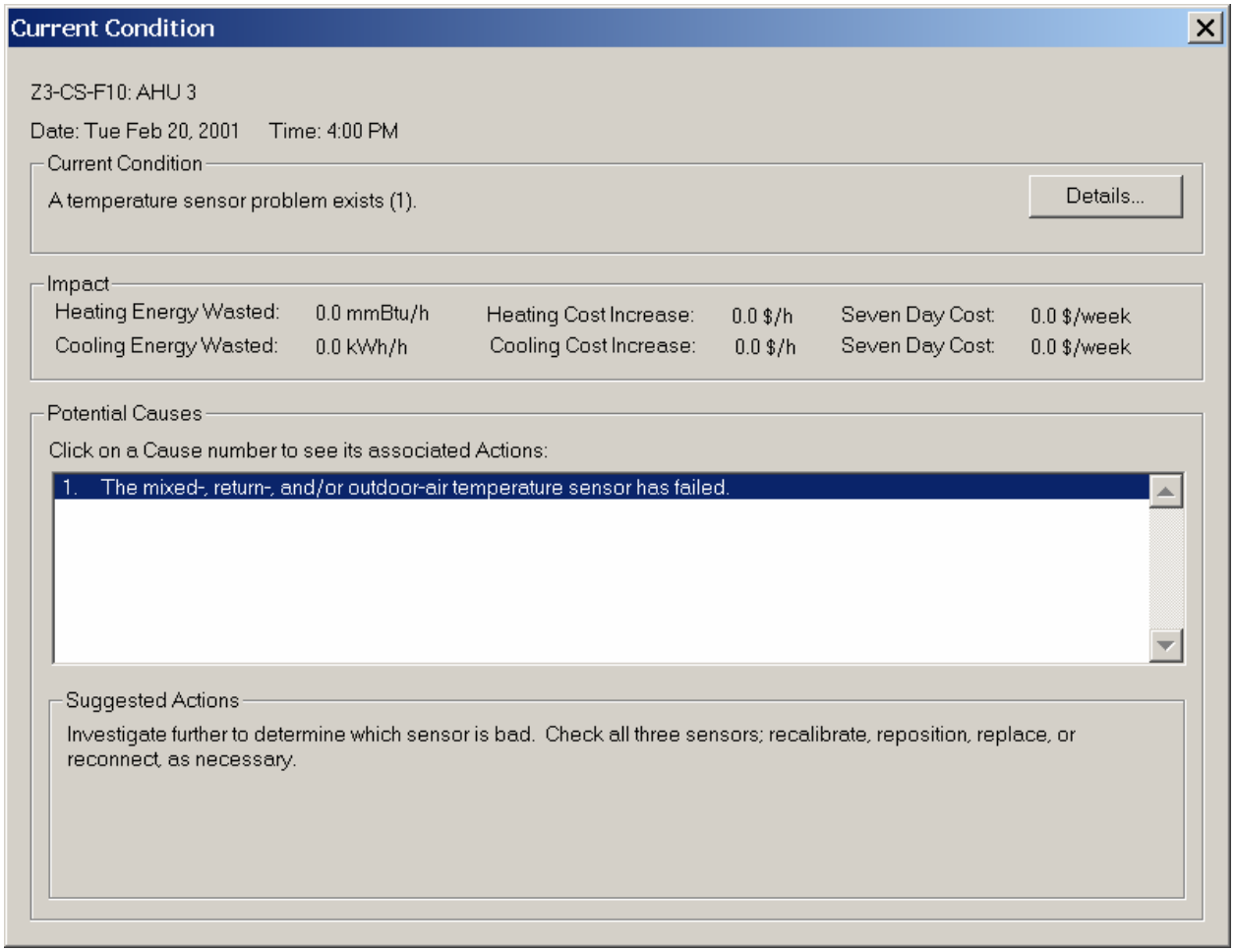



**Figure 44 – Current Conditions Dialogue for AHU-3 on February 20, 2001, at 4:00 p.m. with a Mixed-Air Temperature Sensor Problem (data set Z3-CS-F10)**

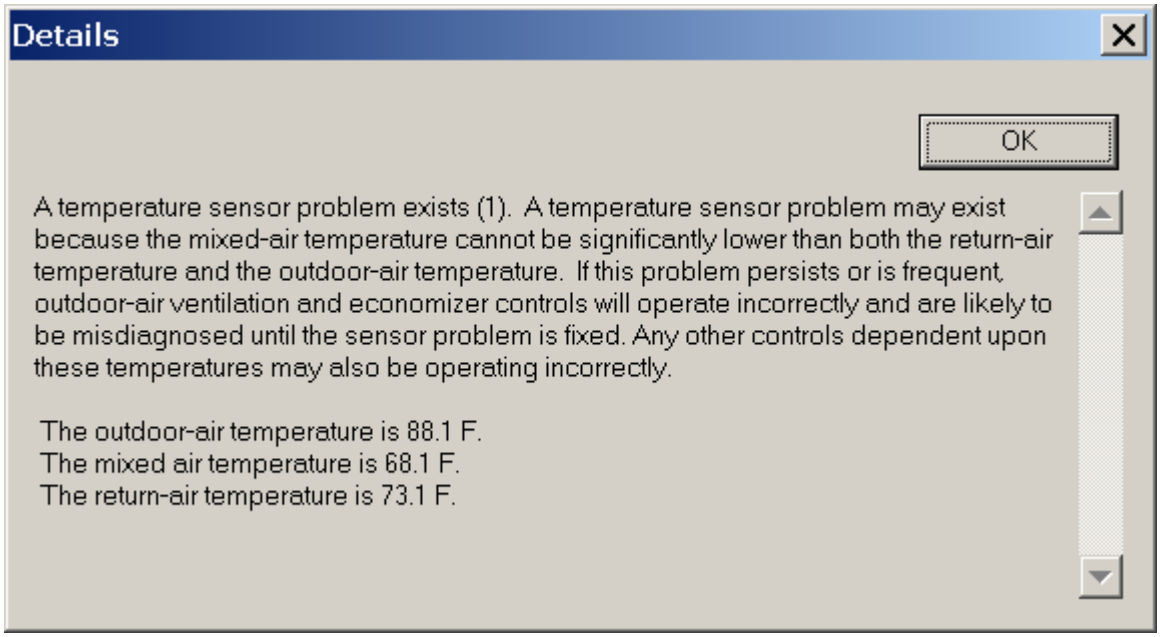



**Figure 45 – Details Dialogue for AHU-3 on February 20, 2001, at 4:00 p.m. with a Mixed-Air Temperature Sensor Problem (data set Z3-CS-F10)**

## *6.5 OAE Results from Blind Tests*

To evaluate the diagnostic capability of the OAE diagnostician to detect faulty AHU operation, NIST generated 15 data sets for use in blind tests. Like the previous tests, all data sets start on the same date irrespective of the season being simulated, and they are at least 3 weeks long. The OAE diagnostic results from the blind test data sets are presented this section.

### 6.5.1 Data Set Z1-SS-F5A

The data set Z1-SS-F5A represents the first of the 15 blind data sets; it has three weeks of blind test data from AHU-1, which serves zone 1 in the VCBT. The simulation used swing-season weather data. Figure 46 shows the screen shot of the OAE diagnostic results for this data set. With the exception of a few gray and white cells, most of the cells are red, which indicates an energy waste.

The Current Condition dialogue for 10:00 a.m. on February 3, 2001, is shown in Figure 47. The conditions for that particular hour indicate that the economizer should be operating fully open (i.e., the outdoor-air dampers), but it is only partially open. Although the OAE generates a list of potential causes for every fault, it displays them only if the certainty of the error is significant. In other words, if the OAE encounters the same problem over and over again, it becomes more and more certain of the problem and only then displays the list of potential causes for that problem. This implementation avoids false alarms when there are apparent transient problems (i.e., non-persistent random problems). Because the 10 a.m. hour on February 3, 2001, was the first occurrence of the problem, the OAE is not certain about the cause of the problem and, therefore, displays none.

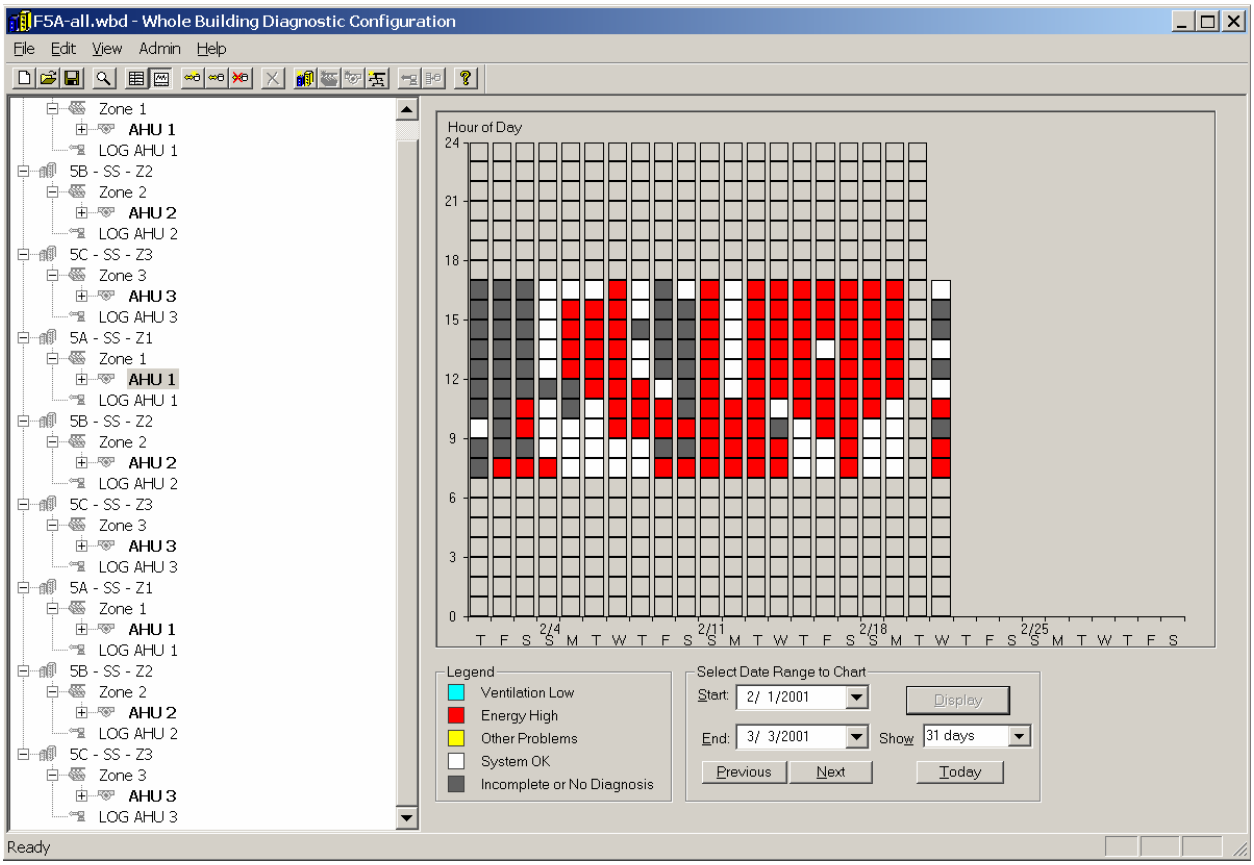



**Figure 46 – OAE Diagnostic Results for AHU-1 for Blind Test Data Set Z1-SS-F5A for a Swing Season with Normal OAE Sensitivity**

The Current Conditions dialog for February 17, 2001, at 3:00 p.m. is shown in Figure 48. Between February 10th and February 17, there were a number of hours of faulty operation; therefore, the OAE became more certain of the fault and lists five possible potential causes. In some cases, depending on the nature of the fault, the list of potential causes reduces over time. However, in this case, the list of potential causes remained the same, even at the end of the simulation period (see Figure 49 and Figure 50).

Because the OAE was properly configured and setup, all causes related to the configuration can be eliminated (1, 3 and 4), which leaves causes 2 and 5. The temperature sensor fault is listed as a potential cause for many problems because it often cannot be ruled out completely. However, if there was a temperature sensor problem, there would be yellow cells. Therefore, it can be concluded that the most likely cause of the problem detected is potential cause number 2; the damper system fails to open completely indicating that the damper is stuck between its normal position (minimum ventilation) and fully open. Also, the order of the potential causes is important. In general, the cause that the OAE believes is most relevant is at the top of the list.

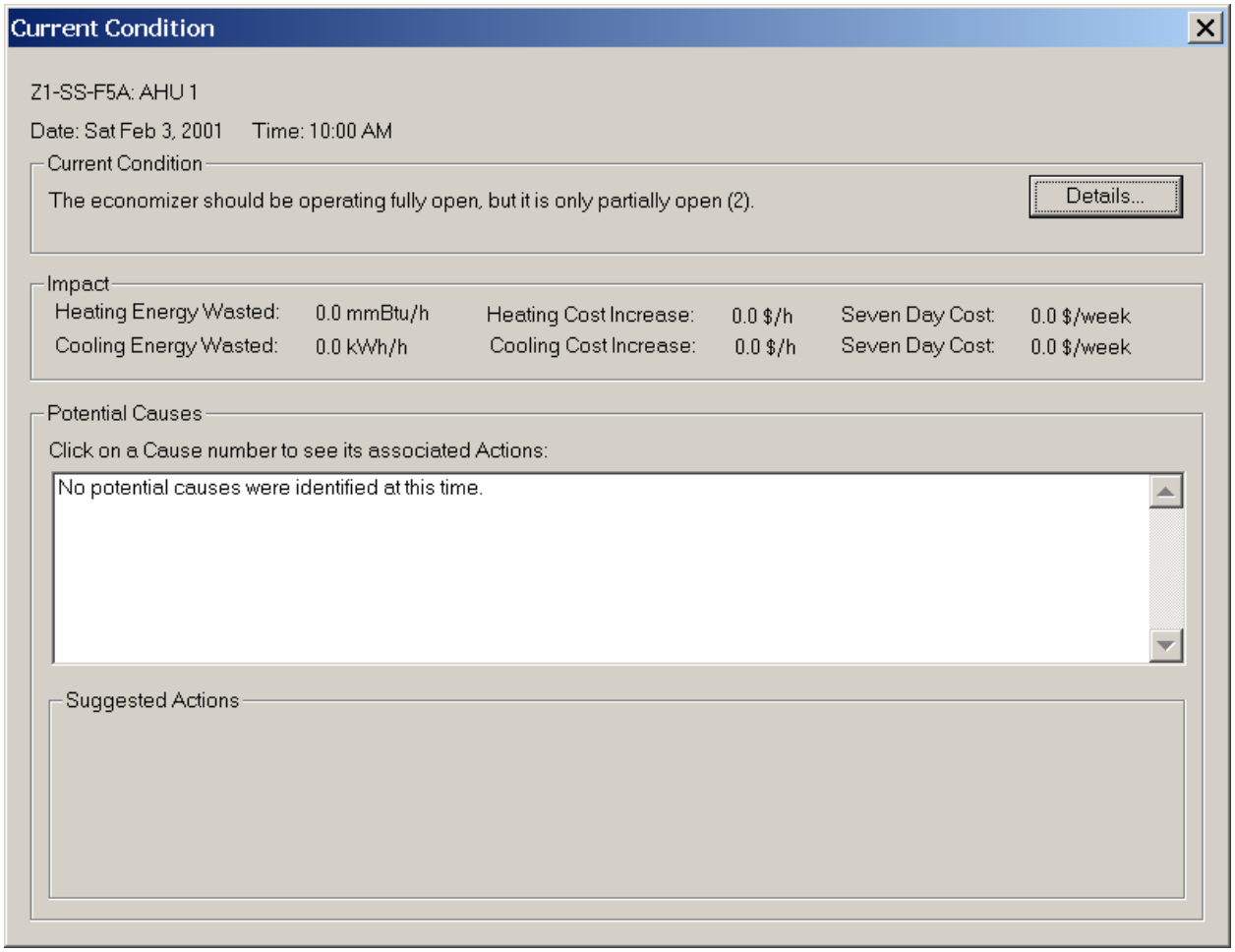



**Figure 47 – Current Conditions Dialogue for AHU-1 on February 3, 2001, at 10:00 a.m. for Blind Test Data Set Z1-SS-F5A with Normal OAE Sensitivity**

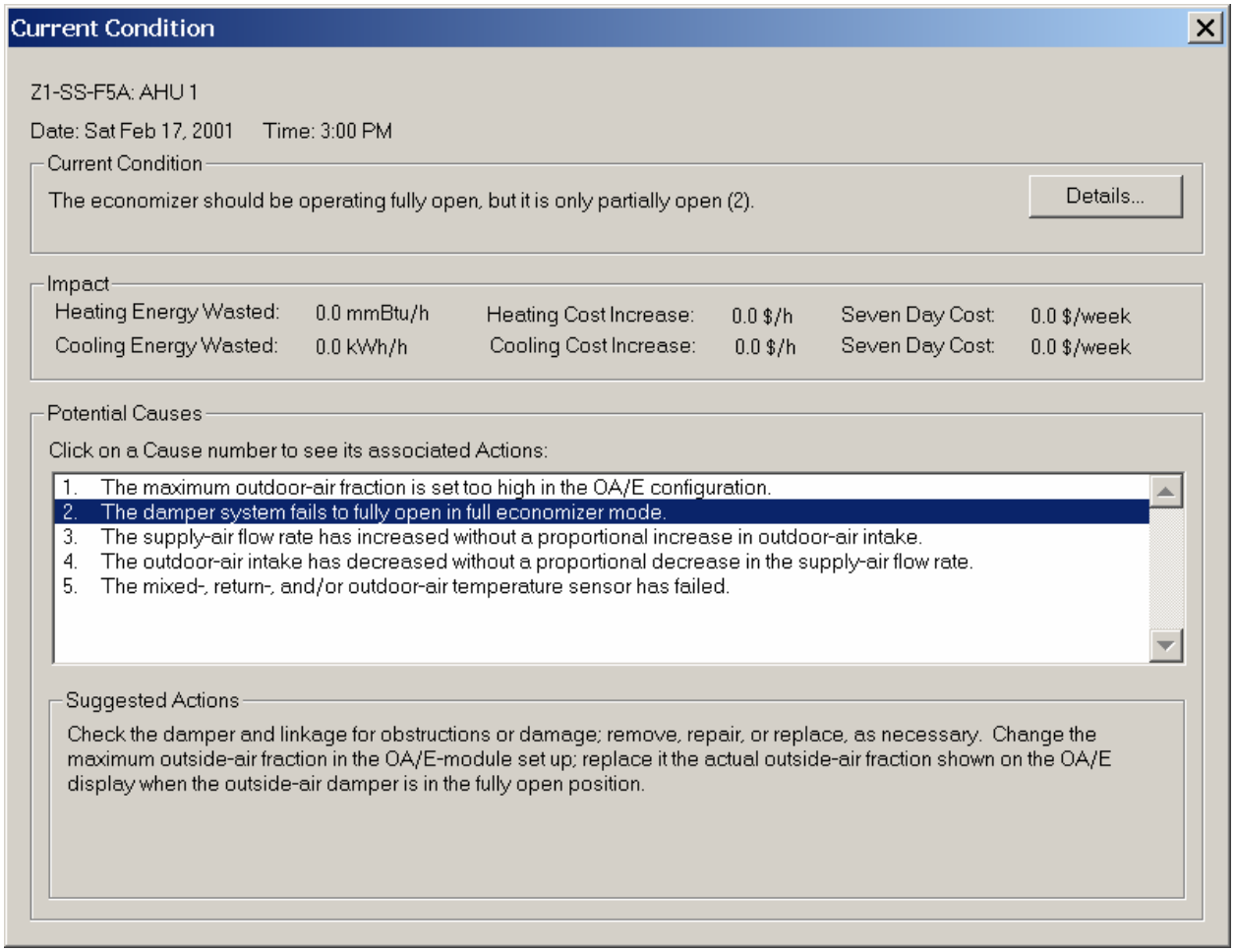



**Figure 48 – Current Conditions Dialogue for AHU-1 on February 17, 2001, at 3:00 p.m. for Blind Test Data Set Z1-SS-F5A with Normal OAE Sensitivity**

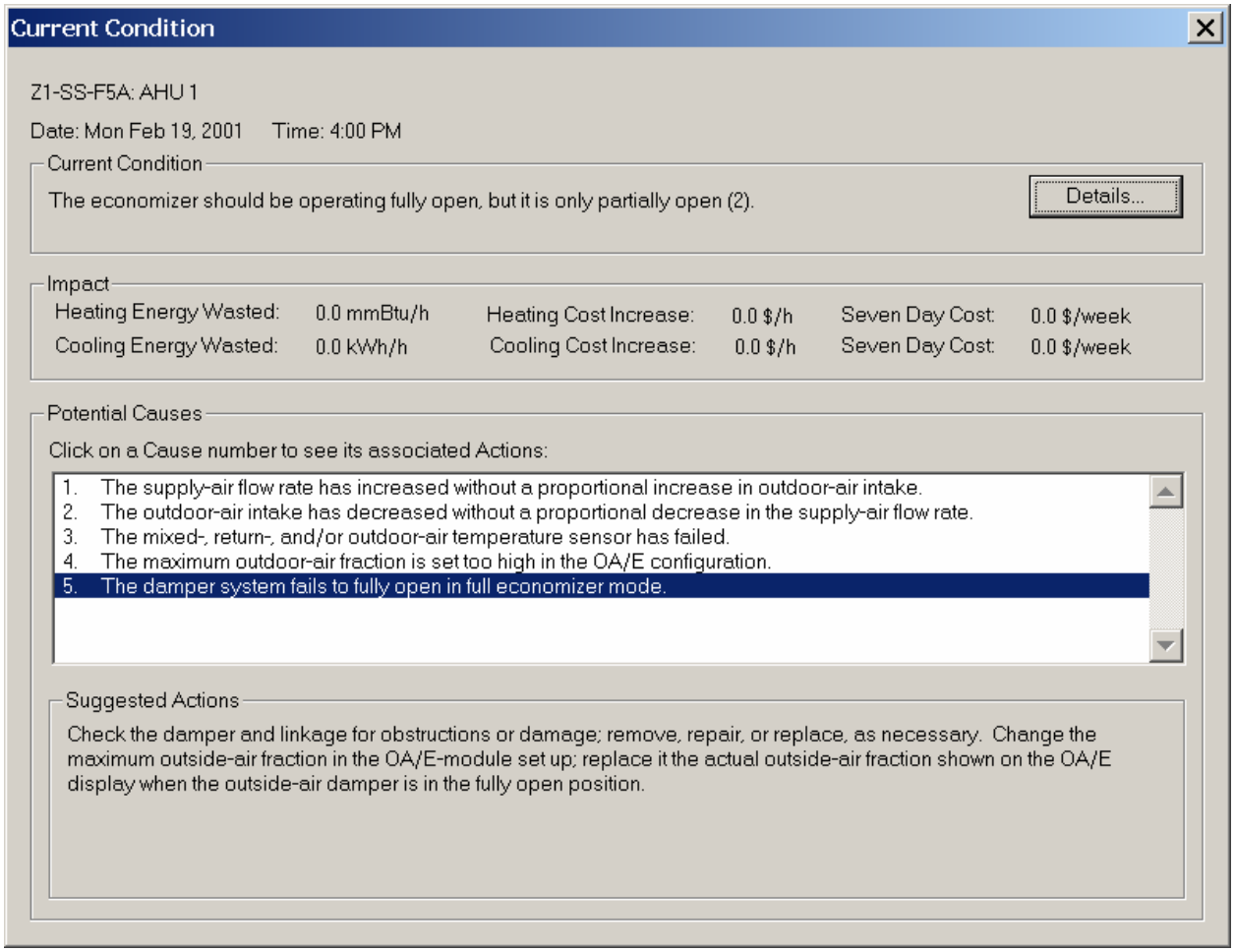



**Figure 49 – Current Conditions Dialogue for AHU-1 on February 19, 2001, at 4:00 p.m. for Blind Test Data Set Z1-SS-F5A**

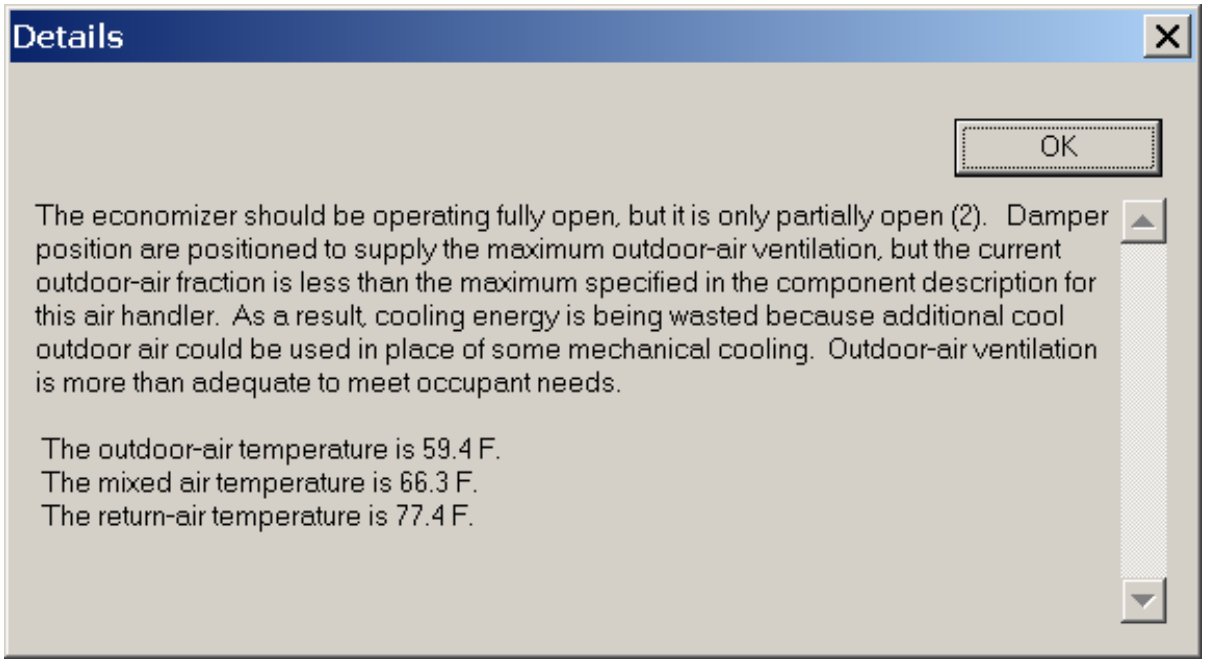



**Figure 50 – Details Dialogue for AHU-1 on February 19, 2001, at 4:00 p.m. for Blind Data Set Z1-SS-F5A**

The frequency of problems reported by the OAE in each major category, the corresponding reliability score and fraction of total hours in each category are shown in Table 3. The reliability score is the cumulative uncertainty calculated from propagating the measurement uncertainty through calculations done by the software. For Z1-SS-F5A test, almost 50% of the time AHU-1 was reporting to have "low economizer flow," indicative of a stuck damper. The frequency analysis shown in Table 3 is not part of the WBD user interface. The information on which it is based comes from the display, as well as the OAE database. Advanced users could perform this analysis, but it is not a feature of the OAE currently.

*For Z1-SS-F5A, both the OAE diagnostic results and the frequency analysis point to a damper that is stuck between its minimum and fully-open positions.*

**Table 3 – Frequency of the Problems for AHU-1 when the Building is Occupied (data set Z1-SS-F5A) with Normal OAE Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | 0.717 | 5 | 2.5 |
| Control Problem – Excess Energy | | 0 | 0.0 |
| Excess Ventilation | 0.869 | 1 | 0.5 |
| Inadequate Ventilation | | 0 | 0.0 |
| Low Economizer Flow | 0.777 | 96 | 48.0 |
| OK but incomplete | 0.702 | 47 | 23.5 |
| Operation OK | 0.759 | 51 | 25.5 |
| Total | | 200 | 100 |

### 6.5.2 Data Set Z2-SS-F5B

The data set Z2-SS-F5A has 3 weeks of blind test data from AHU-2, which serves zone 2 in the VCBT. The simulation was based on swing-season weather data. Figure 51 shows the screen shot of the OAE diagnostic results for this blind test data set. With the exception of a few gray and red cells, most cells are white, which indicates proper AHU operation. We recommend users ignore sporadic indications of operation problems and instead wait for the appearance of several sequential fault indictors or faults occurring in a repetitive pattern over time (e.g., at 1 p.m. on every week day).

Increasing the OAE detection sensitivity caused it to indicate a number of blue cells, as show in Figure 52. In general, blue cells indicate inadequate ventilation when the AHU is not economizing. The list of possible causes for this fault condition is shown in Figure 53. The most likely cause of the fault is either a temperature sensor problem or lack of adequate ventilation.

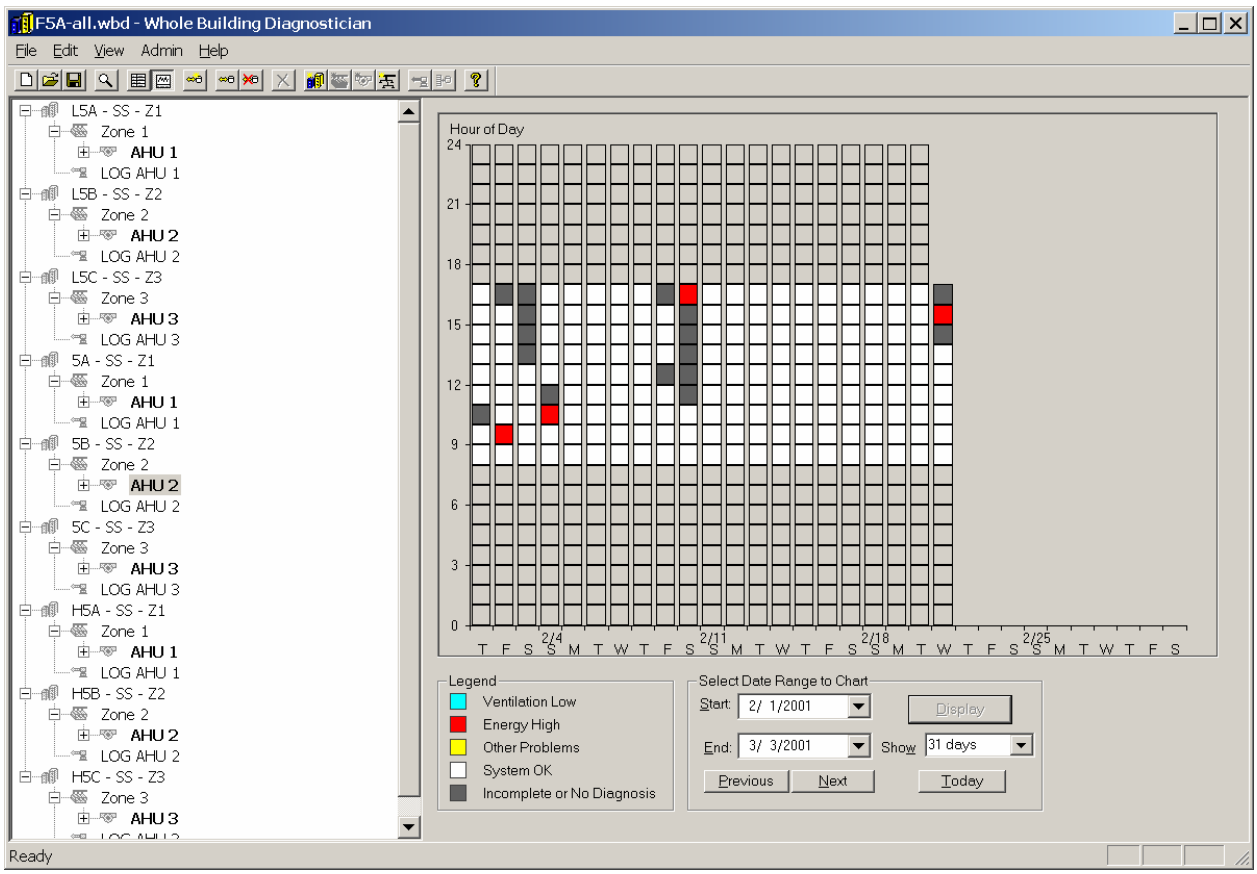



**Figure 51 – OAE Diagnostic Results for AHU-2 with Blind Test Data Set Z2-SS-F5B for a Swing Season with Normal OAE Sensitivity**

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and the fraction of total hours in each category are shown in Table 4. For Z2-SS-F5A test, almost 84% of the time, AHU-2 was reported to be operating properly and 10% of the time it showed inadequate ventilation.

