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Task Report for the

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Project 2.5 – Pattern-Recognition Based Fault Detection and Diagnostics

Task 2.5.3 - Implement and Test Techniques

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Contents

1 Executive Summary

This is the third task report for Project 2.5 – Pattern-Recognition-Based Fault Detection and Diagnostics. It presents work to test the general rule-based approach for automating diagnostics by using it as the basis for a limited testing prototype. This testing prototype automates part of the diagnostic process for chillers in Excel using Visual Basic Applications (VBA). When run against data from actual buildings, the results are consistent with those obtained by an expert interpreting plots from AEC's *ENFORMA HVAC Analyzer*.

The tests validate that rules are effective for automating the AEC diagnostic process. The results also led to recognition of the importance of developing a method by which to detect short-term anomalous chiller behavior and to sort out what information should be presented to users and what should be filtered before display to prevent over-burdening building operators with superfluous information.

The testing software is enclosed with the report for demonstration and examination by the reader.

2 Purpose of This Task Report

This is the third task report for a project whose object is to develop software to automatically detect and diagnose faults in the operation of selected building systems. The purpose of this task is to implement and test the general approach selected for automation of the diagnostics. The purpose of this report is to describe the prototype implementation used to test the approach, to describe the associated algorithm testing and evaluation, to present some example results, and to present conclusions as they relate to using this approach for development of the diagnostic software that will be produced in this project.

3 Project Background

This report describes work from the third task in a six-part project to develop and demonstrate automated pattern recognition fault detection tools. Given the difficulty and complexity of developing fault detection and diagnostic procedures, the project objective has been to automate diagnostic procedures developed previously and used successfully by AEC with its ENFORMA software.

In the first task, diagnostics for chillers and boilers were selected for automation. Cooling towers were subsequently added to this scope due to their strong interactions with chillers.

The second task reviewed techniques from the fields of pattern recognition and data mining for use in automating fault detection and diagnostics. After review of a full range of possible techniques, including data-driven methods such as neural networks, we selected rule-based techniques as the primary approach. The primary reasons for rejecting data-driven methods was the lack of adequate training data to support use of those techniques for the particular HVAC-system related problems selected in the first task. In addition, rule-based approaches appeared well matched to the types of information available and diagnostic techniques used by AEC with *Enforma*.

Based on extensive experience of AEC staff using the ENFORMA product in conducting short-term monitoring and diagnoses for a large number of commercial building projects, the most useful and well-developed diagnostics that AEC has traditionally used with chillers, boilers, and cooling towers were documented using data flow diagrams, data dictionaries, and other written forms. These will be presented in a future report.

Part of the third task (Task 2.5.3: *Implement and Test Techniques*) is the subject of this report. This work involved implementing a set of rules for a representative part of the diagnostic process to test the general approach to automation using rules. This work was necessary to confirm relatively early in the project that the proposed rule-based approach would be feasible and effective as an automated process. The procedures that AEC and others have used with ENFORMA rely heavily on the knowledge and experience of the engineer using the *Enforma*. Confirmation was needed that those diagnostic processes would work as automated procedures. In addition, there are often large amounts of noise in metered data from buildings, and testing was needed to ensure that the planned diagnostics would perform effectively with actual building data.

Three additional tasks are to follow for this project. These tasks are

- Task 2.5.4: Implement User Interface – a task that will demonstrate an initial user interface for end users and link with software that demonstrates the initial pattern recognition algorithms.
- Task 2.5.5: Field Test – a task that will field test the prototype from the previous task and document results.
- Task 2.5.6: Implement full set of diagnostic interpretations and an expanded user interface. This task that will produce the final software deliverable containing the full set of diagnostic capabilities with improvements based on the field test under Task 2.5.5.

