Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program

Final Interface Report and Final Implementation Report

CONSULTANT REPORT

Prepared For:
California Energy Commission
Public Interest Energy Research Program

Prepared By:
Architectural Energy Corporation

Arnold Schwarzenegger, *Governor*

November 2006
Contract #500-03-030
2.2g and 2.3e Deliverables

CALIFORNIA ENERGY COMMISSION

Prepared By:
Stuart Waterbury
Architectural Energy Corporation
2540 Frontier avenue, Suite 201
Boulder. Colorado 80301

Program Director
Vernon Smith
Boulder, Colorado
Commission Contract No. 500-03-030

Prepared For:
Chris Scruton
Contract Manager

Ann Peterson
PIER Buildings Program Manager

Nancy Jenkins
Office Manager
ENERGY EFFICIENCY RESEARCH OFFICE

Martha Krebs, Ph.D.
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

B. B. Blevins
Executive Director

Table of Contents

LIst of Figures

List of Tables

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 integrates the following methods into a suite of web-accessible applications:

- NIST's air-handling unit diagnostics (APAR) [1, 2]; 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 how APAR and the central plant diagnostics have been implemented within the Niagara AX framework.

This report is a combination of the following deliverables:

D2.2e	Draft Report summarizing the capabilities of the APAR and Central plant diagnostic rule sets, and the content and user interface for the diagnostic reports	Prepare draft report summarizing the capabilities of the APAR and central plant diagnostic rule sets, and the content and user interface for the diagnostic reports.
D2.3c	Draft Report describing implementation of FDD in the Niagara platform	Prepare draft report describing the implementation of FDD in the Niagara platform. This report will describe the deployment options, configuration requirements, and user interactions (user interface), including reporting features.

These deliverables were combined because the user interface for the reporting functions is closely tied to the implementation of FDD within the Niagara platform.

2.0 FDD Background

Previous reports [3, 4] have discussed the development and testing of the APAR and central plant fault detection algorithms.

The concepts behind and development of NIST's Air Hander Performance Assessment Rules (APAR) have been well documented in existing reports [1, 2], and will be briefly summarized here. The Air Handling Unit Performance Assessment Ruleset (APAR) consists of a set of rules which are associated with a variety of system modes. For each rule, a true expression is indicative of a fault.

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. 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.

3.0 Implementation within the Niagara environment

Approaches for collecting building performance data were discussed within an earlier report [5]. Based on that investigation, Tridium’s Niagara AX platform was selected for a variety of reasons, including its connectivity benefits with a wide variety of building control devices through BACNET, LONworks, and legacy drivers. Also, with the release of Niagara AX, Tridium has opened up most of the API, which encourages extension of the Niagara framework by third-party developers. For our purposes, this allows the FDD software to run directly within the Niagara framework, rather than as a separate program. With the fault detection routines running directly within the Niagara framework, it is easier to incorporate FDD into existing systems, which eliminates some market acceptance barriers.

3.1 FDD engine implementation

The FDD engine has been developed in java as a separate module. These separate modules are plugged into the Niagara framework using a straightforward installation process that would be familiar to all Systems Integrators that are qualified to install or configure Niagara AX systems.

Since the FDD engine was developed as a separate module (not developed directly within the Niagara environment), the option of incorporating it into different environments is retained. This was a conscious decision so that the development of the engine would not be linked completely to a single controls vendor. However standard capabilities available within the Niagara environment were utilized such as their database, history development, and other features required to provide connectivity between the FDD engine and the data and user interface. Using Niagara features as opposed to creating custom methods provides the most seamless integration within the Niagara environment.

The FDD engine uses historical data as its data source, as opposed to real-time data. The use of historical data allows data to be archived at remote locations and then uploaded periodically to a central location. Using historical data, however, requires that the Systems Integrator responsible for installing the software will have to set up histories for the required points.

3.2 User interface development

Tridium has provided a wide variety of components to facilitate graphical user interface development. These components include tables, tab views, plotting, and others. Custom components were not developed since the Niagara toolkit was complete enough to provide all the functionality the FDD interface required.

The user interface is described in the following sections.

4.0 User Interface

The ENFORMA Building Diagnostics user interface is viewed through a standard browser. A java applet is downloaded the first time the site is accessed. The UI design philosophy utilizes a series of tabs that allow the user to navigate through the various activities associated with using the FDD application. The activities performed through the UI include configuration of the FDD tool and viewing the results.