*For Z2-SS-F5B, the OAE using high sensitivity reported: 1) inadequate ventilation resulting from an outdoor-air damper problem during occupied hours while not economizing or 2) a temperature sensor problem. No problem was detected when the OAE was run at normal sensitivity.*

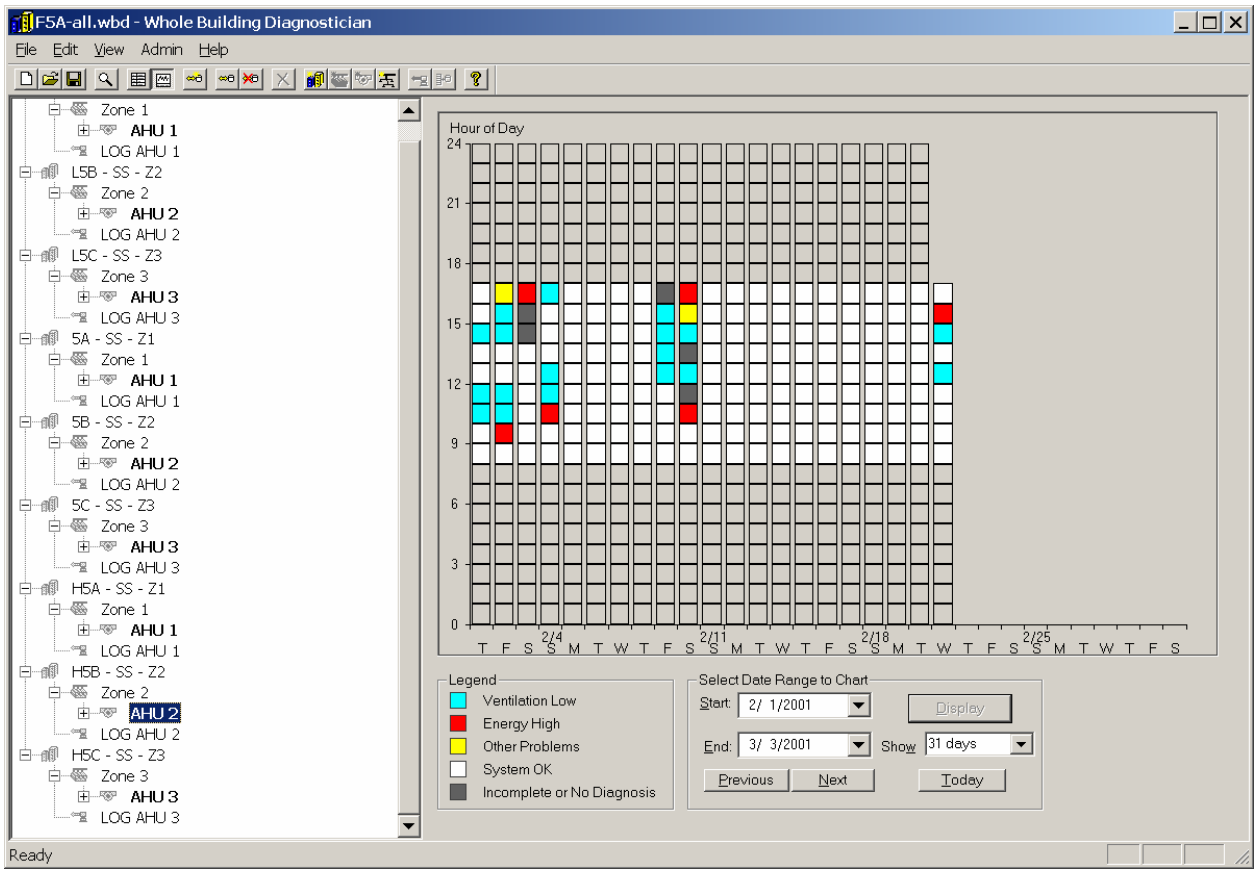



**Figure 52 – OAE Diagnostic Results for AHU-2 for Blind Test Data Set Z2-SS-F5B for a Swing Season with High OAE Sensitivity**

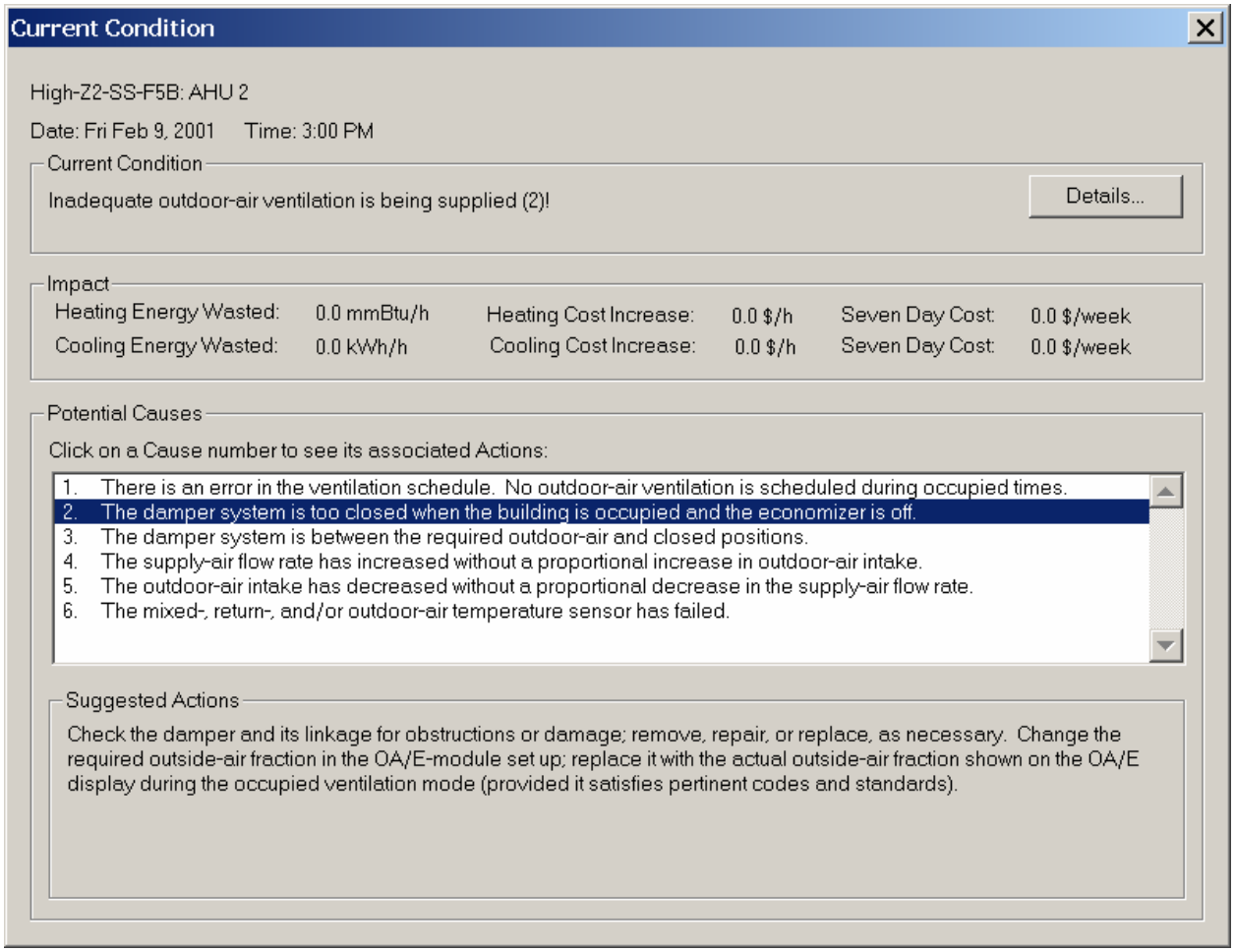



**Figure 53 – Current Conditions Dialogue for AHU-2 on February 9, 2001, at 3:00 p.m. for Blind Test Data Set Z2-SS-F5B**

**Table 4 – Frequency of the Problems for AHU-1 when the Building is Occupied (Z1-SS-F5A) with Normal Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | 0.909 | 2 | 1.1 |
| Control Problem – Excess Energy | | 0 | 0.0 |
| Excess Ventilation | 0.924 | 1 | 0.5 |
| Inadequate Ventilation | 0.923 | 18 | 9.5 |
| Low Economizer Flow | 0.878 | 5 | 2.6 |
| OK but incomplete | 0.958 | 5 | 2.6 |
| Operation OK | 0.569 | 158 | 83.6 |
| Total | | 189 | 100.0 |

### 6.5.3 Data Set Z3-SS-F5C

The data set named Z3-SS-F5A has 3 weeks of blind test data from AHU-3, which serves zone 3 in the VCBT. The simulation was based on swing-season weather data. Figure 54 shows the screen shot of the OAE diagnostic results for this data set with the OAE set at normal sensitivity. With the exception of a few gray cells, most of the cells are white, which indicates proper operation. Increasing the OAE detection sensitivity introduced a few blue and yellow cells (see Figure 55).

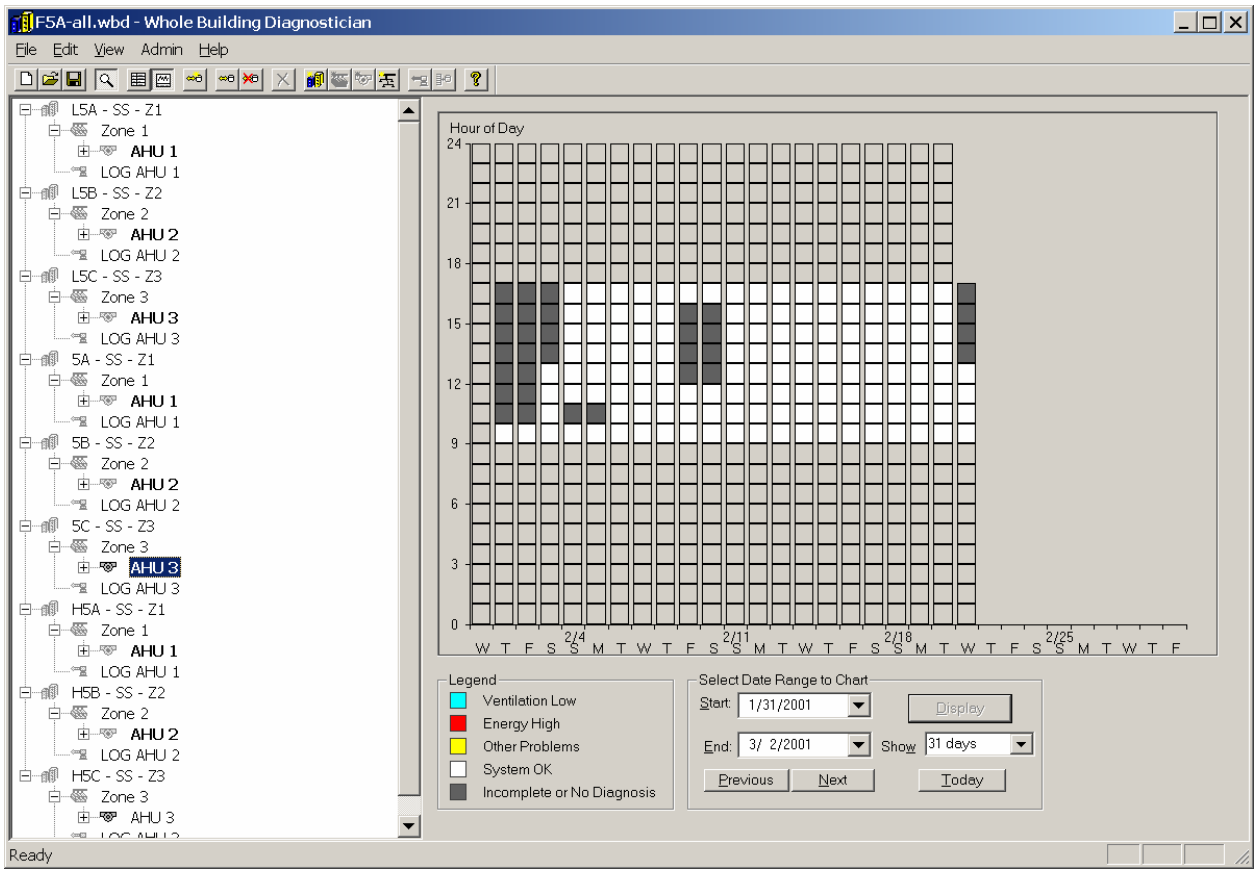



**Figure 54 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-SS-F5C for Swing Season Weather with Normal OAE Sensitivity**

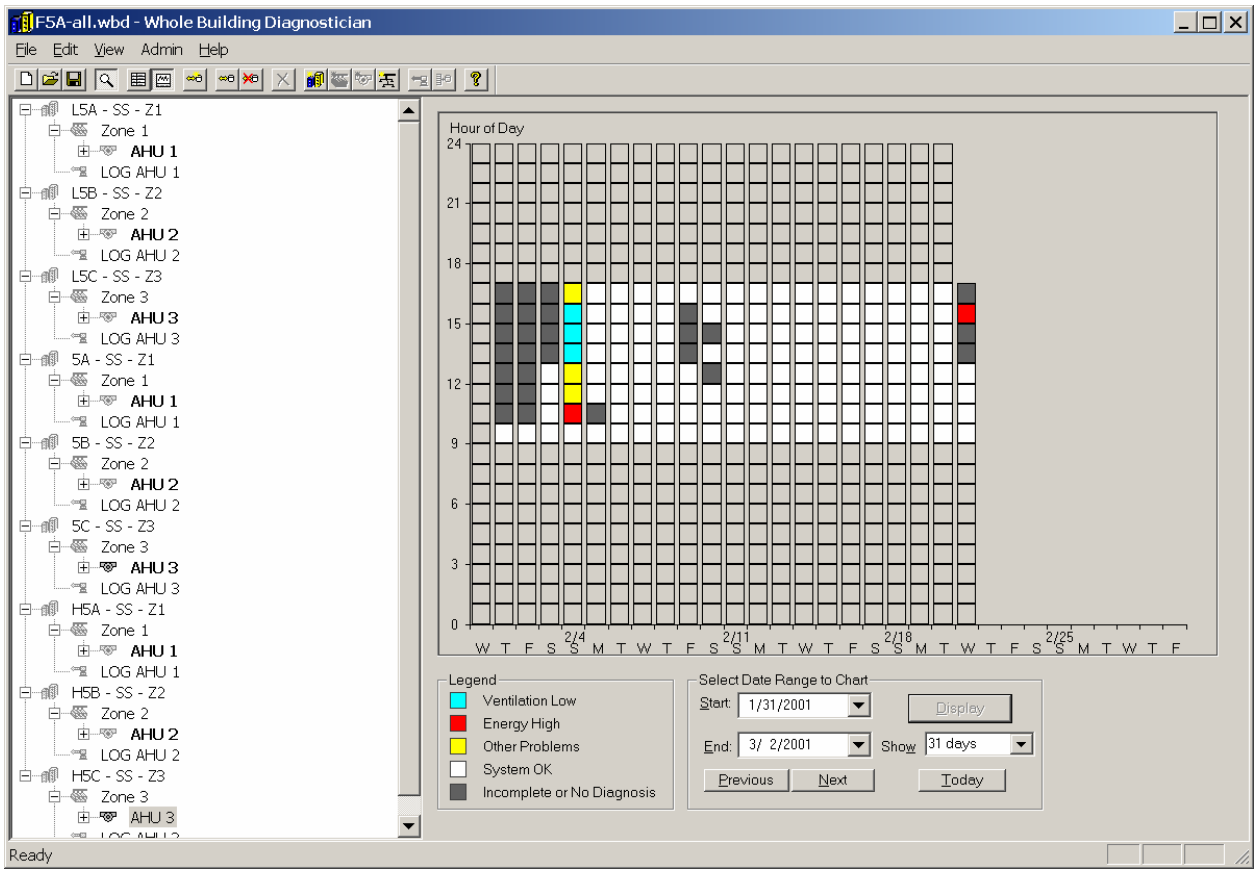



**Figure 55 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-SS-F5C for Swing Season Weather with High OAE Sensitivity**

Further manual analysis indicates that the data set had a return-air temperature sensor that was drifting over the 3-week period, as shown in Figure 56, but the OAE did not detect it. The OAE diagnostician did not detect this drift because conditions during the test made it impossible for the fault to manifest. However, if the problem continued into the summer season, it would have manifested for several hours and thereby provided a basis for detection. For example, on February 4, 2001, the outdoor-air conditions were such that the problem did manifest (Figure 55) for most of the day (7 hours). After February 4, conditions were not favorable for the fault to manifest again. When there are no errors in the measurement of the outdoor-air and the mixed-air temperatures, and the measured outdoor-air temperature is greater than the actual return-air temperature, then a positive bias in the measured return-air temperature (including drift to this state) will be detected when the measured return-air temperature exceeds the measured mixed-air temperature (which is equal to the actual mixed-air temperature because there is no error in the mixed-air temperature measurement for this fault). Under these conditions the measured mixed-air temperature will be less than both the measured outdoor- and return-air temperatures.

In this test data set, however, this condition occurred only for a few hours out of the entire 3-week period. The same fault during the summer season, when the outdoor-air temperature is greater than the return-air temperature most of the time, was detected by the OAE (refer to blind test fault Z3-CS-F9 described later in this section). This fault has little consequence during

swing-season weather and, therefore, the consequence of the OAE not detecting it is minor. Therefore, when the fault has significant consequences (e.g., in summer), the OAE will detect it.

*For Z3-SS-F5C, the OAE diagnostic results indicated that no significant faults occurred. A temperature sensor was drifting but outdoor conditions were not favorable for the fault to manifest and the OAE to detect it.*

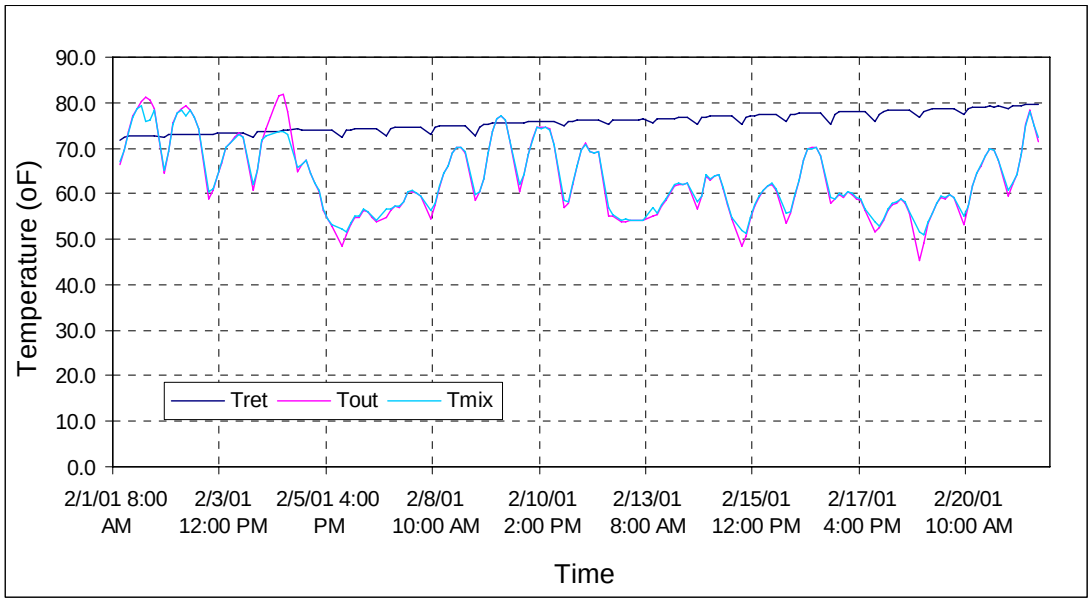



**Figure 56 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z3-SS-F5C**

### 6.5.4 Data Set Z1-HS-F4

The data set Z1-HS-F4 has 3 weeks of blind test data from AHU-1, which serves zone 1 in the VCBT. The simulation was based on heating-season weather data. Figure 57 shows the screen shot of the OAE diagnostic results for this data set for normal OAE sensitivity. With the exception of a few red cells, most cells are white, which indicates proper operation. Increasing the OAE sensitivity did not change the results significantly.

Further manual analysis indicates that the data set had a mixed-air temperature that was drifting over the 3-week period as shown in Figure 58, but the OAE did not detect it.

*For Z1-HS-F4, the OAE diagnostic results indicated that no significant faults occurred.*

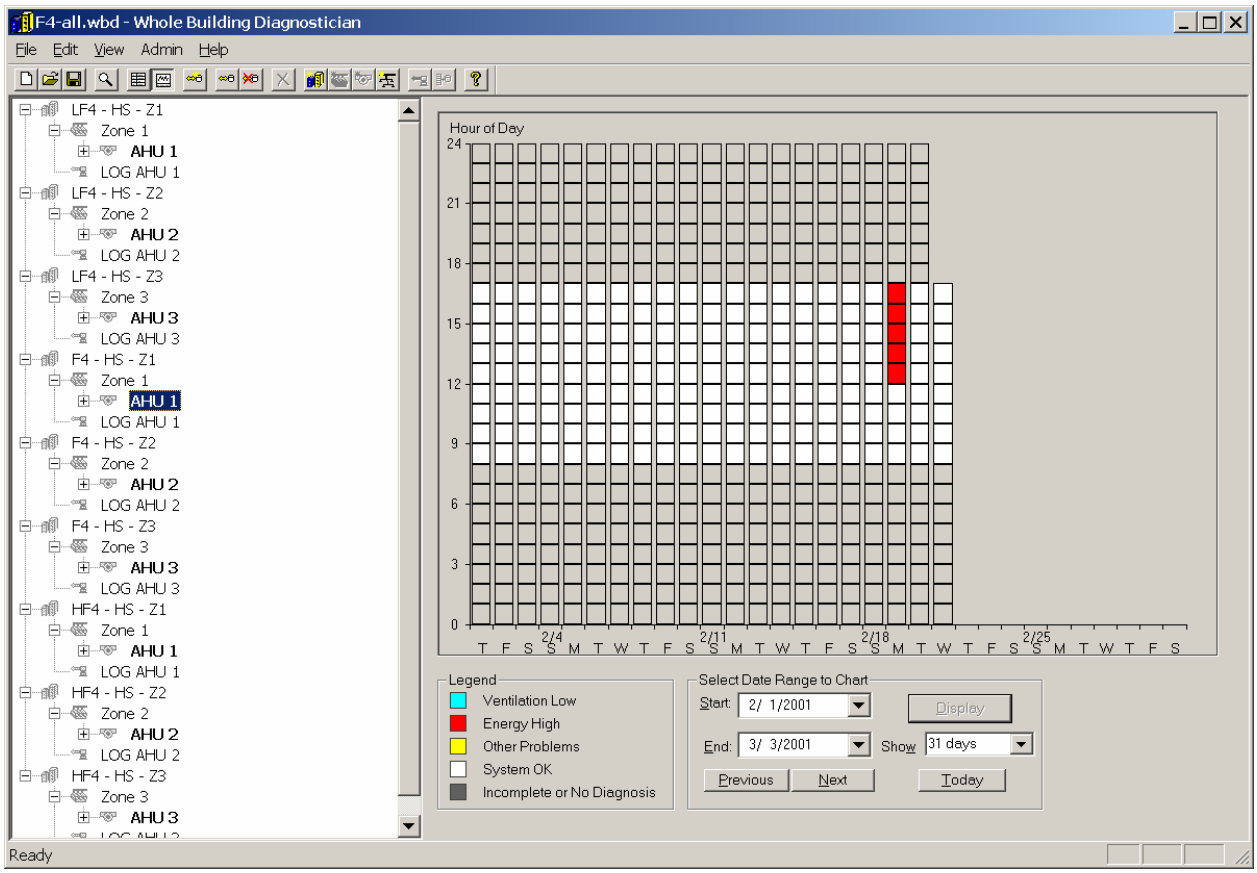



**Figure 57 – OAE Diagnostic Results for AHU-1 with Blind Test Data Set Z1-HS-F4 for Heating-Season Weather with Normal OAE Sensitivity**

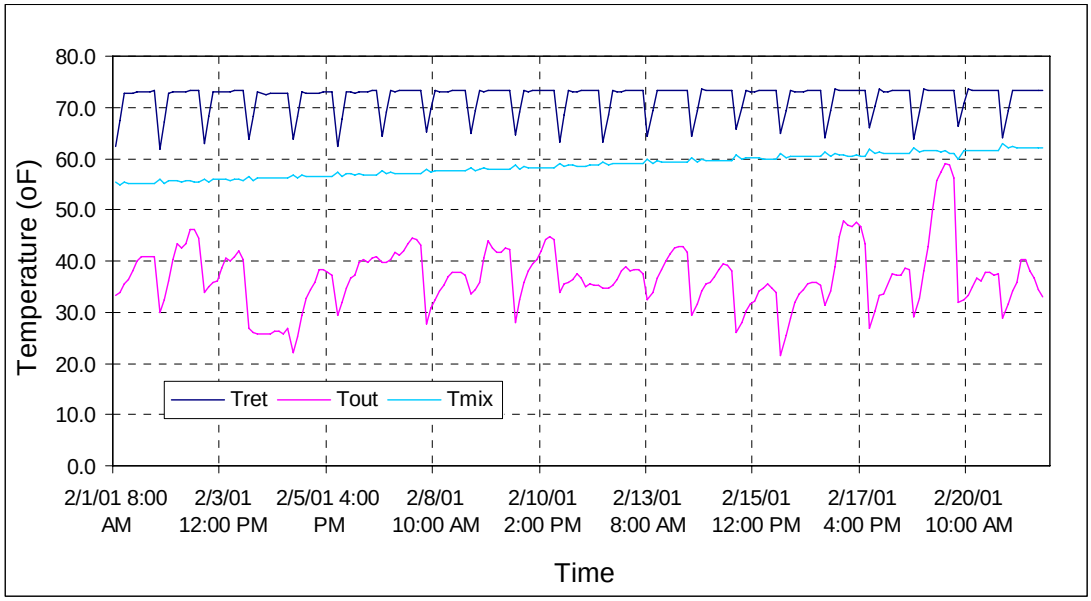



**Figure 58 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z1-SS-F4**

### 6.5.5 Data set Z2-HS-F4

The data set Z2-SS-F4 has 3 weeks of blind test data from AHU-2, which serves zone 2 in the VCBT. The simulation was based on heating-season weather data. Figure 59 shows the screen shot of the OAE diagnostic results for this data set for normal OAE sensitivity. All cells are white, indicating proper operation. Increasing the sensitivity did not change the results.

*For Z2-HS-F4, the OAE diagnostic results reported normal operations without faults.*

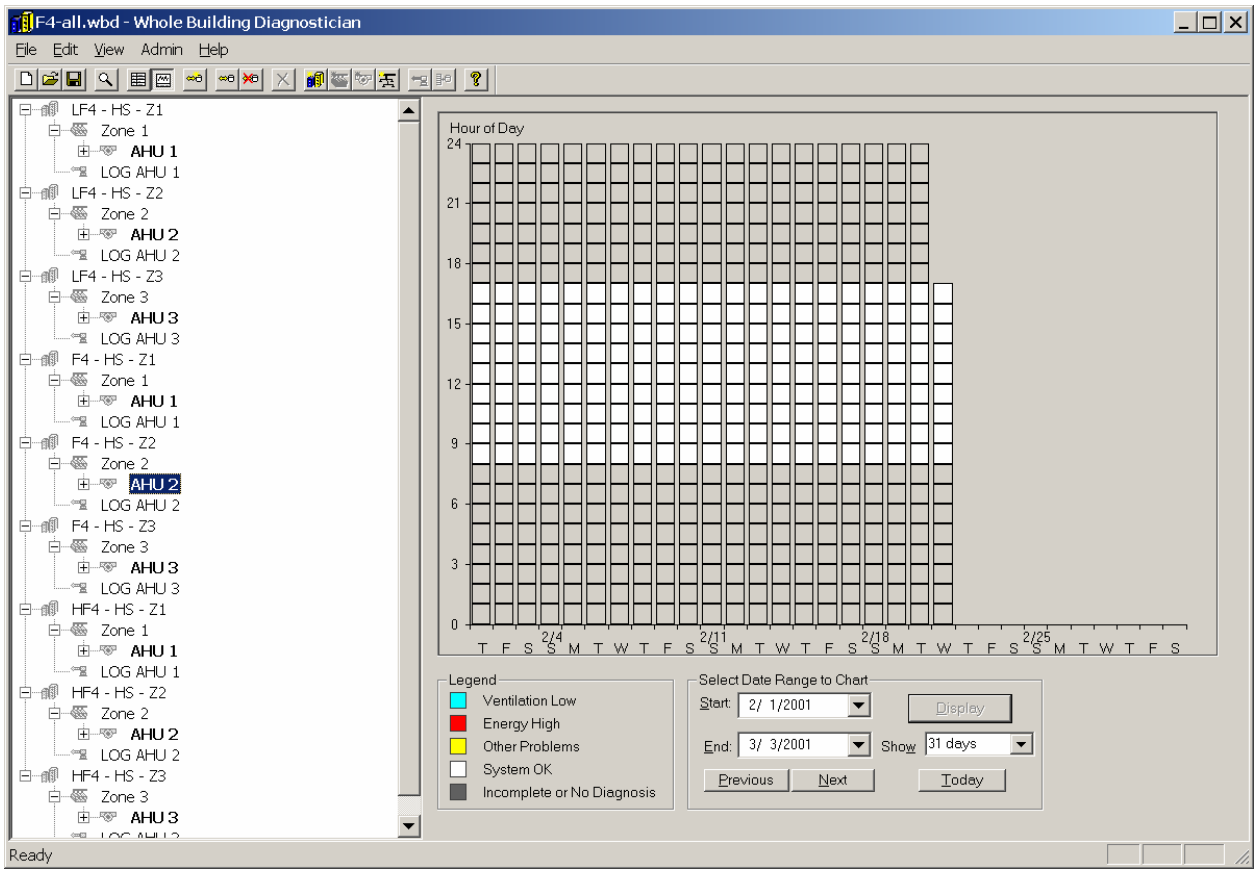



**Figure 59 – OAE Diagnostic Results for AHU-2 for Blind Test Data Set Z2-HS-F4 for Heating Season Weather with Normal OE Sensitivity**

### 6.5.6 Data Set Z3-HS-F4

The data set Z3-SS-F4 has 3 weeks of blind test data from AHU-3, which serves zone 3 in the VCBT. The simulation was based on heating-season weather data. Figure 60 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few white cells, most cells are yellow, indicating a problem in the other problem category (which usually is a temperature-sensor problem).

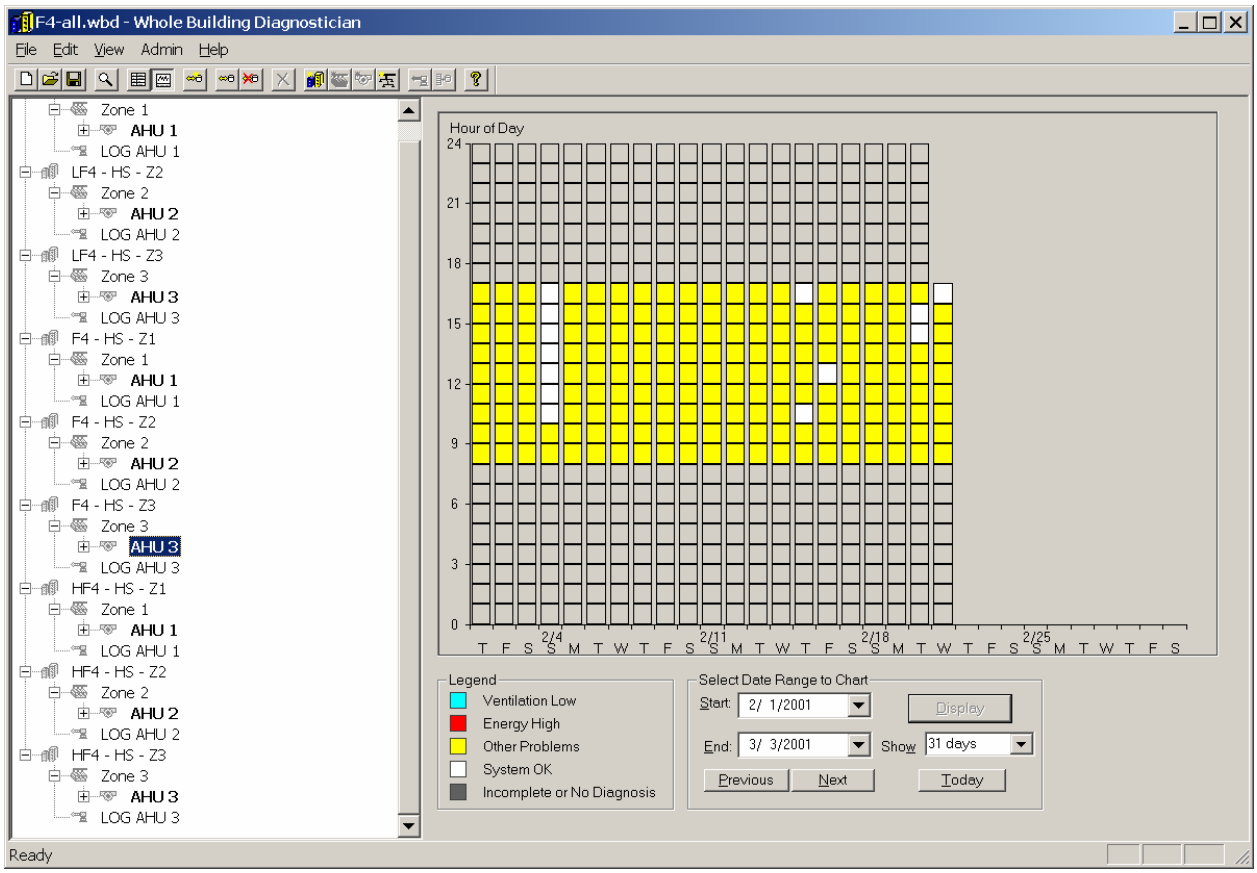



**Figure 60 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-HS-F4 for Heating Season Weather with Normal OAE Sensitivity**

The Current Condition and Details dialogue for 3:00 p.m. on February 15, 2001, is shown in Figure 61 and Figure 62, respectively. The conditions for that hour indicate a temperature sensor problem. The list of potential causes has just one cause, indicating that at least one of the three temperature sensors is faulty (outdoor-, mixed-, or return-air). Because the OAE diagnostician relies on minimum measured data, there is a lack of redundancy to isolate the faulty sensor. However, once the fault is detected, the operator can easily isolate the faulty sensor by checking the three sensors.

The frequency of problems reported by OAE in each major category, the corresponding reliability score, and fraction of total hours in each category are shown in Table 5. For the Z1-HS-F4 test, the OAE reported "Other Problems" 93% of the time, indicative of a temperature sensor problem.

Further manual analysis indicates that the return-air temperature is normal because it is in the expected range; therefore, the mixed-air or the outdoor-air temperature sensor is faulty (Figure 63).

*For Z3-HS-F4, both the OAE diagnostic results and the frequency analysis point to a temperature sensor problem.*

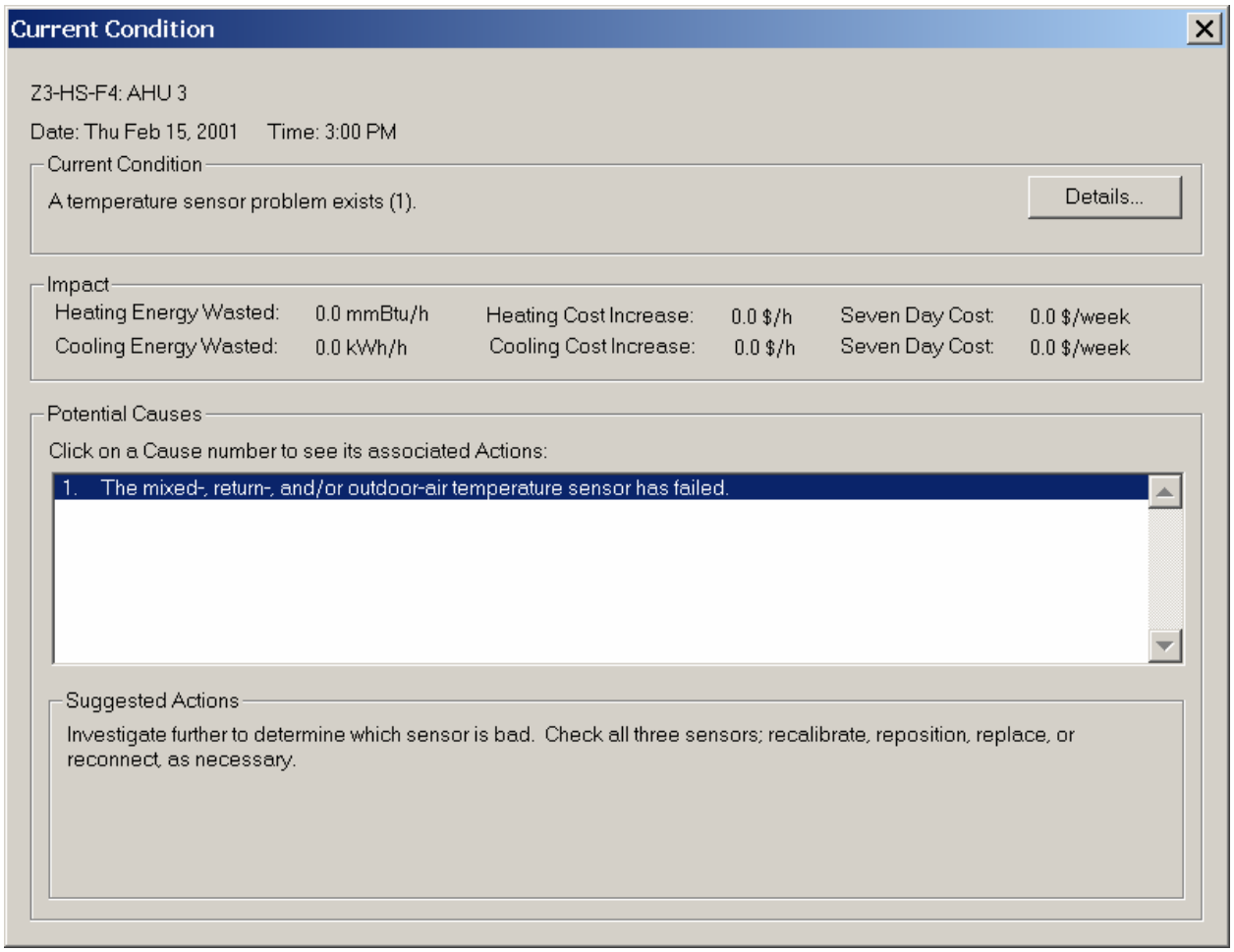



**Figure 61 – Current Conditions Dialogue for AHU-3 on February 15, 2001, at 3:00 p.m. for Blind Test Data Set Z3-HS-F4**

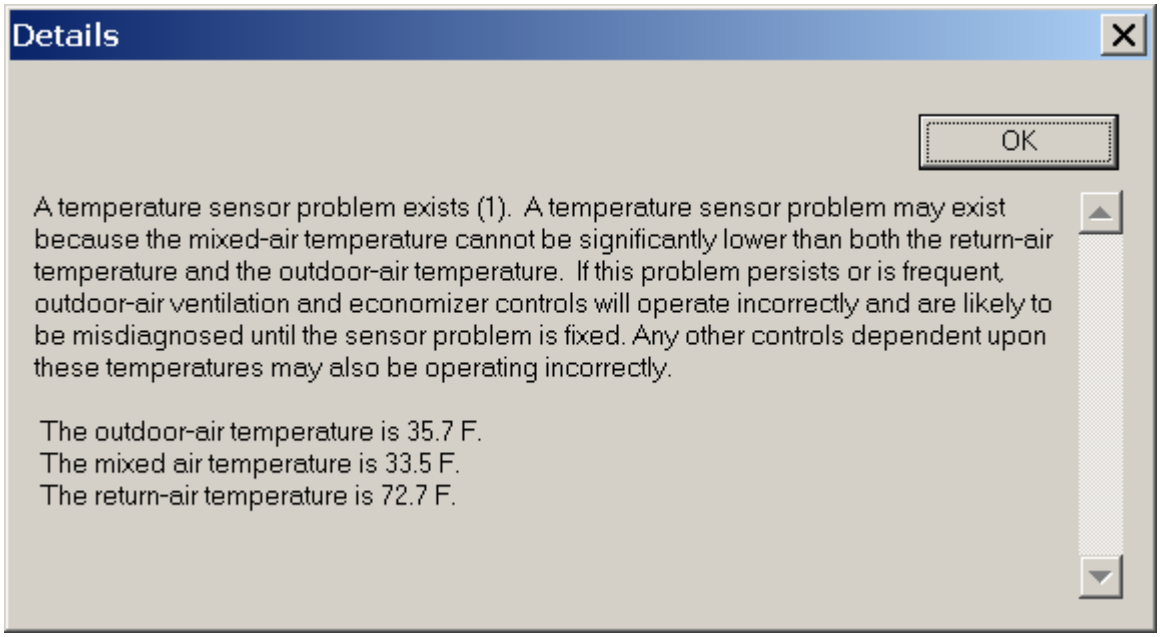



**Figure 62 – Details Dialogue for AHU-3 on February 15, 2001, at 3:00 p.m. Indicating that a Temperature Sensor Problem has Occurred**

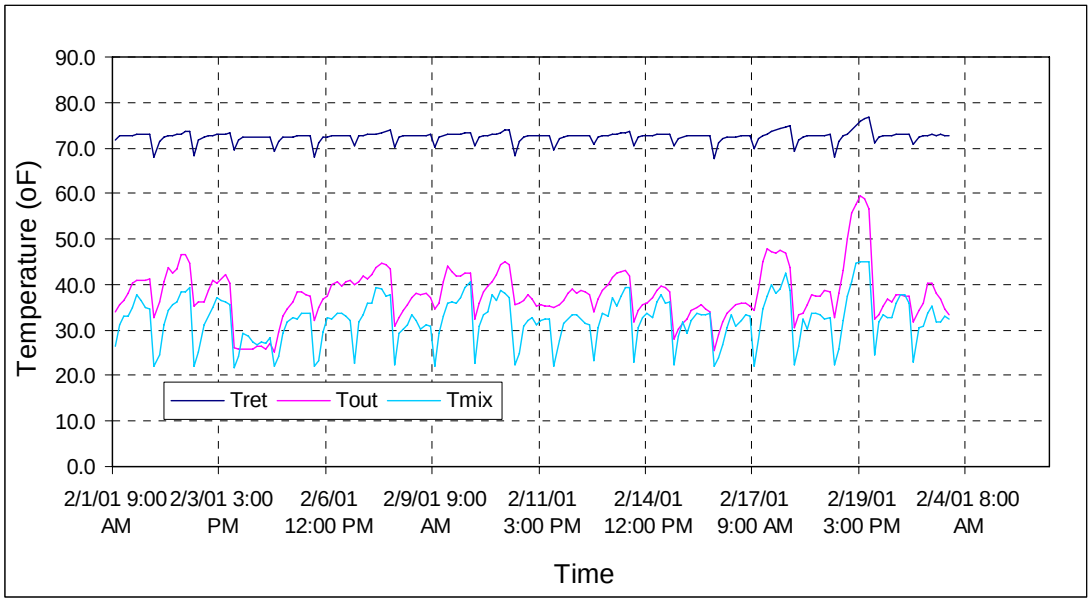



**Figure 63 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z3-HS-F4**

**Table 5 – Frequency of the Problems for AHU-3 when the Building is Occupied (data set Z3-HS-F4) with Normal OAE Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | 0.657 | 176 | 93.1 |
| Control Problem – Excess Energy | | 0 | 0.0 |
| Excess Ventilation | | 0 | 0.0 |
| Inadequate Ventilation | | 0 | 0.0 |
| Low Economizer Flow | | 0 | 0.0 |
| OK but incomplete | | 0 | 0.0 |
| Operation OK | 0.657 | 13 | 6.9 |
| Total | | 189 | 100 |

### 6.5.7 Data Set Z1-SS-F6

The data set Z1-SS-F6 has 3 weeks of blind test data from AHU-1, which serves zone 1 in the VCBT. The simulation was based on swing-season weather data. Figure 64 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. More than half the cells are white (indicating normal operation) and the rest are yellow, blue and red. Although the fault associated with each of the three colors is different, browsing through the colored cells indicates a single common cause shared by many of them, a temperature sensor problem (Figure 65).