4 Description of Prototype Implementation and Algorithm Testing

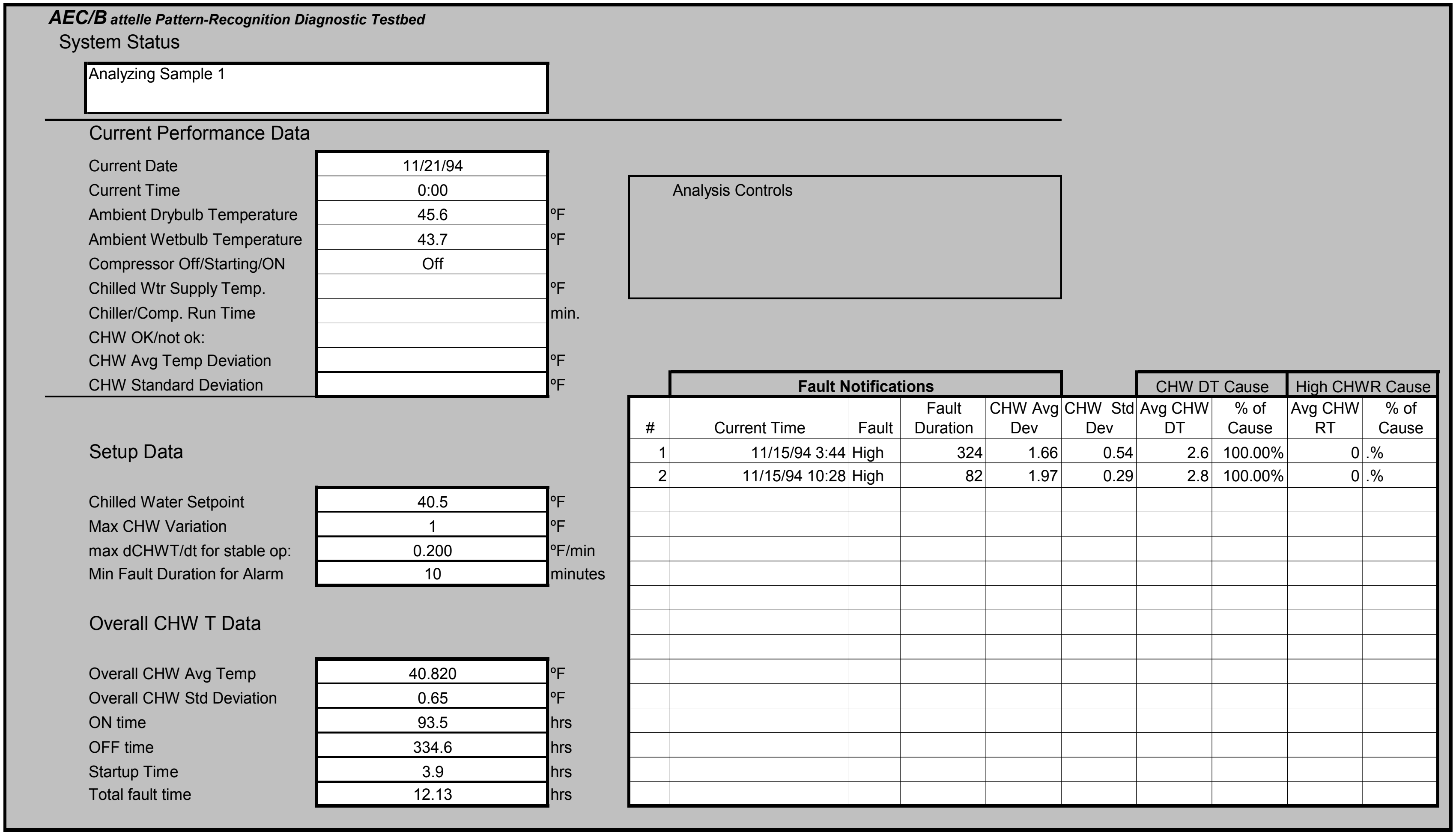
A software prototype that implements chiller control diagnostics was developed by Stuart Waterbury in Excel VBA (Visual Basic for Applications) to test and evaluate the proposed approach for automating fault detection and diagnostics. This prototype system is designed to track and evaluate actual chilled water supply (CHWS) temperatures against the control set point. Similar work was performed using the same software environment to implement boiler hot water control diagnostics; however, the chiller version represents a more substantial and interesting problem. For that reason, this task report focuses on the chiller diagnostics, even though the hot water control diagnostics were also implemented and subjected to similar testing.

4.1 General Description of Prototype and Testing Approach

The prototype chiller control diagnostics were developed in Excel VBA in order to enable quick and flexible development, easy inspection of intermediate results, and easy visualization of data inputs and outputs. Although the eventual final implementations of these diagnostic methods will likely be designed for continuous operation, this prototype uses static building operating data previously acquired through field data collection activities. Multiple datasets were available from the extensive field work that AEC has done using ENFORMA® HVAC Analyzer. Data from five different commercial buildings with chilled water systems were selected for use with this prototype. The datasets for most of the buildings included roughly two weeks of data collected on two to three minute intervals. These data were imported into the Excel spreadsheet.

4.1.1 User Interface for Testing Prototype

Figure 1 shows the user interface screen developed for the prototype. Note that this interface is for algorithm testing, and later user interfaces for diagnostic users may bear little resemblance to this user interface. However, reviewing the interface and the example data it contains may help the reader better understand the scope and nature of the diagnostic prototype. Information appearing in the fields with white backgrounds is dynamic; areas with gray background are static. The dynamic data are organized as follows: 1) system status, 2) current performance data (i.e., values for the current time step from the original data set or data inferred directly from the original data), 3) setup data (i.e., user entered assumptions about the system and diagnostic settings), 4) current calculated values used in the diagnostic processing (mostly intermediate calculations), and 5) a log of abnormal or fault conditions identified during the current diagnostic processing period.