This section describes each of the FDD activities, their associated screens, and how the user interacts with the system. It does not discuss installation of the software or setting up the data histories, which would both be performed by the Systems Integrator.

4.1 Configuration Activities

After histories for the required data points have been set up, the software must be configured so that it will access the data histories and report system faults. Configuring the FDD tool involves defining a site, the number and names of buildings at each site, and the number, type, and names of HVAC equipment located in each building.

4.1.1 Site Tab

Figure 1 shows the Site Tab, which lists each site and the buildings at each site. Buildings and sites are added, renamed, or deleted from this view.

Once sites and buildings have been defined, this tab is also used to select the specific site and building to be viewed in subsequent tabs.

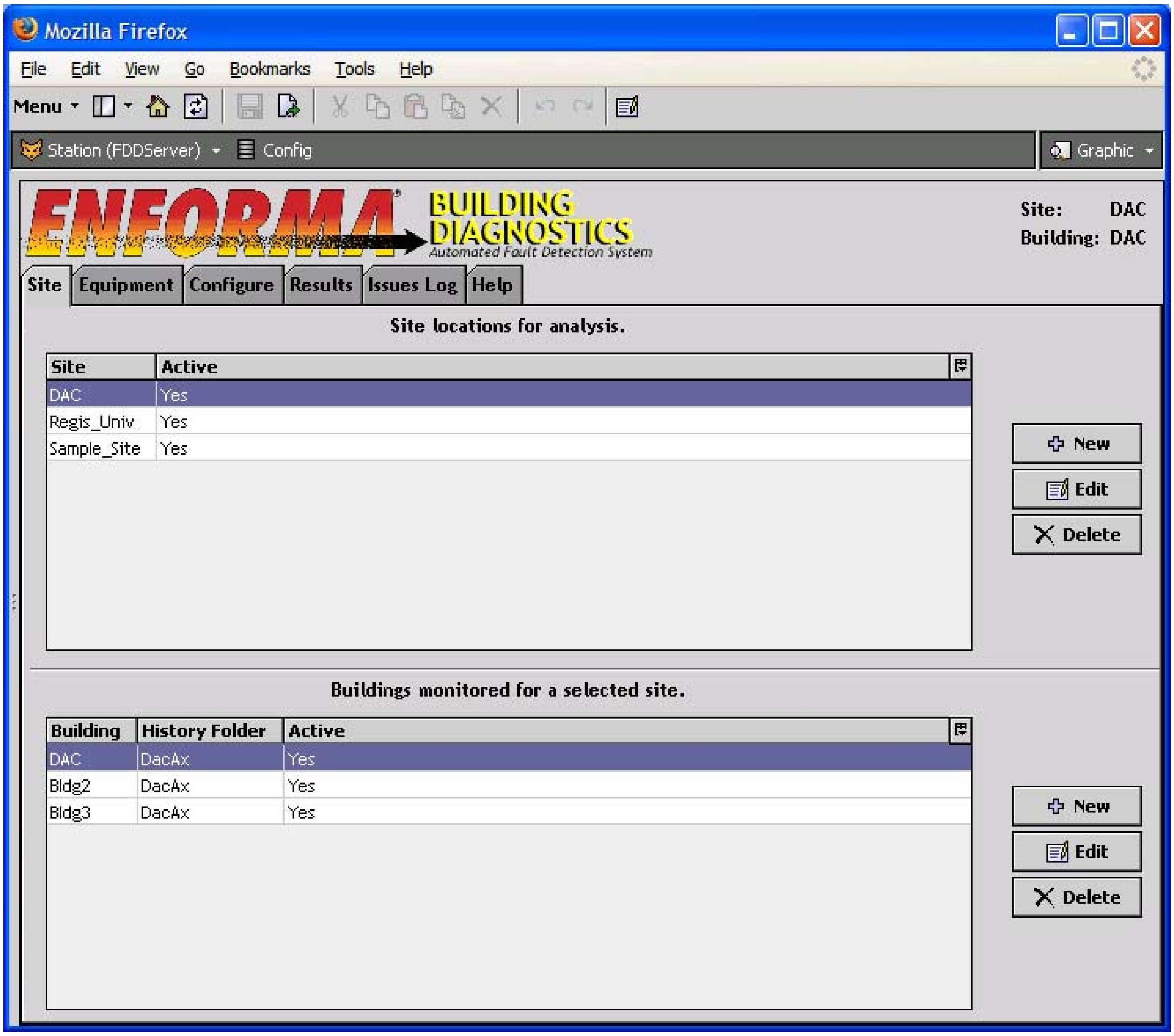


Figure 1. Site screen

4.1.2 Equipment Tab

The equipment tab (Figure 2) is used to define equipment and associate data histories with each selected system.