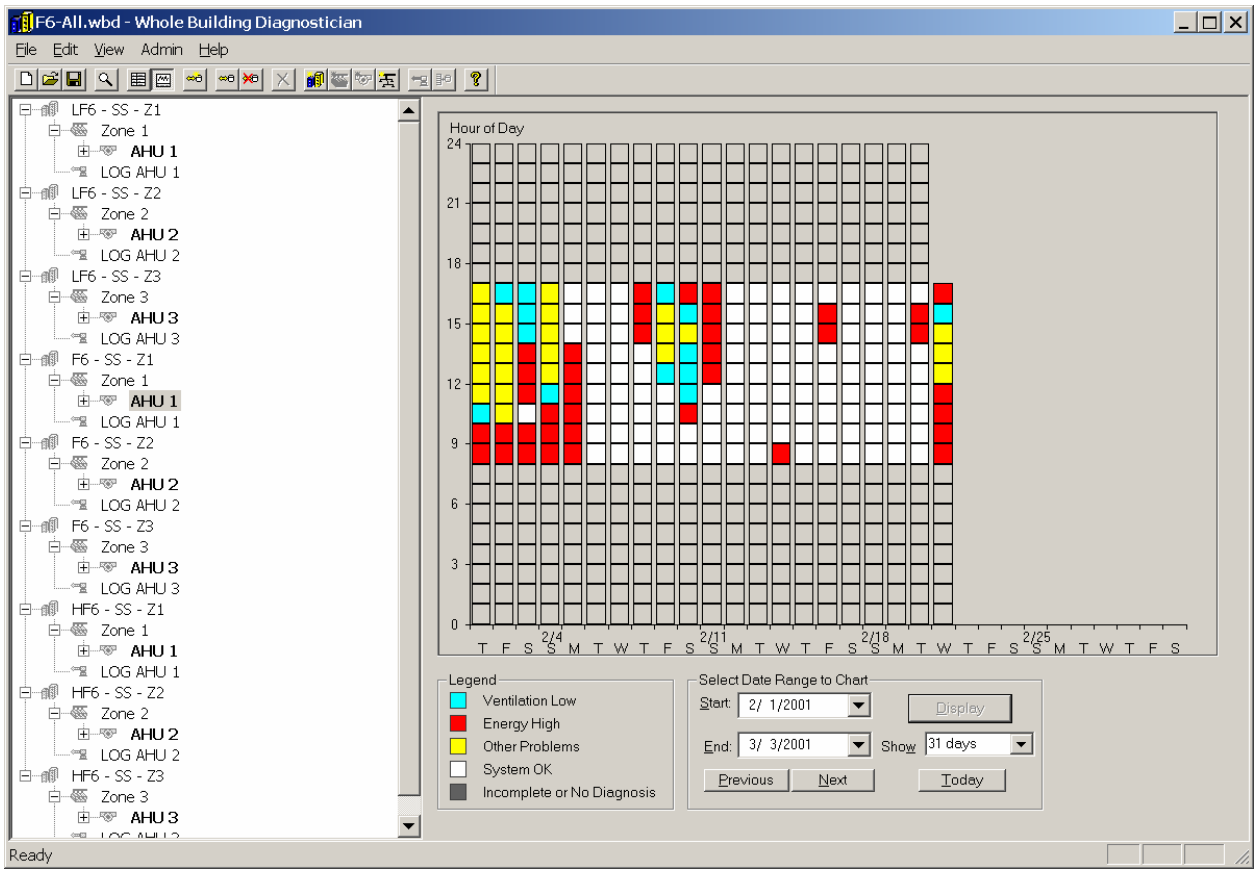



**Figure 64 – OAE Diagnostic Results for AHU-1 for Blind Test Data Set Z1-SS-F6 for Swing Season Weather with Normal OAE Sensitivity**

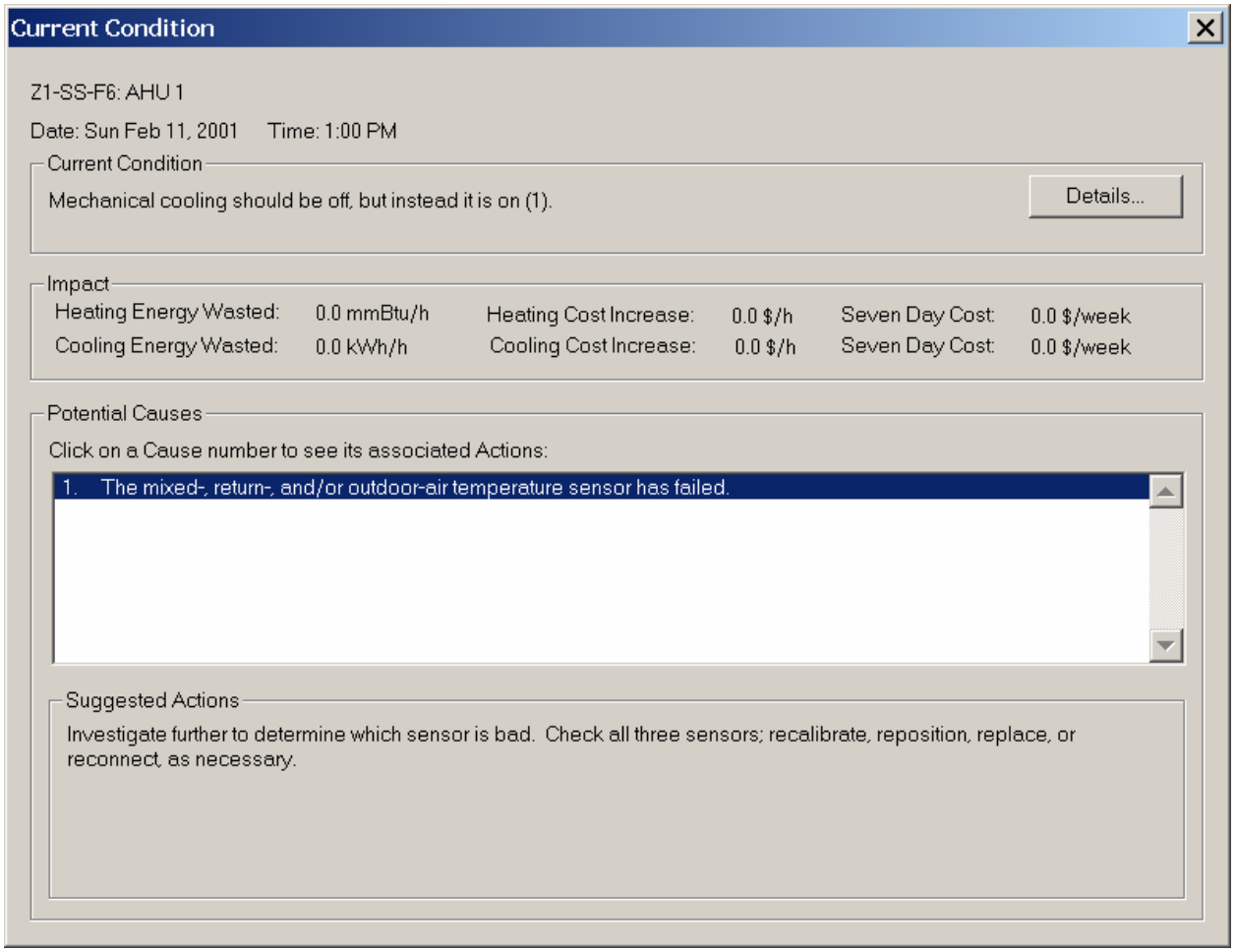



**Figure 65 – Current Conditions Dialogue for AHU-1 on February 11, 2001, at 1:00 p.m. for Blind Test Data Set Z1-SS-F6**

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and fraction of total occupied hours in each category are shown in Table 6. For the Z1-SS-F6 test, 60% of the time the OAE reported normal operation, 33% a control problem, and 7% inadequate ventilation.

Further manual analysis of the raw data indicates that the data set corresponded to a faulty outdoor-air temperature sensor that was reading a constant temperature over the 3 week period, as shown in Figure 66.

*For Z1-SS-F6, the OAE diagnostician reported a temperature sensor problem.*

**Table 6 – Frequency of the Problems for AHU-1 when the Building is Occupied (Z1-SS-F6) with Normal Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | 0.869 | 24 | 12.7 |
| Control Problem – Excess Energy | 0.500 | 38 | 20.1 |
| Excess Ventilation | | 0 | 0.0 |
| Inadequate Ventilation | 0.869 | 13 | 6.9 |
| Low Economizer Flow | | 0 | 0.0 |
| OK but incomplete | | 0 | 0.0 |
| Operation OK | 0.744 | 114 | 60.3 |
| Total | | 189 | 100 |

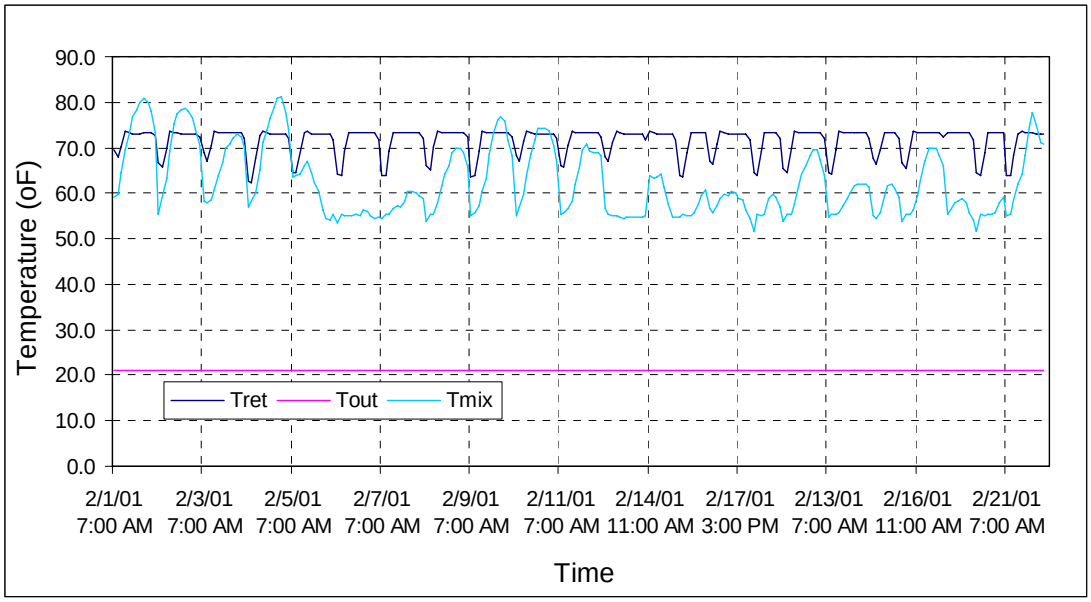



**Figure 66 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z1-SS-F6**

### 6.5.8 Data Set Z2-SS-F6

The data set Z2-SS-F6 has 3 weeks of blind test data from AHU-2, which serves zone 2 in the VCBT. The simulation was based on swing-season weather data. Figure 67 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few yellow, red, blue, and gray cells, most cells are white. Browsing through the colored cells revealed no potential causes for most cells (Figure 68). Increasing the sensitivity of detection did not change the number of colored cells, but a single cause was reported in almost all cases, as shown in Figure 69.

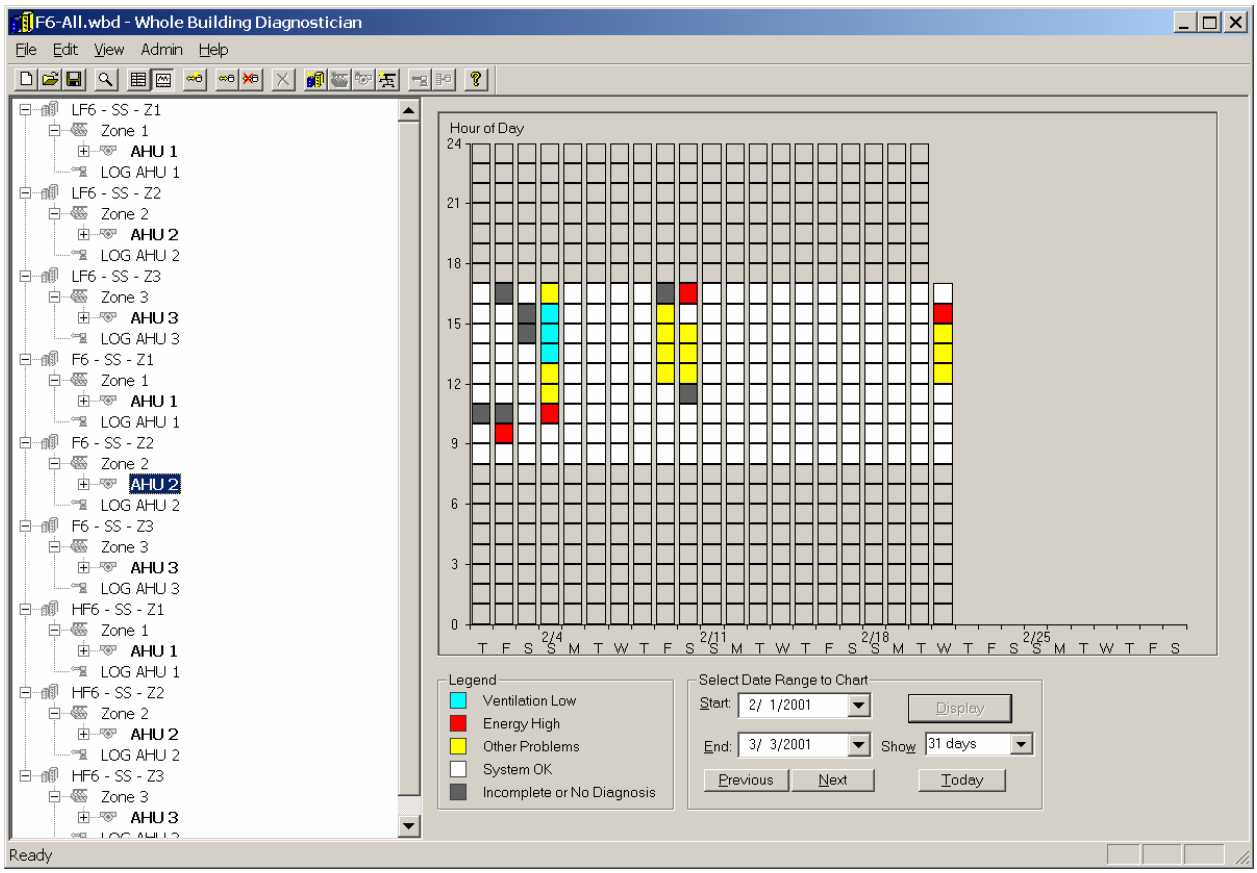



**Figure 67 – OAE Diagnostic Results for AHU-2 for Blind Test Data Set Z2-SS-F6 for Swing Season Weather with Normal OAE Sensitivity**

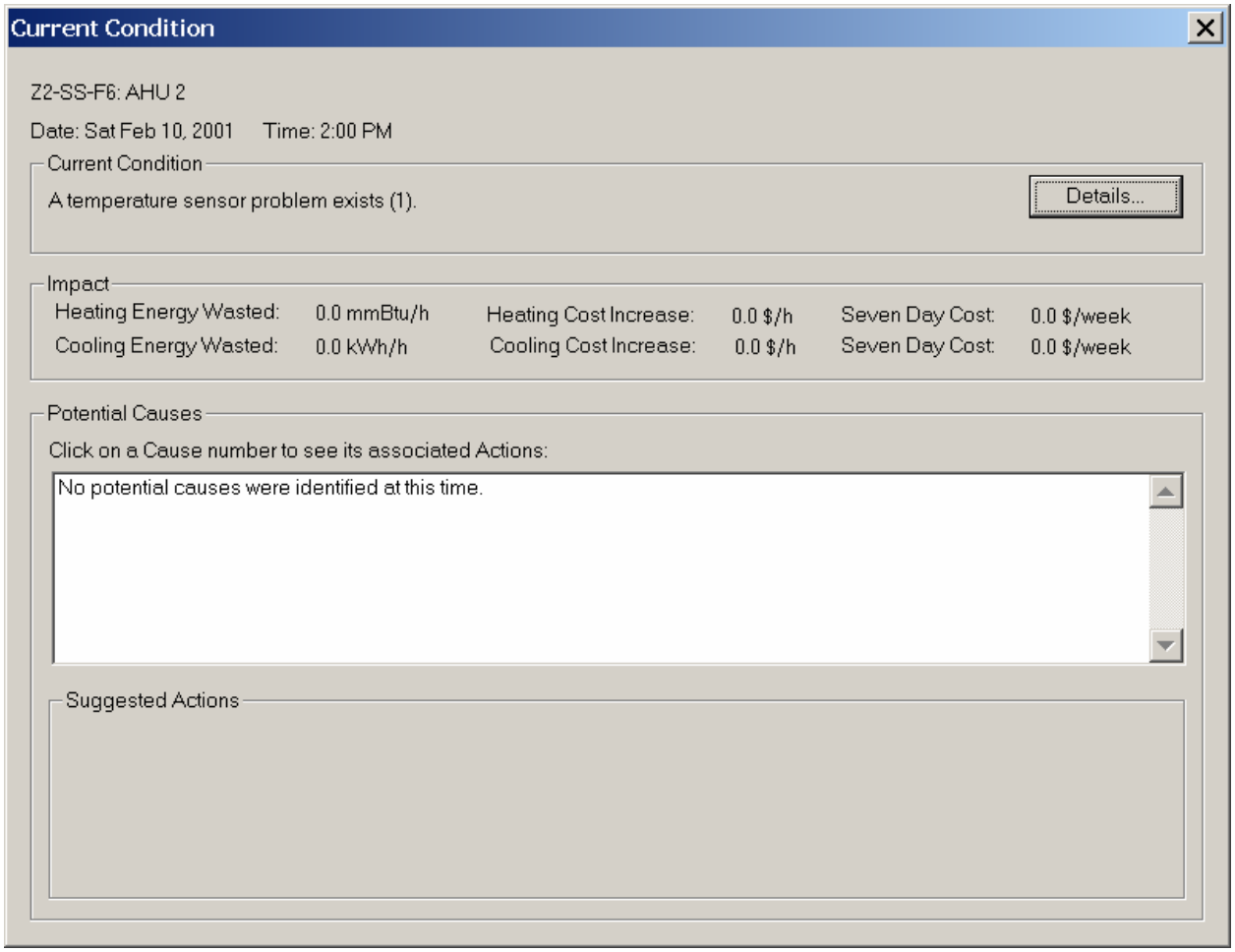



**Figure 68 – Current Conditions Dialogue for AHU-2 on February 10, 2001, at 2:00 p.m. for Blind Test Data Set Z2-SS-F6 with the Normal OAE Sensitivity Setting**

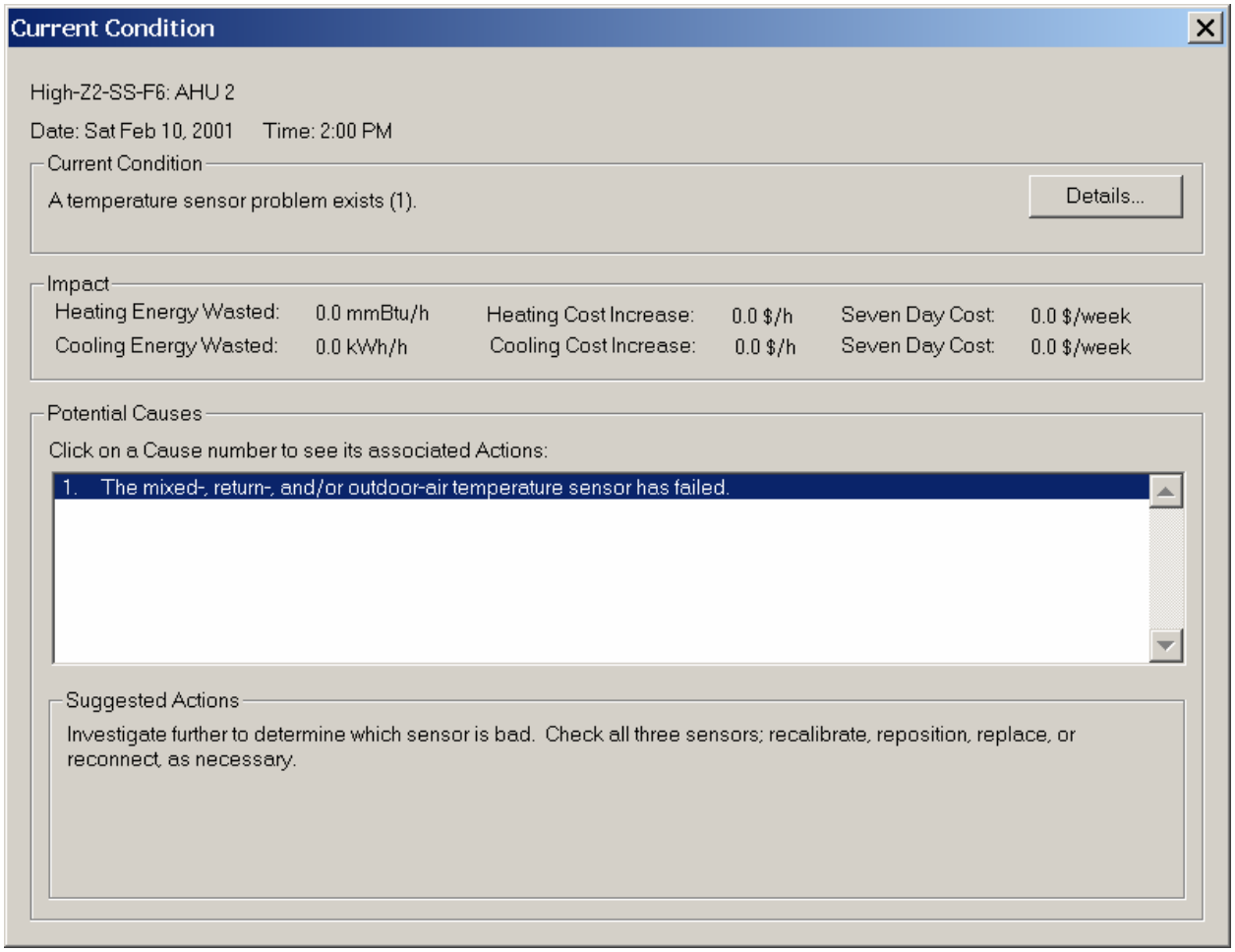



**Figure 69 – Current Conditions Dialogue for AHU-2 on February 10, 2001, at 2:00 p.m. for Blind Test Data Set Z2-SS-F6 with the High OAE Sensitivity Setting**

The frequency of problems reported by the OAE in each major category, the corresponding reliability score and fraction of total occupied hours in each category are shown in Table 7. For data set Z2-SS-F6, 86% of the time the OAE reported normal operation, 7% control problem, 2% inadequate ventilation, 2% low economizer flow, and 4% incomplete diagnosis.

**Table 7 – Frequency of the Problems for AHU-2 when the Building is Occupied (Z2-SS-F6) with Normal OAE Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | 0.657 | 13 | 6.9 |
| Control Problem – Excess Energy | | 0 | 0.0 |
| Excess Ventilation | | 0 | 0.0 |
| Inadequate Ventilation | 0.657 | 3 | 1.6 |
| Low Economizer Flow | 0.802 | 4 | 2.1 |
| OK but incomplete | 0.775 | 7 | 3.7 |
| Operation OK | 0.542 | 162 | 85.7 |
| Total | | 189 | 100 |

A closer look at raw data indicates a drift in the return-air temperature sensor. The drift could not be detected on a consistent basis because of unfavorable outdoor-air conditions. When the conditions were favorable (conditions not favorable for economizing, i.e., when outdoor-air temperature > return-air temperature) for the fault to manifest, for example, on February 4, 9, and 10, the OAE detected the fault and reported a temperature sensor problem. Because the outdoor-air temperature for most times in this data set was lower than the return-air temperature, it did not affect the AHU operation. If the fault had continued into the summer season, it would have manifested more often because the outdoor air would have been warmer than the return air (conditions not favorable of economizing). Under those conditions, the measured mixed-air temperature should be between the measured outdoor- and return-air temperatures. If the measured mixed-air temperature were not in this range, a fault would be detected by the OAE. For more detailed explanation refer to section 6.5.3.

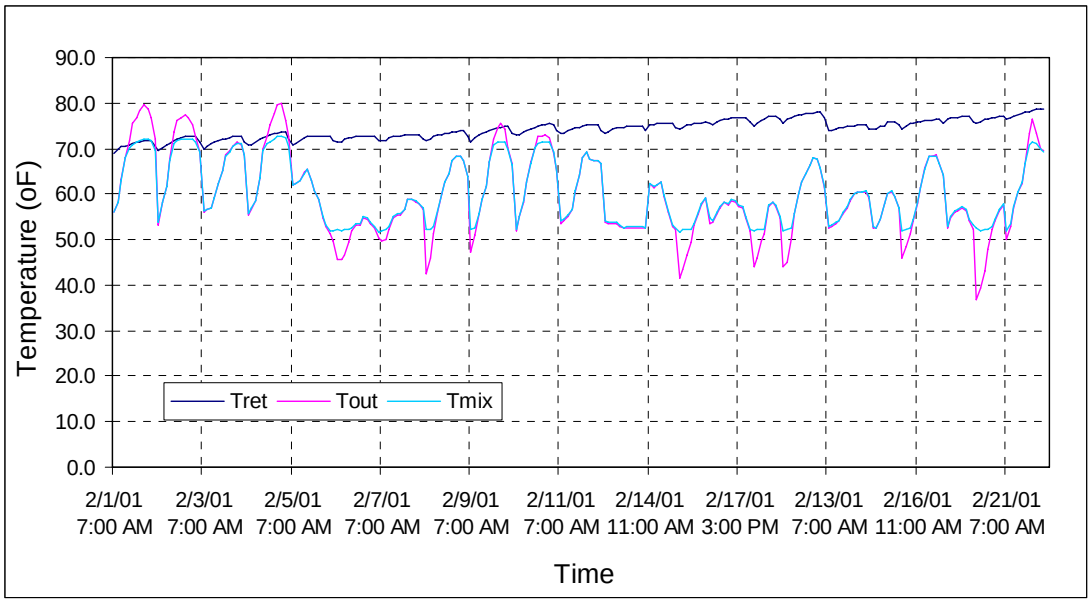



**Figure 70 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z2-SS-F6**

*For Z2-SS-F6, the OAE diagnostician reported a temperature sensor problem.*

### 6.5.9 Data Set Z3-SS-F6

The data set Z3-SS-F6 has three weeks of blind test data from AHU-3, which serves zone 3 in the VCBT. The simulation was based on swing-season weather data. Figure 71 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and white cells, most of the cells are red, indicating energy waste. Browsing through the red cells reveals that the common problem reported is that the economizer should be operating fully open but it is only partial open (Figure 72). There are five to six potential causes reported for most cells, as shown in Figure 72. With the exception of potential causes 1 and 4, the other three causes are related to configuration/setup of the diagnostician. Therefore, the fault is attributable to the outdoor-damper system not fully opening when conditions are favorable for economizing either because the damper is stuck or the economizer controls are not properly functioning.

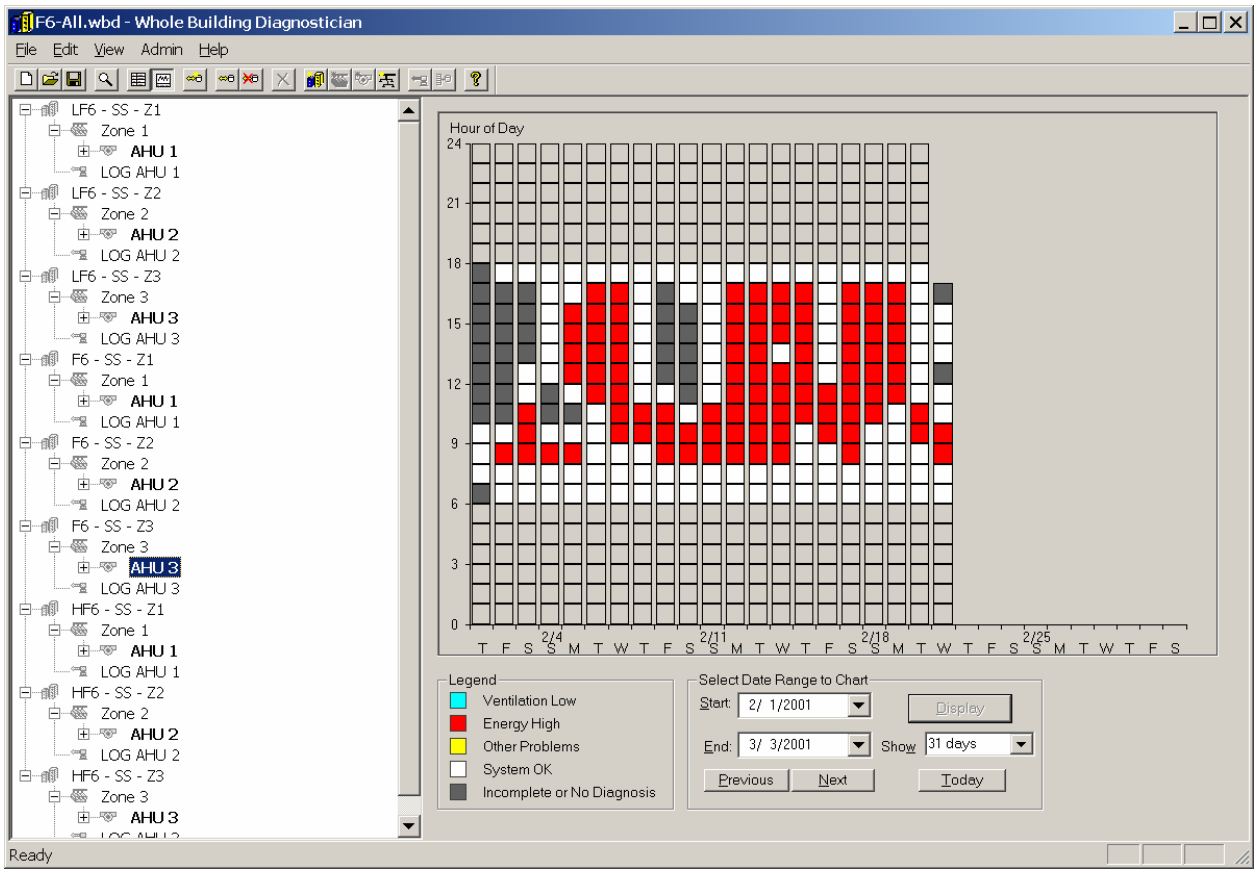



**Figure 71 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-SS-F6 for Swing-Season Weather with Normal OAE Sensitivity**

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and fraction of total occupied hours in each category are shown in Table 8. For data set Z3-SS-F6, 50% of the time the OAE reported low economizer flow, 18% incomplete diagnosis and 32% normal operation.

