# Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program

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## *Deliverable D2.2d – Final Report on Plant Diagnostics Implementation & Testing*

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# 1.0 Introduction

Several subcontractors under the PIER-funded *Energy Efficient & Affordable Small Commercial and Residential Buildings Program* (PIER Contract # 400-99-011) developed and tested methods to diagnose problems with HVAC system performance. This project will integrate the following methods into a suite of web-accessible applications:

- NIST's air-handling unit diagnostics (APAR); and
- Diagnostics for chillers, cooling towers, and associated equipment, developed under prior PIER sponsored research (Project 2.5, Pattern Recognition Based FDD) based on the ENFORMA® HVAC Diagnostics Analyzer.

This document describes the initial investigation, testing, and modifications required to implement plant diagnostics based on the ENFORMA® HVAC Diagnostics Analyzer. The plant diagnostics to be implemented here include chillers, cooling towers, and their associated equipment.

# 2.0 ENFORMA background

Architectural Energy Corporation began work on the development of the ENFORMA® portable diagnostic solutions software in 1992. It was completed in 1997. The ENFORMA software was the first portable application to perform HVAC system diagnostics based on operational data[1]. It has been described as semi-automated because an operator, usually an engineer, has to examine the data plots to fully perform the diagnostics.

During the prior PIER sponsored Research Project 2.5, Pattern Recognition Based FDD, one of the goals was to automate the diagnostic process. This project focused on implementation of automated techniques for plant equipment, and in particular chillers and cooling towers and associated equipment. Although the project was named "Pattern Recognition Based FDD," the techniques that were developed were more rule-based than pattern based. While investigating NIST's APAR structure, it was apparent that many of the rules developed for plant fault detection could fit well within that framework. Using a single rule framework would facilitate maintenance and updates.

Background on APAR can be found in Bushby et al 2001 [3] and House et al 2001 [4].

One difference between air handlers and central plants is that each air handler operates independently of the others. Each unit can be evaluated independently. Central plants, on the other hand, are systems of components which can be arranged in a wide variety of configurations. Examples of these configuration types are:

- Single or multiple chillers serving one or more air handlers,
- Heat rejection to one or more cooling towers.
- Primary only or primary-secondary chilled water distribution.

System-level diagnostics can provide information on the interaction of individual components, and can be useful. However, component-level (individual chillers, cooling towers, etc.) can identify problems that might be unidentified when examining complete systems. Therefore, component-level diagnostics will be the focus of the first release of plant FDD. The current APAR framework is well suited for component-level fault detection. As with APAR, much of the fault detection will be performed during steady-state operation. Transient faults, other than those associated with incorrect interlocks, will not be evaluated at this time.

Air handler fault detection using APAR uses a set of rules defined for several distinct operating modes. When an air handler switches modes, fault detection was suspended for a period of time to allow the AHU operation to stabilize. A chiller, on the other hand, can operate in only two states: on or off. These will be the operating modes for the chiller.

# 3.0 Plant FDD Development

Plant FDD as developed under Project 2.5 developed an Excel/Visual Basic application that examined chillers and cooling towers, and a C++ application that compared the chilled water supply water temperature to the desired setpoint. Because of the desire to implement these rules in the APAR framework, the rules were reconfigured, and then implemented in the MATLAB environment. Once these rules were implemented, they were tested using data sets developed from short-term ENFORMA diagnostic monitoring. Finally, the MATLAB code was converted to java code for implementation into the FDD engine.

Appendix A reproduces the fault detection categories developed under Project 2.5. The faults are categorized into the following subsystems:

- Chiller
- Cooling tower
- Chilled water loop
- Chiller/Cooling tower
- Chiller/Chilled water loop

For the reasons discussed in the previous section, the initial implementation of Plant FDD examines individual components rather than systems of components. Therefore, the components to be evaluated will be chiller and cooling towers, and their respective pumps, as discussed in sections 3.1 and 3.2.

In APAR, several operational modes were identified that were based on the positions of the hot water and chilled water valves, and the mixed air damper. For plant FDD, the concept of multiple operational modes does not apply, since the configuration of the individual chillers or cooling towers (position of valves and dampers) does not change. Therefore, the equipment is evaluated as follows:

- The chiller can operate in only two states: on or off.
- The cooling tower is active whenever the condenser pump is on and generating flow through the cooling tower. The cooling tower fan, depending on its capability, either cycles on and off if it is a single-speed fan, or modulates between off and full speed if it is controlled by a variable speed drive. Although the fan or fans modulate, the cooling tower operational state for the purposes of FDD is considered either on or off, as determined by the state of the condenser pump: when there is flow through the cooling tower, the tower is considered on.

There are two classes of rules: those that are evaluated under steady-state conditions, and those that are evaluated under non-steady-state conditions. The non-steady-state rules include those that may be associated with transient problems, such as improper interlocks between equipment (chiller running without condenser and chilled water pumps, for example). The steady-state rules are based on the original APAR structure and evaluate the performance of the equipment after it has been operating in a single mode for the required amount of time. These rules are evaluated using data that has been processed using an exponentially weighted moving average filter, similar to the techniques used for APAR. The non-steady state rules are evaluated using unfiltered data.

The steps we used to implement the plant rule set are as follows:

- Implement the plant rule set into the APAR framework.
- Test these rules with datasets collected during previous field tests.
- Modify the code as necessary based on testing.
- Translate the Matlab version to java.

The development of the rule set is discussed in this section. Testing is described in Section 5.0

## 3.1 Chiller fault detection

Table 3-1 shows the faults that are detected by the FDD engine. In general, they can be categorized into categories of temperature maintenance, schedule, cycling, and interlocks with other equipment.

Table 3-1. Chiller Faults

| Monitored Parameter | Fault Category | Fault | Notes |
|---|---|---|---|
| Chilled Water Supply Temperature Maintenance | Chilled Water Supply Temperature not Maintained Correctly | The chilled water supply temperature is too high | 1 |
| | | The chilled water supply temperature is too low | 1 |
| Chiller Schedule | Chiller Schedule is Incorrect / in Error / Corrupt / Inefficient / not Followed | The chiller is on when it should be off. Energy is being wasted. | 2 |
| Compressor Cycling | Compressor Cycling is Abnormal | The compressor is cycling on too frequently. It is not staying off for the minimum required off time. | 3 |
| | | The compressor is cycling off too frequently. It is not staying on for the minimum required on time. | 3 |
| Compressor and Condenser Pump Interlock (for water-cooled condensers only) | Compressor is Improperly Interlocked with Condenser Pump | The compressor is on while the condenser pump is off. The chiller cannot reject heat and this could damage the compressor. | 4 |
| | | The condenser pump is on excessively while the chiller is off. | 3 |
| Compressor and Primary Chilled Water Pump(s) Interlock | Compressor and Primary Chilled Water Pump(s) are not Interlocked Properly | The compressor is not properly interlocked with the primary chilled water pumps. The chiller is operating while the chilled water pump is off. The chiller is operating without a load. Damage to the compressor may result. | 4 |
| | | The compressor is not properly interlocked with the primary chilled water pumps. The primary chilled water pumps are cycling on too much in advance of the compressor and | 4 |

| | | | |
|---|---|---|---|
| | | wasting energy. | |

Notes:

1. Supply temperature is compared to setpoint.
2. Schedule rules for chillers verify that the chiller is not on when they are scheduled off.
3. Cycling rules compare minimum on and off time for equipment to actual time that the equipment actually runs.
4. Interlock rules evaluate if all equipment is operating in proper sequence.