***AEC/B** attelle Pattern-Recognition Diagnostic Testbed*

System Status

Analyzing Sample 1

Current Performance Data

Current Date	11/21/94	
Current Time	0:00	
Ambient Drybulb Temperature	45.6	ºF
Ambient Wetbulb Temperature	43.7	ºF
Compressor Off/Starting/ON	Off	
Chilled Wtr Supply Temp.		ºF
Chiller/Comp. Run Time		min.
CHW OK/not ok:		
CHW Avg Temp Deviation		ºF
CHW Standard Deviation		ºF

Analysis Controls

Setup Data

Chilled Water Setpoint	40.5	ºF
Max CHW Variation	1	ºF
max dCHWT/dt for stable op:	0.200	ºF/min
Min Fault Duration for Alarm	10	minutes

Overall CHW T Data

Overall CHW Avg Temp	40.820	ºF
Overall CHW Std Deviation	0.65	ºF
ON time	93.5	hrs
OFF time	334.6	hrs
Startup Time	3.9	hrs
Total fault time	12.13	hrs

	Fault Notifications					CHW DT Cause		High CHWR Cause	
#	Current Time	Fault	Fault Duration	CHW Avg Dev	CHW Std Dev	Avg CHW DT	% of Cause	Avg CHW RT	% of Cause
1	11/15/94 3:44	High	324	1.66	0.54	2.6	100.00%	0	.%
2	11/15/94 10:28	High	82	1.97	0.29	2.8	100.00%	0	.%

Figure 1. User Interface of Algorithm Testing Prototype

4.1.2 Diagnostic Processing

The diagnostic process embodied in the prototype can be roughly described as consisting of the following four steps:

1. Load set points and other criteria into the analysis framework.
2. Perform an initial pass through the time-series data set to determine the maximum valid chilled water (CHW) temperature difference and CHW return temperature. These values are used in evaluating some potential causes of high CHW temperature.
3. While processing the data record for each time step, determine the operating status of the chiller. Operating status is designated using the following three-category classification:
    - Off
    - Startup sequence (on but not yet at steady state)
    - On (at steady state)
4. Perform a final pass through the data set, performing the following procedure: for all records with the chiller operating in a steady-state mode,
    - Determine if CHW supply temperature is within specifications (i.e., setpoint plus or minus the specified throttling range).
    - If CHW supply temperature is not within specifications, evaluate two possible causes:

        1) excessive CHW return temperature; i.e., too large a load from the secondary (air side) cooling system

        2) inadequate CHW temperature difference; i.e., inadequate cooling provided by the chiller.

One of the functions of such a system will be to notify building operating personnel when there is a problem. Since it is normal for CHW temperatures to occasionally fall outside of the "normal" range for brief periods of time, this prototype has been designed to notify the user (in the case of this prototype, by adding a notification entry to the log) only after the fault has persisted for a set period of time. This is to prevent sending notices to the user too frequently or in the absence of a fault that required operator attention. Otherwise the operator would quickly find the system annoying, leading to the messages being ignored or the system defeated.

An important dimension of the problem of automating fault detection is to achieve an appropriate balance between system sensitivity (i.e., the ability to detect even minor faults) and immunity from falsely reporting fault conditions. While it is easy to change the various settings that determine whether conditions are out of specification or of sufficient duration for the fault conditions to be reported, determining what these settings should be is a challenge. We discuss in the Conclusions section of this report some options that warrant further evaluation as strategies for developing appropriate settings.

4.2 Scope and Functionality of Spreadsheet Implementation

As was stated previously, this prototype compares the CHWS temperature to the desired set point and generates notifications when the CHWS temperature remains out of specification for a stipulated length of time. In addition to this basic fault detection function, there are diagnostic extensions to this process that determine why the CHWS temperature may be out of specification. The following extensions were implemented:

- Difference (DT) between the chilled water return temperature and chilled water supply temperature less than represented in the design specification

- CHW return temperature too high, indicating that the load is greater than the chiller can serve.