*For Z3-SS-F6, the OAE diagnostician reported low economizer flow caused by the outdoor-air damper being stuck or improper economizer control.*

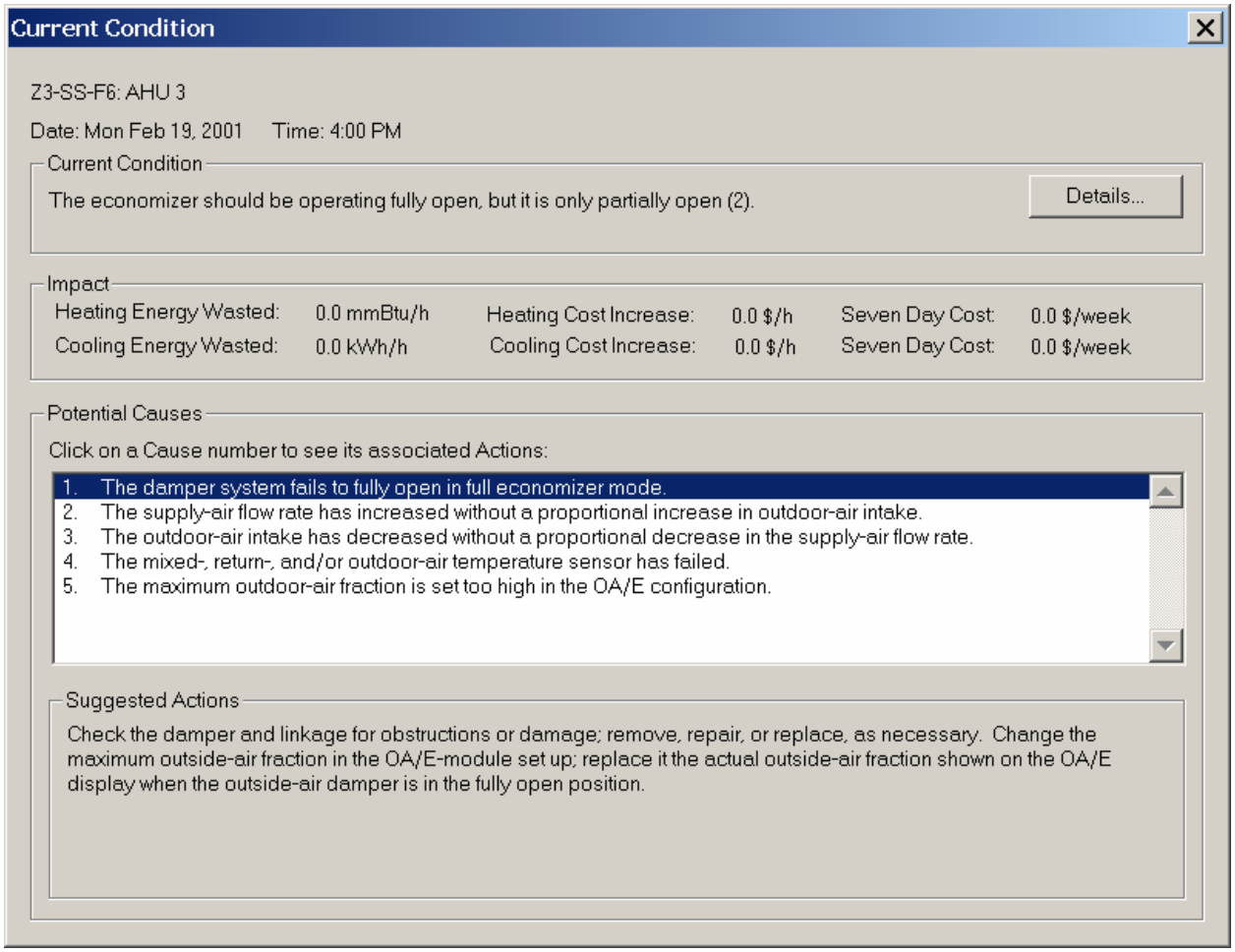



**Figure 72 – Current Conditions Dialogue for AHU-3 on February 19, 2001, at 4:00 p.m. for Blind Test Data Set Z3-SS-F6**

**Table 8 – Frequency of the Problems for AHU-3 when the Building is Occupied (data set Z3-SS-F6) with Normal OAE Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | | 0 | 0.0 |
| Control Problem – Excess Energy | | 0 | 0.0 |
| Excess Ventilation | | 0 | 0.0 |
| Inadequate Ventilation | | 0 | 0.0 |
| Low Economizer Flow | 0.553 | 96 | 50.8 |
| OK but incomplete | 0.621 | 33 | 17.5 |
| Operation OK | 0.583 | 60 | 31.7 |
| Total | | 189 | 100.0 |

### 6.5.10 Data Set Z1-SS-F8

The data set Z1-SS-F8 has 3 weeks of blind test data from AHU-1, which serves zone 1 in the VCBT. The simulation was based on swing-season weather data. Figure 73 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and white cells, most of the cells are colored (yellow, red and blue). When a significant number of cells are yellow, it generally indicates a faulty temperature sensor. Browsing through the yellow cells confirms that the problem is a faulty temperature sensor (Figure 74).

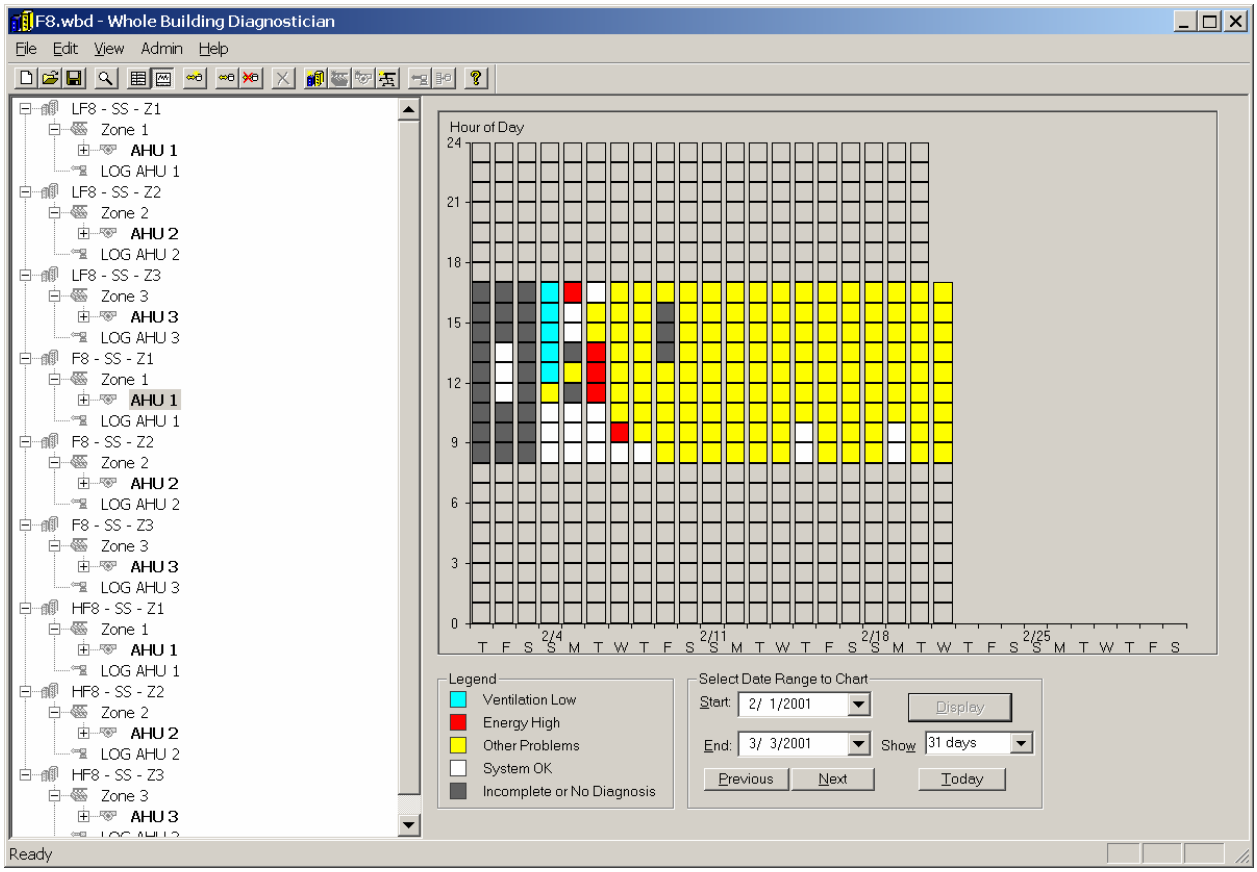



**Figure 73 – OAE Diagnostic Results for AHU-1 for Blind Test Data Set Z1-SS-F8 for Swing-Season Weather with Normal OAE Sensitivity**

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and fraction of total occupied hours in each category are shown in Table 9. For data set Z1-SS-F8, over 68% of the time the OAE reported control problems (other problems), 2% inadequate ventilation, 15% incomplete diagnosis, and 11% fault-free operation.

A closer look at the raw data indicates that no fault with the return-air temperature sensor exists because it is in the expected range, so either the outdoor- or the mixed-air temperature sensor is faulty (Figure 75).

*For Z1-SS-F8, the OAE diagnostician reported a temperature sensor problem.*

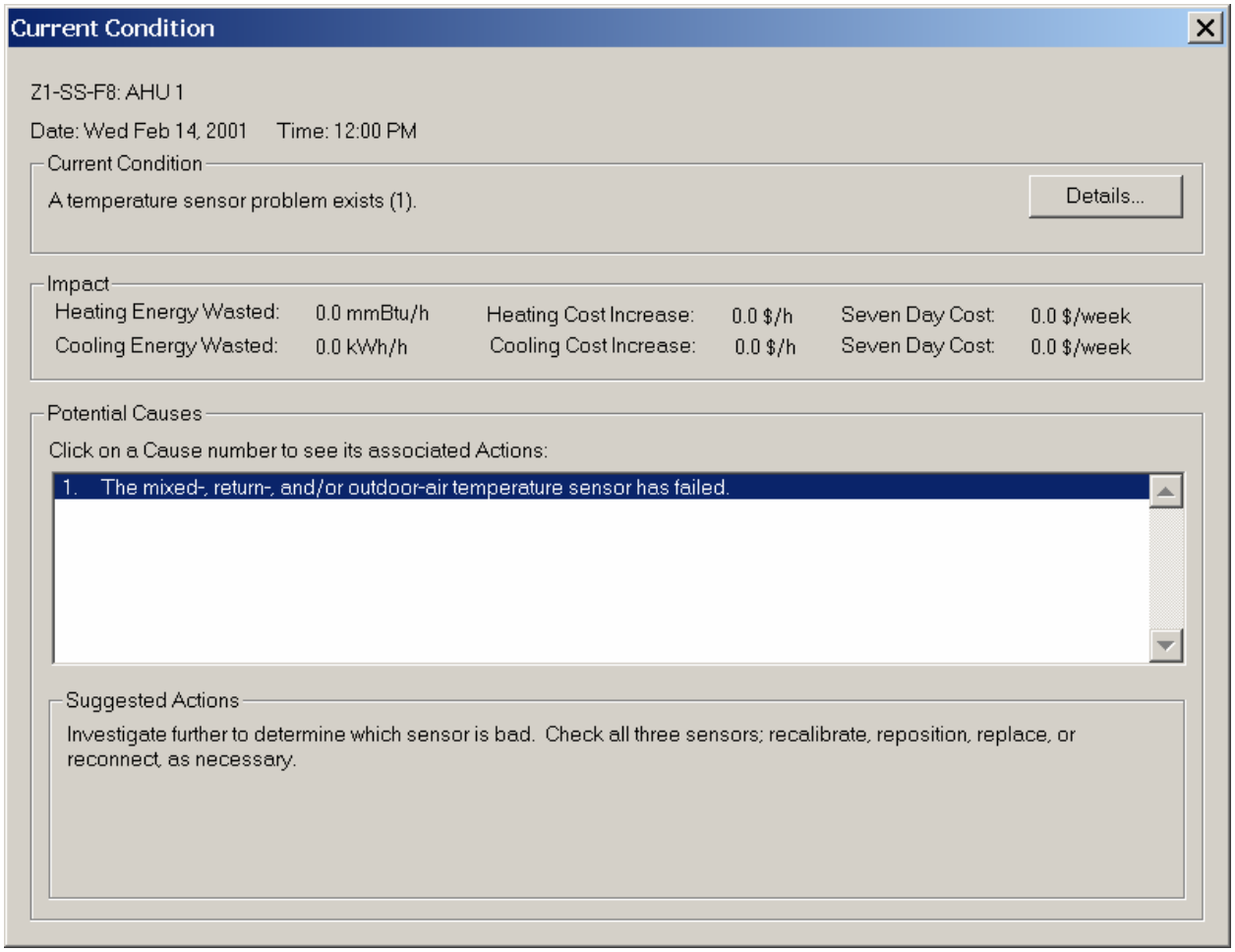



**Figure 74 – Current Conditions Dialogue for AHU-1 on February 14, 2001, at 12:00 p.m. for Blind Test Data Set Z1-SS-F8**

**Table 9 – Frequency of the Problems for AHU-3 when the Building is Occupied (data set Z1-SS-F8) with Normal OAE Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | 0.889 | 129 | 68.3 |
| Control Problem – Excess Energy | 0.500 | 1 | 0.5 |
| Excess Ventilation | | 0 | 0.0 |
| Inadequate Ventilation | 0.667 | 5 | 2.6 |
| Low Economizer Flow | 0.954 | 4 | 2.1 |
| OK but incomplete | 0.655 | 29 | 15.3 |
| Operation OK | 0.642 | 21 | 11.1 |
| Total | | 189 | 100.0 |

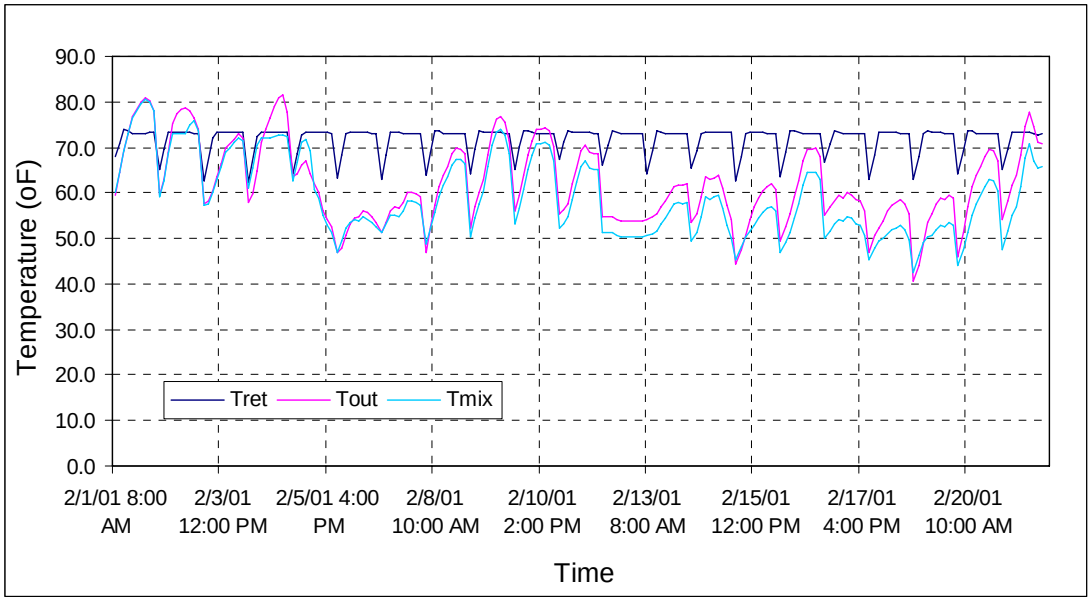



**Figure 75 – Time Series Plot of the Measured Return-, Outdoor-, and Mixed-air Temperatures for Data Set Z1-SS-F8**

### 6.5.11 Data Set Z2-SS-F8

The data set Z2-SS-F8 has 3 weeks of blind test data from AHU-2, which serves zone 2 in the VCBT. The simulation was based on swing-season weather data. Figure 76 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and red cells, most of the cells are white, indicating normal operation. Increasing the sensitivity of detection introduced a number of blue cells, as shown in Figure 77. Browsing a number of these blue cells indicates that the fault is attributable to inadequate ventilation during occupied hours while not economizing; however, a number of different potential causes are listed for the fault, as shown in Figure 78. The most likely causes of the fault are that the outdoor-air damper is stuck in a fully-closed position and that a temperature sensor has failed.

*For Z2-SS-F8, the OAE diagnostician reported that either the outdoor-air damper is stuck in a fully-closed position or a temperature sensor has failed when set at high sensitivity. At normal sensitivity, no problem was detected.*

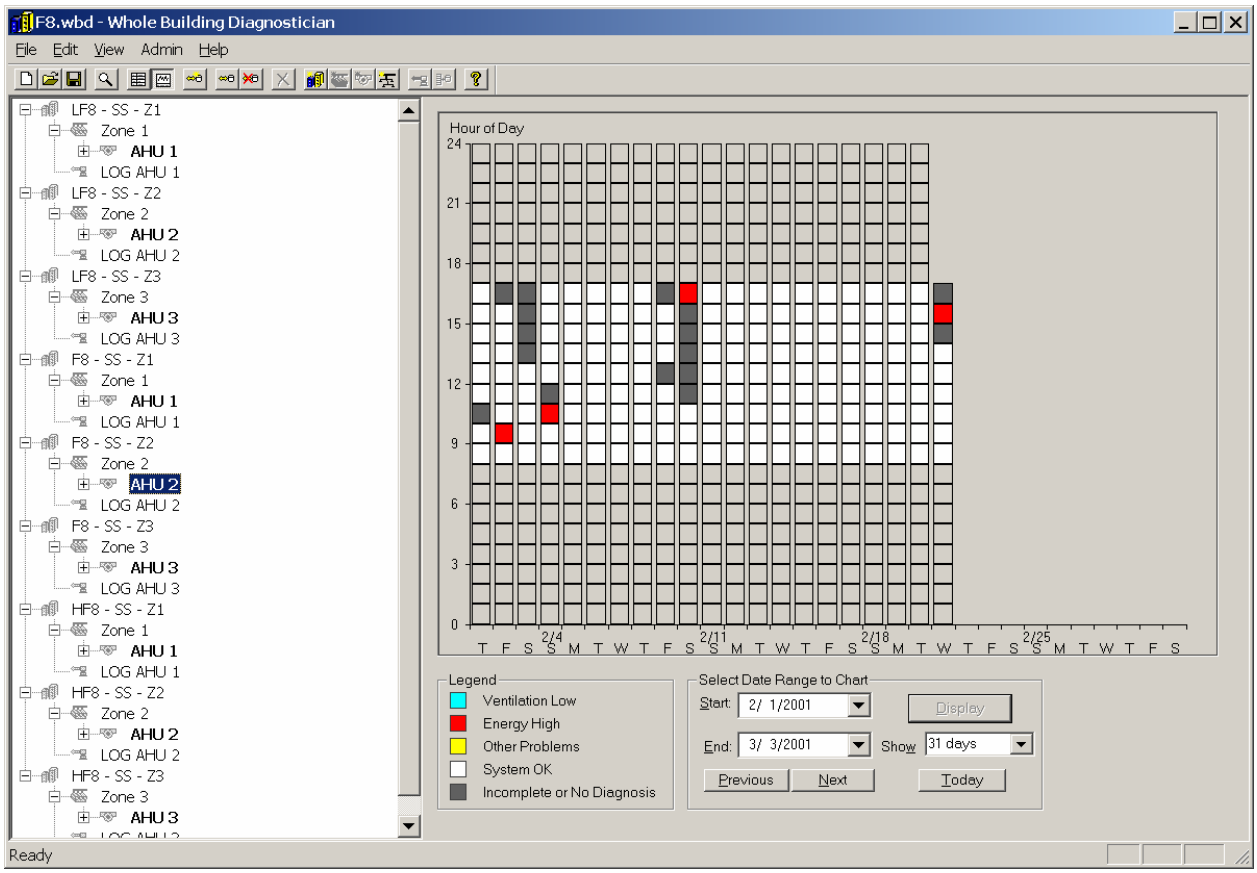



**Figure 76 – OAE Diagnostic Results for AHU-1 for Blind Test Data Set Z2-SS-F8 for Swing-Season Weather with Normal OAE Sensitivity**

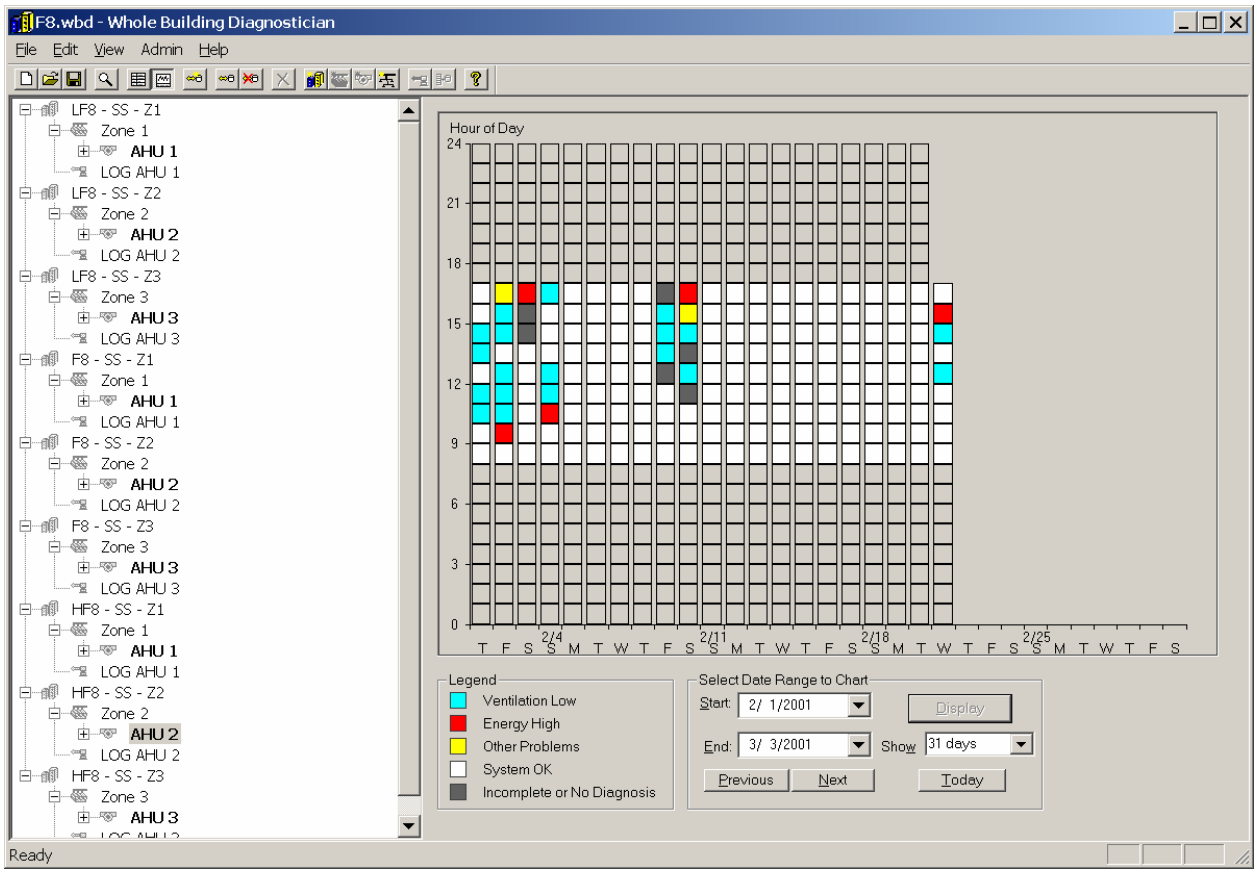



**Figure 77 – OAE Diagnostic Results for AHU-2 for Blind Test Data Set Z2-SS-F8 for Swing-Season Weather with High OAE Sensitivity**

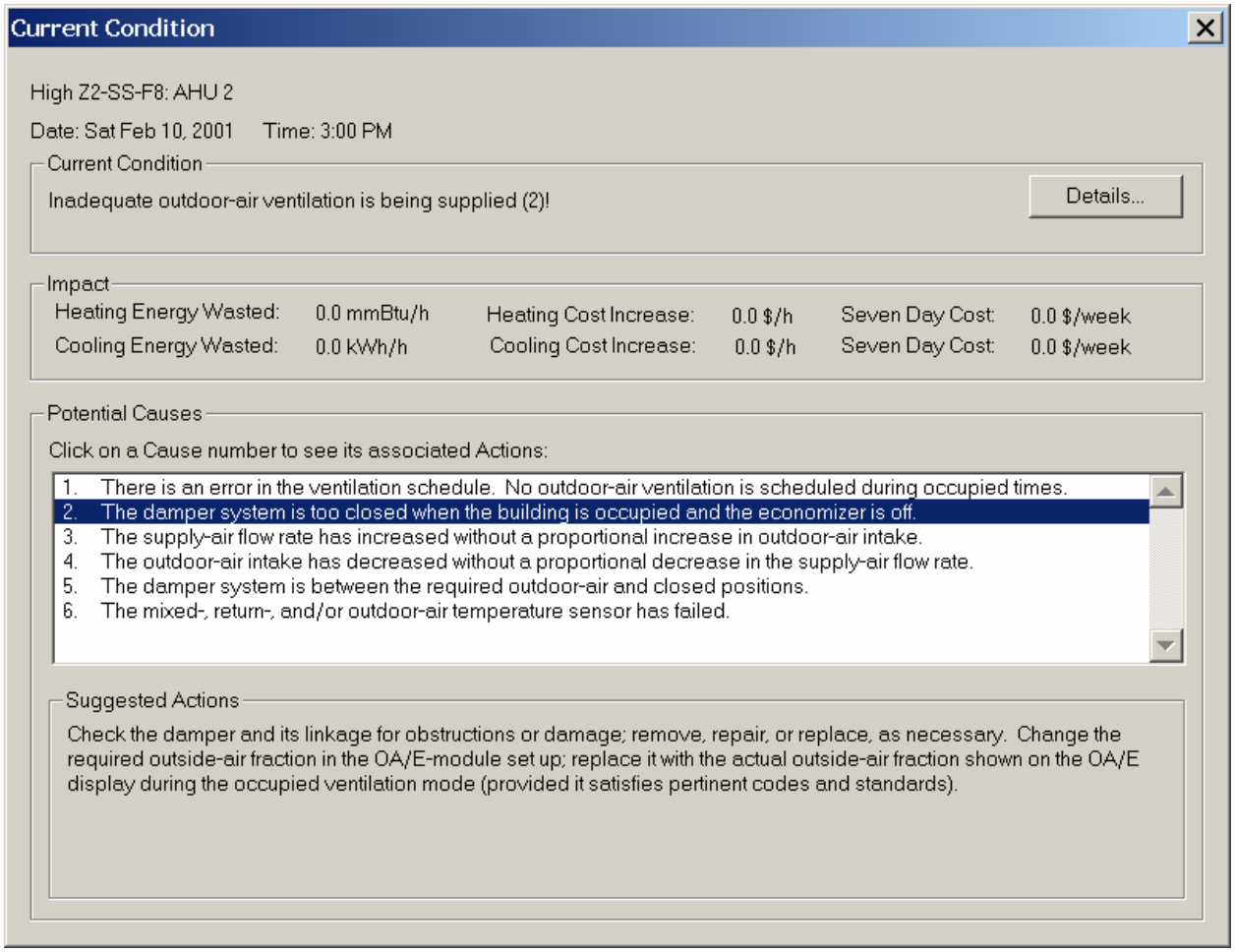



**Figure 78 – Current Conditions Dialogue for AHU-2 on February 10th, 2001, at 3:00 P.M. for Blind Test Data Set Z2-SS-F8**

### 6.5.12 Data Set Z3-SS-F8

The data set Z3-SS-F8 has 3 weeks of blind test data from AHU-3, which serves zone 3 in the VCBT. The simulation was based on swing-season weather data. Figure 79 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and white cells, most of the cells are red, indicating energy waste. Browsing through the red cells reveals a common problem, the economizer should be operating fully open, but it is only partially open (Figure 80). The list of potential causes for the fault include two configuration issues, two related to air flow, one in which the outdoor-air damper is stuck between fully open and its minimum position, and one in which the outdoor-air damper is not fully open.

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and the fraction of total occupied hours in each category are shown in Table 10. For the Z3-SS-F8 data set, almost 50% of the time is reported by the OAE as having low economizer flow, 18% with incomplete diagnosis, and 32% with normal operation.

*For Z3-SS-F8, the OAE diagnostician reports a damper stuck between the minimum and fully open positions.*

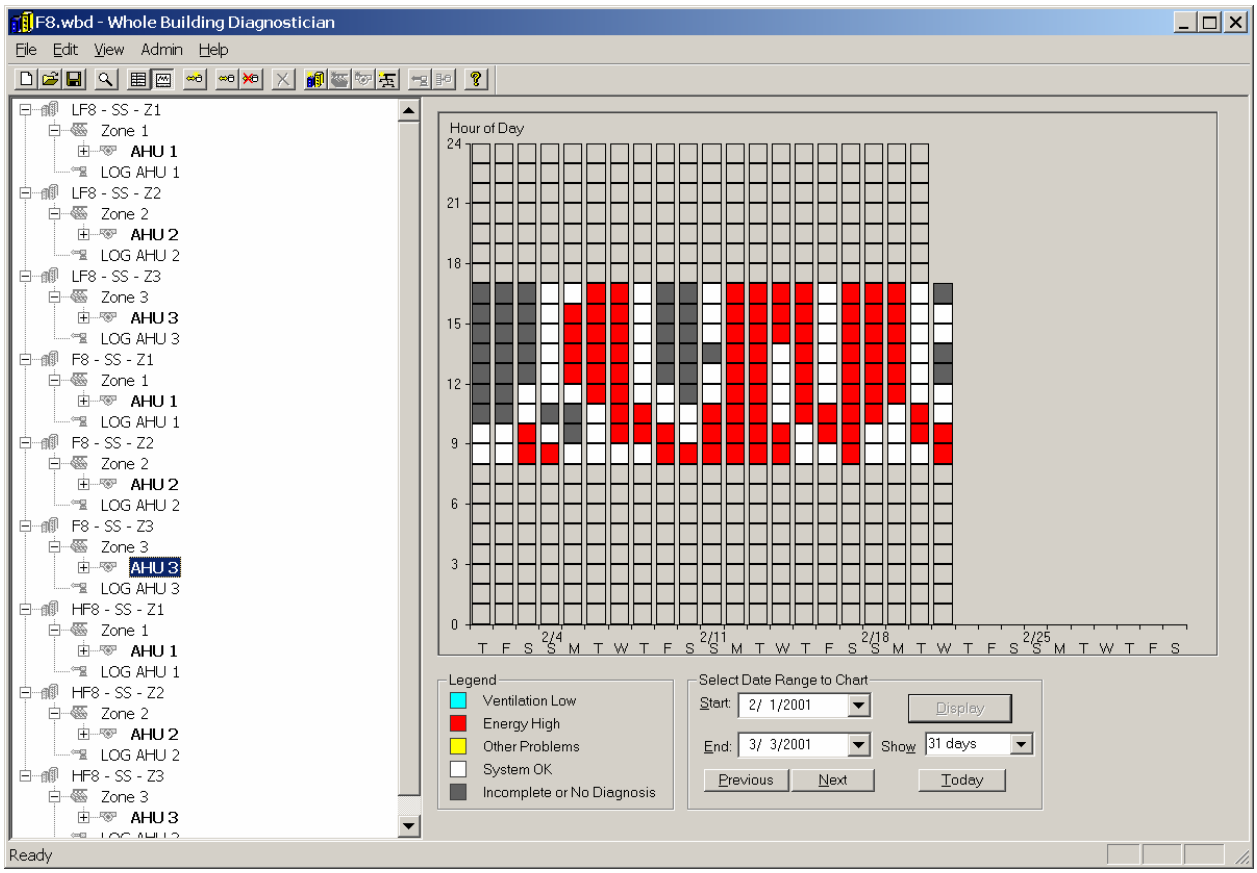



**Figure 79 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-SS-F8 for Swing-Season Weather with Normal OAE Sensitivity**

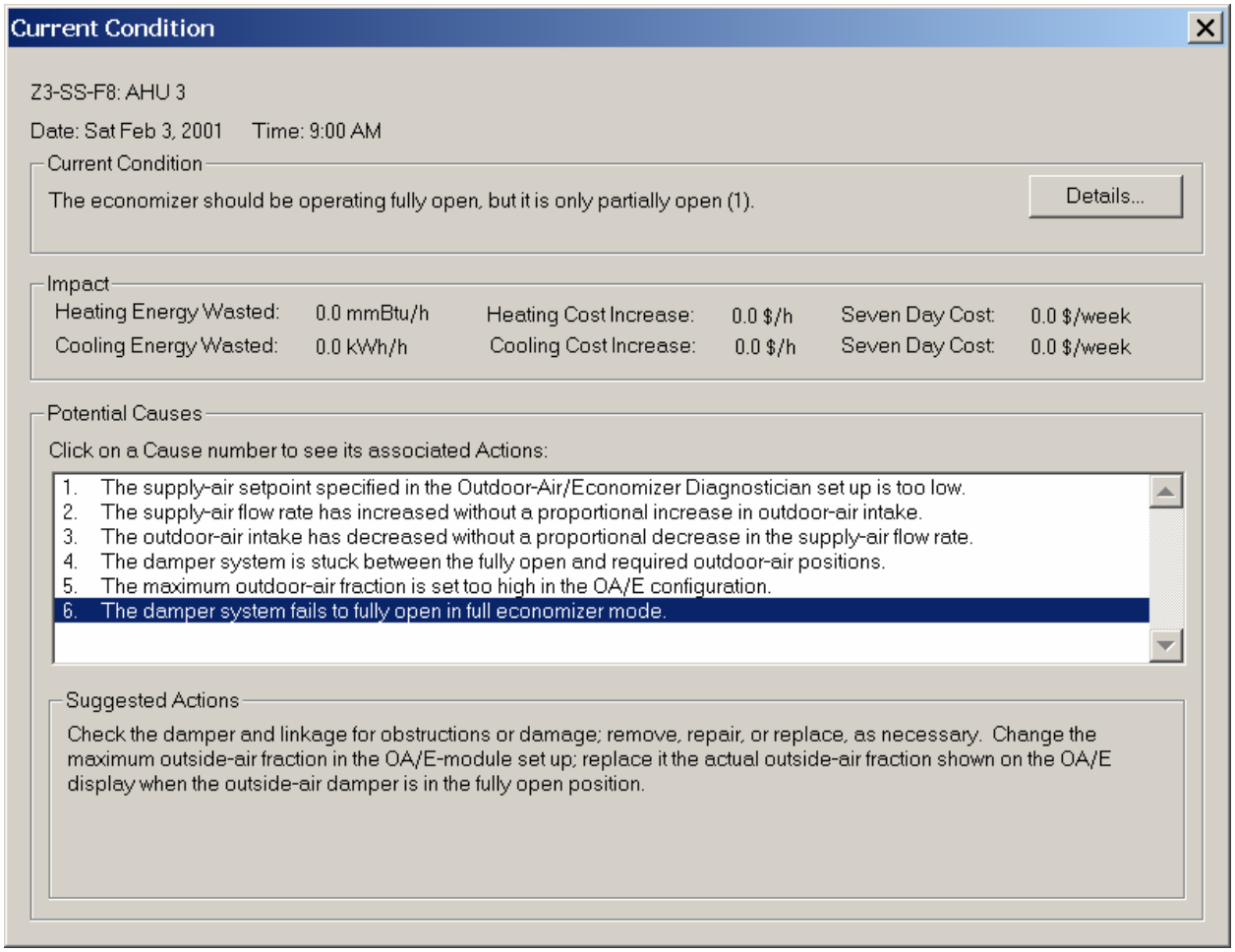



**Figure 80 – Current Conditions Dialogue for AHU-3 on February 3, 2001, at 9:00 a.m. for Blind Test Data Set Z3-SS-F8**

**Table 10 – Frequency of Problems for AHU-3 when the Building is Occupied (data set Z3-SS-F8) with Normal OAE Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | | 0 | 0.0 |
| Control Problem – Excess Energy | | 0 | 0.0 |
| Excess Ventilation | | 0 | 0.0 |
| Inadequate Ventilation | | 0 | 0.0 |
| Low Economizer Flow | 0.550 | 97 | 48.7 |
| OK but incomplete | 0.618 | 37 | 18.6 |
| Operation OK | 0.593 | 65 | 32.7 |
| Total | | 199 | 100.0 |

### 6.5.13 Data Set Z1-CS-F9

The data set Z1-CS-F9 has 3 weeks of blind test data from AHU-1, which serves zone 1 in the VCBT. The simulation was based on cooling-season weather data. Figure 81 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray cells, most cells are white, indicating proper AHU operation. However, increasing the sensitivity of detection introduced many blue cells, as shown in Figure 82. Browsing through the blue cells indicates inadequate ventilation during occupied hours. The list of potential causes is long, as shown in Figure 83; however, most of them are related (inadequate ventilation).

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and the fraction of total unoccupied hours in each category are shown in Table 11. For the Z1-CS-F9 data set, over 50% of the time, the OAE reported inadequate ventilation flow, and the rest of the time, it reported incomplete or normal operation.