## 3.2 Cooling tower fault detection

The cooling tower faults are shown in Table 3-2. Similar to the chiller fault detection, temperature control and minimum cycling times are also being monitored, as well as interlocks between the cooling tower fan and the condenser pump. In addition, the cooling tower range (difference between inlet and outlet temperature) and approach (difference between ambient wet bulb and outlet temperature) are also being evaluated. These are discussed in more detail in 3.2.1 and 3.2.2.

**Table 3-2. Cooling Tower Faults**

| Monitored Parameter | Fault Category | Fault | Notes |
|---|---|---|---|
| Cooling Tower Fan Cycling | Cooling Tower Fan Cycling Problem | The cooling tower fan is not staying off long enough during cycling. | 3 |
| | | The cooling tower fan is not staying on long enough during cycling. | 3 |
| Sump Temperature Control | Sump Temperature is Improperly Controlled | The condenser water supply temperature is above setpoint. | 1 |
| | | The condenser water supply temperature is below setpoint. | 1 |
| Cooling Tower Approach | Cooling Tower Approach Problem | Cooling tower approach temperature is greater than design and the condenser water supply temperature setpoint is not being met. | 5 |
| | | Cooling tower approach temperature is less than design, likely due to sensor error. | 6 |
| Cooling Tower Range | Cooling Tower Range Problem | Cooling tower range is less than design range and the condenser water supply setpoint is not being met. Heat rejection by the cooling tower is less than expected and the cooling tower is likely performing at less than its capacity. | 7 |
| | | Cooling tower range is greater than design range, possibly due to sensor error. | 6 |
| High Ambient Conditions | High Wet Bulb Temperature | Ambient wet bulb temperature is too high for cooling tower to meet condenser water supply setpoint. | 8 |

| | | | |
|---|---|---|---|
| Cooling Tower Fan Staging | Cooling Tower Fan Staging Problem | The condenser water supply temperature is above setpoint, but the cooling tower fans are running at less than full capacity. As a result, the cooling tower is not maintaining the sump temperature as low as it should. | 9 |
| | | A fan is on even though the sump temperature is below the “off” set point. This indicates a fan staging problem, and energy is being wasted. All cooling tower fans should be off. | Deferred |
| Cooling Tower Fan(s) and Condenser Pump Interlock | Cooling Tower Fan(s) and Condenser Pump are not Interlocked Properly | The cooling tower fan is running with the condenser pump off. The fans should be off when the condenser pump is not operating. | 4 |

Notes:

1. Supply temperature is compared to setpoint.
2. Schedule rules for chillers verify that the chiller is not on when they are scheduled off.
3. Cycling rules compare minimum on and off time for equipment to actual time that the equipment actually runs.
4. Interlock rules evaluate if all equipment is operating in proper sequence.
5. A high approach temperature (Condenser water supply temperature – Wet bulb temperature) under design conditions can indicate that the cooling tower is not as effective as it should be.
6. If the approach temperature is reported as being less than the design approach temperature, this is likely a sensor error since it would mean that the cooling tower sump temperature is closer to the ambient wet bulb temperature than was designed, which is not likely.
7. Under design conditions, the cooling tower range (inlet – outlet temperature) should be at a maximum value, to reject maximum heat. If the range is less than this value, then the heat rejection rate is likely less than design. This will likely cause the cooling tower temperatures to increase.
8. If the ambient wet bulb temperature is high, then it may be impossible for the cooling tower to cool the condenser water sufficiently to reach the condenser water supply setpoint. Under these conditions, not meeting the setpoint is expected, and is not an indication of a cooling tower fault. Reporting high wet bulb conditions will provide an explanation as to why the cooling tower is not meeting setpoint.
9. The cooling tower fan modulates to control the sump temperature. The modulation can be accomplished by cycling a single-speed fan on and off, or by selecting low or high speed if a dual-speed fan is installed, or by varying the motor speed using a variable speed drive. Under high load conditions the fan should be running constantly at high speed. If the condenser water supply setpoint is not met and the fans are not running constantly at high speed, there is likely a control problem.

### 3.2.1 Cooling tower approach fault detection

The function of the cooling tower is to reject heat from the chiller. It does this by circulating water through the tower, either with the cooling tower fan(s) on or off. Under low load conditions, or when it is cool outside, the fans operate at low speed. As the outdoor wet bulb temperature increases, the fan operation increases to ensure that the temperature of the water leaving the cooling tower (condenser water supply) meets the condenser water supply setpoint. The difference between the outdoor wet bulb and the condenser water supply temperatures is the cooling tower approach temperature. Under design conditions, when the wet bulb temperature is highest and the heat rejected by the cooling tower is at a maximum, the cooling tower fan will be operating continuously at its highest speed.

In most cases, instrumentation required to accurately measure the cooling tower heat rejection is not present, and so heat rejection cannot be used as an input for fault detection. However, approach is a good indicator of cooling tower performance. One of the goals of fault detection using approach is to determine if the cooling tower performance has been degraded. If the tower performance has degraded, then it may not be possible for the tower to reach the design approach temperature, even with the fans operating continuously.

### 3.2.2 Cooling tower range fault detection

The flow through the cooling tower is often nearly constant, and so the temperature difference between the cooling tower inlet and outlet temperatures (range) is proportional to the heat rejected by the cooling tower. Therefore, the cooling tower range will always be proportional to the amount of heat rejected by the chiller. However, if the heat rejection capability of the cooling tower is degraded, either through reduced airflow (fan problem, obstructions, etc.), through reduced heat transfer surface area (plugging of the fill), or some other problem, the tower water temperatures will increase the difference between the cooling tower temperatures and the outdoor wet bulb temperature, which will increase the capability of the cooling tower to reject heat.

Because of the characteristic of the cooling tower temperatures to increase to achieve the required range, range by itself is not as indicative of cooling tower problems. However, if the condenser water supply setpoint is not being met and the cooling tower range is less than its design, then there may be a problem with the cooling tower that is decreasing its performance.

If the cooling tower range is greater than design, this is likely a sensor error since the maximum range is influenced by the design and application of the tower. Unless the flow or tower characteristics have changed, the range normally cannot be greater than its design value.

# 4.0 Development of Plant FDD outputs

Similar to the APAR fault detection engine, the Plant FDD engine generates an output record for each input record. In other words, if five-minute data are entering the engine, five-minute results are generated. Although useful for testing the FDD engine, it is less useful for a production deployment of FDD, and so a more compact output has been developed. This more compact output consists of hourly and daily summaries, as described below. These summaries can also be displayed in a graphical form for easy scanning.