The activities in the equipment tab include adding equipment and associating data histories with the measures required to perform the automated fault detection. The histories, which must be pre-defined, are associated with the measures by selecting each measure and clicking the “Edit” button, which then displays the Edit Measure dialog, shown in Figure 3. The appropriate History Archive is selected from the dropdown list shown in the Edit Measure dialog.

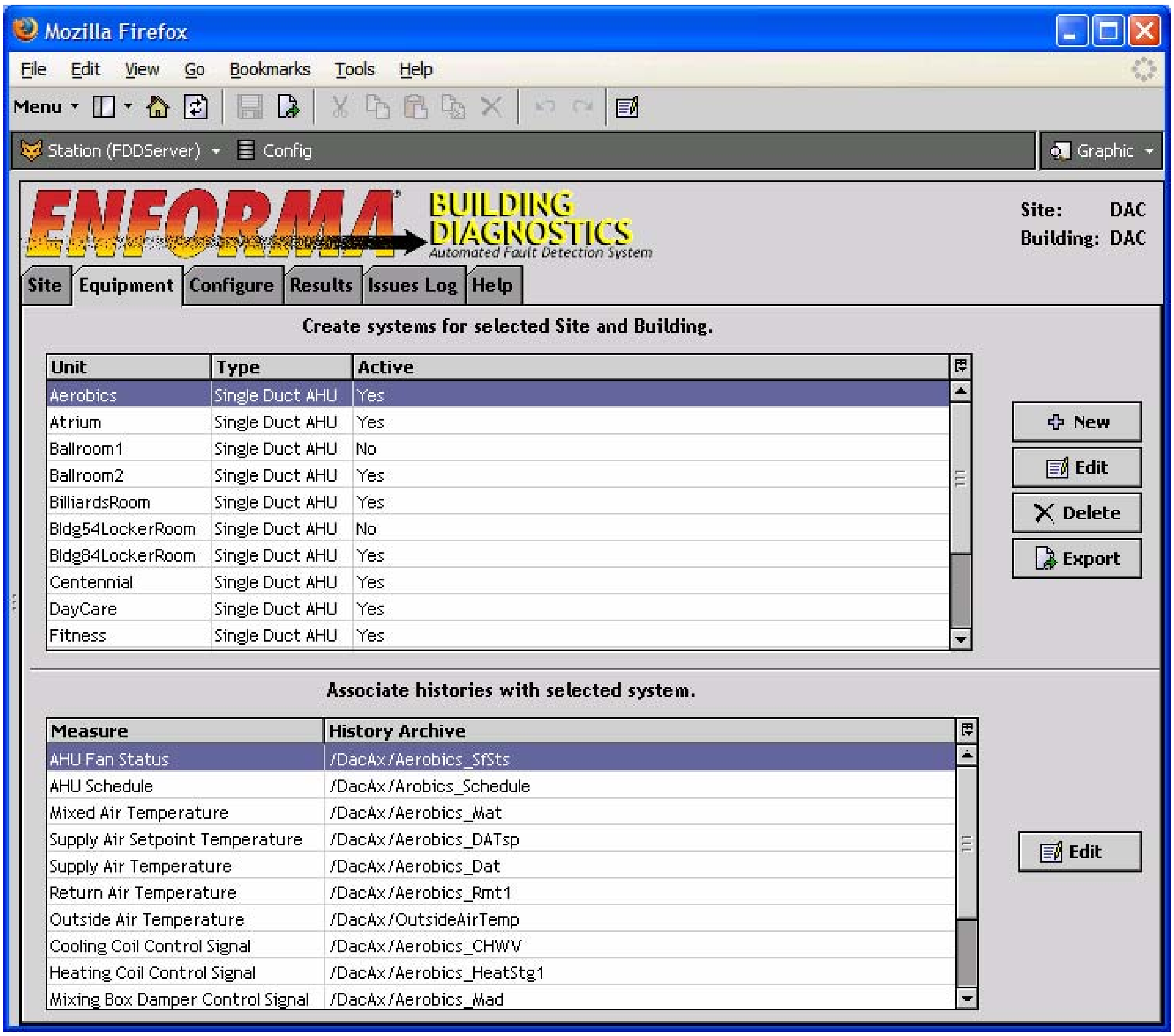


Figure 2. Equipment definition screen

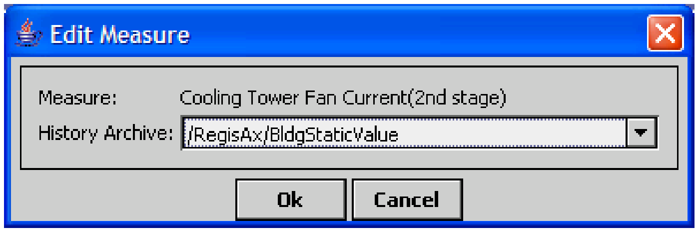


Figure 3. Map history with required measure

4.1.3 Configure Tab

Configuring the FDD tool for each piece of equipment is performed under the Configure tab (Figure 4). These activities include enabling and disabling rules as necessary, and setting the Diagnostic Constants. Although the capability exists to disable rules, in general, it is best to keep all rules enabled.