*For Z1-CS-F9, the OAE diagnostician reported normal operation using normal sensitivity setting; however, when the sensitivity setting was increased, it reported an outdoor-air damper stuck between minimum and closed position, which represents faulty operations.*

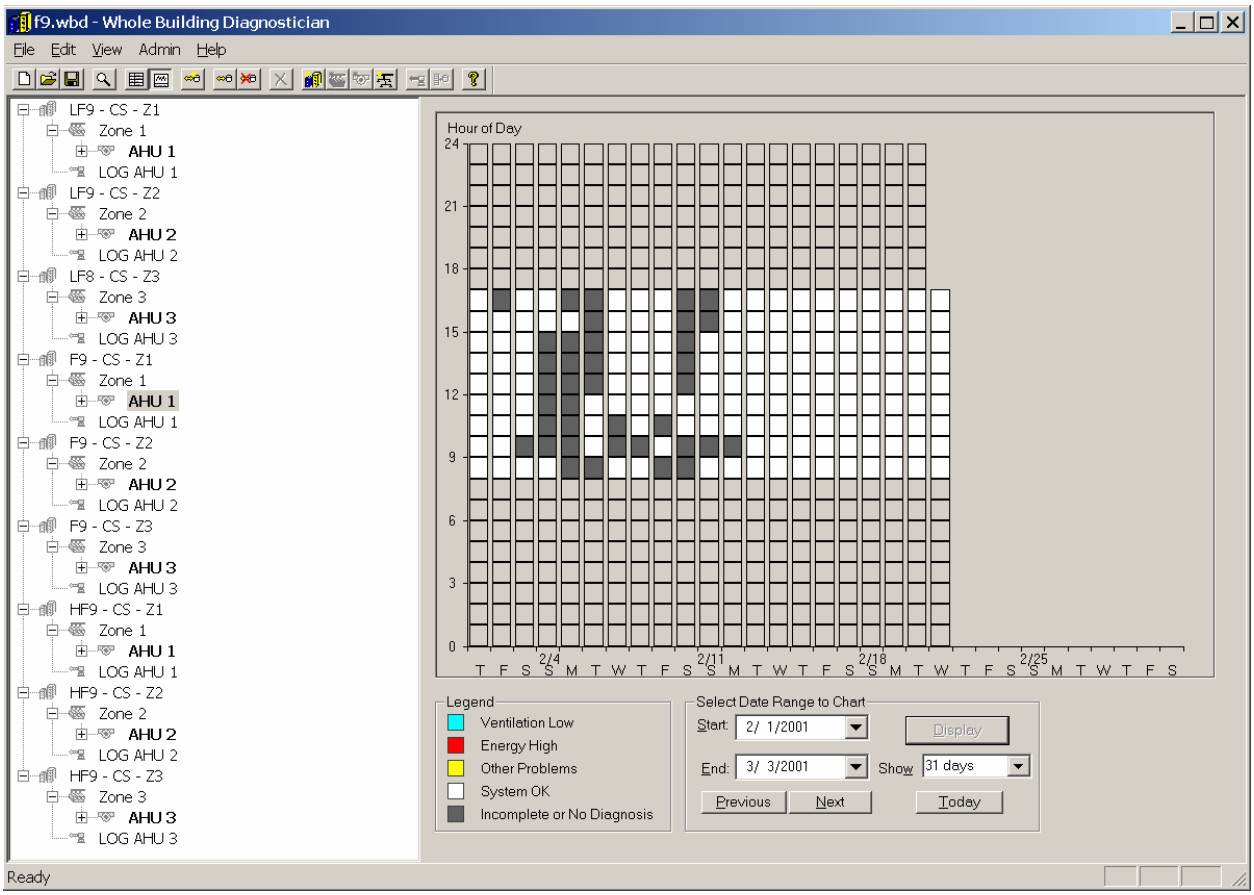



**Figure 81 – WBD's Diagnostic Results View for AHU-1 with Blind Test Data Z1-CS-F9 from Cooling Season with Normal Sensitivity**

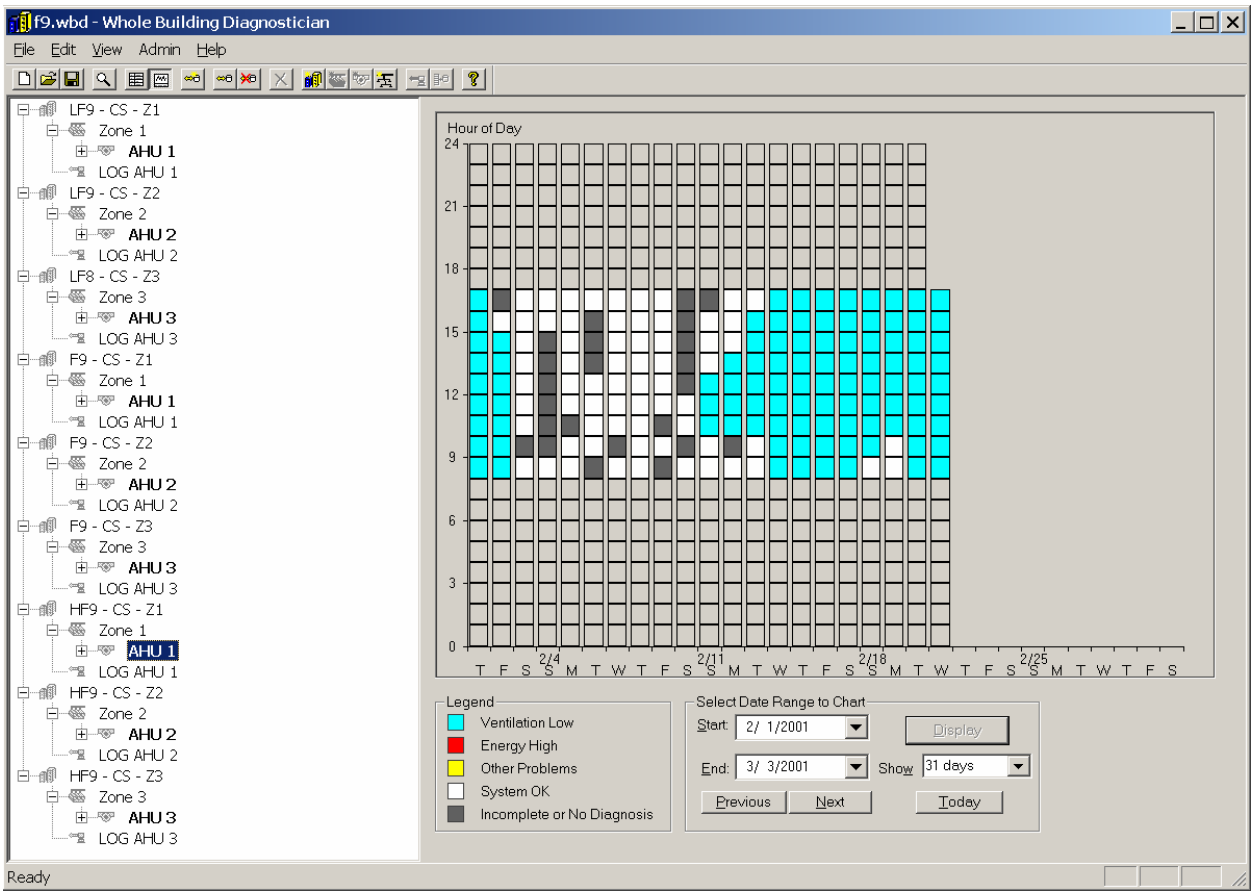



**Figure 82 – OAE Diagnostic Results for AHU-1 for Blind Test Data Set Z1-CS-F9 for Cooling Season Weather with High OAE Sensitivity**

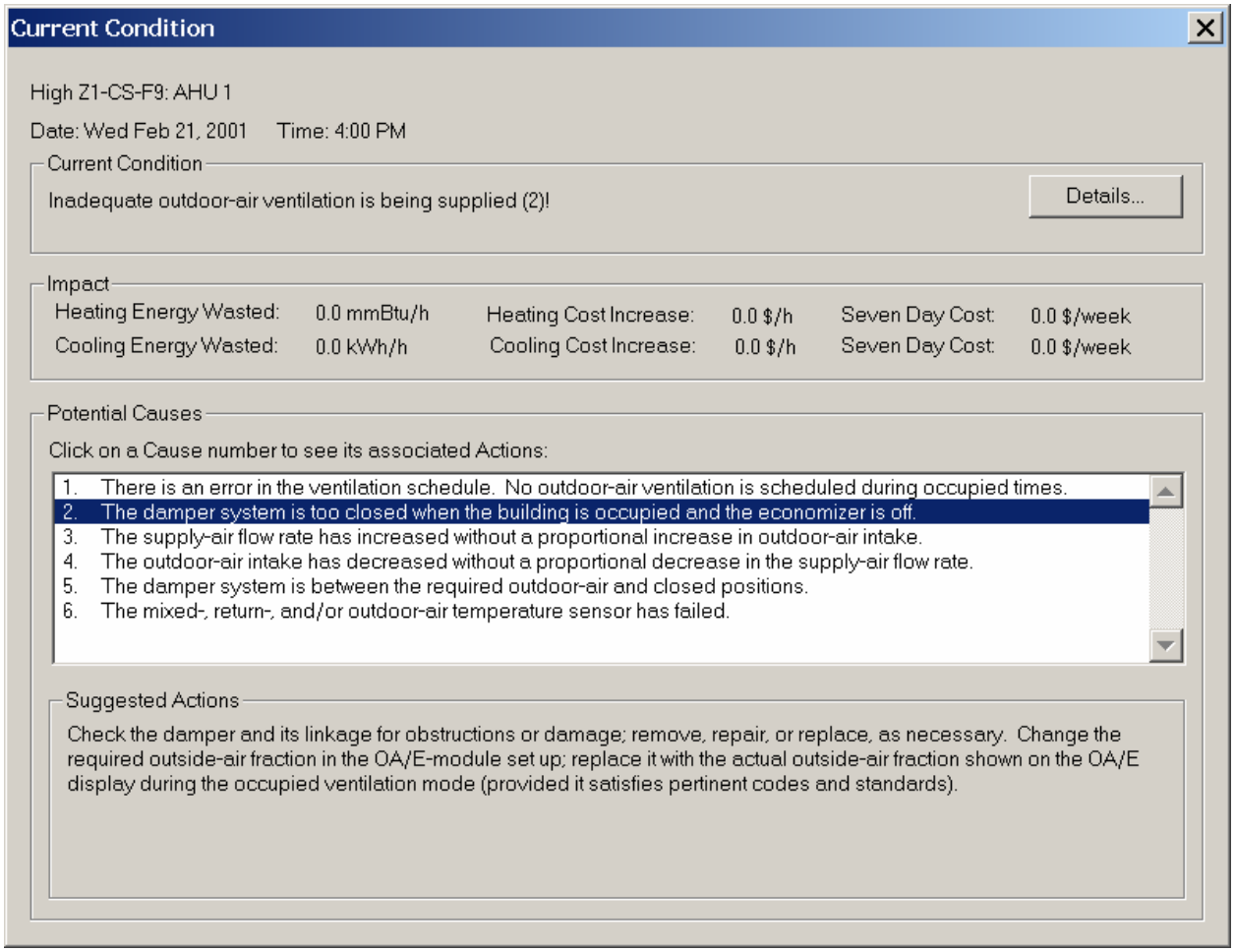



**Figure 83 – Current Conditions Dialogue for AHU-1 on February 21, 2001, at 4:00 p.m. for Blind Test Data Set Z1-CS-F9**

**Table 11 – Frequency of Problems for AHU-1 when the Building is Occupied (data set Z1-CS-F9) with High OAE Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | | 0 | 0.0 |
| Control Problem – Excess Energy | | 0 | 0.0 |
| Excess Ventilation | | 0 | 0.0 |
| Inadequate Ventilation | 0.923 | 98 | 51.9 |
| Low Economizer Flow | | 0 | 0.0 |
| OK but incomplete | 0.826 | 24 | 12.7 |
| Operation OK | 0.907 | 67 | 35.4 |
| Total | | 189 | 100.0 |

### 6.5.14 Data Set Z2-CS-F9

The data set Z2-CS-F9 has 3 weeks of blind test data from AHU-2, which serves zone 2 in the VCBT. The simulation was based on cooling-season weather data. Figure 84 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and white cells, most cells are red indicating an energy wasting problem. Browsing through many of the red cells reveals that the economizer is operating even when conditions are not favorable for economizing. The list of potential causes for the fault is long, as shown in Figure 85; however, many of these causes are related. The most probable cause of the fault is an economizer controller failure.

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and the fraction of total hours in each category are shown in Table 12. For the Z2-CS-F9 test, over 70% of the time, the OAE reported excess ventilation flow, and the rest of the time, it mostly reported incomplete or normal operation.

*For Z2-CS-F9, the OAE diagnostician reported a controller failure or that the outdoor-air damper stuck in a fully-open position.*

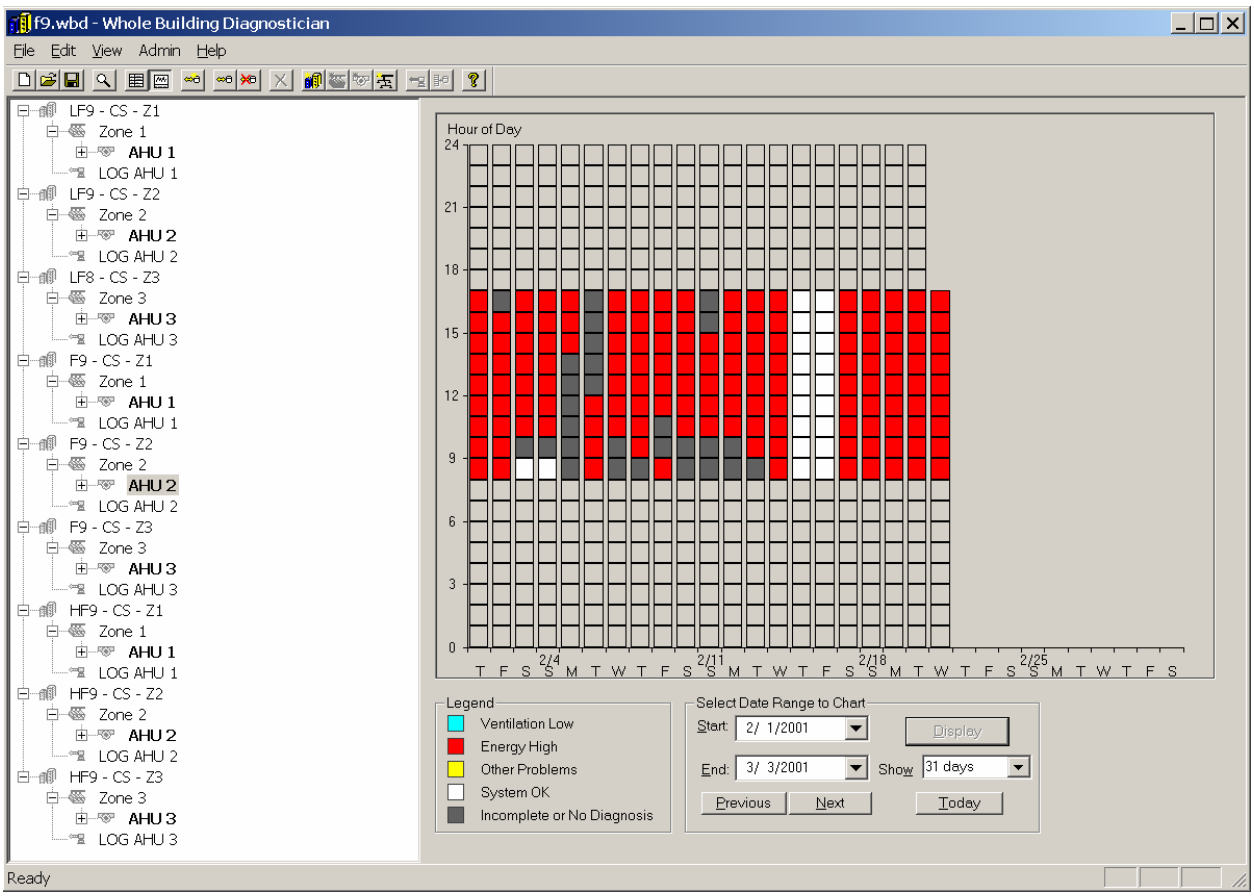



**Figure 84 – OAE Diagnostic Results for AHU-2 for Blind Test Data Set Z2-CS-F9 for Cooling Season Weather with Normal OAE Sensitivity**

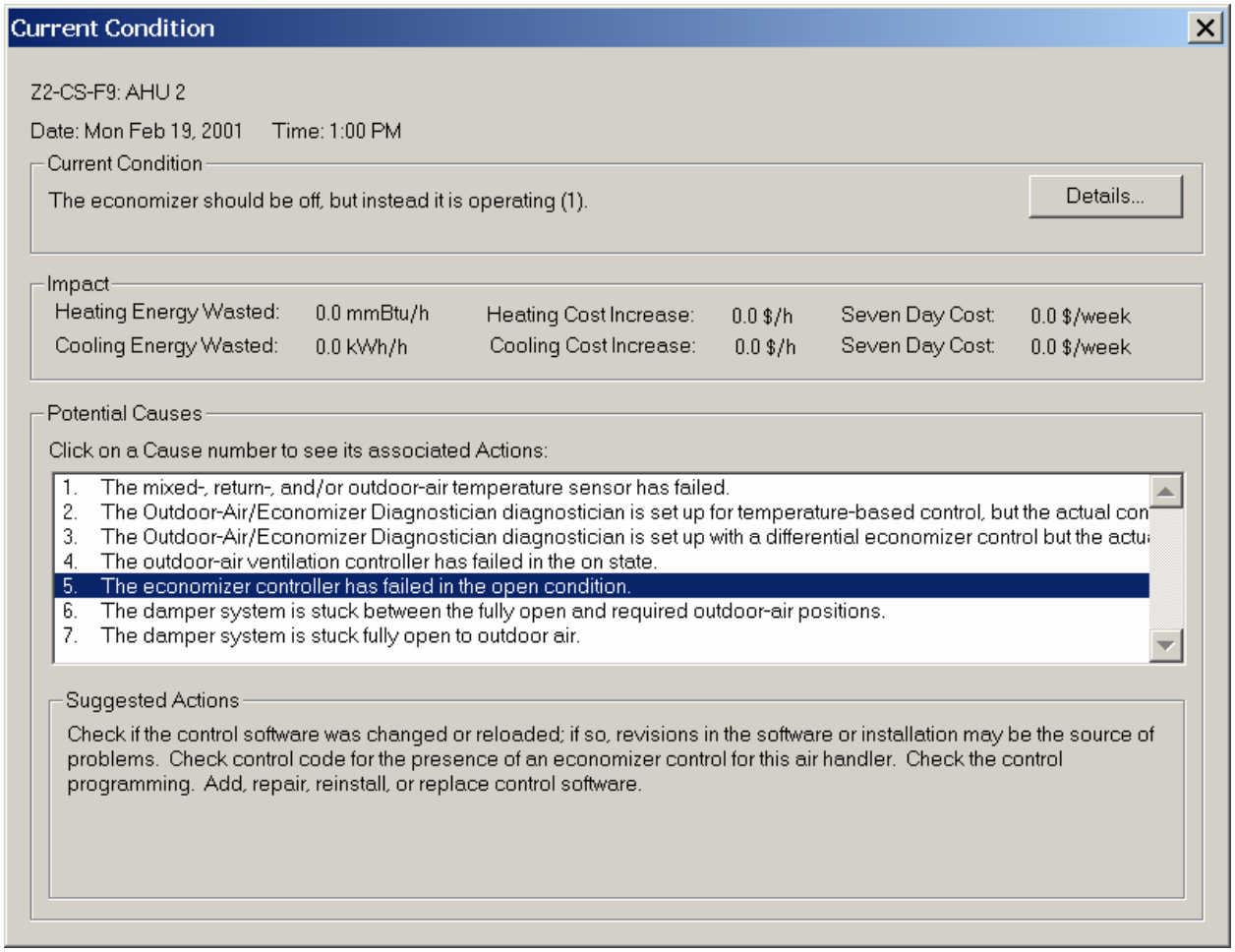



**Figure 85 – Current Conditions Dialogue for AHU-2 on February 19, 2001, at 1:00 p.m. for Blind Test Data Set Z2-CS-F9**

**Table 12 – Frequency of Problems for AHU-2 when the Building is Occupied (data set Z2-CS-F9) with Normal OAE Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | | 0 | 0.0 |
| Control Problem – Excess Energy | | 0 | 0.0 |
| Excess Ventilation | 0.875 | 136 | 72.0 |
| Inadequate Ventilation | | 0 | 0.0 |
| Low Economizer Flow | 0.657 | 5 | 2.6 |
| OK but incomplete | 0.653 | 28 | 14.8 |
| Operation OK | 0.656 | 20 | 10.6 |
| Total | | 189 | 100.0 |

### 6.5.15 Data Set Z3-CS-F9

The data set Z3-CS-F9 has 3 weeks of blind test data from AHU-3, which serves zone 3 in the VCBT. The simulation was based on cooling-season weather data. Figure 86 shows the screen shot of the OAE diagnostic results for this data set with normal OAE sensitivity. With the exception of a few gray and white cells, most cells are yellow. Browsing through many of the yellow cells reveals a common problem: a faulty temperature sensor. The list of potential causes for the fault has just one cause, as shown in Figure 87. However, as previously noted, the OAE diagnostician cannot distinguish which of the three sensors is faulty (outdoor-, mixed- or return-air temperature sensor).

The frequency of problems reported by the OAE in each major category, the corresponding reliability score, and the fraction of total hours in each category are shown in Table 13. For the Z3-CS-F9 test, over 55% of the time, the OAE reported a control problem (Other). The rest of the time, it reported incomplete diagnosis or normal operation. A closer look at the raw data indicates a drifting return-air temperature sensor (Figure 88), but the OAE could detect that there was a temperature sensor problem. It could not isolate the problem to one sensor or indicate the specific nature of the problem as drifting.

*For Z3-CS-F9, the OAE diagnostician reported a temperature sensor problem.*

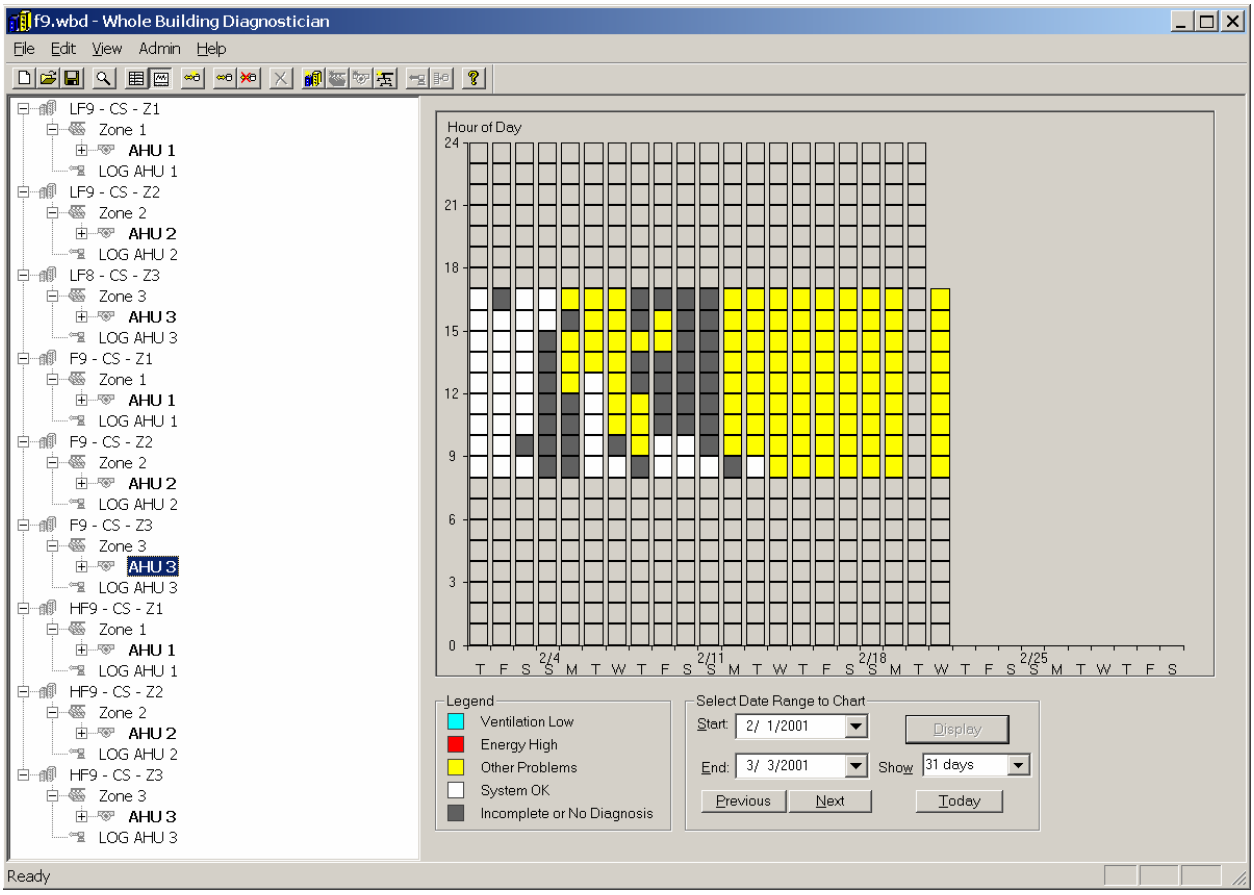



**Figure 86 – OAE Diagnostic Results for AHU-3 for Blind Test Data Set Z3-CS-F9 for Cooling Season Weather with Normal OAE Sensitivity**

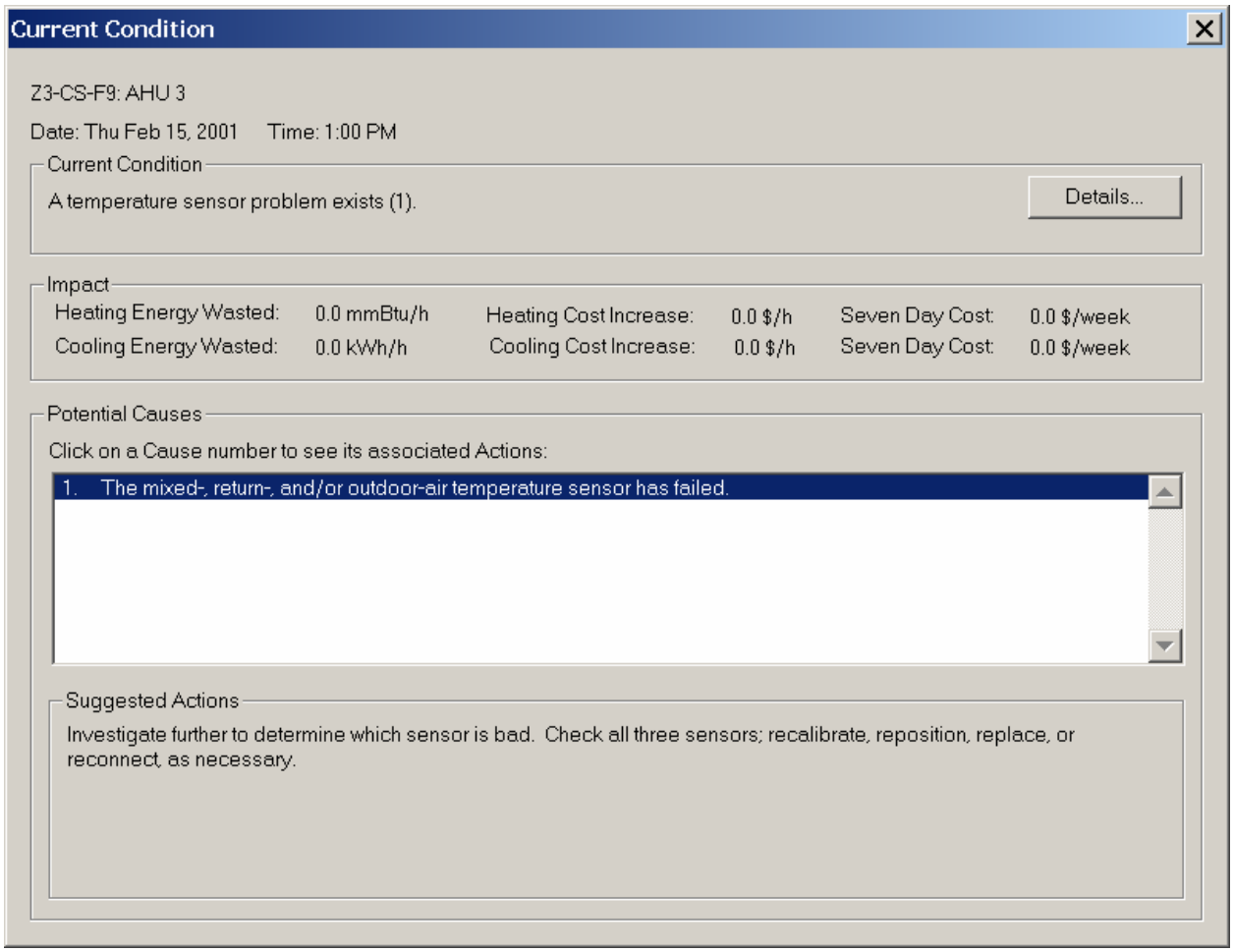



**Figure 87 – Current Conditions Dialogue for AHU-3 on February 15, 2001, at 1:00 p.m. for Blind Test Data Set Z3-CS-F9**

**Table 13 – The frequency of Problems for AHU-2 when the Building is Occupied (data set Z3-CS-F9) with Normal OAE Sensitivity**

| Category of Operational States | Reliability Score | Number of Occurrences | Fraction of Total Occupied Hours (%) |
|---|---|---|---|
| Control Problem | 0.663 | 100 | 55.6 |
| Control Problem – Excess Energy | | 0 | 0.0 |
| Excess Ventilation | | 0 | 0.0 |
| Inadequate Ventilation | | 0 | 0.0 |
| Low Economizer Flow | | 0 | 0.0 |
| OK but incomplete | 0.635 | 41 | 22.8 |
| Operation OK | 0.655 | 39 | 21.7 |
| Total | | 180 | 100 |

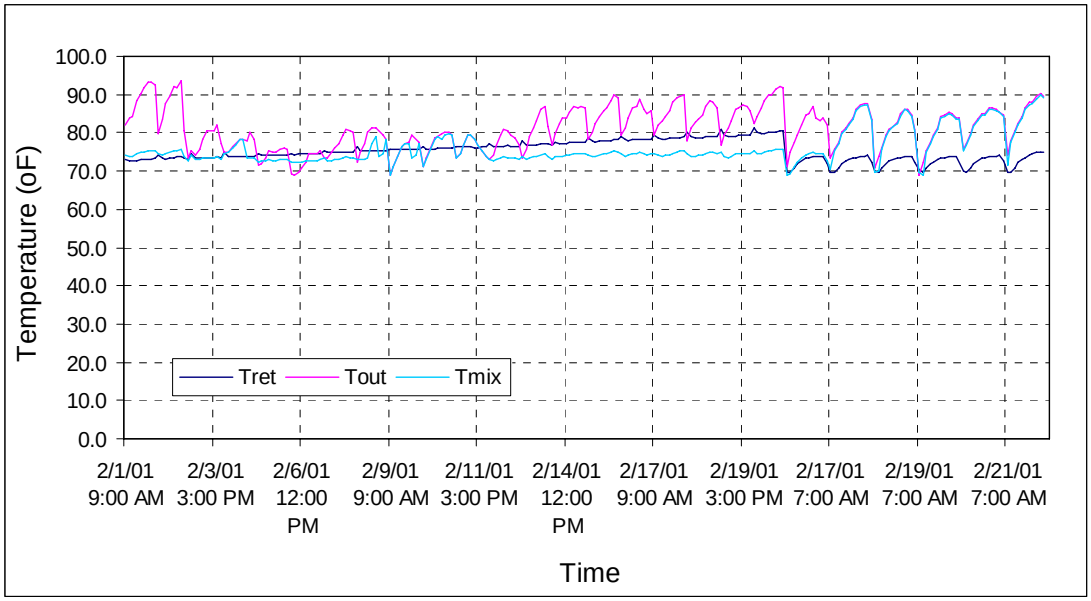



**Figure 88 – Time Series Plot of the measured Return-, Outdoor-, and Mixed-air Temperatures for the Z3-CS-F9 Test**

# 7 WBE Results

The results from automated processing of end-use energy consumption data sets with fault-free operation, operation with known faults for non-blind tests, and operation with faults for blind tests are presented in this section. All data sets have at least 12 months of data, although faulty operations generally span only a few months.

The Whole-Building Energy (WBE) diagnostician tracks end uses at the whole-building level, such as whole-building total electricity use, whole-building total thermal energy (cooling or heating) use, chiller or packaged unit energy consumption, or HVAC electricity consumption other than the chiller. Internally, the WBE modeling engine uses time of day, day of the year, day of the week, outdoor-air dry-bulb temperature, and relative humidity (or dew point) as independent variables. The WBE module is currently being extended (as part of another task under the same project – Task 2.6) to support the use of up to five independent variables selected by an expert user, such as plug loads, occupancy loads, meals served, etc., to model the end-uses.

The WBE module uses a daily energy consumption index (ECI) to show deviations in the actual energy consumption from the expected energy consumption. The expected energy consumption is estimated based on the baseline model that is automatically developed with historical energy consumption. The daily energy consumption index (ECI) for 1 day is calculated as follows:

$$ECI = \frac{\sum_{h=0}^{23} Actual_h}{\sum_{h=0}^{23} Predicted_h}$$

where $ECI$ is the energy consumption index, $Actual_k$ is the actual consumption for the $k^{th}$ hour, and $Predicted_k$ is the predicted consumption for the $k^{th}$ hour.

If the actual energy consumption and the estimated expected energy consumption are the same, by definition, the ECI equals 1.0. As the actual energy consumption deviates from the expected, the ECI values also deviate from 1.0. In general, ECI values between 0.9 and 1.0 are considered good. However, because of measurement errors and the inability to measure all the independent variables that strongly influence energy consumption, ECI values between 0.8 and 1.2 are thought to be reasonable[4]. The sensitivity of fault detection (or detection of abnormal operation) can be adjusted to provide more or fewer faults depending on the user preference.

## 7.1 Basic Description of the WBE User Interface

The user interface for the WBE tool displays the energy consumption index (ECI) as a time-series of daily results for major end-use categories, as shown in Figure 89. There are three primary end-uses (thermal energy, chiller (or packaged unit) electric, and HVAC electric) and

[4] The WBE actually uses a statistical measure that depends on the size of the deviation as well as how well that energy consumption is known for those conditions (related to the variance of the historical data) and only alerts the user when the deviations about 1.0 are statistically significant.

two derived end-uses (total building electric and total building energy)[5]. The total building electric includes the chiller, HVAC, lights, and equipment electric consumption.

After the data are processed, the WBE diagnostician alerts the building operator when the difference between the actual and expected end-use consumption is statistically significant, i.e., if the ECI values are significantly greater than or less than 1.0. When the deviation is statistically significant, the WBE alerts the operator with an enlarged red square as shown in **Figure 90**. Unlike the OAE diagnostician, the WBE diagnostician does not provide a list of potential causes for abnormal consumption, although it does estimate the cost of the energy impact just like the OAE diagnostician (Figure 91). Like the OAE, the WBE diagnostician also has five levels of sensitivity that control sensitivity of detection and false alarms.