A basic and important criterion for diagnostics automated as part of this project has been that they require relatively few, easily obtained measurements. The measurements that are currently required are:

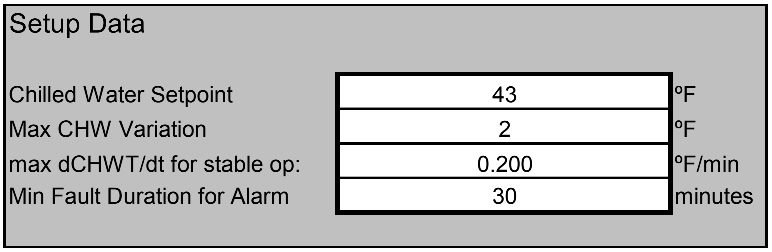
- CHW supply temperature
- CHW return temperature
- Chiller power (or current)
- Chilled water pump power, current, or status (on/off)

More sophisticated diagnoses of the causes for out of specification CHWS temperatures might be possible with additional measurements.[1]

4.3 Diagnostic Example From Prototype

The following section shows example results generated from one of the data sets used to test this prototype. The data for this example were collected at a hospital in Newport, RI, during a particularly hot period in August 1995. During this period, the CHWS temperature occasionally exceeded acceptable limits resulting in the system being unable to maintain comfort conditions.

Figure 2 lists the setup data for this example. The CHWS setpoint was 43°F, with +/- 2°F permitted variation (or throttling range). For these test runs, the fault duration threshold was set to 30 minutes—the time that the CHWS temperature can remain of out of specification before a fault notification is generated. (Some results shown later in this example were generated with this setting changed to 10 and 125 minutes.)


Setup Data

Chilled Water Setpoint	43	°F
Max CHW Variation	2	°F
max dCHWT/dt for stable op:	0.200	°F/min
Min Fault Duration for Alarm	30	minutes

Figure 2. Setup Data

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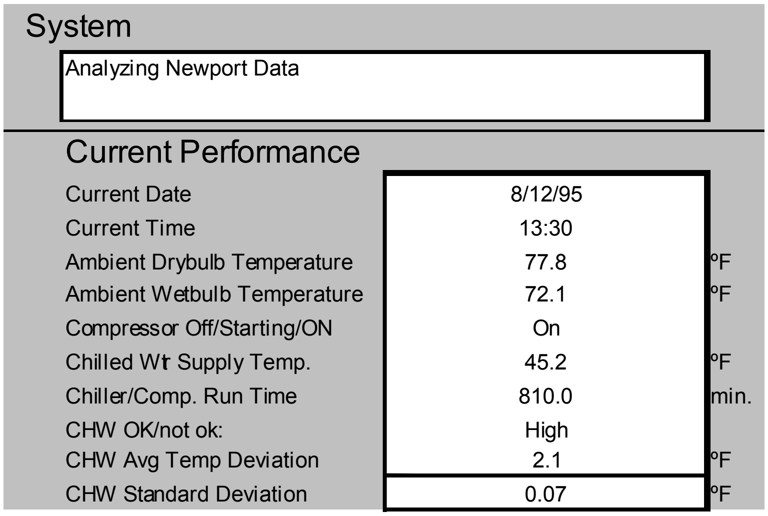
[1] Some aspects of chiller operation that aren't being evaluated currently but that could prove useful are listed below; however, adding these to our diagnostics would require additional measurements. In addition, some of these diagnostics are already being handled adequately by the chiller control system using interlocks, as they are related to safety or equipment protection.

- Low or high refrigerant pressure (requires pressure transducers integrated into the chiller)
- Flow interlocks (already part of most control systems)
- Current limiting
- Flow rates that are substantially different from design
- Chiller efficiency (requires flow meter).

Figure 3 shows a snapshot of the data at a specific point in time. As the dataset is processed, the fields in Figure 3 are constantly updated. At the time step shown, the CHWS temperature has exceed the setpoint plus throttling range by 0.2°F. The processing results displayed in this portion of the interface determines only that the CHWS temperature has exceeded the limit; other processing determines if a notification needs to be generated.