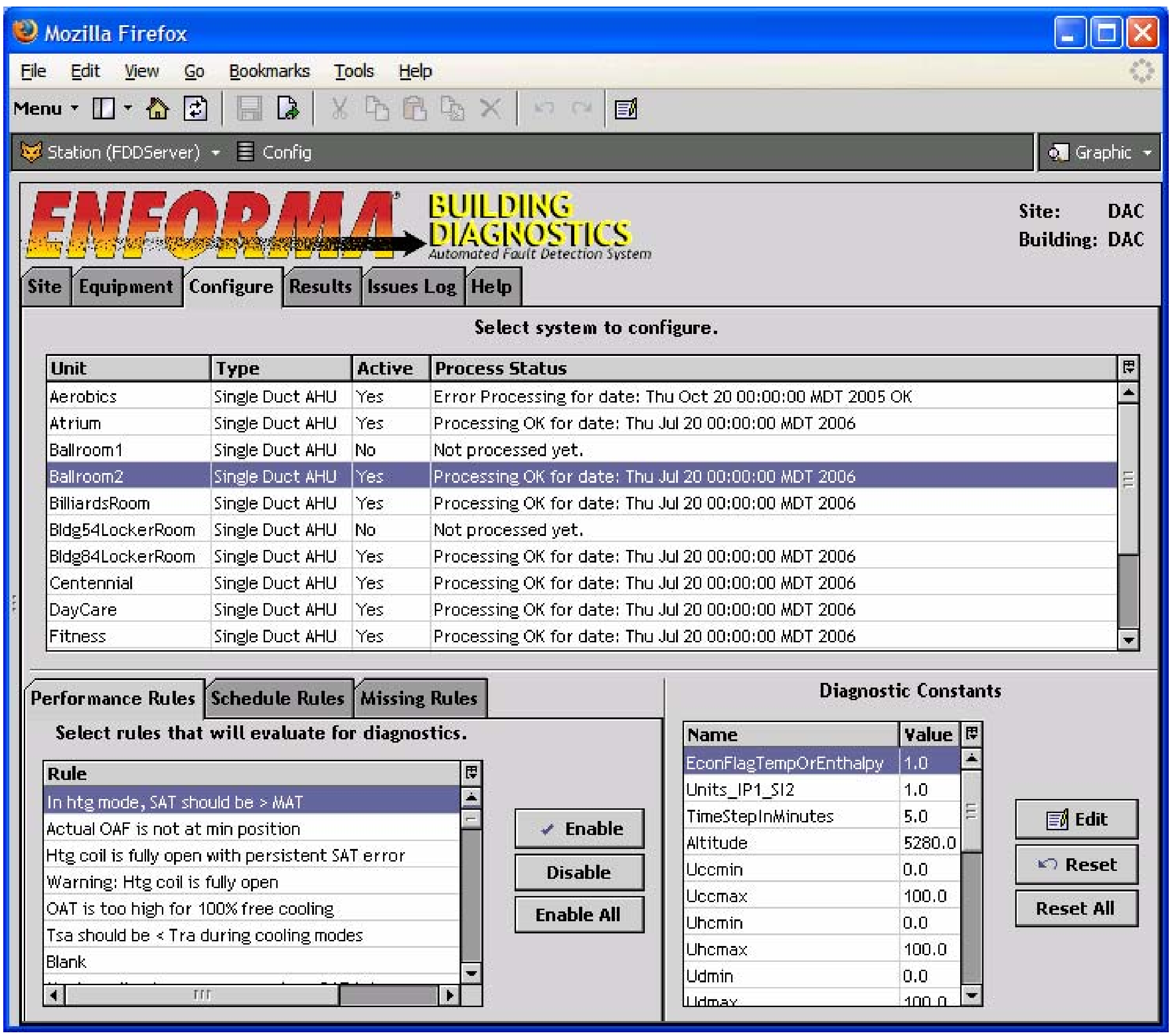


Figure 4. Configure screen

Appendix A describes each of the diagnostic constants. Default values are included, but some must be changed for site conditions. These considerations are also discussed in Appendix A.