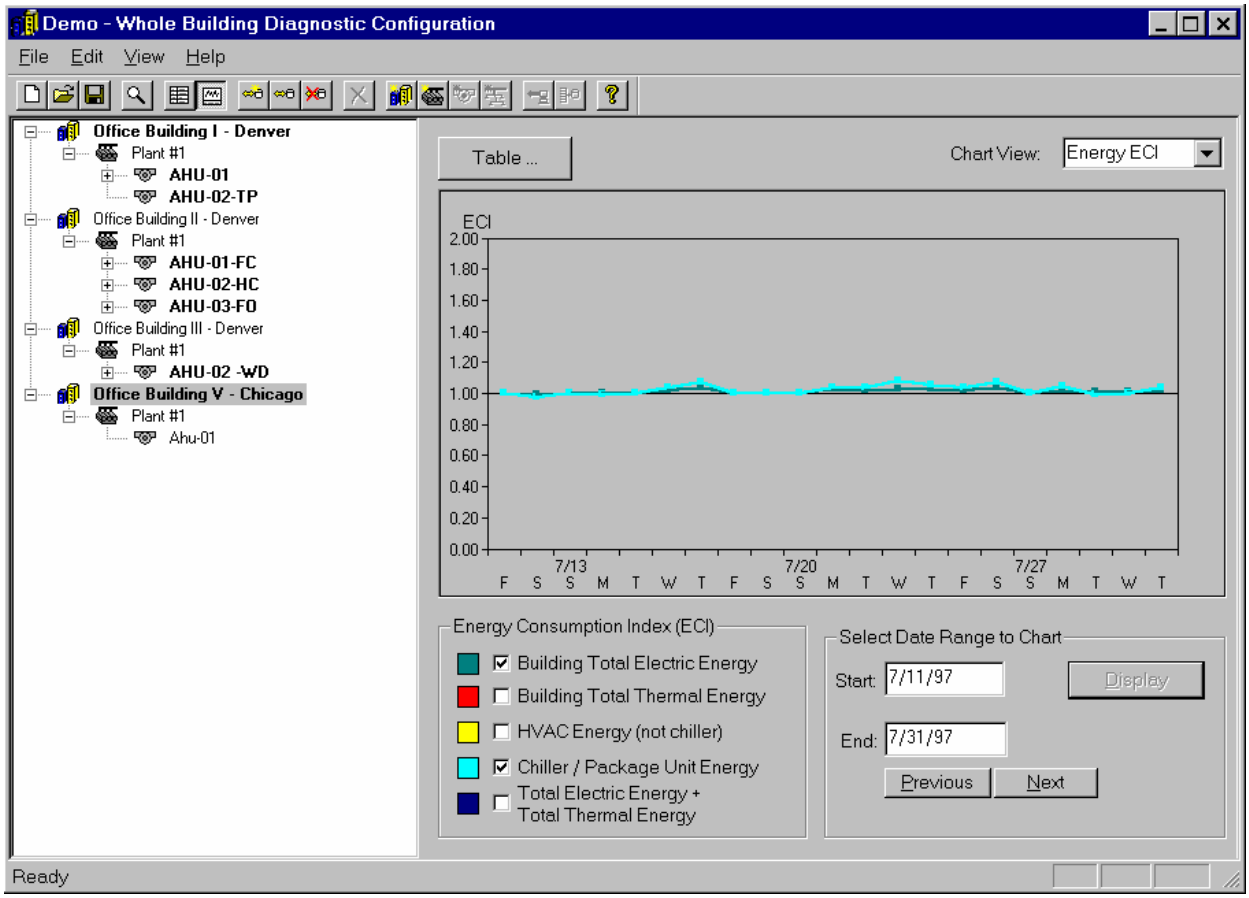



**Figure 89 – WBE Screen Shot Showing ECI Values in the Normal Range**

[5] The WBE is being enhanced as part of another California Energy Commission PIER project. These enhancements will allow users to select both dependent and independent variables of their choice.

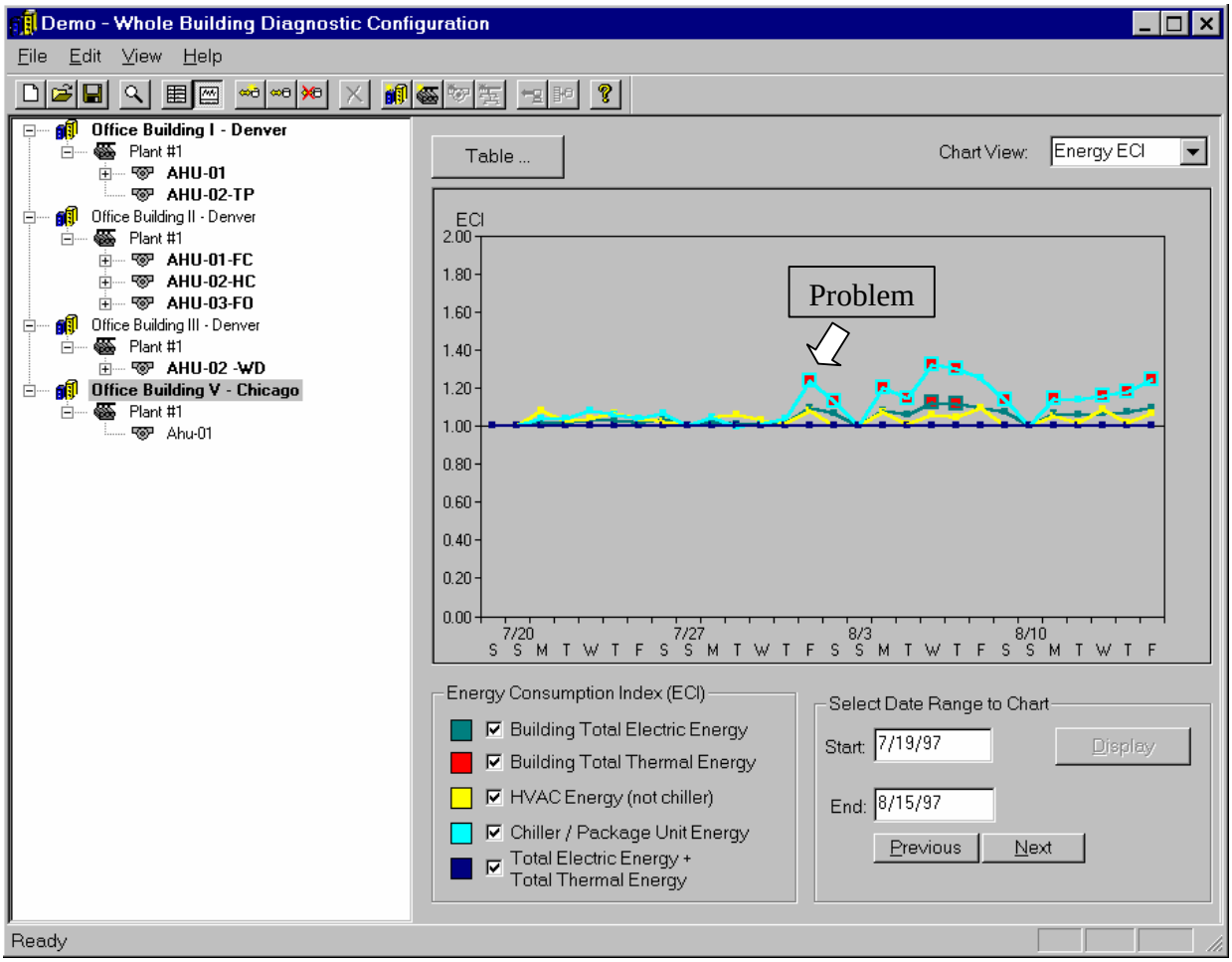



**Figure 90 – WBE Screen Shot Showing Abnormal Values of the ECI**

ECI Problem Details

Office Building V - Chicago

| Date | Problem Detected | ECI Type | ECI Value | Today's Cost | Seven Day Cost |
|---|---|---|---|---|---|
| 08/06/1997 | Electric energy consumption is higher than normal. Consumption this hour is 11559 kWh. | Building Total Electric Energy | 1.1203 | $99/day | $695/week |
| 08/06/1997 | Chiller consumption is higher than normal. Consumption this hour is 4744 kWh. | Chiller/Package Unit Energy | 1.3227 | $93/day | $648/week |

**Figure 91 – ECI Problem Details for August 4, 20002**

## 7.2 Naming Convention for the Data sets

The naming convention used for the WBE blind tests has two parts, each separated by a dash (e.g., WBE-F13). The first part is common to all data sets (WBE) and the second part represents the fault number assigned by NIST (e.g., F13).

## 7.3 WBE Results from Normal Operation (Training Data)

In this section, the results from processing the data from normal building operations are presented. Unlike the OAE, which does not use a reference model, the WBE automatically builds a reference model using data collected during early use of the tool (training data), which is used to make estimates of expected energy consumption, which are then used to identify abnormal consumption. For testing purposes, the WBE diagnostician was trained with data that are representative of proper building operation. Separate training data sets provided by NIST were used to create the reference model before blind testing using data sets corresponding to abnormal consumption (i.e., faults).

### 7.3.1 Thermal Energy Training Data

The screen shot of the WBE diagnostic tool showing the results (ECI values) for an entire year for the thermal energy end-use is shown in Figure 92. There are several days when ECI values for the thermal energy end-use are greater than 1.2 and some of them are significantly higher than 1.2, indicating that the training data set has large unexplained variations in thermal energy use. Although there are several days with high ECI values, the WBE has tagged just one day as a problem. Because the model uncertainty is high (as indicated by high ECI values), in the future, identification of abnormal thermal energy consumption using the reference model will be difficult. Unless the deviation in the thermal energy consumption is significantly larger than the model uncertainty, the deviation may not be detected.

For the WBE to mark a day as a problem the magnitude of the difference between actual and expected energy use should be high, the uncertainty of the difference should be less than the detection threshold. Unless there is significant increase/decrease in consumption WBE may be able to mark the day as faulty, because the magnitude of the thermal energy consumption is extremely low in this data set, (between 0 and 1.2 million Btu/hr with a daily average winter consumption of approximately 3 million Btu/day).

### 7.3.2 Chiller Electric Energy Training Data

The WBE diagnostic results for chiller electricity consumption are shown Figure 93. Although there are a few days with high ECI values, most of the ECI values are close to 1.0, indicating that the reference model based on training data is adequate and has low uncertainty. Therefore, the reference model for the chiller electricity consumption should make identifying deviations from normal consumption much easier than for thermal energy consumption.

### 7.3.3 HVAC Electric Energy Training Data

The WBE diagnostic results for HVAC electric consumption under normal conditions are shown in Figure 94. Like for the chiller, the ECIs for HVAC electric consumption are close to 1.0 with only a few exceptions. Therefore, the reference model for the HVAC electric consumption is adequate.

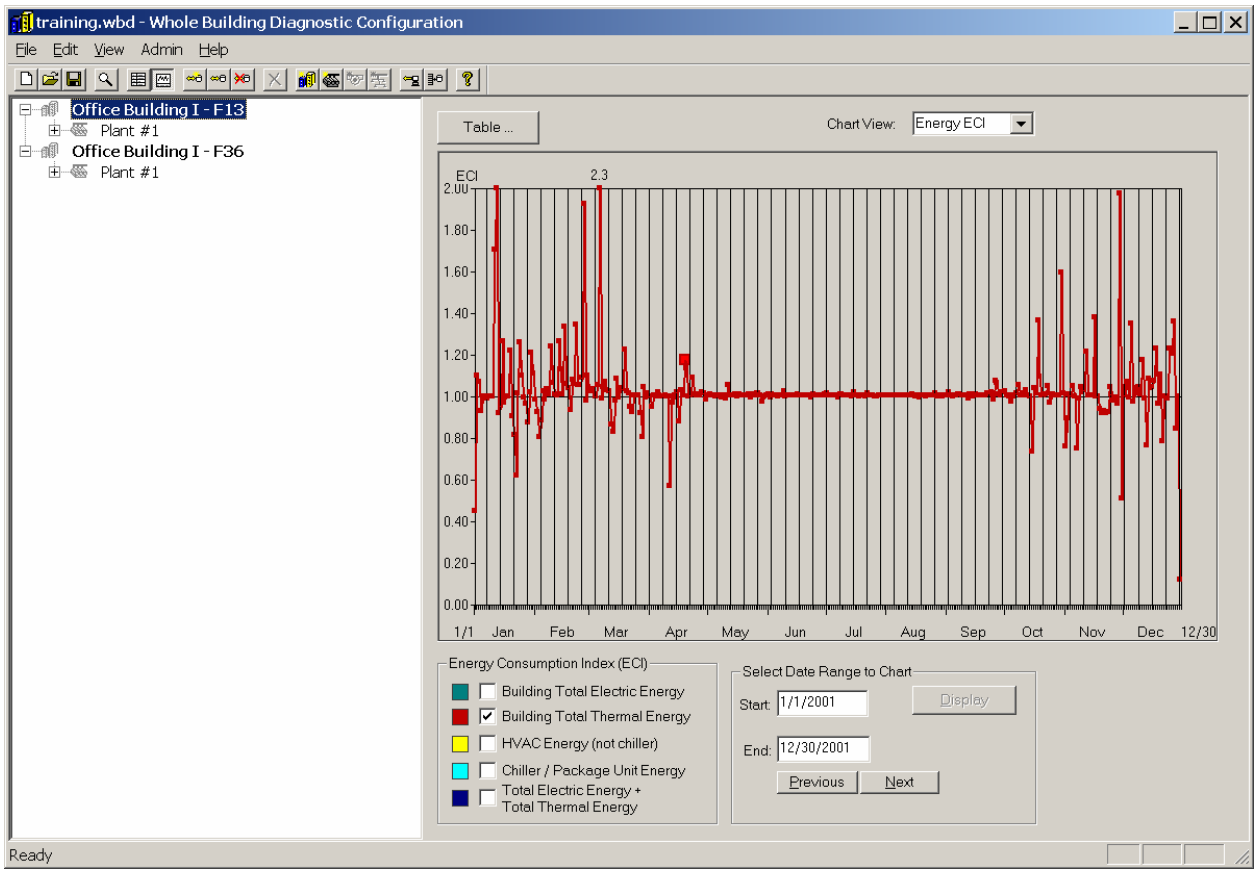



**Figure 92 – WBE Diagnostic Results for Thermal Energy for Training Data**

### 7.3.4 Lighting and Equipment Electric Energy Training Data

The ECIs for electricity consumption by lighting and equipment are not explicitly calculated by WBE, but the total electricity consumption includes lighting and equipment consumption in addition to HVAC and chiller electric consumption. The results for the total electricity consumption are shown in Figure 95. There appears to be some seasonal variation of ECIs with lower ECIs in the summer and higher ECIs in the fall. As a result, it may be difficult to identify deviations in lighting and equipment electricity consumption during the summer and fall months because of high uncertainty in the training model.

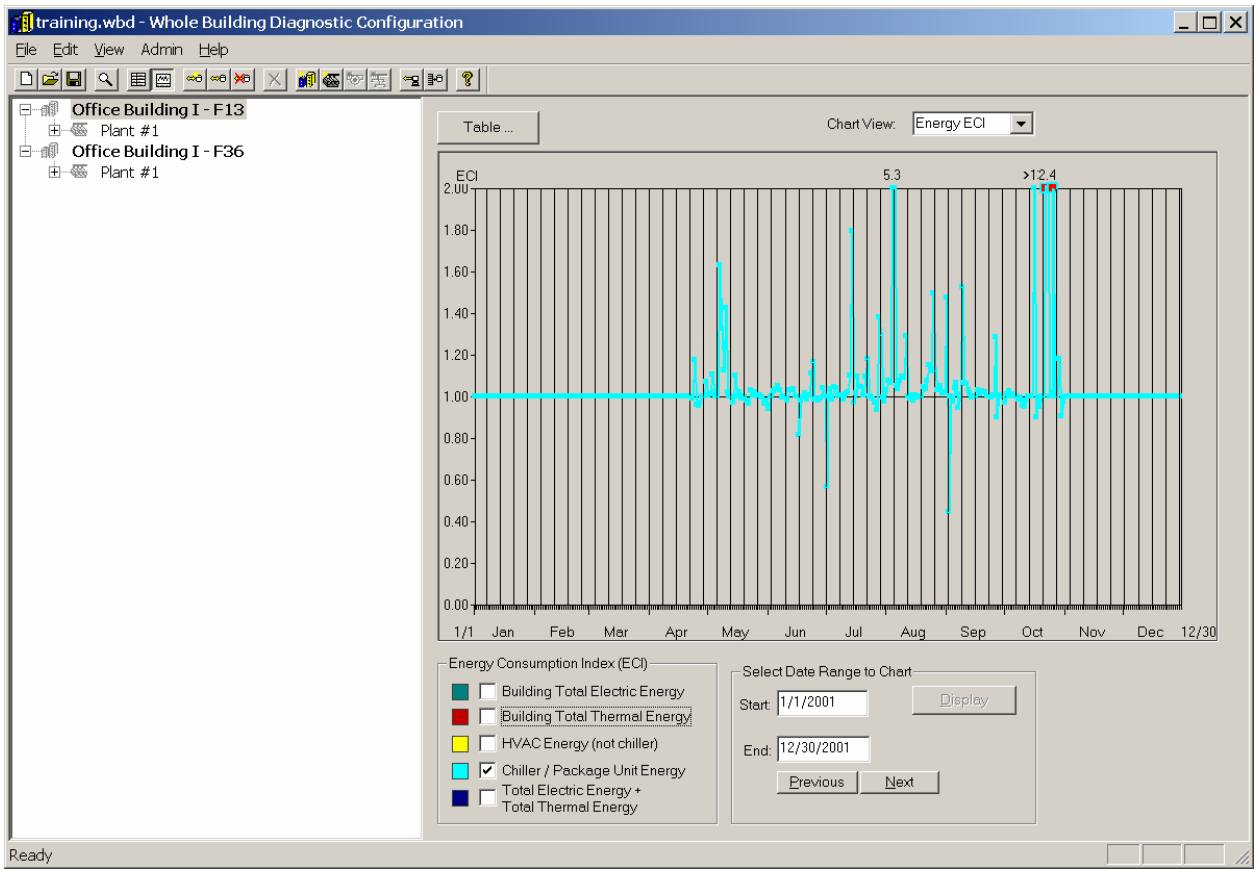



**Figure 93 – WBE Diagnostic Results for Chiller Electricity Use for Training Data**

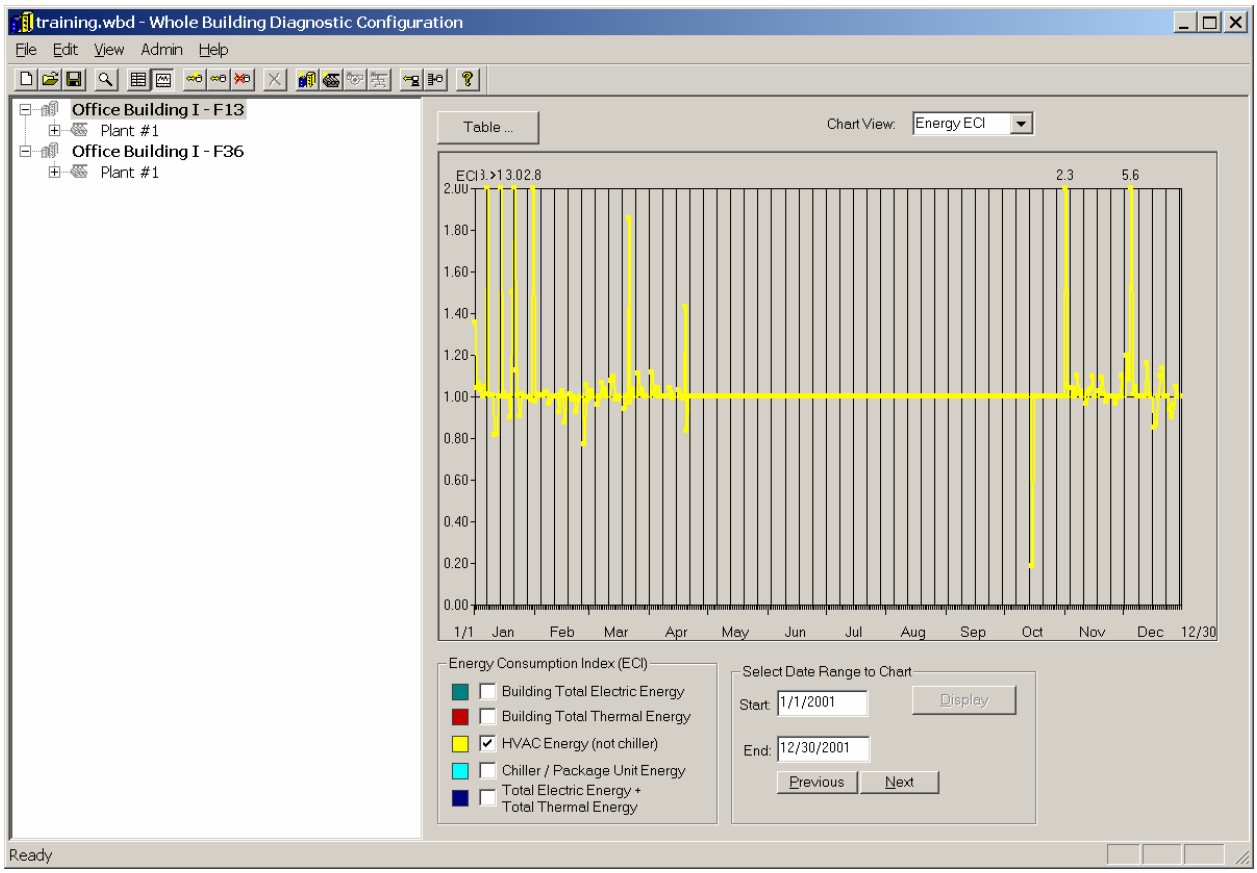



**Figure 94 – WBE Diagnostic Results for HVAC Electricity Use for Training Data**

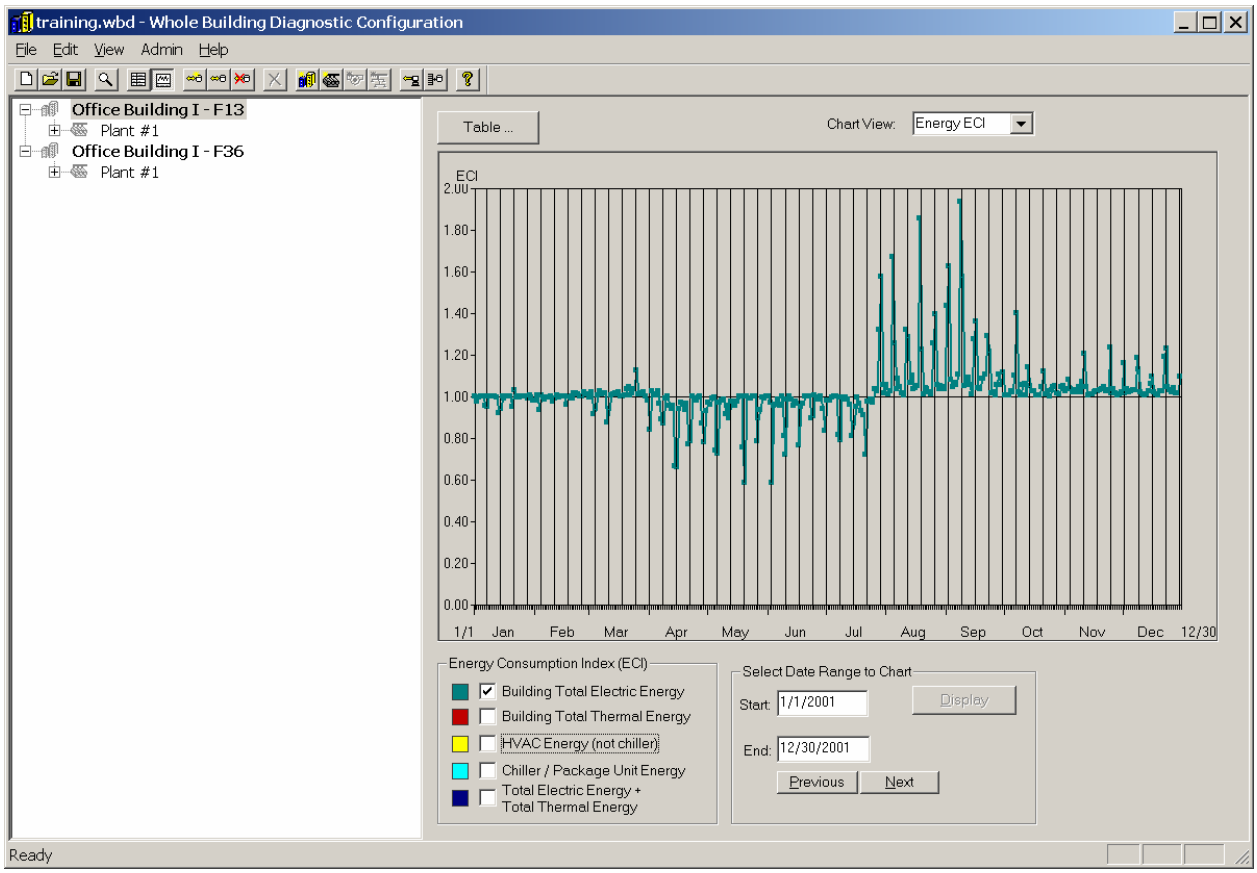



**Figure 95 – WBE Diagnostic Results for Total Electric Energy Use for Training Data**

## *7.4 WBE Results from Known Faults Operation*

After validating the configuration of building parameters and the ability of the simulation to generate fault-free data, the next step was to confirm the capability of the simulation to generate "faulty data" that represents improper building operations. Using the simulation, NIST generated two data sets with known faults: 1) an average increase of 15% in chiller energy consumption from May 16 to August 31, 2002, and 2) an average increase of 20% in thermal energy consumption from February 1 to April 30, 2002. Like the training data, each of the "faulty data" sets was 1 year long.

### 7.4.1 Faulty Chiller Operation (WBE–F13)

The WBE diagnostic results for the WBE-F13 data set are shown in Figure 96. With the exception of a couple of days in October 2002, most of the abnormal consumption occurs during May and August, as shown in shown in Figure 97. When a large red square is double-clicked, it shows the ECI value for the day and also the energy and cost impacts associated with the deviation, as shown in Figure 98. The results confirm that the WBE-F13 test has "faulty" data for the specified time period.

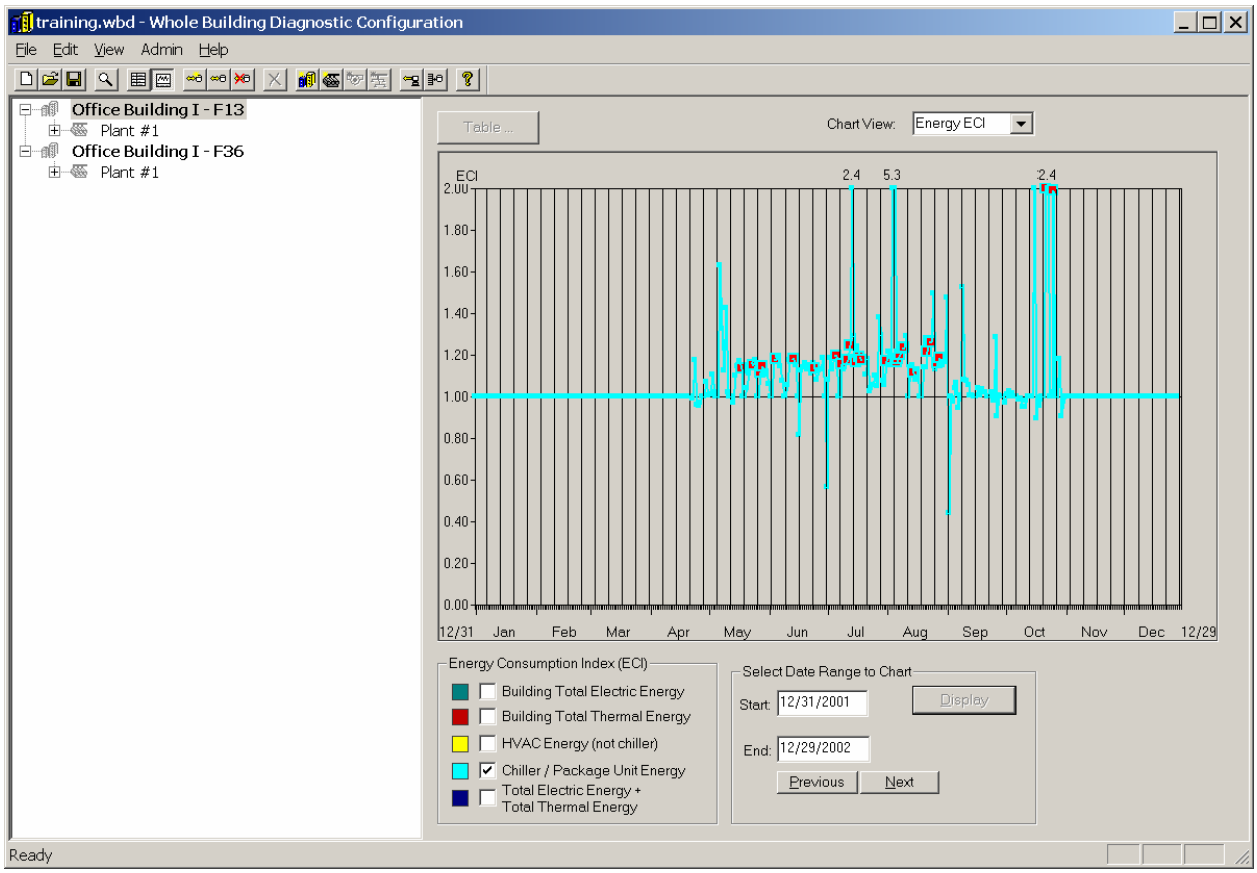



**Figure 96 – WBE Diagnostic Results for Chiller Electricity Use for the WBE-F13 Fault Data Set (December 31, 2001, through December 29, 2002)**

### 7.4.2 Faulty Boiler Operation

The WBE diagnostic results for the WBE-F36 data set are shown in Figure 99. Although there are several days when ECI values are high through the year, the WBE has identified only a few days between February and April as problems, as shown in Figure 100. A sample ECI problem detail for April 22, 2002, is shown in Figure 101; the cost impact for the day is only $2. Considering that the training data for this end-use varied widely and that the WBE had problems building a good model for this end-use, the results are not surprising. Although the results from the WBE are not conclusive, the "faulty" operation reported by the WBE is limited to the February through April as simulated. It appears that if the deviation in thermal energy consumption is significant (compared to the model for normal consumption), the WBE can identify abnormal consumption.

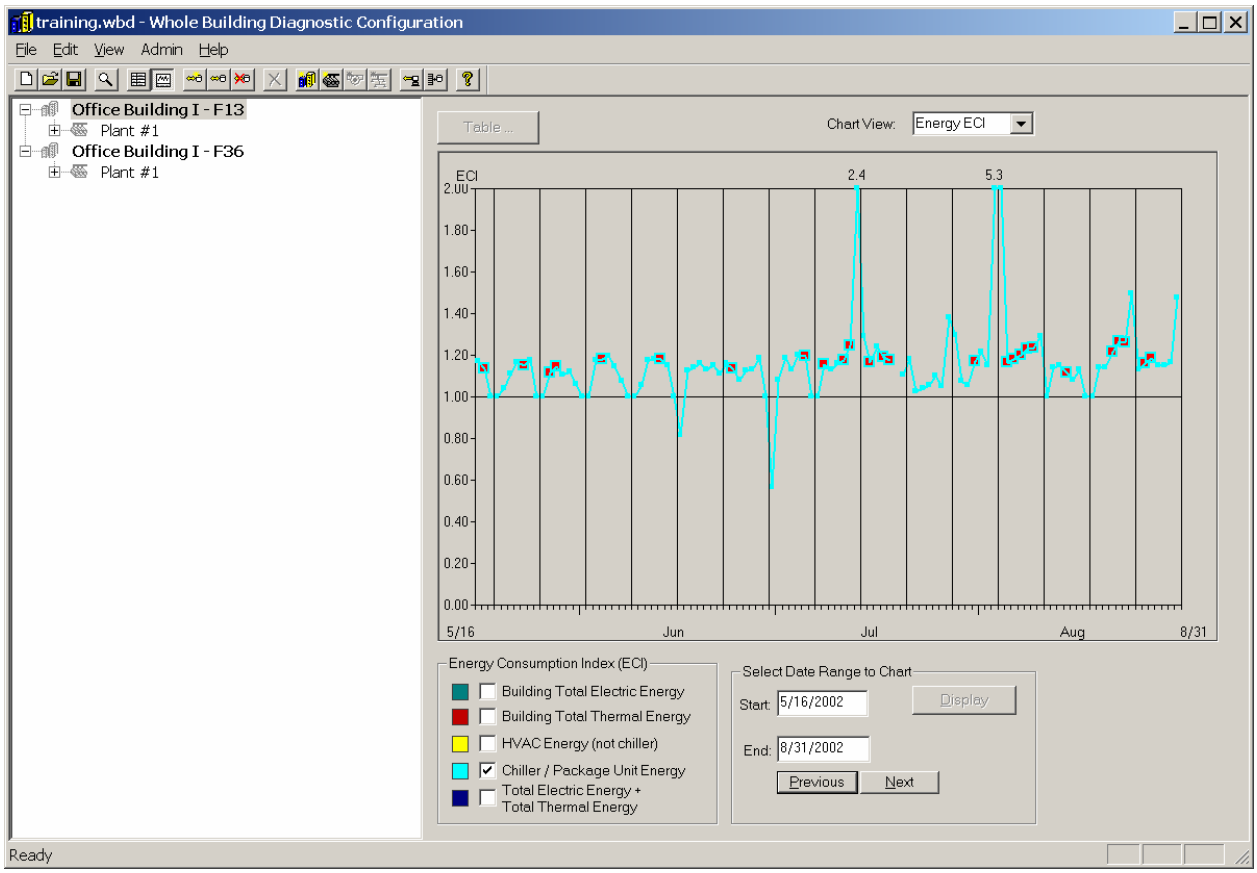
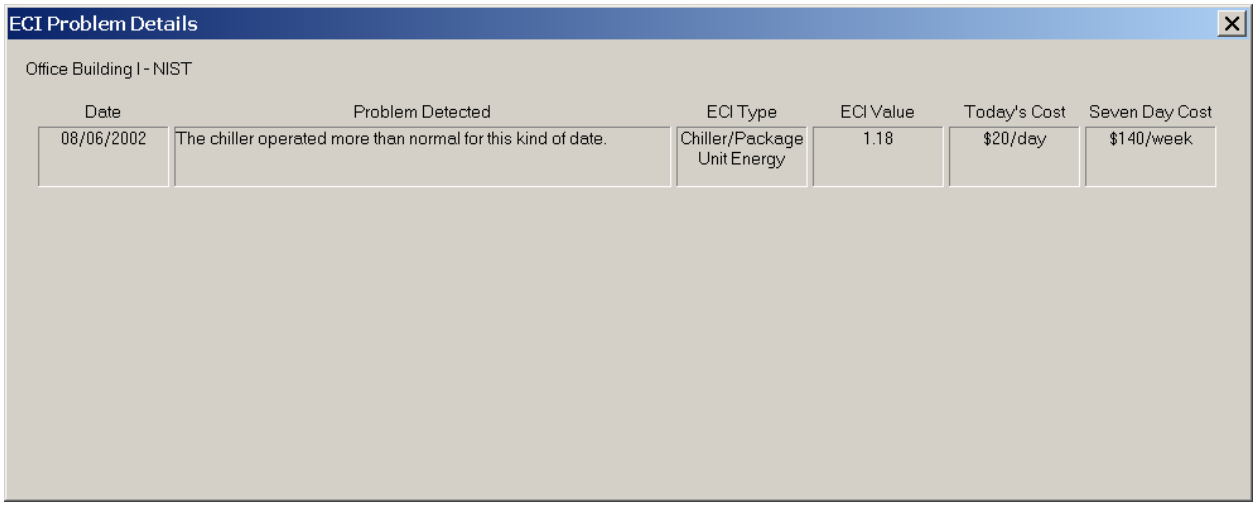



**Figure 97 – WBE Diagnostic Results for Chiller Electricity Use for the WBE-F13 Fault Data Set (May 15 through August 31, 2002)**



ECI Problem Details

Office Building I - NIST

| Date | Problem Detected | ECI Type | ECI Value | Today's Cost | Seven Day Cost |
|---|---|---|---|---|---|
| 08/06/2002 | The chiller operated more than normal for this kind of date. | Chiller/Package Unit Energy | 1.18 | $20/day | $140/week |