The summaries present data only when rules are violated. This avoids cluttering the summaries with periods of normal operation.

See Section 5.0, Plant FDD testing, for the samples of each of these outputs.

## 4.1 Hourly summary

The hourly summary indicates the rules that were violated (what faults were detected) during that hour. The hourly rule violation summary shows the amount of time that the component violated each rule.

There are two classes of rules for the chiller and cooling tower: comparison rules and interlock rules. Comparison rules, which compare actual operation to expected operation using data that has been filtered using a weighted moving average algorithm. Comparison rules are evaluated after the system has reached a steady-state condition. Interlock rules, on the other hand, are evaluated using unfiltered raw data since these rules evaluate conditions that are usually transient in nature.

## 4.2 Daily summary

The daily summaries are calculated in a manner similar to the hourly summaries, but are based on operation for an entire day. They are quite useful for obtaining a quick snapshot of the performance of the system.

# 5.0 Plant FDD testing

Several datasets have been developed using data collected with MicroDataLogger™ data acquisition equipment during field diagnostic monitoring on a variety of projects. Inputs not available for these tests include setpoints and schedules. For testing, these were estimated and were only used to observe the response of the ruleset.

A description of each dataset and the fault detection results are presented in the following sections.

## 5.1 Sample1-Parameter set 1

Sample 1 is a large VAV system with a chiller and single-speed cooling tower located in Virginia.

The parameters used for Sample 1 are shown in Table 5-1. In some instances they have been chosen to demonstrate the functionality of the FDD engine. For example, CTFMinOn and CTFMinOff, the parameters used to check for cooling tower cycling, have purposely been set quite low.

**Table 5-1. Sample 1 parameters**

| Parameter | Value | Description |
|---|---|---|
| epsilon_tCHW | 2 | Threshold for comparing temperature differences in the chilled water loop |
| epsilon_tCondW | 4 | Threshold for comparing temperature differences in the condenser water loop (cooling tower) |
| rule_delay | 15 | Amount of time that rule violation must exist |
| timestep | 2 | Data frequency in minutes |
| ChillMinOff | 15 | Amount of time that chiller must remain off before turning on again |
| ChillMinOn | 15 | Amount of time that chiller must remain on before turning off again |
| ChilMinCurrent | 10 | Current or power threshold for determining that chiller is on |
| PCHWPMinCurrent | 2 | Current or power threshold for determining that primary chilled water pump is on |
| SecCHWPMinCurrent | 2 | Current or power threshold for determining that secondary chilled water pump is on |
| CFMinCurrent | 2 | Current or power threshold for determining that condenser fan is on |
| CPMinCurrent | 2 | Current or power threshold for determining that condenser pump is on |
| SecCHWPMinCurrent | 2 | Current or power threshold for determining that secondary chilled water pump is on |
| CTFMinOn | 3 | Amount of time that cooling tower fan must remain on before turning off again |
| CTFMinOff | 3 | Amount of time that cooling tower fan must remain off before turning on again |
| CTFMinCurrent | 2 | Current or power threshold for determining that cooling tower fan is on |
| CTMinApp | 11 | Cooling tower approach under design conditions |
| CTMaxRange | 8 | Cooling tower range under design conditions |
| CPMinOff | 3 | Amount of time that the condenser pump must remain off before turning on again |
| CPMinOn | 3 | Amount of time that the condenser pump must remain on before turning off again |
| CTFanConfig | 1 | Cooling tower configuration:<br>1: Single speed fan;<br>2: Two-speed fan;<br>3: VFD-controlled fan |

Daily results for the Sample 1 cooling tower are shown in Table 5-2. On day 1, the condenser water supply temperature was above the setpoint, as well as the approach being greater than design. These variables are shown in Figure 5-1, plotted as a function of the ambient wet bulb temperature. Wet bulb temperature is used for the independent variable since load is often proportional to it. Notice that CWS is below setpoint when the wetbulb temperature is low, and exceeds the setpoint as the wetbulb temperature increases. At low wet bulb temperatures, the approach is high, which is appropriate. However, the approach does not decrease (actually increases somewhat) as the wet bulb temperature increases. Since the CWS is too high, the high approach is now a fault.

On day 3, the cooling tower fan is not staying on long enough during cycling. Since the cooling tower has a single speed fan, it is normal for the fan to cycle. However, the parameters have been set so that any time the fan is on for less than three minutes, it is a fault.

**Table 5-2. Sample 1 Daily Cooling Tower Fault Summary**

| Day | Rule | Hours Violated | Fault description |
|---|---|---|---|
| 1 | 3 | 9.033 | CWS temperature is above setpoint. |
| 1 | 5 | 9.033 | Cooling tower approach temperature is greater than design and CWS setpoint is not being met. |
| 2 | 3 | 16.167 | CWS temperature is above setpoint. |
| 2 | 5 | 12.567 | Cooling tower approach temperature is greater than design and CWS setpoint is not being met. |
| 3 | 2 | 0.433 | The cooling tower fan is not staying on long enough during cycling. |
| 4 | 2 | 0.133 | The cooling tower fan is not staying on long enough during cycling. |
| 11 | 2 | 0.1 | The cooling tower fan is not staying on long enough during cycling. |
| 11 | 4 | 0.033 | CWS temperature is below setpoint. |
| 12 | 2 | 0.5 | The cooling tower fan is not staying on long enough during cycling. |
| 13 | 2 | 0.067 | The cooling tower fan is not staying on long enough during cycling. |
| 14 | 2 | 0.367 | The cooling tower fan is not staying on long enough during cycling. |
| 15 | 2 | 0.467 | The cooling tower fan is not staying on long enough during cycling. |
| 18 | 2 | 0.167 | The cooling tower fan is not staying on long enough during cycling. |
| 13 | 4 | 0.033 | Compressor is cycling on too quickly. Actual off time is less than minimum required off time. |