4.2 View results

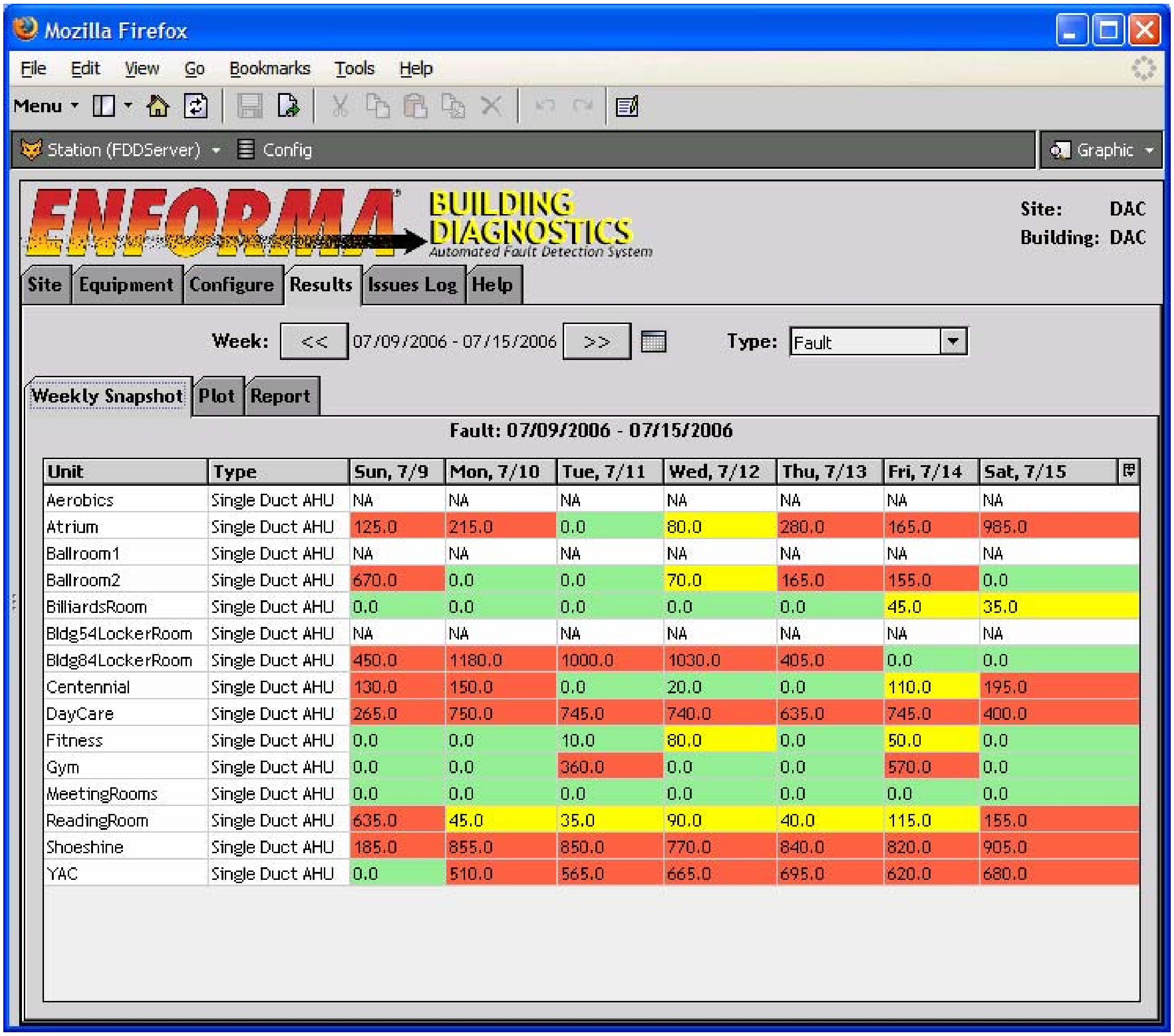
4.2.1 Weekly Snapshot

Viewing and interpreting a large amount of information in a single glance is one of the goals of the Snapshot view, which provides a color-coded representation of the condition of each system being evaluated. Green indicates that the system is ok, whereas yellow and red indicate potential problems at increasing thresholds.

There are several “Types” of snapshots available: Fault, Schedule, and Data Availability. The Fault snapshot displays the degree of faulty operation for each component in terms of fault-minutes, where a fault-minute is the sum of the duration of each fault encountered during the day. Multiple faults can occur at once, so it is possible to for the fault-minute sum to be greater than the period that the unit actually ran during the day.

The Schedule snapshot shows the number of minutes that the system was not operating in accordance with the EMS or baseline schedule.

The Data snapshot lists the sum of the minutes that each of the required data histories were missing. For example, if one data history was missing for an entire day, the value would be 1440. If four histories were missing for six hours, the value would also be 1440, and so forth.



Unit	Type	Sun, 7/9	Mon, 7/10	Tue, 7/11	Wed, 7/12	Thu, 7/13	Fri, 7/14	Sat, 7/15
Aerobics	Single Duct AHU	NA	NA	NA	NA	NA	NA	NA
Atrium	Single Duct AHU	125.0	215.0	0.0	80.0	280.0	165.0	985.0
Ballroom1	Single Duct AHU	NA	NA	NA	NA	NA	NA	NA
Ballroom2	Single Duct AHU	670.0	0.0	0.0	70.0	165.0	155.0	0.0
BilliardsRoom	Single Duct AHU	0.0	0.0	0.0	0.0	0.0	45.0	35.0
Bldg54LockerRoom	Single Duct AHU	NA	NA	NA	NA	NA	NA	NA
Bldg84LockerRoom	Single Duct AHU	450.0	1180.0	1000.0	1030.0	405.0	0.0	0.0
Centennial	Single Duct AHU	130.0	150.0	0.0	20.0	0.0	110.0	195.0
DayCare	Single Duct AHU	265.0	750.0	745.0	740.0	635.0	745.0	400.0