**Figure 98 – ECI Problem Details from the WBE Module for August 6, 2002**

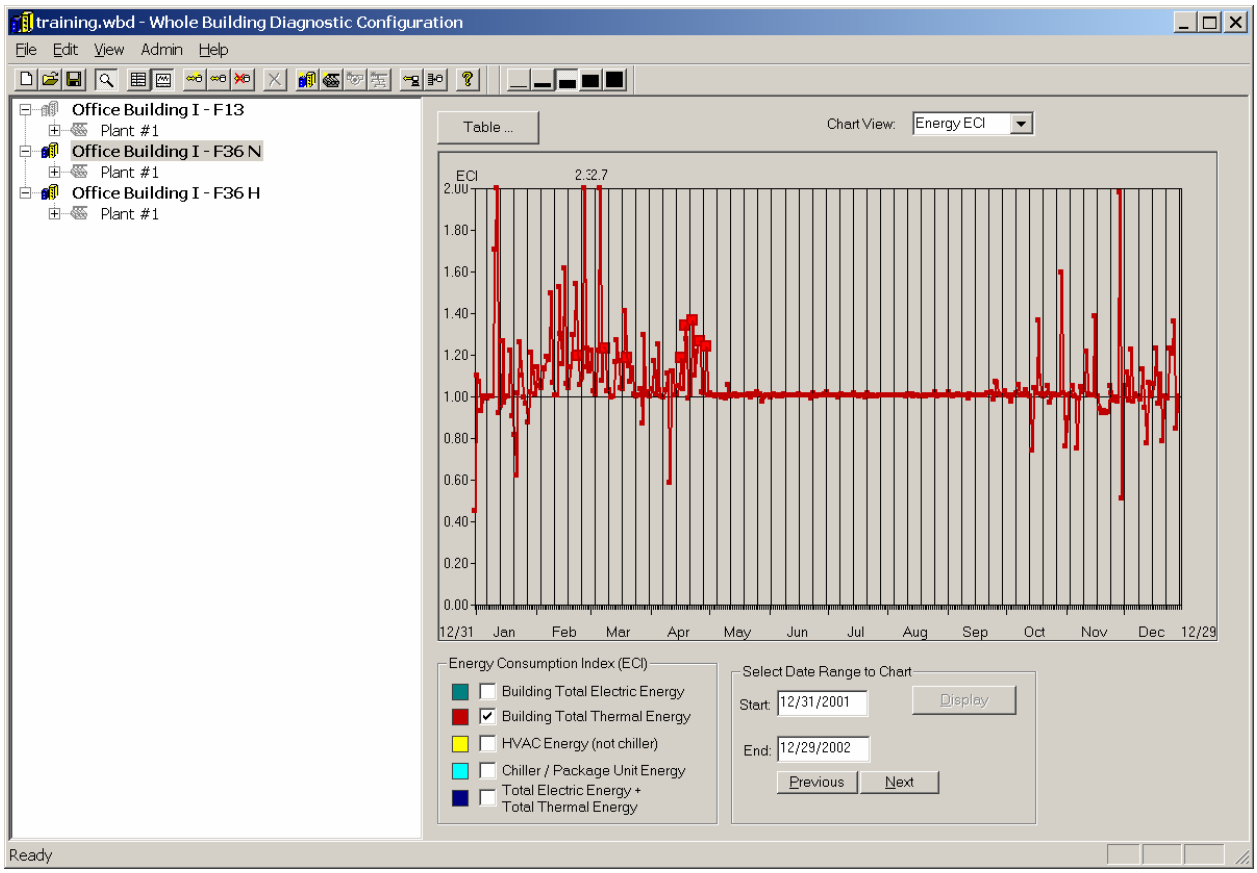



**Figure 99 – WBE Diagnostic Results for Thermal Energy Use for the WBE-F36 Fault Data Set with Normal Sensitivity (December 31, 2001, through December 29, 2002)**

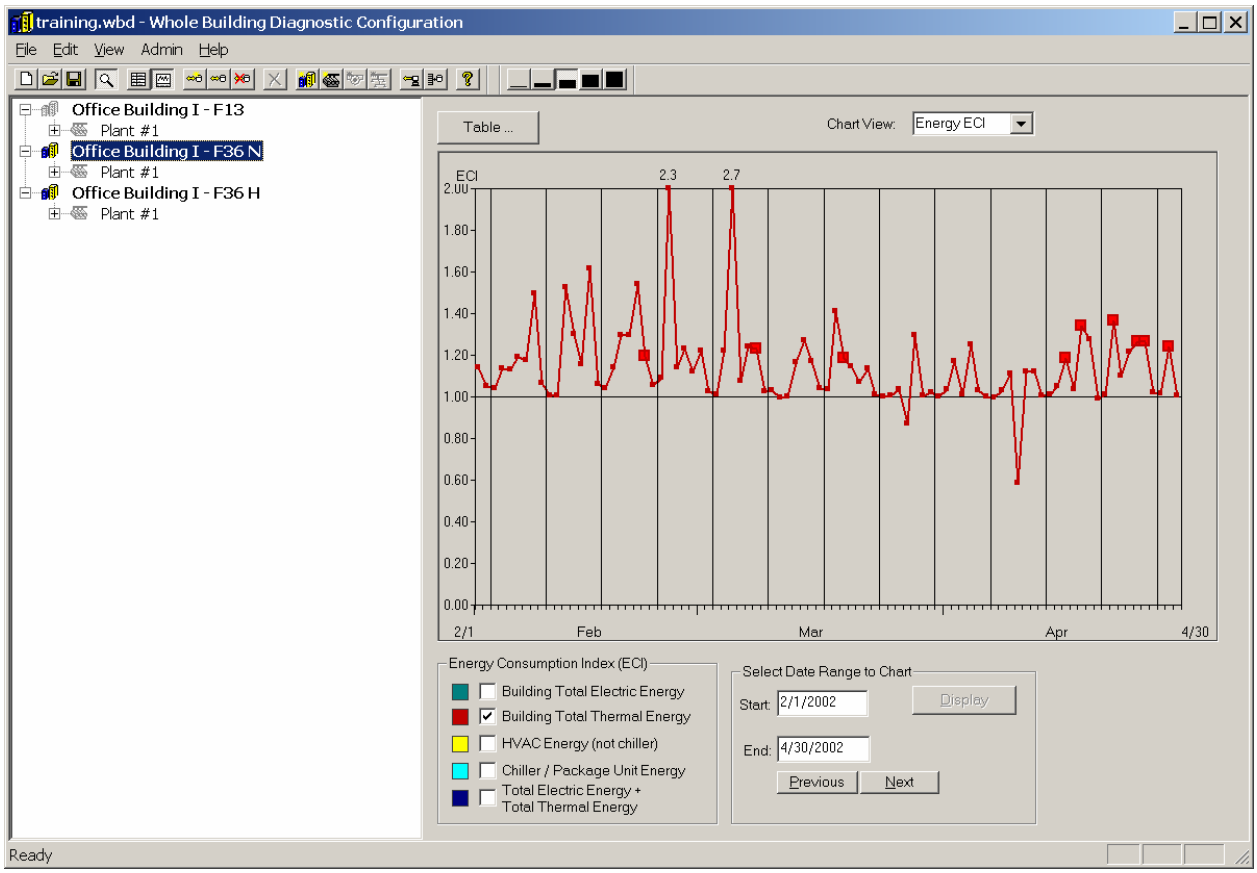
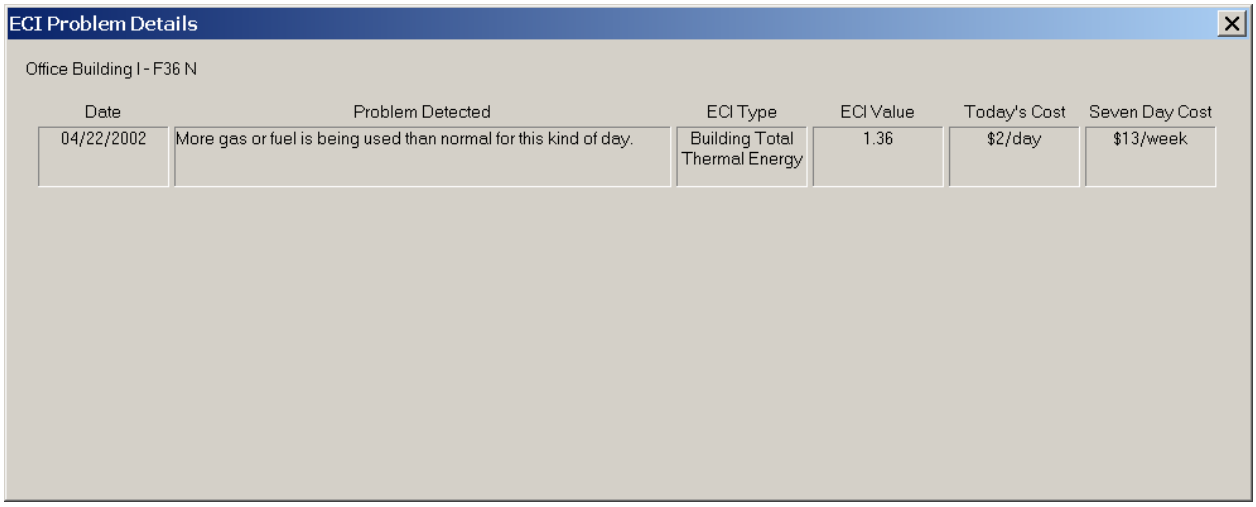



**Figure 100 – WBE Diagnostic Results for Thermal Energy Use for the WBE-F36 Fault Data Set with Normal Sensitivity (February 1, 2001, through December 29, 2002)**




| Date | Problem Detected | ECI Type | ECI Value | Today's Cost | Seven Day Cost |
|---|---|---|---|---|---|
| 04/22/2002 | More gas or fuel is being used than normal for this kind of day. | Building Total Thermal Energy | 1.36 | $2/day | $13/week |

**Figure 101 – ECI Problem Details from the WBE Module for April 22, 2002**

## *7.5 WBE Results from Blind Tests*

To evaluate the diagnostic capability of the WBE diagnostician to detect deviations in major building end-use consumption, NIST generated four data sets for blind tests. Like the previous tests (normal and non-blind fault data sets), all blind-test data sets are 1 year long. Results from processing the blind test data sets are presented in this section.

### 7.5.1 Data Set WBE-FB1

The data set WBE-FB1 represents the first of the four blind-test data sets and has end-use consumption data for lights and equipment, chiller, HVAC electricity (excluding chillers), and boiler energy consumption. The WBE diagnostic results for WBE-FB1 are shown in Figure 102. Although there are several days where ECI values are significantly different from 1.0, the WBE has only identified 1 day as a problem for boiler thermal energy consumption and two days for chiller electricity consumption (marked by circles in sub-figures (b) and (d)). Because the deviation in consumption did not persist for a prolonged period, it is considered normal operation.

*WBE Result: The data for all end-uses in blind test WBE-FB1 represent normal building operation.*

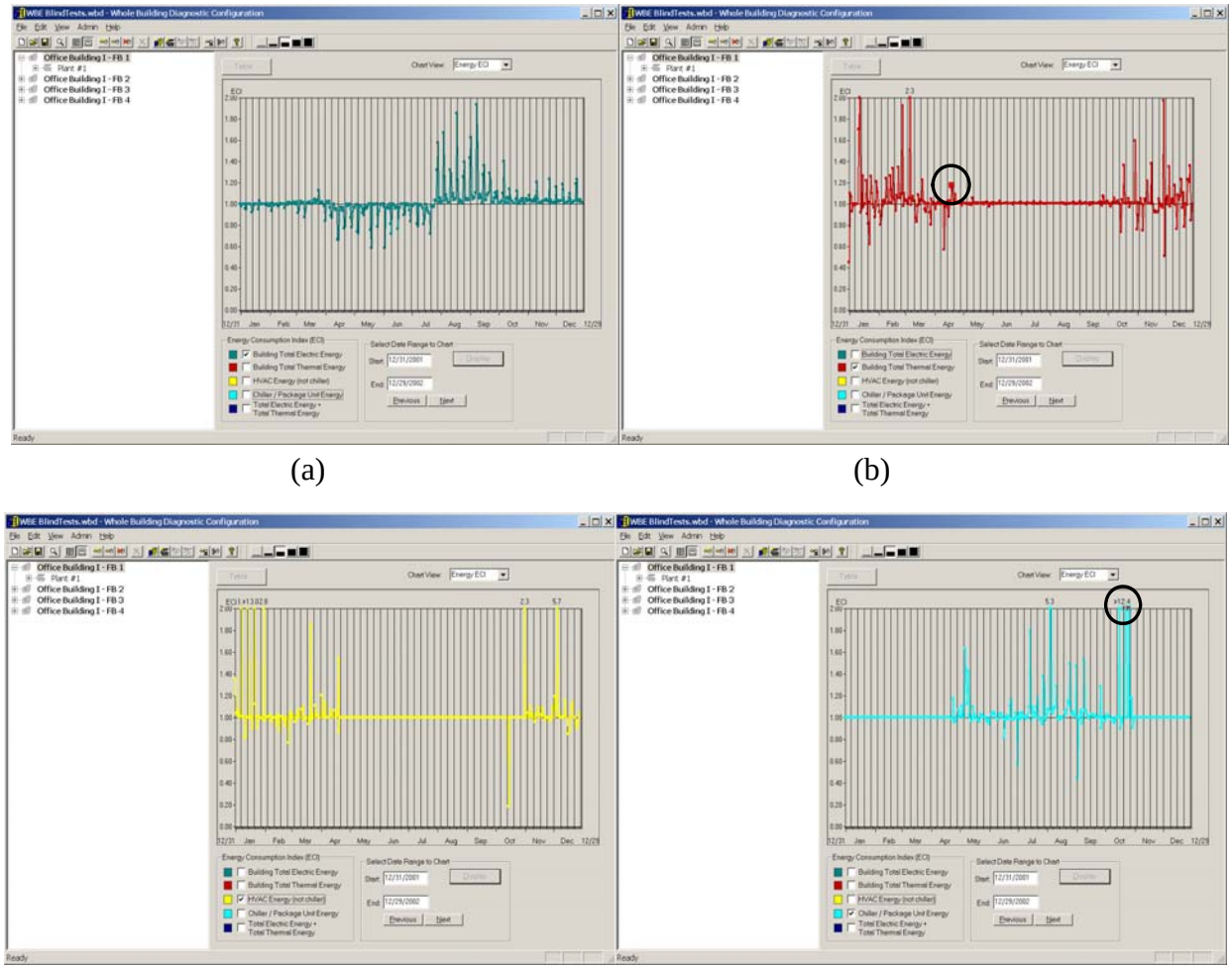


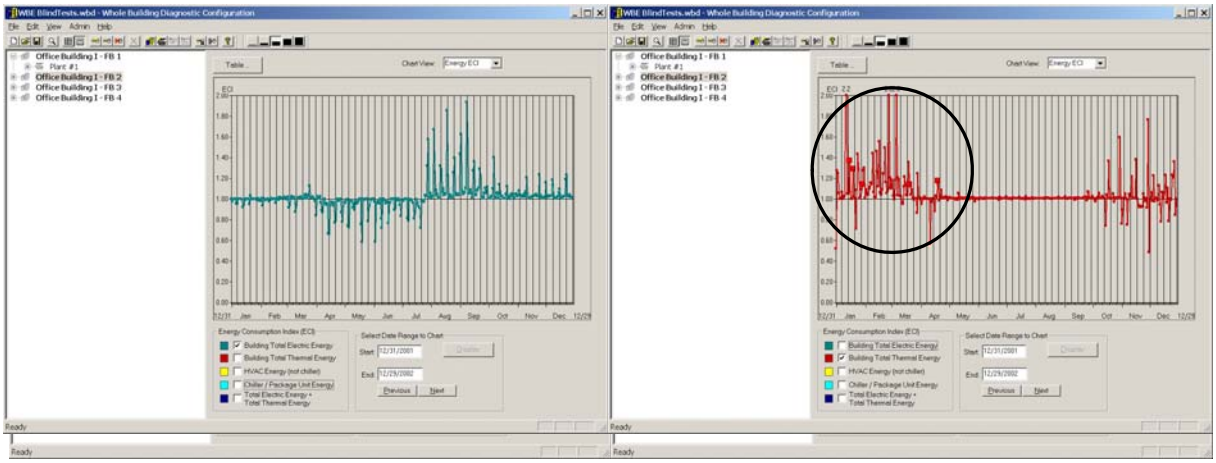

**Figure 102 – WBE Diagnostic Results for (a) Total Electricity, (b) Thermal Energy, (c) HVAC Electricity and (d) Chiller Electricity for the WBE-FB1 Fault Data Set with Normal Sensitivity (December 31, 2001, through December 29, 2002)**

### 7.5.2 Data Set WBE-FB2

The data set WBE-FB2 represents the second of the four blind-test data sets and has end-use consumption data for lights and equipment, chiller, HVAC electricity (excluding chillers), and boiler energy consumption. The WBE diagnostic results for WBE-FB2 are shown in Figure 103. Although there are several days where ECI values are significantly different from 1.0 for total electricity use and thermal energy consumption, the WBE identified problems with thermal energy consumption and 2 days for chiller electricity consumption (marked by circles in sub-figures (b) and (d)). Because the deviation in chiller energy consumption did not persist for a prolonged period, it is considered normal operation by the WBE. However, the WBE identified several days as having problems for thermal energy consumption, as shown in Figure 104. It appears that the actual thermal energy consumption is significantly different from expected for several days between January 14 and April 20, 2002. An ECI problem detail for one of the problem days is shown in Figure 105.

*WBE Result: The data for all end-uses with the exception of the thermal energy end-use for blind-test WBE-FB2 represent normal building operation. Thermal energy end-use shows an increase in consumption for January 14 through April 20, 2002.*

(a) (b)



(c) (d)

**Figure 103 – WBE Diagnostic Results for (a) Total Electricity, (b) Thermal Energy, (c) HVAC Electricity and (d) Chiller Electricity for the WBE-FB2 Fault Data set with Normal Sensitivity (December 31, 2001, through December 29, 2002)**

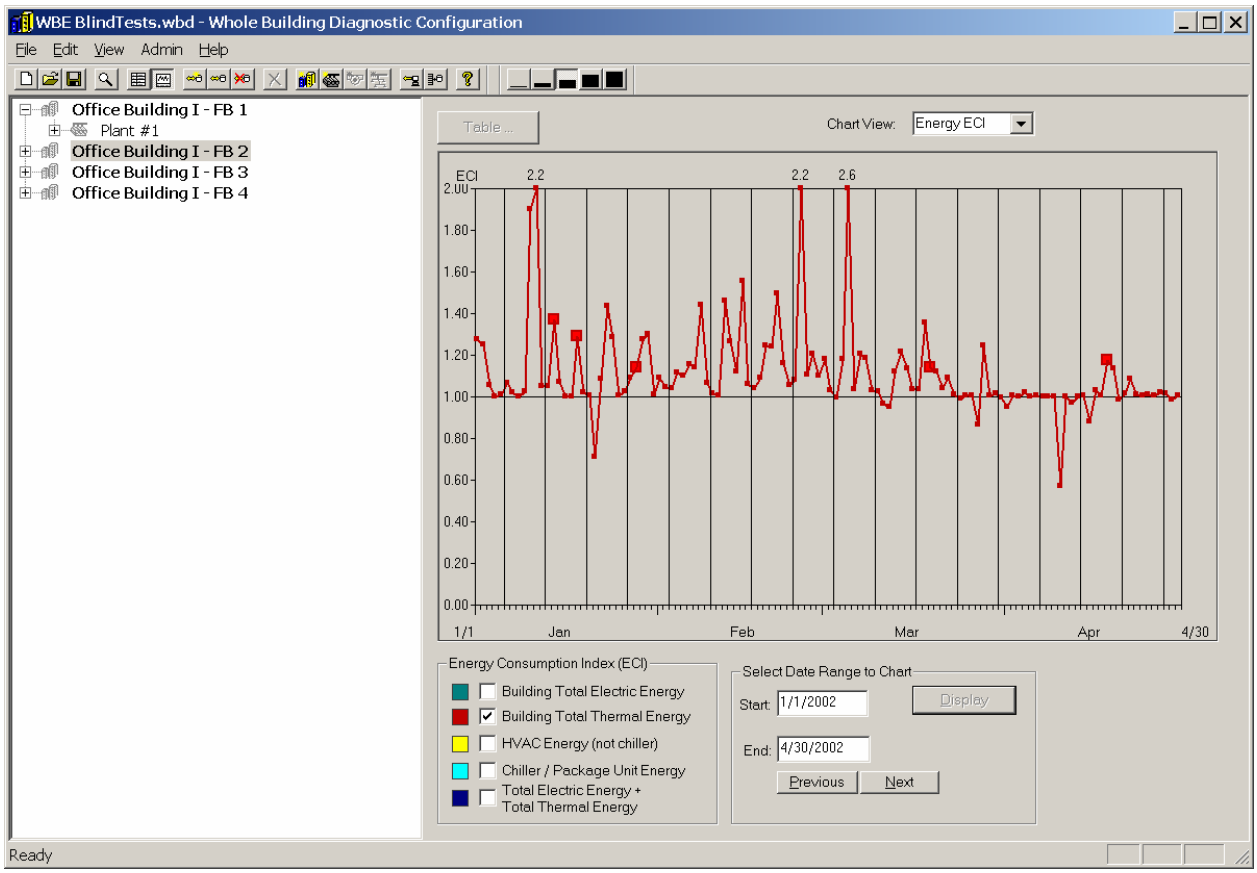
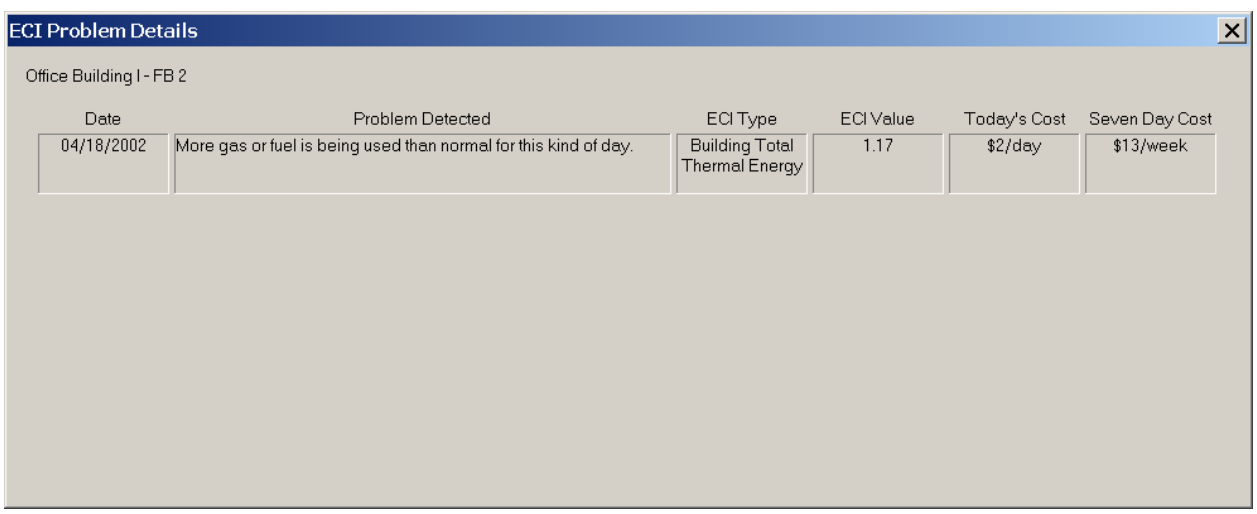



**Figure 104 – WBE Diagnostic Results for Thermal Energy Consumption for the WBE-FB2 Fault Data Set with Normal Sensitivity (January 1 through April 30, 2002)**




| Date | Problem Detected | ECI Type | ECI Value | Today's Cost | Seven Day Cost |
|---|---|---|---|---|---|
| 04/18/2002 | More gas or fuel is being used than normal for this kind of day. | Building Total Thermal Energy | 1.17 | $2/day | $13/week |

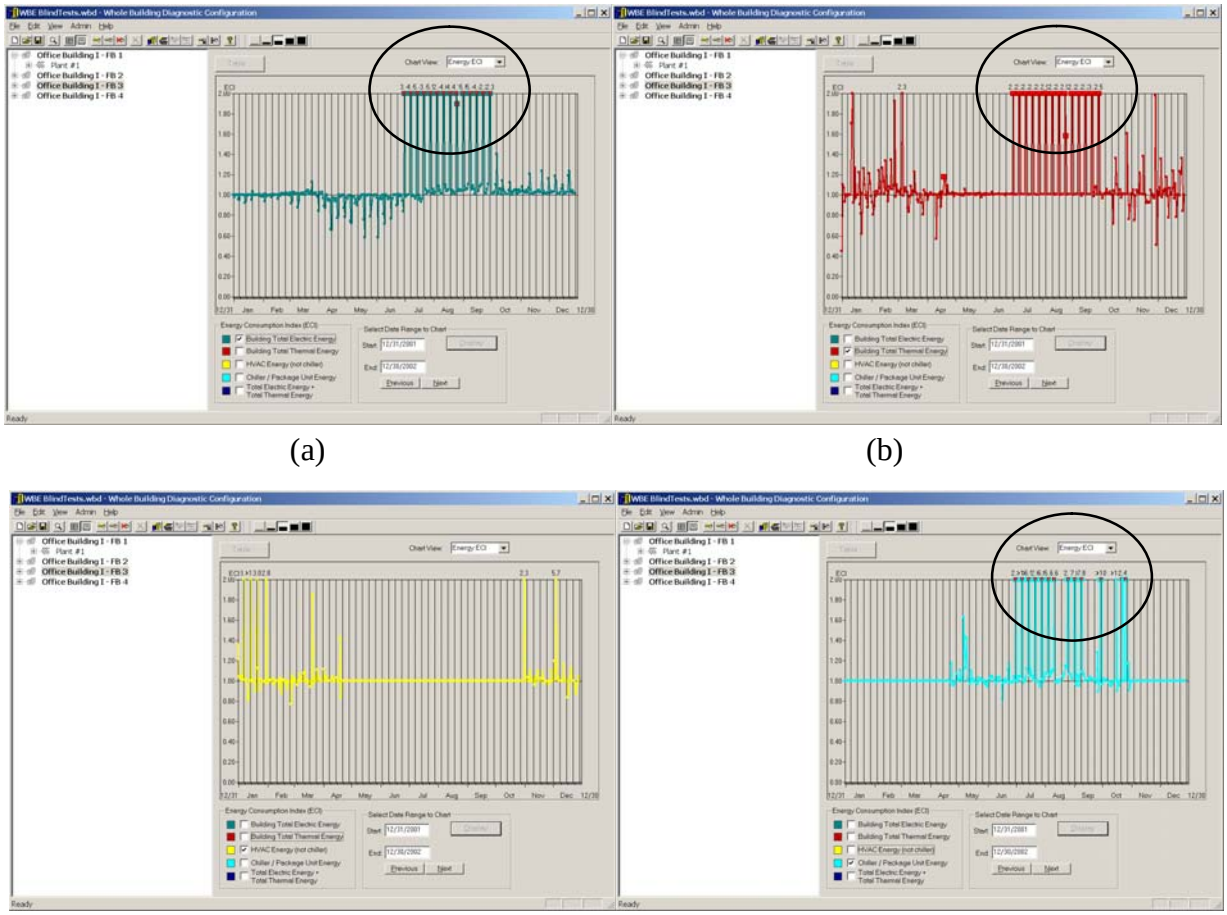
**Figure 105 – ECI Problem Details from the WBE Module for April 18, 2002**

### 7.5.3 Data Set WBE-FB3

The data set WBE-FB3 represents the third of the four blind-test data sets and has end-use consumption data for lights and equipment, chiller, HVAC electricity (excluding chillers), and

boiler energy consumption. The WBE diagnostic results for WBE-FB3 are shown in Figure 106. The WBE has identified an increase in consumption for all end-uses with the exception of HVAC electricity (marked by ellipses in sub-figures (a), (b) and (d)). More detailed screen shots of individual end-uses are shown in Figure 107, Figure 108, and Figure 109. The increase in consumption for all three end-uses occurs only on weekends and spans the same time period (June 30 through September 30, 2002). Because the increase in the total electric energy consumption (Figure 107) and chiller electric energy consumption (Figure 109) coincide, the problem is probably related to the chiller electricity use.

*WBE Result: Data for all end-uses with the exception of the HVAC electric energy end-use for blind test WBE-FB3 represent abnormal building operation during weekends for the time period spanning June 30 through September 30, 2002.*



(a) (b)

(c) (d)

**Figure 106 – WBE Diagnostic Results for (a) Total Electricity, (b) Thermal Energy, (c) HVAC Electricity and (d) Chiller Electricity for the WBE-FB3 Fault Data Set with Normal Sensitivity (December 31, 2001, through December 29, 2002)**

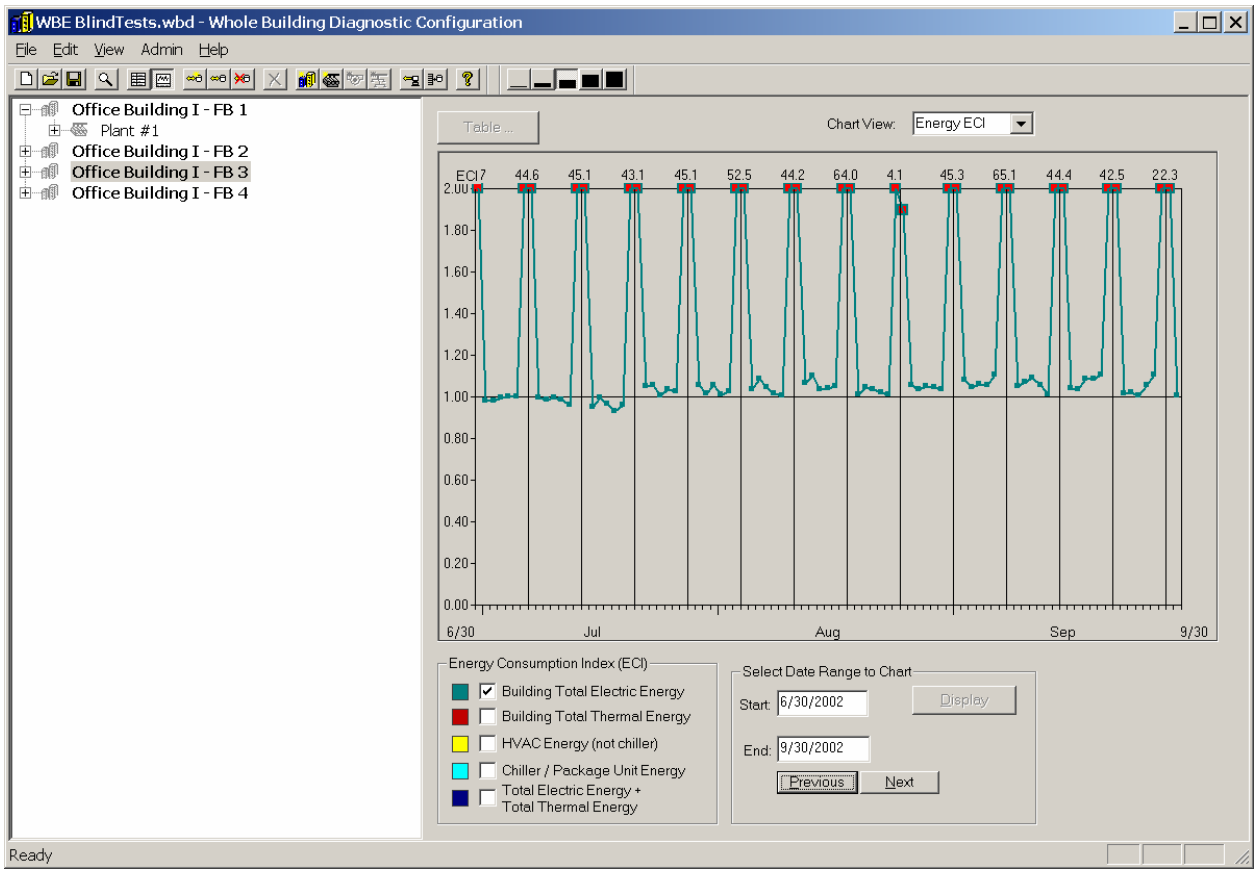



**Figure 107 – WBE Diagnostic Results for Total Electricity Consumption for the WBE-FB3 Fault Data Set with Normal Sensitivity (June 30 through September 30, 2002)**

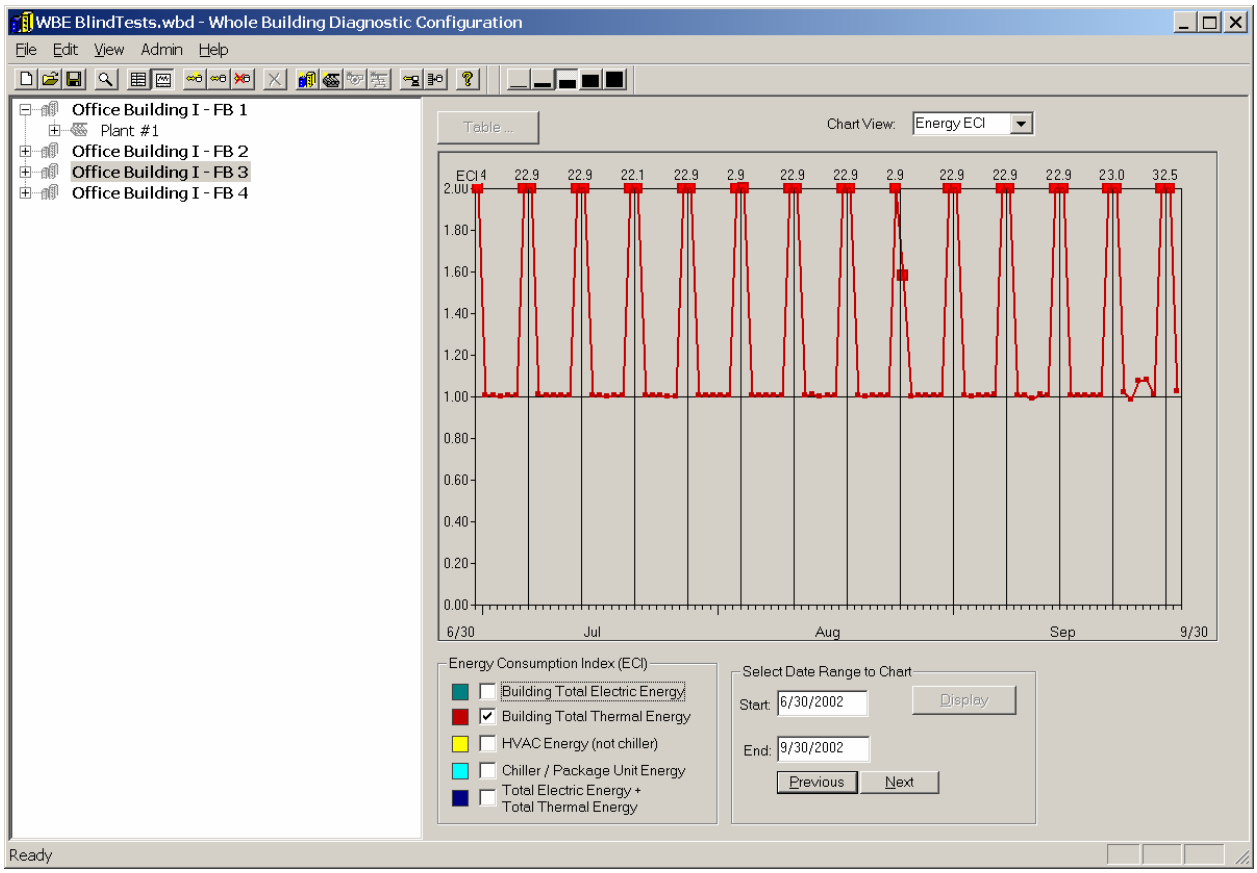



**Figure 108 – WBE Diagnostic Results for Thermal Energy Consumption for the WBE-FB3 Fault Data Set with Normal Sensitivity (June 30 through September 30, 2002)**