System

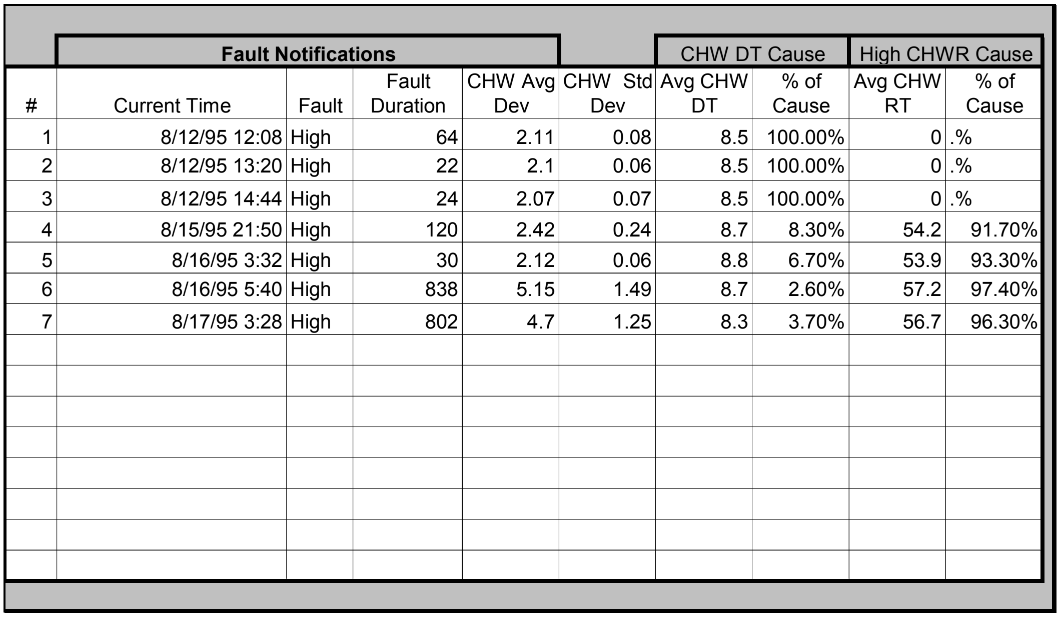
Analyzing Newport Data

Current Performance

Current Date	8/12/95	
Current Time	13:30	
Ambient Drybulb Temperature	77.8	°F
Ambient Wetbulb Temperature	72.1	°F
Compressor Off/Starting/ON	On	
Chilled Wtr Supply Temp.	45.2	°F
Chiller/Comp. Run Time	810.0	min.
CHW OK/not ok:	High	
CHW Avg Temp Deviation	2.1	°F
CHW Standard Deviation	0.07	°F

Figure 3. Sample System Status

The table shown in Figure 4 lists all the notifications generated for the combination of building dataset and diagnostic settings for this data set. Included in this reporting are the time that the fault started (Current Time), the duration of the fault (Fault Duration), the deviation of the CHWS temperature from the desired set point (CHW Avg Dev), and whether the cause is due to low delta T or high CHWR temperature (CHW DT Cause).



	Fault Notifications					CHW DT Cause		High CHWR Cause	
#	Current Time	Fault	Fault Duration	CHW Avg Dev	CHW Std Dev	Avg CHW DT	% of Cause	Avg CHW RT	% of Cause
1	8/12/95 12:08	High	64	2.11	0.08	8.5	100.00%	0	.%
2	8/12/95 13:20	High	22	2.1	0.06	8.5	100.00%	0	.%
3	8/12/95 14:44	High	24	2.07	0.07	8.5	100.00%	0	.%
4	8/15/95 21:50	High	120	2.42	0.24	8.7	8.30%	54.2	91.70%
5	8/16/95 3:32	High	30	2.12	0.06	8.8	6.70%	53.9	93.30%
6	8/16/95 5:40	High	838	5.15	1.49	8.7	2.60%	57.2	97.40%
7	8/17/95 3:28	High	802	4.7	1.25	8.3	3.70%	56.7	96.30%

Figure 4. Fault Notifications

To evaluate these results, several plots are presented below.   shows the CHWS temperature and the notification periods for a portion of the dataset. Notice that when the allowable fault duration period is increased to 125 minutes, the shorter fault periods at the left no longer generate fault notifications.

 illustrates potential causes of high CHWS temperature. The CHW temperature difference (CHW DT) and the CHWR temperature are plotted versus the CHWS temperature. When the CHWS temperature is between 42.5°F and 44.5°F, the CHW DT varies as the load varies. There is a similar result for the CHWR temperature; it generally ranges between 46 and 53°F. However, when the CHWS temperature increases beyond 45°F, the CHWDT plateaus at around 9°F, because the chiller cannot generate any more cooling. Since the CHW DT has reached its maximum value, the CHWR temperature rises as the CHWS rises. The data shown here are indicative of a chiller that cannot meet the load. Referring back to Figure 4, notification 6 and 7, the major cause of the notification is high CHWR temperature. We believe this kind of diagnostic interpretation can be automated and reliably point to the probable cause of the CHW control problem.