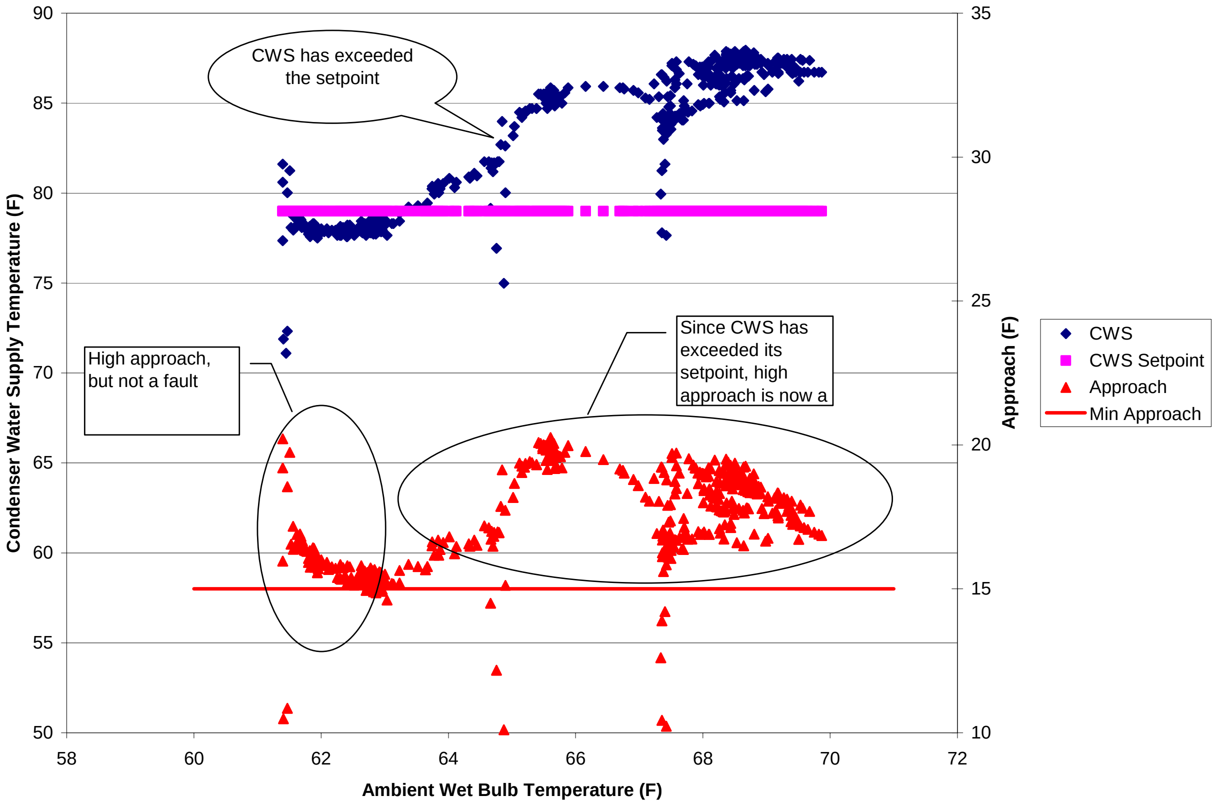



**Figure 5-1. Sample 1 day 1 cooling tower faults**

On day 3, the cooling tower fan is not staying on long enough during cycling. Since the cooling tower has a single speed fan, it is normal for the fan to cycle. For testing purposes, the parameters have been set so that any time the fan is on for less than three minutes, it is a fault. Since the data has been sampled at two-minute intervals, any time that the fan runs for a single time step, it is considered a fault. The cooling tower fan power is shown in Figure 5-2. Notice the spikes of power scattered throughout the period. These spikes indicate run periods of two minutes, which is less than the required three minutes. Each of these spikes represent a rule violation (fault).

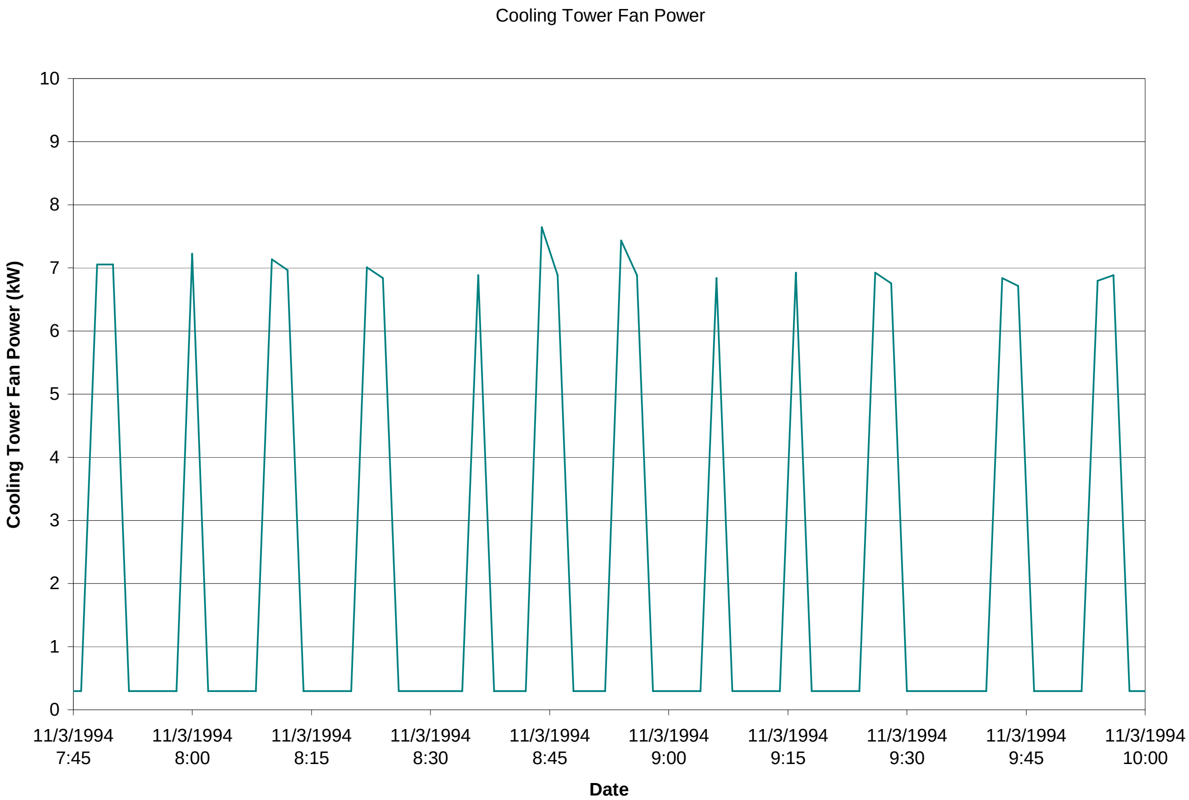



**Figure 5-2. Sample 1 cooling tower fan cycling**

The daily chiller fault summary is shown Table 5-3. The only faults detected were occasional cycling faults, where the on and off times were shorter than required by the parameters.

**Table 5-3. Sample 1 daily chiller fault summary**

| Day | Rule | Hours Violated | Fault description |
|---|---|---|---|
| 13 | 4 | 0.033 | Compressor is cycling on too quickly. Actual off time is less than minimum required off time. |
| 14 | 4 | 0.033 | Compressor is cycling on too quickly. Actual off time is less than minimum required off time. |
| 15 | 5 | 0.033 | Compressor is cycling off too quickly. Actual on time is less than minimum required on time. |

## 5.2 Sample1-Parameter Set 2

Many faults were detected in the previous data set. To illustrate how the parameter selection can affect fault detection, a new set of parameters was developed. This new set changed the parameters shown in Table 5-4.