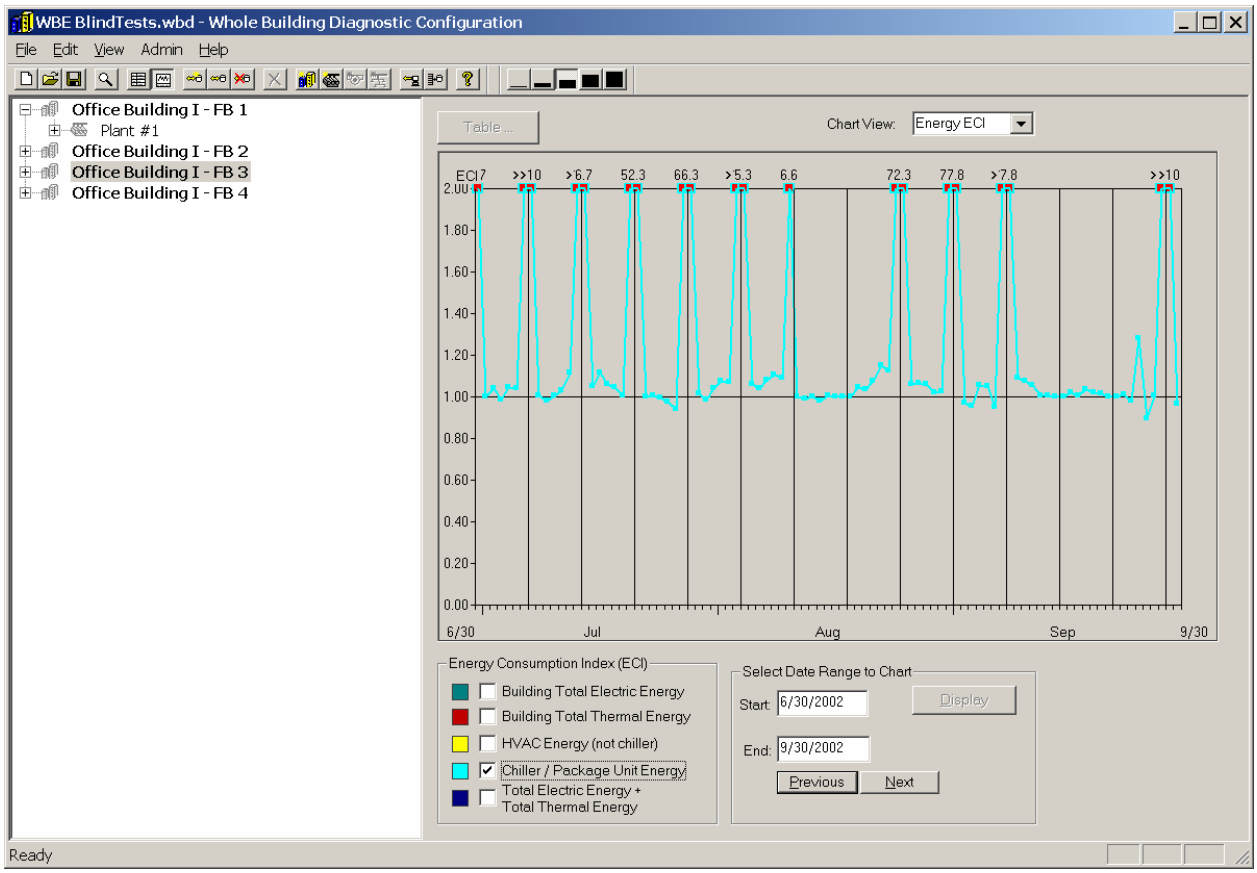
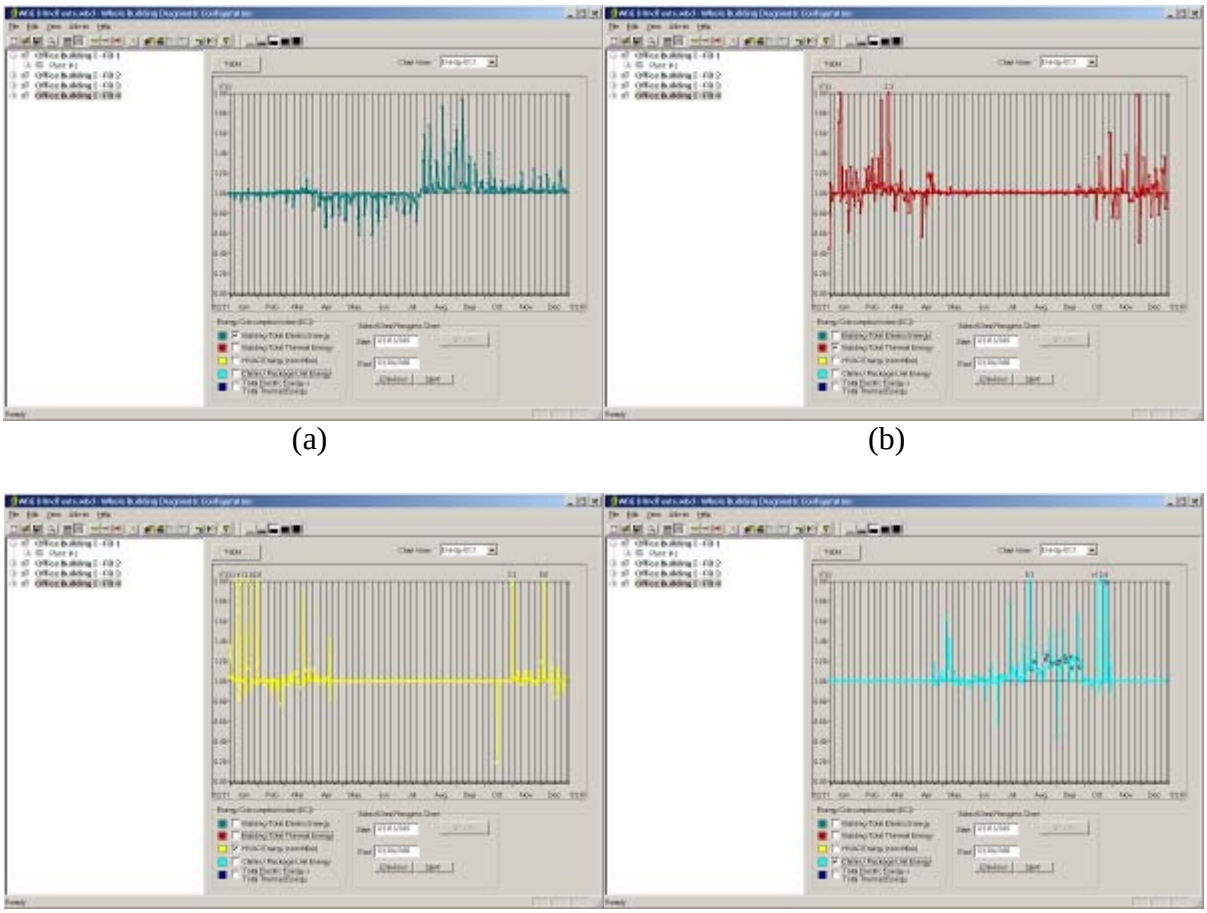



**Figure 109 – WBE Diagnostic Results for Chiller Electricity Consumption for the WBE-FB3 Fault Data Set with Normal Sensitivity (June 30 through September 30, 2002)**

### 7.5.4 Data Set WBE-FB4

The data Set WBE-FB4 represents the last of the blind-test data sets and has end-use consumption data for lights and equipment, chiller, HVAC electricity (excluding chillers), and boiler energy consumption. The WBE diagnostic results for WBE-FB4 are shown in Figure 110. The WBE has identified an increase in consumption for chiller electricity consumption (marked by circles in sub-figure (d)). A more detailed screen shot of the affected time span is shown in Figure 111. The increase in chiller electric energy consumption spans from August 1 through September 30, 2002. Although it is not from a 2-month view of the results, closer examination reveals that the chiller consumption may be increasing gradually over a time period spanning from the middle of June through the end of September, 2002 (Figure 110).

*WBE Result: Data for all end-uses with the exception of the chiller electricity use for the blind test WBE-FB4 represents normal building operation. The chiller electricity consumption appears to be gradually increasing from June through September 2002, although the WBE only identified problems for the time span of August through September 2002.*



(a) (b)

(c) (d)

**Figure 110 – WBE Diagnostic Results for (a) Total Electricity, (b) Thermal Energy, (c) HVAC Electricity, and (d) Chiller Electricity for the WBE-FB4 Fault Data Set with Normal Sensitivity (December 31, 2001, through December 29, 2002)**

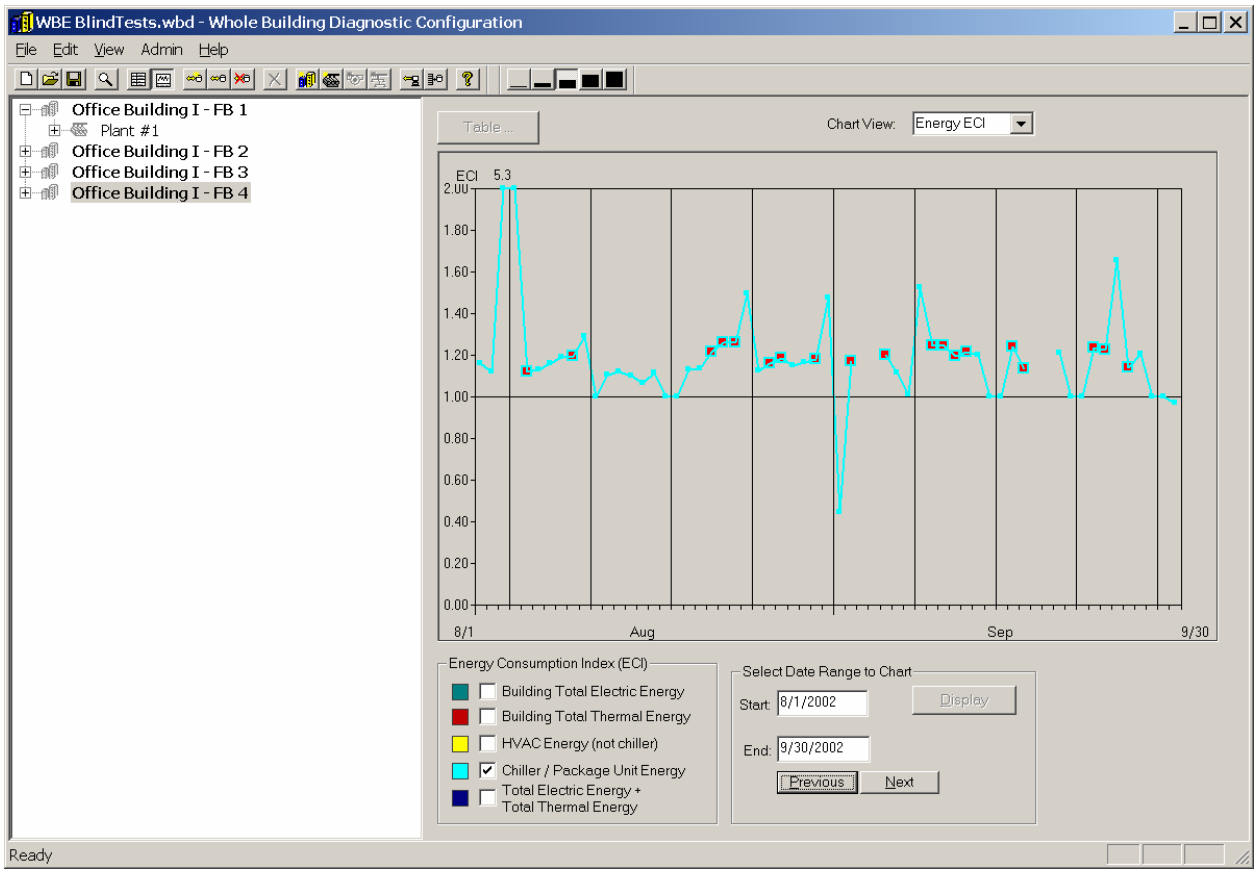



**Figure 111 – WBE Diagnostic Results for Chiller Electricity Consumption for the WBE-FB4 Fault Data Set with Normal Sensitivity (August 1 through September 30, 2002)**

# 8 Summary of Blind Test Results

In this section the results from the OAE and the WBE diagnostic modules are compared with the actual faults instigated in the VCBT environment.

## *8.1 Comparison of Faults Identified by the OAE with Actual Faults*

Faults detected and diagnosed by the OAE diagnostician and the actual faults instigated in the VCBT environment are compared in Table 14. The blind test is identified by number in the first column of the table; the second column lists the major fault categories that were identified by the OAE for each blind test. The categories that were more frequently identified are listed first. There are three major fault categories: 1) inadequate or low ventilation (blue), 2) energy waste (red) and 3) other problem (controls, sensors, simultaneous heating and cooling). In general, the most frequently identified fault category represents the actual fault. Although there are only three major fault categories, there are a number of faults that fall into each of the three categories.

The OAE also provides a detailed description of each fault. Depending on the type of fault and method of instigation, a fault can manifest in different categories based on the prevailing conditions, as is the case for some of the blind tests.

The fourth column in Table 14 lists the possible causes that the OAE reports. Because the list gets refined and changes over time, the most commonly listed causes are provided in Table 14. The order of the list is significant because the most likely cause will rise to the top if the fault continues for a significant amount of time. Column five shows the actual fault instigated in the VCBT environment (or the cause of the fault). Column six provides the overall result of the test by indicating whether the findings of the WBE are correct, false positive, false negative, or inconclusive. Comments are provided in the last column of the table.

Although in Section 6.5 most of the results were based on normal sensitivity with few at high, it did not include any discussion of results with low sensitivity setting. For comparison the results of all three settings (low, normal and high) are summarized in Table 14. The shaded row for each test identifies the conclusion from analysis of blind test data.

**Table 14 – Comparison of the Results from the OAE Diagnostician with Actual Faults.**

| Test | Sensitivity Setting | OAE Diagnostician | | Actual Fault Instigated (VCBT Simulation) | Test Result | Comments |
|---|---|---|---|---|---|---|
| | | Detection – Fault Categories[6] | Diagnosis – List of Possible Causes[7] | | | |
| Z1-SS-F5A | Low | 1. Energy waste - Not fully economizing. | 1. Maximum Outdoor-Air Fraction (OAF) is set too high in the OAE configuration.<br>2. Damper System fails to fully open in economizer mode.<br>3. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.<br>5. Supply-air set point incorrectly set too low.<br>6. O/A damper stuck between minimum[8] and fully closed position. | Recirculation air damper leakage | Correct | |

[6] Fault categories have been ordered by frequency of occurrence. In cases where the OAE could not identify any faulty operation, none of the categories identified is highlighted.
[7] The highlighted item is the most likely of the list of possibilities presented to the user; the selection is based on user discrimination of the results.
[8] Minimum position refers to the required minimum to meet the minimum ventilation requirements during occupied hours when mechanical cooling or heating is operating.

| | | | | | | |
|---|---|---|---|---|---|---|
| | Normal | **1. Energy waste - Not fully economizing.** | 1. Maximum Outdoor-Air Fraction (OAF) is set too high in the OAE configuration.<br>**2. Damper System fails to fully open in economizer mode.**<br>3. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. | Recirculation air damper leakage | Correct | |
| | High | 1. Energy waste - Not fully economizing. | 1. Maximum Outdoor-Air Fraction (OAF) is set too high in the OAE configuration.<br>2. Damper System fails to fully open in economizer mode.<br>3. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. | Recirculation air damper leakage | Correct | |
| Z2-SS-F5B | Low | 1. Normal Operation | | Normal operation | Correct | |
| | Normal | 1. Normal Operation | | Normal operation | Correct | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | High | **1. Inadequate ventilation - during occupied hours while NOT economizing.**<br>2. Energy waste.<br>3. Other Problem. | 1. Error in entering ventilation schedule.<br>2. **O/A (outdoor-air) damper system is too closed during occupied hours when the economizer is off.**<br>3. **O/A damper stuck between minimum and fully closed position.**<br>4. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>5. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.<br>6. Temperature sensor problem. | Normal operation | Correct | At normal sensitivity OAE indicated normal operation; however, when the sensitivity was increased OAE reported that the damper position was correctly positioned but the OAF was too low. |
| Z3-SS-F5C | Low | 1. Normal Operation | | Return-Air temperature sensor drift | False negative | |
| | Normal | 1. Normal Operation | | Return-Air temperature sensor drift | False negative | |
| | High | 1. Other problem - temperature sensor problem.<br>2. Energy waste.<br>3. Inadequate ventilation – during occupied hours while NOT economizing. | 1. O/A damper system is stuck between fully open and minimum position.<br>2. Supply-air set point incorrectly set too low.<br>3. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate. | Return air temperature sensor drift | False negative | The drift in the return-air temperature sensor was not detectable because of the choice of the outdoor conditions for the test. Refer to the report for more details. |

| | | | | | | |
|---|---|---|---|---|---|---|
| Z1-HS-F4 | Low | 1. Normal operation. | | Supply-air temperature sensor drift | False negative | |
| | Normal | 1. Normal operation. | | Supply-air temperature sensor drift | False negative | |
| | High | **1. Energy waste.** | 1. Maximum OAF is set too high in the OAE configuration.<br>**2. Supply-air set point incorrectly set too low.**<br>3. O/A damper system fails to fully open in full economizer mode.<br>4. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>5. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.<br>6. O/A damper stuck between fully open and minimum position. | Supply-air temperature sensor drift | False negative | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Z2-HS-F4 | Low | 1. Normal operation. | | Normal Operation | Correct | |
| | Normal | 1. Normal operation. | | Normal Operation | Correct | |
| | High | 1. Normal operation. | | Normal Operation | Correct | |
| Z3-HS-F4 | Low | **1. Other problem - temperature sensor problem.** | **1. Mixed-, return- and/or outdoor-air temperature sensor has failed.** | Mixed-air temperature sensor failure | Correct | |
| | Normal | **1. Other problem - temperature sensor problem.** | **2. Mixed-, return- and/or outdoor-air temperature sensor has failed.** | Mixed-air temperature sensor failure | Correct | |
| | High | 1. Other problem - temperature sensor problem. | 3. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Mixed-air temperature sensor failure | Correct | |
| Z1-SS-F6 | Low | **1. Other Problem - temperature sensor problem.**<br>2. Energy waste.<br>3. Inadequate ventilation – during occupied hours while NOT economizing. | **1. Mixed-, return- and/or outdoor-air temperature sensor has failed.** | Outdoor-air temperature sensor failure | Correct | |
| | Normal | **1. Other Problem - temperature sensor problem.**<br>2. Energy waste.<br>3. Inadequate ventilation – during occupied hours while NOT economizing. | **1. Mixed-, return- and/or outdoor-air temperature sensor has failed.** | Outdoor-air temperature sensor failure | Correct | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | High | **1. Other Problem - temperature sensor problem.**<br>2. Energy waste.<br>3. Inadequate ventilation – during occupied hours while NOT economizing. | **1. Mixed-, return- and/or outdoor-air temperature sensor has failed.** | Outdoor-air temperature sensor failure | Correct | |
| Z2-SS-F6 | Low | 1. Normal Operation. | | Return-air temperature sensor drift | False negative | |
| | Normal | **1. Other problem - temperature sensor problem**<br>2. Energy waste<br>3. Inadequate ventilation – during occupied hours while NOT economizing. | 1. **Mixed-, return- and/or outdoor-air temperature sensor has failed.** | Return-air temperature sensor drift | False negative | |
| | High | 1. Other problem - temperature sensor problem<br>2. Energy waste<br>3. Inadequate ventilation – during occupied hours while NOT economizing. | 1. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Return-air temperature sensor drift | False negative | |
| Z3-SS-F6 | Low | 1. Normal Operation | | Outdoor-air damper stuck at minimum position | False negative | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Normal | **1. Energy waste – low economizer flow.** | 1. Maximum OAF is set too high in the OAE configuration.<br>**2. O/A damper system fails to fully open in full economizer mode.**<br>3. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.<br>5. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Outdoor-air damper stuck at minimum position | Correct | |
| | High | 1. Energy waste – low economizer flow. | 1. Maximum OAF is set too high in the OAE configuration.<br>2. O/A damper system fails to fully open in full economizer mode.<br>3. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.<br>5. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Outdoor-air damper stuck at minimum position | Correct | |
| Z1-SS-F8 | Low | 1. Other problem - temperature sensor problem. | 1. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Mixed-air temperature sensor drift | Correct | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Normal | 1. **Other problem - temperature sensor problem.** | 1. **Mixed-, return- and/or outdoor-air temperature sensor has failed.** | Mixed-air temperature sensor drift | Correct | |
| | High | 1. Other problem - temperature sensor problem. | 1. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Mixed-air temperature sensor drift | Correct | |
| Z2-SS-F8 | Low | 1. Normal operation. | | Normal operation | Correct | |
| | Normal | 1. Normal Operation. | | Normal operation | Correct | |
| | High | **1. Inadequate ventilation – during occupied hours while NOT economizing.**<br>2. Other Problem - temperature sensor problem.<br>3. Energy waste. | 1. Error in entering ventilation schedule.<br>**2. O/A damper system is too closed during occupied hours when the economizer is off.**<br>3. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>4. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.<br>5. **O/A damper stuck between minimum and fully closed position.**<br>6. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Normal operation | False Positive | At normal sensitivity OAE indicated normal operation; however, when the sensitivity was increased OAE reported that the damper position was correctly positioned but the OAF was too low. |
| Z3-SS-F8 | Low | 1. Normal operation. | | Recirculation-air damper leakage | False negative | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Normal | 1. **Energy waste - not fully economizing.** | 1. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>2. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.<br>3. Temperature sensor problem.<br>4. Maximum OAF is set too high in the OAE configuration.<br>5. **Damper system fails to fully open in economizer mode.** | Recirculation-air damper leakage | Correct | |
| | High | 1. Energy waste - not fully economizing. | 1. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>2. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.<br>3. Temperature sensor problem.<br>4. Maximum OAF is set too high in the OAE configuration.<br>5. Damper system fails to fully open in economizer mode. | Recirculation-air damper leakage | Correct | |
| Z1-CS-F9 | Low | 1. Incomplete diagnosis. | | Supply-air temperature sensor failure | False negative | |
| | Normal | 1. Normal operation. | | Supply-air temperature sensor failure | False negative | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | High | **1. Inadequate ventilation – during occupied hours while NOT economizing.** | **1.** Error in entering ventilation schedule. **O/A damper system is too closed during occupied hours when the economizer is off.**<br>2. Supply-air flow increased without a proportional increase in outdoor-air intake.<br>3. Outdoor-air intake decreased without a proportional decrease in supply-air flow rate.<br>4. **O/A damper stuck between minimum and fully closed position.**<br>5. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Supply-air temperature sensor failure | Correct | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Z2-CS-F9 | Low | 1. Energy waste – excess outdoor-air. | 1. OAE is set up for temperature based economizer, but the actual control may be based on enthalpy.<br>2. OAE is set up with differential economizer controls, but the actual controls may be based on high limit.<br>3. O/A ventilation controller failed in open state.<br>4. Economizer controller failed in open condition<br>**5.** O/A damper system is stuck between fully open and minimum position.<br>6. O/A damper is stuck in fully open position.<br>7. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Economizer control logic fault | Correct | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Normal | **1. Energy waste – excess outdoor-air.** | 1. OAE is set up for temperature based economizer, but the actual control may be based on enthalpy.<br>2. OAE is set up with differential economizer controls, but the actual controls may be based on high limit.<br>**3. O/A ventilation controller failed in open state.**<br>**4. Economizer controller failed in open condition**<br>**5. O/A damper system is stuck between fully open and minimum position.**<br>6. **O/A damper is stuck in fully open position.**<br>7. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Economizer control logic fault | Correct | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | High | 1. Energy waste – excess outdoor-air. | 1. OAE is set up for temperature based economizer, but the actual control may be based on enthalpy.<br>2. OAE is set up with differential economizer controls, but the actual controls may be based on high limit.<br>3. O/A ventilation controller failed in open state.<br>4. Economizer controller failed in open condition<br>5. O/A damper system is stuck between fully open and minimum position.<br>6. O/A damper is stuck in fully open position.<br>7. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Economizer control logic fault | Correct | |
| Z3-CS-F9 | Low | 1. Incomplete diagnosis. | | Return-air temperature sensor drift | False negative | |
| | Normal | **1. Other problem - temperature sensor problem.** | **1. Mixed-, return- and/or outdoor-air temperature sensor has failed.** | Return-air temperature sensor drift | Correct | |
| | High | 1. Other problem - temperature sensor problem. | 1. Mixed-, return- and/or outdoor-air temperature sensor has failed. | Return-air temperature sensor drift | Correct | |

## 8.2 Comparison of Faults Identified by WBE with Actual Faults

The results from the tests of the WBE diagnostician are summarized in **Error! Not a valid bookmark self-reference.**. Each blind test is identified by number in the first column of the table; the second column indicates whether or not there was an abnormal condition detected in the data set, and the end-use with the abnormal condition is identified as well. Unlike the OAE diagnostician, the WBE only identifies abnormal conditions but does not provide a list of possible causes of the abnormal condition. By resolving total building energy consumption into major energy use categories, it does, however, enable the user to identify the end use responsible for abnormal energy consumption detected at the whole-building level. Column three shows the actual fault that was simulated, and column four provides the overall result of the test by indicating whether the findings of the WBE are correct, false positive, false negative, or inconclusive. Comments are provided in the last column of the table.

**Table 15 – Comparison of the Results from the WBE Diagnostician with Actual Faults**

| Test | WBE Diagnostic Results | Actual Fault Instigated in Simulations | Test Result | Comments |
|---|---|---|---|---|
| WBE-FB1 | Normal | WBE23: 10 % increase in HVAC electrical consumption (April 1 – June 30, 2002) | False Negative | Because the magnitude of HVAC consumption is low (15 kWh/day); at 10% change doesn't result in a cost impact i.e., greater than $10/day; therefore, WBE (as designed) didn't detect this fault |

| Test | WBE Diagnostic Results | Actual Fault Instigated in Simulations | Test Result | Comments |
|---|---|---|---|---|
| WBE-FB2 | Higher than normal thermal energy consumption from January 14 through April 30, 2002 | WBE35: 15 % increase in boiler gas consumption (1 January 1 - March 31, 2002) | Correct | There was a statistically significant increase in thermal energy consumption only for a few days; generally, this is not considered a problem, but because the ECI values were greater than 1 and also given the problem with training, this end-use, it is identified as a problem. |
| WBE-FB3 | Higher than normal thermal and chiller energy consumption during weekends June 30 through September 30, 2002, for thermal energy consumption and June 30 through September 30, 2002, for chiller energy consumption | WBE09: Scheduling problem – same internal loads weekdays and weekends (July 1 through September 30, 2002) | Correct | |
| WBE-FB4 | Higher than normal chiller energy consumption August 1 through September 30, 2002 | WBE22: Progressively developing increase in chiller electrical energy consumption (electricity consumption increases linearly from 0 % to 25 % increase) (July 1 through September 30, 2002) | Correct | Because the fault was progressive, WBE didn't detect it until the fault was significant (after August 1, 2002) |

# 9 Summary and Recommendations

In addition to generating several data sets representing normal operations and know faults, 15 blind data sets for testing the capabilities of the OAE diagnostician and 4 blind data sets for testing the WBE diagnostician were generated. Data sets for the OAE were generated using the VCBT emulation environment, and data sets for the WBE were generated using just the HVACSIM$^+$ simulation environment. The VCBT emulation and the simulation for the WBE data were successful in generating data representing normal and faulty operations.

## *9.1 Outdoor-Air Economizer Diagnostician*

Of the 15 data sets for the OAE, 12 data sets represented "faulty" AHU operation and 3 data sets represented normal operation. The OAE was successful in detecting faulty operation with 10 of the 12 "faulty" data sets. In addition to detecting the faults, the OAE diagnostician also provides a list of possible causes for the fault. Because diagnosing the cause of the actual fault with limited sensor information is difficult, the OAE provides a list of potential causes rather than a single cause. In most cases, the list of potential causes contained the actual cause of the fault. The OAE was successful in detecting and diagnosing a variety of mechanical and control faults including stuck and leaking dampers, sensor drift, sensor failure, and control logic and sequencing errors.

The OAE was unsuccessful in detecting the faults in two data sets because the conditions were not favorable for detection of the fault, i.e., the fault did not have a significant adverse impact on either the ventilation requirement or the energy consumption. If the fault conditions persisted beyond the three-week period and data were available, conditions would have become more favorable for detection of these faults as the weather changed and the OAE would have then detected them.

The OAE successfully identified all three normal data sets as being fault free with a normal sensitivity setting. However, when the sensitivity of detection was increased, the OAE reported that two data sets that were labeled fault free by NIST had lower than expected outdoor-air fractions (OAFs) for a number of hours. A sample message from the OAE is shown in Figure 113; it states that although the outdoor-air damper position was correct, the outdoor-air fraction computed from the measured values of the outdoor-, mixed- and return-air temperatures was significantly lower than expected. Examination of the three-week trend of the OAF revealed that the average OAF during the three-week period was less than 6% when the expected value was 15%.

In general, the OAF is somewhat uncertain because it is estimated as the ratio of two temperature differences, which are often small because the temperatures are close to one another. When they are small, for example, during the swing season (spring and fall), the OAF has a potential for even taking negative values because of uncertainty in temperature measurements. Figure 112 shows the distribution of OAF for one test when the conditions were not favorable for economizing. When the outdoor conditions are not favorable for economizing, the expected OAF should be around 0.15 for this test. However, as seen from Figure 112, the OAF is negative for over half the time and significantly biased (i.e., thirty two of the values are below 15% while

only 5 are above 15%). Although we expect the calculated OAF to be uncertain, ordinarily data from the field will not have this degree of bias around the expected value (see Figure 112); it will be more symmetric about the expected value, unless a fault is present. Because the OAF was less than the expected value for many hours, the OAE reported faulty operation when the sensitivity setting was set to high. Additional field tests may be required to understand this phenomenon better and its effects on fault detection.

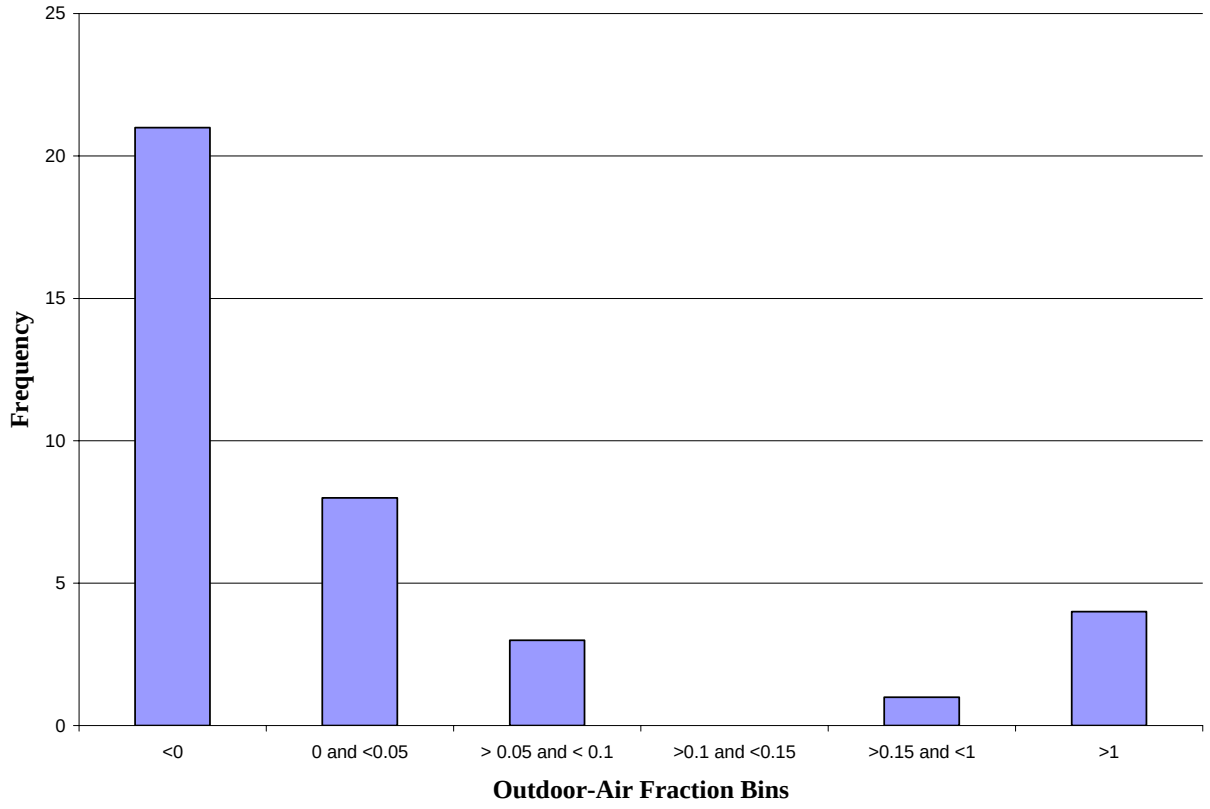



**Figure 112 – Distribution of Outdoor-Air Fraction for Conditions When it is not Favorable for Economizing (i.e. expected Outdoor-Air Fraction is 0.15)**

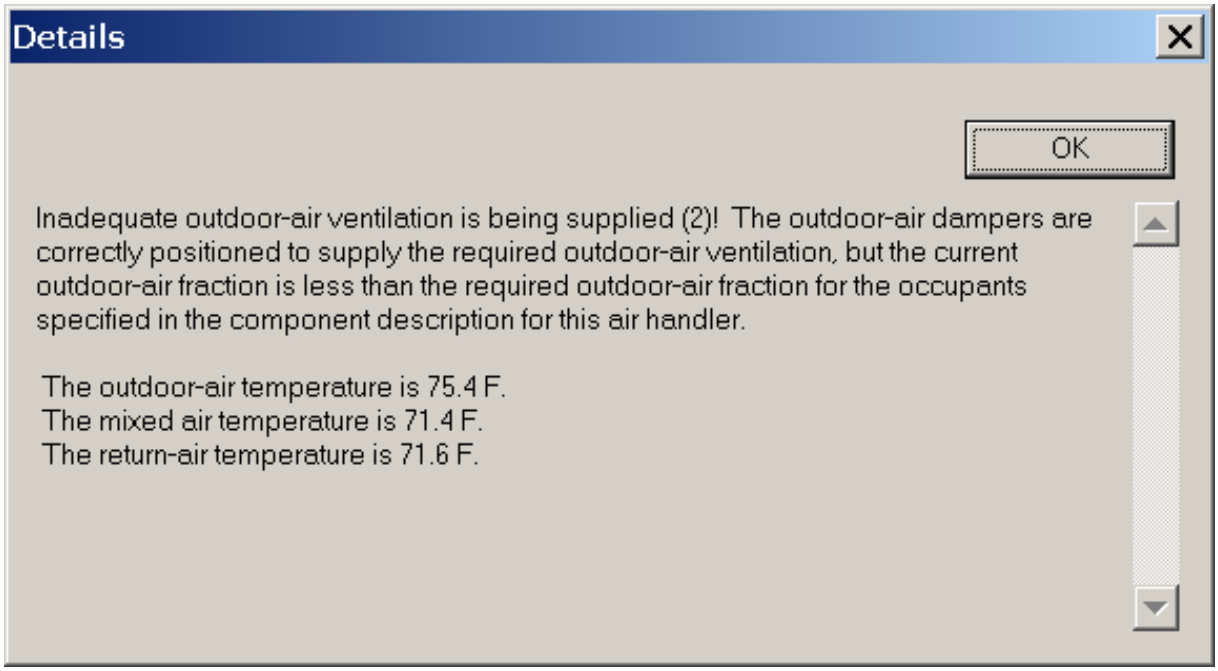



**Figure 113 – Screen Shot Showing Details Message for F5B-SS-Z2**

## *9.2 Whole-Building Energy Module*

NIST generated four blind data sets to test the capabilities of the WBE diagnostician. The WBE successfully identified faults for three of the data sets. The fourth data set was created for a 10% increase in HVAC electric energy consumption for a 2-month period. The WBE did not identify the fault for this end-use because the magnitude of the difference between expected and actual consumptions was low and the corresponding cost impact was small. The WBE has a threshold for energy cost impact of $10/day, i.e., if the energy cost impact does not exceed $10/day, the WBE does not report a fault. In this case, the energy cost impact was less than $1/day and, therefore, no fault was reported.

## *9.3 Recommendations*

As reported earlier, diagnosing the cause of the fault with limited sensor data is difficult because of lack of physical redundancy. In addition, proper selection of sensitivity settings for both OAE and WBE modules is critical in balancing fault detection sensitivity against the rate of false alarms. Additional laboratory and field tests are required to establish more definitive guidelines for users, but even then, the selection of sensitivity settings will depend on the preferences of the users.

Three specific recommendations from this study include:

- Develop analytical techniques to improve isolation of the causes of faults without additional sensors
- Study impact of sensitivity settings further
- Develop guidance for operators for selecting sensitivity settings.

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