Fitness	Single Duct AHU	0.0	0.0	10.0	80.0	0.0	50.0	0.0
Gym	Single Duct AHU	0.0	0.0	360.0	0.0	0.0	570.0	0.0
MeetingRooms	Single Duct AHU	0.0	0.0	0.0	0.0	0.0	0.0	0.0
ReadingRoom	Single Duct AHU	635.0	45.0	35.0	90.0	40.0	115.0	155.0
Shoeshine	Single Duct AHU	185.0	855.0	850.0	770.0	840.0	820.0	905.0
YAC	Single Duct AHU	0.0	510.0	565.0	665.0	695.0	620.0	680.0

Figure 5. Snapshot view

When the Results tab is first displayed, it shows the results for the current week. If desired, the forward and back buttons on each side of the date can scroll the view back or forward by one week. Alternately, the calendar button can be clicked which will display a calendar. Select the desired week to choose another period for viewing. When done with the calendar, it may be closed.

The snapshot view provides an overview of the health of each system evaluated by the FDD tool. However, it does not provide specific information about the faults that were detected. To learn more about the results for a specific system, cells can be highlighted by clicking on them. To view the results for multiple days, click on the first cell of interest and then drag to later days. Once the mouse button has been released, the selected cells will be highlighted, and the labels for the Plot and Report tabs will change from black to red, to indicate that details are available under those tabs.

4.2.2 Report tab

The report tab will display hourly results or a daily summary, depending on whether a single day has been selected in the snapshot view, or multiple days have been selected, respectively. Figure 6 shows the hourly view. This lists the hour that the fault was detected, the mode, the number of minutes that the fault existed, and finally a description of the fault. The hourly view is useful since it indicates during which hour a fault occurred, but it can be rather lengthy if many different faults occurred during a day.