**Table 5-4. Sample 1 parameter changes**

| Parameter | Old Value | New Value | Description |
|---|---|---|---|
| epsilon_tCondW | 4 | 5 | Threshold for comparing temperature differences in the condenser water loop (cooling tower) |
| CTFMinOn | 3 | 1 | Amount of time that cooling tower fan must remain on before turning off again |

The effects of changing epsilon_tCondW will be to increase the allowable difference between the condenser water supply temperature and its setpoint, and the allowable difference between the cooling tower approach and its design approach. Changing CTFMinOn from three minutes to one minute will allow the cooling tower fan to cycle on two-minute intervals.

The cooling tower daily fault summary is shown in Table 5-5. The CWS and approach faults were detected as before, although the duration of the faults was reduced. However, the cycling faults have been completely eliminated. This indicates that careful parameter selection is necessary to properly identify component faults.

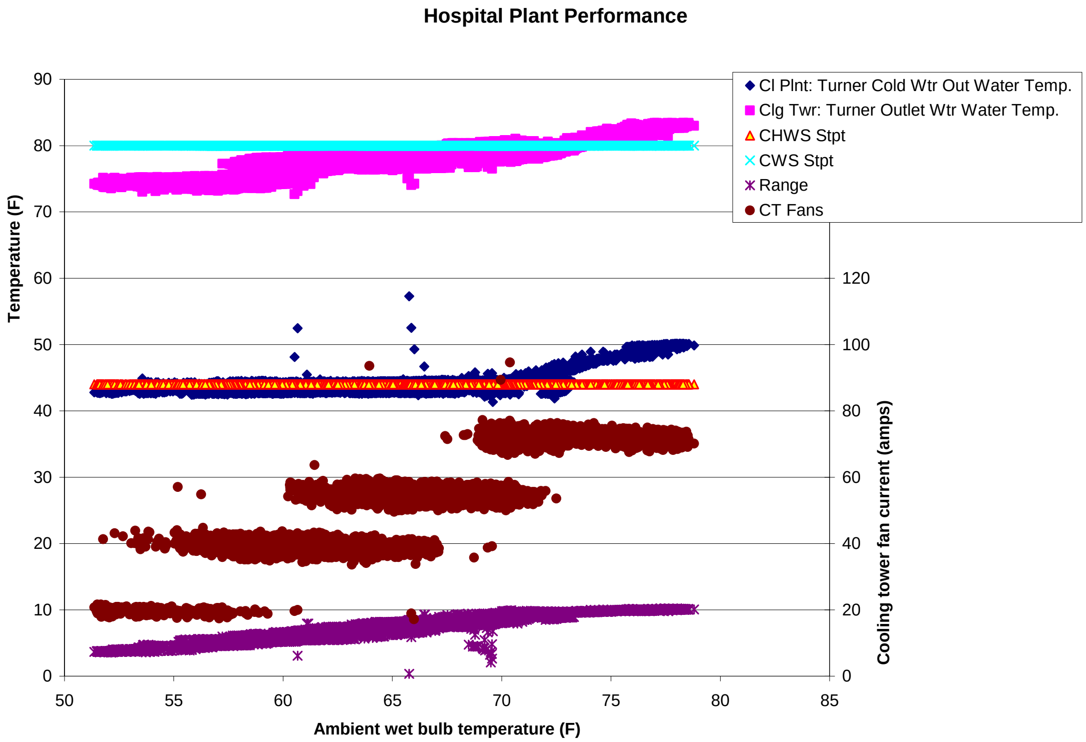
**Table 5-5. Sample 1 daily cooling tower fault summary - new parameters**

| Day | Rule | Hours Violated | Fault Description |
|---|---|---|---|
| 2 | 3 | 8.9 | CWS temperature is above setpoint. |
| 2 | 5 | 8.9 | Cooling tower approach temperature is greater than design and CWS setpoint is not being met. |
| 3 | 3 | 16.1 | CWS temperature is above setpoint. |
| 3 | 5 | 6.133 | Cooling tower approach temperature is greater than design and CWS setpoint is not being met. |

## 5.3 Hospital – Parameter Set 1

This sample consists of two weeks of data from an east coast medical facility. The HVAC system consists of several air handlers serving patient areas, operating rooms, and office space. The chiller serves these AHUs, and rejects heat to a cooling tower with four fan speed levels (two fans, each with two speeds).

Data were collected in mid-August during design-day level weather conditions. The load on the chiller has been increased over the years, and on design days, is greater than the chiller capacity, which is a known problem at this site. This is best illustrated in Figure 5-3, which shows a variety of temperatures and the cooling tower fan current as a function of ambient wet bulb temperature. The chilled water supply temperature begins to exceed its setpoint as soon as the wet bulb temperature exceeds 70°F. The cooling tower fan, which operates at four stages, is operating at full speed at that time. Notice that the condenser water supply temperature is also increasing. At the very bottom of the plot, the cooling tower Range is also shown, which reaches its maximum value of about 10°F at 70°F wet bulb. In essence, above 70°F, the system is at capacity, and temperatures are increasing.




## Figure 5-3.  Hospital plant performance

The parameters used for the Hospital sample are shown in Table 5-6.  As before, some of the parameters have been chosen to demonstrate the functionality of the FDD engine.  For example, epsilon_tCondW, the parameter used to evaluate temperatures and temperature differences associated with the cooling tower loop, is set at 2°F, which is the same as epsilon_tCHW.  Cooling tower loop temperatures are often not as well controlled as the CHW temperatures, especially when the cooling tower does not have a variable speed fan.

**Table 5-6. Hospital parameter set 1**

| Parameter | Value | Description |
|---|---|---|
| epsilon_tCHW | 2 | Threshold for comparing temperature differences in the chilled water loop |
| epsilon_tCondW | 2 | Threshold for comparing temperature differences in the condenser water loop (cooling tower) |
| rule_delay | 15 | Amount of time that rule violation must exist |
| timestep | 2 | Data frequency in minutes |
| ChillMinOff | 15 | Amount of time that chiller must remain off before turning on again |
| ChillMinOn | 15 | Amount of time that chiller must remain on before turning off again |
| ChilMinCurrent | 10 | Current or power threshold for determining that chiller is on |
| PCHWPMinCurrent | 2 | Current or power threshold for determining that primary chilled water pump is on |
| SecCHWPMinCurrent | 2 | Current or power threshold for determining that secondary chilled water pump is on |
| CFMinCurrent | 2 | Current or power threshold for determining that condenser fan is on |
| CPMinCurrent | 2 | Current or power threshold for determining that condenser pump is on |
| CPMinCurrent | 2 | Current or power threshold for determining that secondary chilled water pump is on |
| CTFMinOn | 5 | Amount of time that cooling tower fan must remain on before turning off again |
| CTFMinOff | 5 | Amount of time that cooling tower fan must remain off before turning on again |
| CTFMinCurrent | 2 | Current or power threshold for determining that cooling tower fan is on |
| CTMinApp | 2 | Cooling tower approach under design conditions |
| CTMaxRange | 14 | Cooling tower range under design conditions |
| CPMinOff | 5 | Amount of time that the condenser pump must remain off before turning on again |
| CPMinOn | 5 | Amount of time that the condenser pump must remain on before turning off again |
| CTFanConfig | 1 | Cooling tower configuration:<br>1: Single speed fan;<br>2: Two-speed fan;<br>3: VFD-controlled fan |

The cooling tower fault summary is shown in Table 5-7. Notice that the CWS temperature is both below and above the setpoint. Although this might be a useful diagnostic, in this case it is likely due to the CWS setpoint used in the dataset not being accurate. Recall that the setpoint information in the data file was artificially created since the setpoint is an output from the EMS, which was not logged by the portable data loggers. An additional dataset that uses an alternate CWS setpoint, as well as a different value for epsilon_tCondW, will be discussed later.