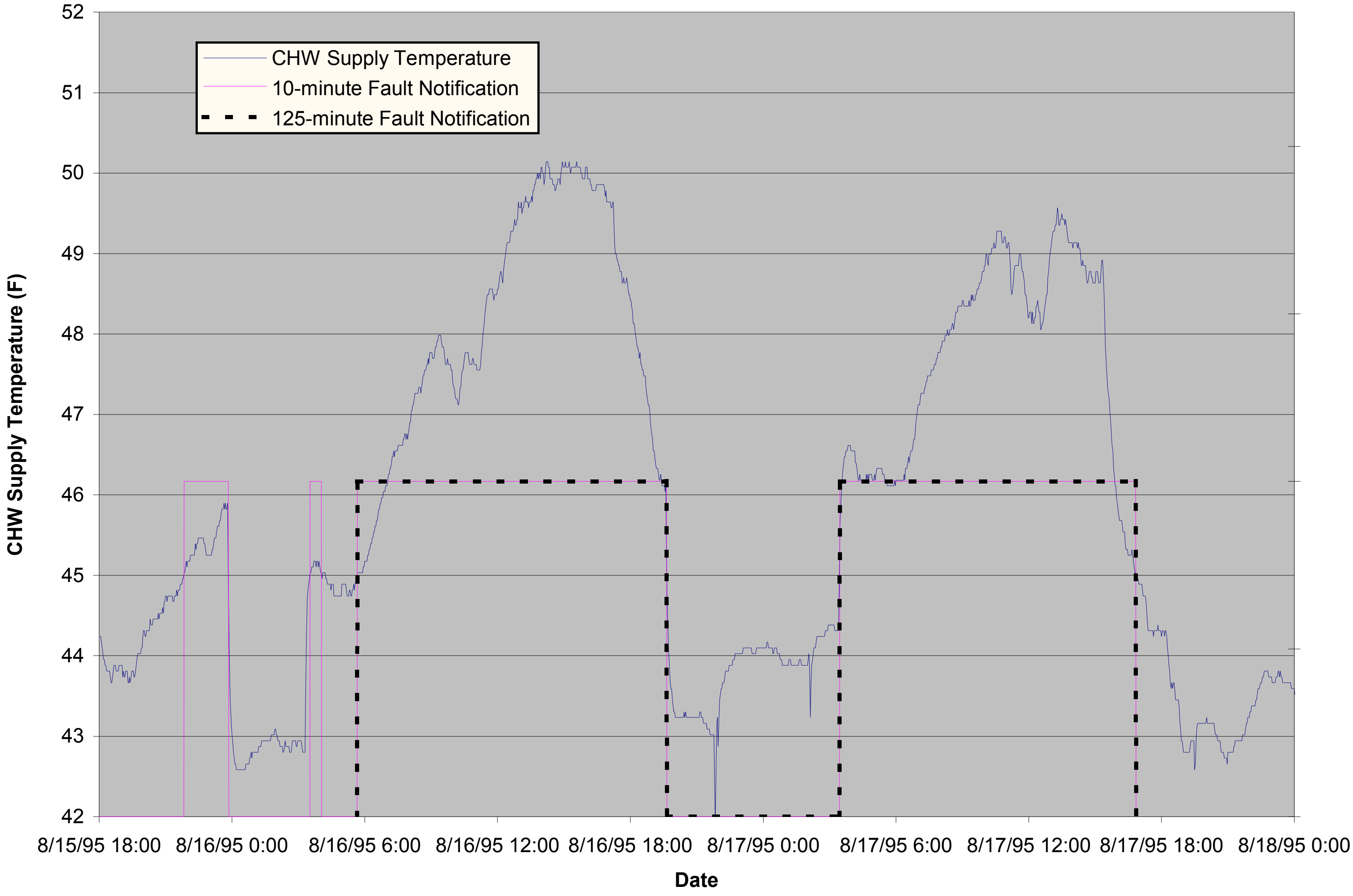


Figure 5. CHWS Temperature and Notification Periods

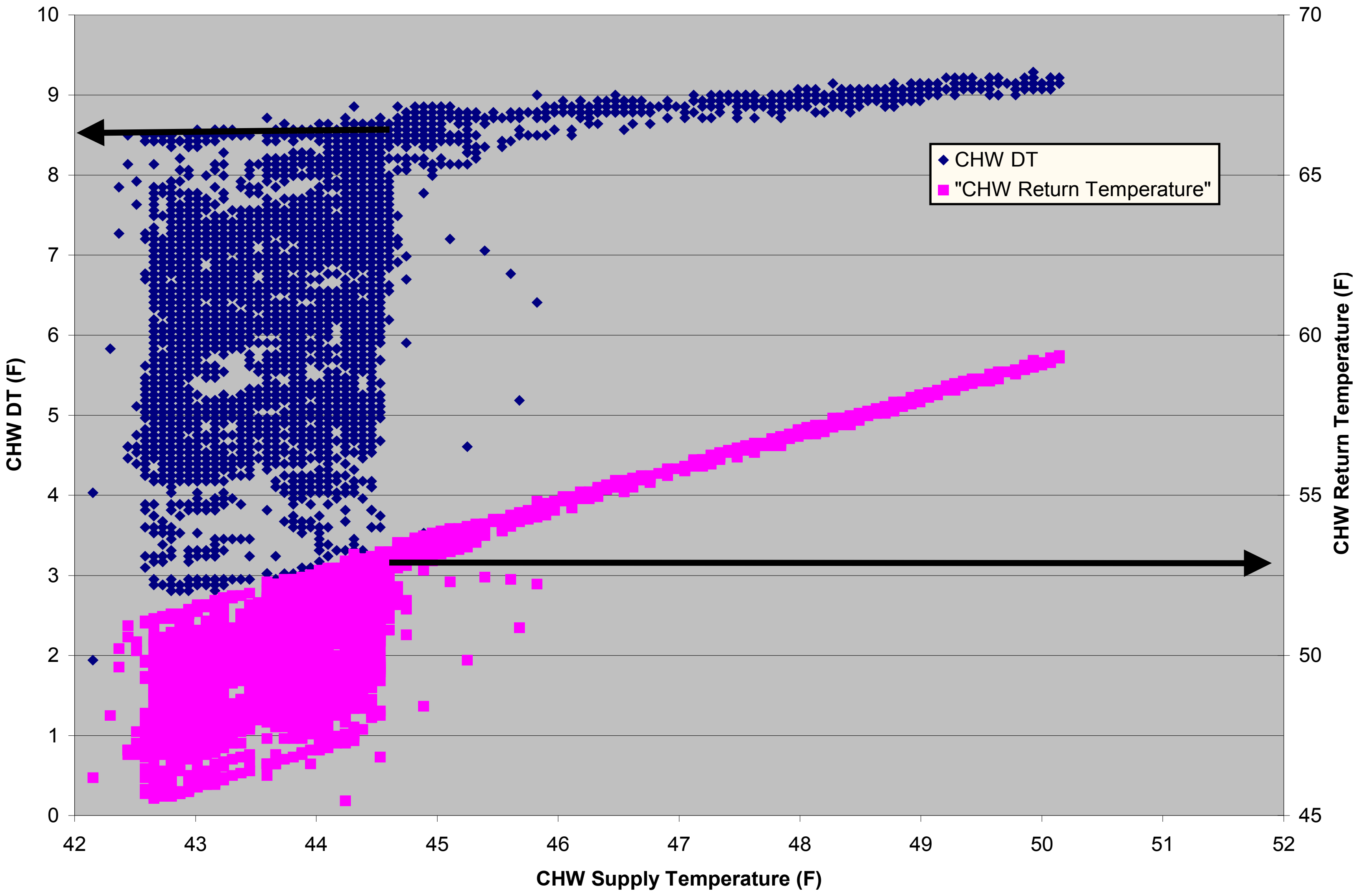


Figure 6. Chiller Operational Criteria versus CHWS Temperature

5 Conclusions

This prototyping and testing exercise produced results that are generally encouraging with respect to the use of the proposed rule-based approach to automating fault detection and diagnostics. The Excel VBA prototype enabled us to take the procedures that we had captured from AEC's experience with ENFORMA, implement them in a software environment using rules, and run them on some real-world data, producing valid results. While the prototype implementation emulates a diagnostic that runs on a periodic basis, this experience lends good support for use of these same methods in a continuous monitoring mode of operation.

A copy of the software is attached for demonstration viewing by the user. Instructions are included in Appendix A.

An issue that has emerged clearly from the prototyping and testing is the importance of certain setup parameters, in particular those that determine how sensitive the procedure is in reporting mild and short-duration aberrations in chilled water control. There are several different ways that this issue could be addressed, and work planned under the remaining project tasks will address how best to handle this issue. We plan to look at several options. [2]

While not the focus of this report, prototyping and testing of similar diagnostics for boilers were performed as part of this task. Boiler diagnostics present similar problems to chiller CHWS diagnostics, with the exception that hot water supply (HWS) temperature setpoints usually vary as a function of ambient temperature. Boilers represent a less substantial problem than chillers because there are fewer parameters that warrant monitoring and because there are few, if any, interactions. With boilers, the diagnostics focus on hot water supply temperature, hot water return temperature, and pump status. We did not look at such issues as boiler standby losses or boiler efficiency due to the additional measurements that would be required.