**Table 5-7. Hospital cooling tower daily fault summary**

| Day | Rule | Hours Violated | Fault description |
|---|---|---|---|
| 2 | 4 | 13.07 | CWS temperature is below setpoint. |
| 3 | 1 | 0.03 | The cooling tower fan is not staying off long enough during cycling. |
| 3 | 4 | 9.73 | CWS temperature is below setpoint. |
| 4 | 4 | 1.50 | CWS temperature is below setpoint. |
| 5 | 3 | 6.03 | CWS temperature is above setpoint. |
| 5 | 5 | 6.03 | Cooling tower approach temperature is greater than design and CWS setpoint is not being met. |
| 5 | 7 | 6.03 | Cooling tower range is less than design range and CWS setpoint is not being met. |
| 6 | 3 | 2.17 | CWS temperature is above setpoint. |
| 6 | 4 | 1.10 | CWS temperature is below setpoint. |
| 6 | 5 | 2.17 | Cooling tower approach temperature is greater than design and CWS setpoint is not being met. |
| 6 | 7 | 2.17 | Cooling tower range is less than design range and CWS setpoint is not being met. |
| 7 | 4 | 16.07 | CWS temperature is below setpoint. |
| 8 | 4 | 22.50 | CWS temperature is below setpoint. |
| 9 | 4 | 20.13 | CWS temperature is below setpoint. |
| 10 | 1 | 0.03 | The cooling tower fan is not staying off long enough during cycling. |
| 10 | 4 | 5.87 | CWS temperature is below setpoint. |
| 11 | 4 | 16.97 | CWS temperature is below setpoint. |
| 12 | 4 | 21.77 | CWS temperature is below setpoint. |
| 13 | 4 | 20.57 | CWS temperature is below setpoint. |
| 14 | 4 | 24.00 | CWS temperature is below setpoint. |

Table 5-8 shows the daily chiller fault summary. The most prevalent fault shown in this table is that the chilled water supply temperature is above setpoint for over 12 hours on both day five and six. On days three and ten, the compressor cycled on too quickly after being off, and the primary CHW pump was running without the chiller. Figure 5-4 shows the period on day 3 with the rule three and four violations. Rule four violation, the chiller compressor cycling on in less than 15 minutes (the value of ChilMinOff), indicates short-cycling of the chiller. If this happens regularly, it could lead to chiller damage and shortened life. However, the parameters for Rule 13 which is associated with detecting if the CHW pump is running without chiller operation, may be set to too low of a threshold. In this dataset, they were set for 4 minutes. In a transient situation such as what was experienced on Day 3, it is likely that the CHW pump would continue to operate, if possible, to avoid other issues. With these results in mind, the parameters can be reset to values that will result in fewer “false positives”. This is discussed in the next section.

**Table 5-8. Hospital chiller daily fault summary**

| Day | Rule | Hours Violated | Fault description |
|---|---|---|---|
| 3 | 4 | 0.03 | Compressor is cycling on too quickly. Actual off time is less than minimum required off time. |
| 3 | 13 | 0.07 | Primary CHW pump is running without chiller operation. |
| 5 | 1 | 12.30 | CHWS temperature is above setpoint |
| 6 | 1 | 12.20 | CHWS temperature is above setpoint |
| 10 | 4 | 0.03 | Compressor is cycling on too quickly. Actual off time is less than minimum required off time. |
| 10 | 13 | 0.10 | Primary CHW pump is running without chiller operation. |

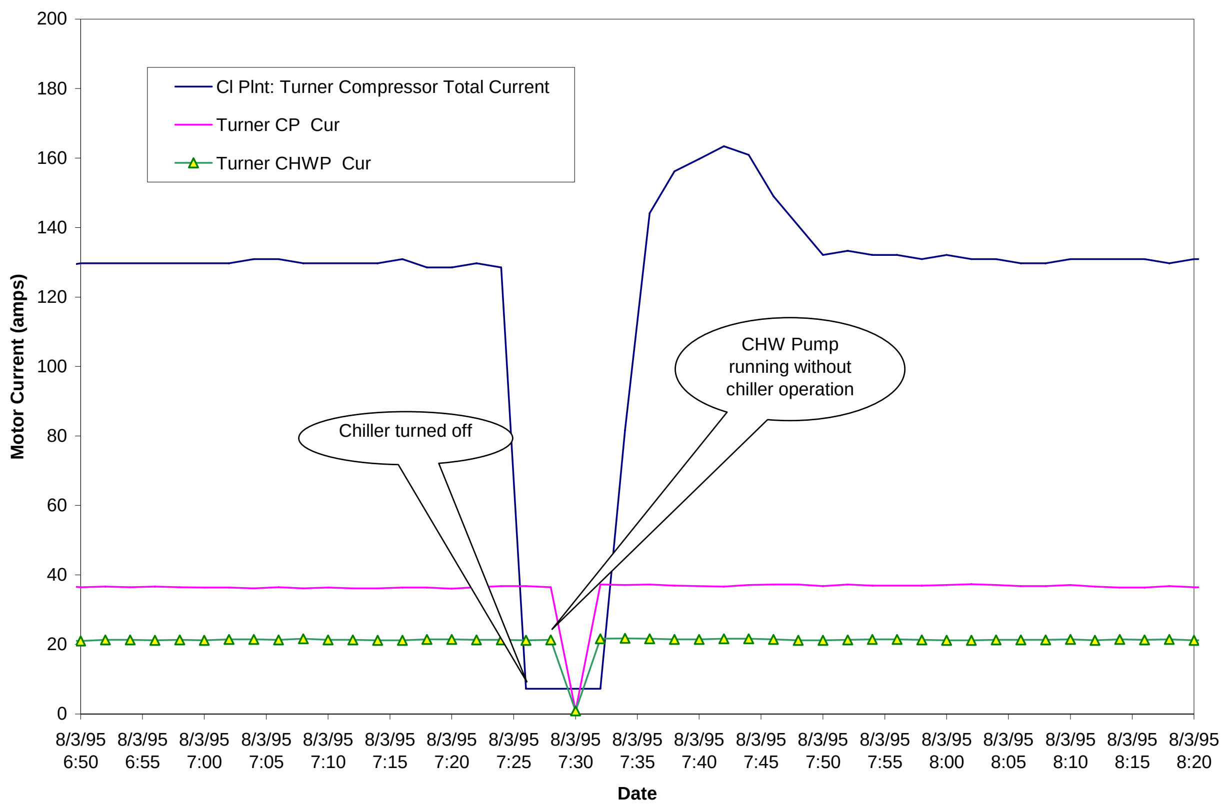



**Figure 5-4. Hospital chiller interlock fault - Day 3**

## 5.4 Hospital- Parameter set 2

Several faults were detected while using Parameter Set 1. To illustrate how the parameter selection can affect fault detection, a new set of parameters was developed. The parameters that were changed are shown in Table 5-9.

**Table 5-9. Hospital parameter changes**

| Parameter | Old Value | New Value | Description |
|---|---|---|---|
| epsilon_tCondW | 2 | 4 | Threshold for comparing temperature differences in the condenser water loop<br>(cooling tower) |
| Interlock_rule_delay | 4 | 7 | Amount of time that equipment that should be operating together can be operating individually. |

In addition, the condenser water setpoint was decreased by 2°F. The effects of changing epsilon_tCondW will be to increase the allowable difference between the condenser water supply temperature and its setpoint, and the allowable difference between the cooling tower approach and its design approach. Changing Interlock_rule_delay from four minutes to seven minutes will be to allow equipment to operate longer without proper interlock.

The daily fault summary for the cooling tower is shown in Table 5-10. The number of CWS temperature faults has dropped considerably, showing only those that are of longer duration.

**Table 5-10. Hospital daily cooling tower fault summary - parameter set 2**

| Day | Rule | Hours Violated | Fault description |
|---|---|---|---|
| 3 | 1 | 0.03 | The cooling tower fan is not staying off long enough during cycling. |
| 5 | 3 | 6.03 | CWS temperature is above setpoint. |
| 5 | 5 | 2.07 | Cooling tower approach temperature is greater than design and CWS setpoint is not being met. |
| 5 | 7 | 0.93 | Cooling tower range is less than design range and CWS setpoint is not being met. |
| 6 | 3 | 2.17 | CWS temperature is above setpoint. |
| 9 | 4 | 1.50 | CWS temperature is below setpoint. |
| 10 | 1 | 0.03 | The cooling tower fan is not staying off long enough during cycling. |
| 12 | 4 | 1.70 | CWS temperature is below setpoint. |
| 13 | 4 | 0.50 | CWS temperature is below setpoint. |

Table 5-11 shows the fault summary for the chiller. The fault associated with the chilled water pump running without the chiller has been eliminated.

**Table 5-11. Hospital daily chiller fault summary - parameter set 2**

| Day | Rule | Hours Violated | Fault description |
|---|---|---|---|
| 3 | 4 | 0.03 | Compressor is cycling on too quickly. Actual off time is less than minimum required off time. |
| 5 | 1 | 12.30 | CHWS temperature is above setpoint |
| 6 | 1 | 12.20 | CHWS temperature is above setpoint |
| 10 | 4 | 0.03 | Compressor is cycling on too quickly. Actual off time is less than minimum required off time. |

These results show that days five and six have significant problems with the CHWS temperature being too high, as well as attendant problems with the cooling tower. The data in Figure 5-5 has been filtered to show only the data for these periods. The cooling tower fans are, for the most part, running at full speed, the chilled water supply temperature is rising about its setpoint, and the CWS temperature is rising.  The cooling tower range is essentially constant at 10 °F.  In short, the cooling plant is no longer maintaining temperatures.

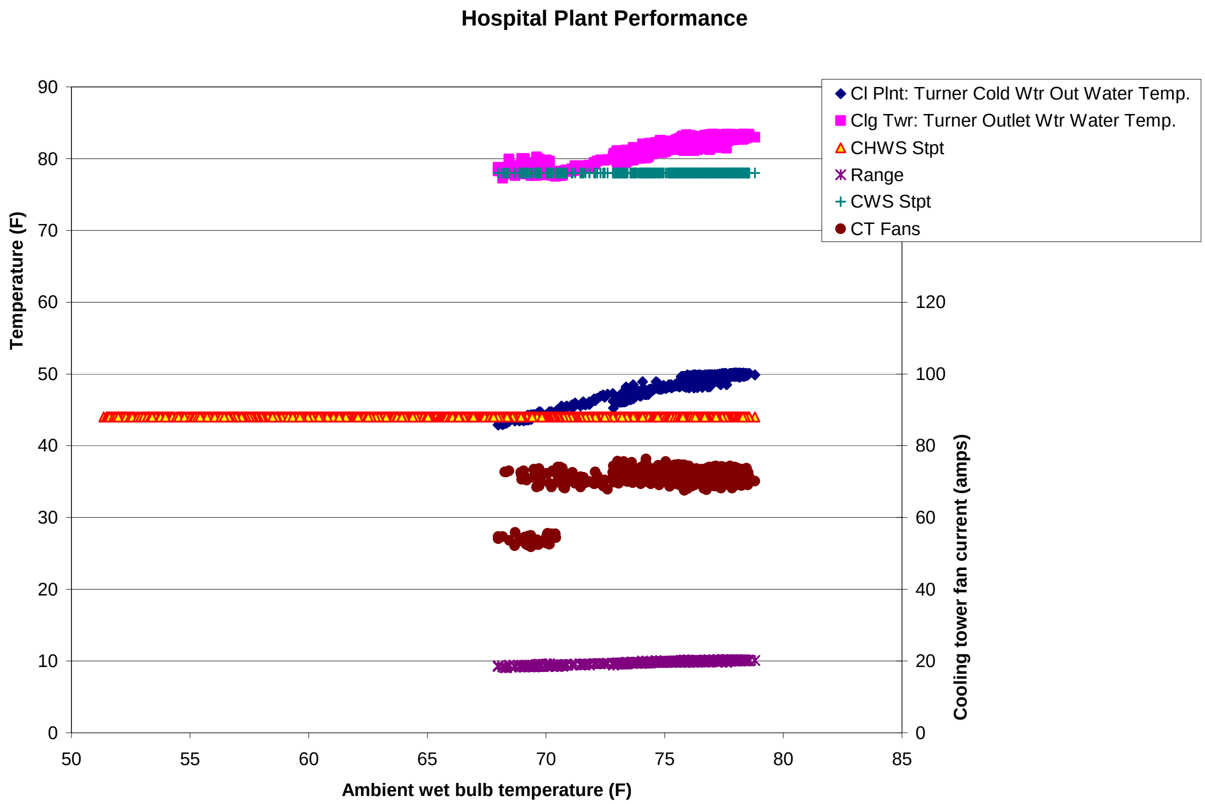



**Figure 5-5.  Hospital Performance during significant fault period**

# 6.0 Potential Causes

As with air handlers, determining the single cause that resulted in a chiller or cooling tower fault is difficult because of the wide range of potential causes.  Because of this, the development of the plant diagnostic system has focused on fault detection rather than cause identification. The goal of any fault detection system should be to announce that a fault has occurred to the operator so that action can be taken to resolve the problem.  Waiting several months to allow the system to determine the actual cause will result in months of sub-optimal operation.  Therefore, it is more expedient to provide a list of potential causes to the system operator rather than to attempt to reduce the list of causes.