The boiler diagnostics that were implemented appear to work well, indicating that the rule-based approach selected is appropriate for implementation of the AEC boiler diagnostics. The same issue of

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[2] These options include:

- Automatically tune these setup values using a diagnostic installation procedure. The procedure might run the chiller through a typical start-up sequence and set thresholds automatically based on the observed operating data. This strategy might also work with longer term data, such as from the first few days, weeks, or even the first season the chiller is operational. In addition to generating the startup parameters, the reliability and accuracy of the measurements should be established; commissioning the system will likely result in better performance from the diagnostics.
- Alternatively, recommended tuning parameters could be developed during use of the software in field tests of the final software product.
- An option that may be compatible with either of the above approaches would be to make these tuning parameters customizable by the building operator. A convenient method could be developed to enable an operator to reduce the system sensitivity following an event (or events) determined to represent a false positive fault detection. This sensitivity tuning might be simplified to give the user the ability to change the sensitivity of the diagnostics without the complexity of tuning each parameter individually. This approach has been used successfully by Battelle with the Whole-Building Diagnostician.

determining when to issue a fault notification to the user exists with boilers and should be amenable to the same techniques that are being developed for use with chillers.

6 References

Architectural Energy Corporation (AEC). 2000. *ENFORMA, Demonstration and Installation CD-ROM, HVAC Analyzer v3.116, Lighting Evaluation System v.2.2, MicroDataLogger-DataManager Software v3.0.2.1.* Boulder, Colorado.

Architectural Energy Corporation (AEC). *ENFORMA Portable Diagnostic Solutions HVAC Analyzer User's Guide.* Boulder, Colorado.

Microsoft Corporation. 1985-1997. *Microsoft Excel.* Redmond, Washington.

Microsoft Corporation. 1987-1996. *Microsoft Visual Basic.* Redmond, Washington.

7 Appendix A: Instructions for Use of the Test Prototype

The following is a brief description of how to use the CHW Diagnostics prototype. Four data sets have been provided as input data. They are listed in the table below.

1. To run an analysis, first select which data set in the table you will run. Suggested values for CHW setpoint and maximum allowable CHW variation are provided in Table 1. Change these values in the "UI Mockup" sheet of the file.
2. Click the button labeled **Run Analysis.** A dialog box will be displayed to allow selection of a data set. Select the desired data set and click **OK**. At this point, the analysis procedure will proceed automatically.
   Hint: Since the dialog doesn't completely disappear when you click **OK**, to view all the fields on the UI Mockup sheet, move the dialog box to another position on the screen before clicking OK.

Chilled Water Setpoint:	The desired CHW supply temperature
Max CHW Variation:	The maximum allowable CHW supply temperature, positive or negative.
max dCHWT/dt for stable operation:	The criteria used to determine when the chiller has reached "steady-state" operation.
Minimum Fault Duration for Alarm:	The minimum amount of time that a fault must exist before a notification is issued in the lower right-hand table.

Table 1. Data sets and suggested inputs

		Suggested values for inputs:			
Data set:	**Location, building type**	**Chilled Water Setpoint**	**Max CHW Variation**	**max dCHWT/dt for stable op**	**Minimum Fault Duration for Alarm**
Newport Data	Newport, RI; Newport hospital	43	2	0.2	30
Dade County Ch2	Dade Cty FL; Dade County prison	45	3	0.2	20
MethodistHosp#2	Houston, TX; Hospital	42	1.8	0.2	30
Sample 1	Sample project provided with Enforma® software	41	2	0.2	10

The fault notifications are listed in the fault notification table, which is in the lower right corner of the UI mockup. Table 2 shows the headers in the fault notification table, and Table 3 provides definitions for the headers.

Table 2. Fault Notification Headers

Fault Notifications					CHW DT Cause		High CHWR Cause	
Current Time	Fault	Fault Duration	CHW Avg Dev	CHW Std Dev	Avg CHW DT	% of Cause	Avg CHW RT	% of Cause

Table 3. Description of Fault Notification Headers

Field	Description
Current Time	Time that the fault started
Fault	The fault (CHWS too high; CHWS too low)
Fault Duration	The duration of the fault in minutes
CHW Avg Dev	The average deviation of the CHWS temperature from the setpoint
CHW Std Dev	The standard deviation of the difference between CHWS temperature and the setpoint.
CHWDT Cause	Evaluation of whether the CHW Delta Temperature was the cause of CHWS not meeting specification.
Avg CHW DT	The average CHW DT during the notification period
% of Cause	The percent of time during the notification period that the CHW DT was determined to be the cause of CHWS not meeting specification.
CHWR Cause	Evaluation of whether the CHW Return Temperature was the cause of CHWS not meeting specification.
Avg CHW RT	The average CHW Return Temperature during the notification period
% of Cause	The percent of time during the notification period that the CHWRT was determined to be the cause of CHWS not meeting specification.