# 7.0 Conclusions

The results from these data sets show that this implementation of plant fault detection can successfully identify faults in cooling towers and chillers.  In addition, equipment that is operating systems do not generate false positives, which is perhaps just as important to ensure that the system is used and trusted.

# 8.0 References

[1] Architectural Energy Corporation (AEC), 2000. ENFORMA, Demonstration and Installation CD-ROM, HVAC Analyzer v3.116. Boulder, Colorado.

[2] Battelle, 2002. Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program, Project 2.5 - Pattern-Recognition Based Fault Detection and Diagnostics. Submitted to the California Energy Commission. Boulder, CO: Architectural Energy Corporation.

[3] Bushby, S.T., Castro, N.S., Schein, J, House, J.M., 2001, "Testing AHU rule-based diagnostic tool & VAV diagnostic tool using the VCBT", Energy Efficient and Affordable Small Commercial and Residential Buildings Research Program Task Report

[4] House, J.M., Vaezi-Nejad, H., and Whitcomb, J.M., 2001, "An Expert Rule Set for Fault Detection in Air-Handling Units," ASHRAE Transactions, Vol. 107, Pt. 1.

[5] AEC, 2005. Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program. APAR Rules Implementation & Testing. Submitted to the California Energy Commission. Boulder, CO: Architectural Energy Corporation.

# Appendix A: Performance and Operational Parameters Monitored by the Automated Diagnostic Tool and Specific Faults Identified

| Subsystem | Monitored Parameter | Fault Category | Fault |
|---|---|---|---|
| **Chiller** | Chilled Water Supply Temperature Maintenance | Chilled Water Supply Temperature not Maintained Correctly | The chilled water supply temperature is too high |
| | | | The chilled water supply temperature is too low |
| | Chiller Schedule | Chiller Schedule is Incorrect/in Error/Corrupt/Inefficient/not Followed | The chiller is on when it should be off. Energy is being wasted. |
| | Compressor Cycling | Compressor Cycling is Abnormal | The compressor is cycling on too frequently. It is not staying off for the minimum required off time. |
| | | | The compressor is cycling off too frequently. It is not staying on for the minimum required on time. |
| | Compressor and Condenser Fan Interlock (for air-cooled condensers only) | Compressor is Improperly Interlocked with Condenser Fan | The compressor is on while the condenser fan is off. The chiller cannot reject heat and this could damage the compressor |
| | | | The condenser fan is on while the compressor is off. The fan is running unnecessarily and wasting energy. |
| | Compressor and Condenser Pump Interlock (for water-cooled condensers only) | Compressor is Improperly Interlocked with Condenser Pump | The compressor is on while the condenser pump is off. The chiller cannot reject heat and this could damage the compressor. |
| | | | The condenser pump is cycling unnecessarily frequently. Repeated frequent cycling will shorten the life of the condenser pump. |
| | | | The condenser pump is turning on too much in advance of the compressor and wasting energy. |
| **Cooling Tower** | Cooling Tower Fan Cycling | Cooling Tower Fan Cycling Problem | The cooling tower fan is not staying off long enough during cycling. |
| | | | The cooling tower fan is not staying on long enough during cycling. |
| | *Sump Temperature Control* | Sump Temperature is Improperly Controlled | The cooling tower fan is off but should be on. As a result, the condenser water is not being cooled sufficiently. |
| | | | The cooling tower fan is on but it should be off. Energy is being wasted. |

| | | | |
|---|---|---|---|
| | Cooling Tower Approach | Cooling Tower Approach Problem | The cooling tower approach is greater than the Approach Benchmark provided in set up. Heat rejection from the cooling tower is less than expected. |
| | Cooling Tower Fan Staging | Cooling Tower Fan Staging Problem | The Sump temperature is above the cooling tower fan "on" set point, but all cooling tower fans are not on. This indicates a problem with the fan staging and, as a result, the cooling tower is not maintaining the sump temperature as low as it should. |
| | | | A fan is on even though the sump temperature is below the "off" set point. This indicates a fan staging problem, and energy is being wasted. All cooling tower fans should be off. |
| | Cooling Tower Range | Cooling Tower Range Problem | The cooling tower range is below its benchmark. As result, heat rejection by the cooling tower is less than expected and the cooling tower is performing at less than its capacity. |
| **Chilled Water Loop** | Supply Fan(s) and the Primary-Loop Chilled Water Pumps Interlock | Supply Fan(s) and the Primary-Loop Chilled Water Pumps are not Interlocked Properly | The is possibly a problem with the supply fan control. |
| | | | This chilled water pump is being operated unnecessarily and is wasting energy. The chilled water pump should not operate unless at least one of the supply fans in an air handling unit served by the chilled water pump is on. |
| | Supply Fan(s) and the Secondary-Loop Chilled Water Pumps Interlocked | Supply Fan(s) and the Secondary-Loop Chilled Water Pumps are not Interlocked Properly. | Possible problem with secondary chilled water pump control—check to see if loads in the spaces served are being met for all supply fans that are part of air handlers served by this secondary chilled water loop and that is on when the secondary chilled water pump is off. |
| | | | The secondary chilled water pump and some of the supply fans that are served by it are not interlocked properly. This secondary chilled water pump is operating unnecessarily when all supply plans it serves are off and, as a result, is wasting energy. The secondary chilled water pump should not operate unless at least one of the supply fans in an air handler served by this pump is on. |
| | Secondary and Primary Loop Chilled Water Pumps Interlock | Secondary and Primary Loop Chilled Water Pumps are not Interlocked Properly | The secondary chilled water pumps that are on are wasting energy. Secondary chilled water pumps should only operate when the primary CHW pump is operating. |
| **Chiller / Cooling Tower** | Cooling Tower Fan(s) and Condenser Pump Interlock | Cooling Tower Fan(s) and Condenser Pump are not Interlocked Properly | The cooling tower fan and condenser pump are not interlocked properly. Energy is being wasted because the cooling tower fan should be off when the condenser pump is not operating. |

| | | | |
|---|---|---|---|
| | | | The interlock between the condenser pump and the cooling tower may not be properly implemented. The cooling tower fan may be off when the condenser pump is running, but this should not always be the case. |
| **Chiller / Water Loop** | Compressor and Primary Chilled Water Pump(s) Interlock | Compressor and Primary Chilled Water Pump(s) are not Interlocked Properly | The primary chilled water pumps are not interlocked properly with the compressor. The condenser pump is cycling on and off unnecessarily. Repeated frequent cycling will shorten the life of the pump. |
| | | | The compressor is not properly interlocked with the primary chilled water pumps. The chiller is operating without a load. Energy is being wasted and damage to the compressor may result. |
| | | | The compressor is not properly interlocked with the primary chilled water pumps. Water side economizing is not being used, and the primary chilled water pumps are cycling on too much in advance of the compressor and wasting energy. |