Both the hourly and daily summary views have an "Add Issue" button which displays the Add Issue dialog (Figure 10). This is discussed in more detail in section 4.2.4.

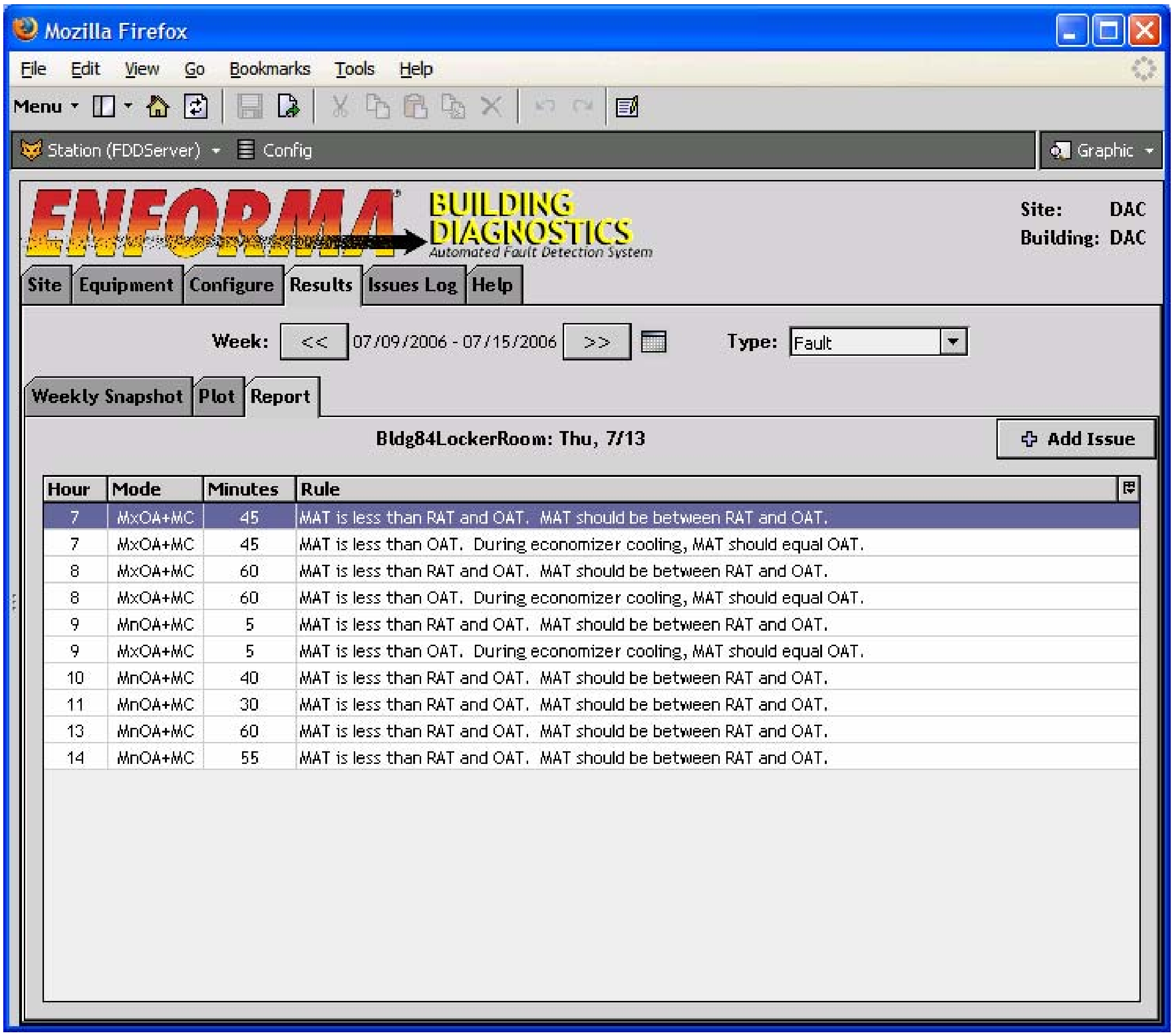


Figure 6. Report tab - Hourly view

Figure 7 shows the daily view. This lists the date that the fault was detected, the mode, the number of minutes that the fault existed during the day, and finally a description of the fault. It provides a compact summary of the faults. This is often more readable than the hourly view, but of course does not provide indication of when during each day the faults actually happened.

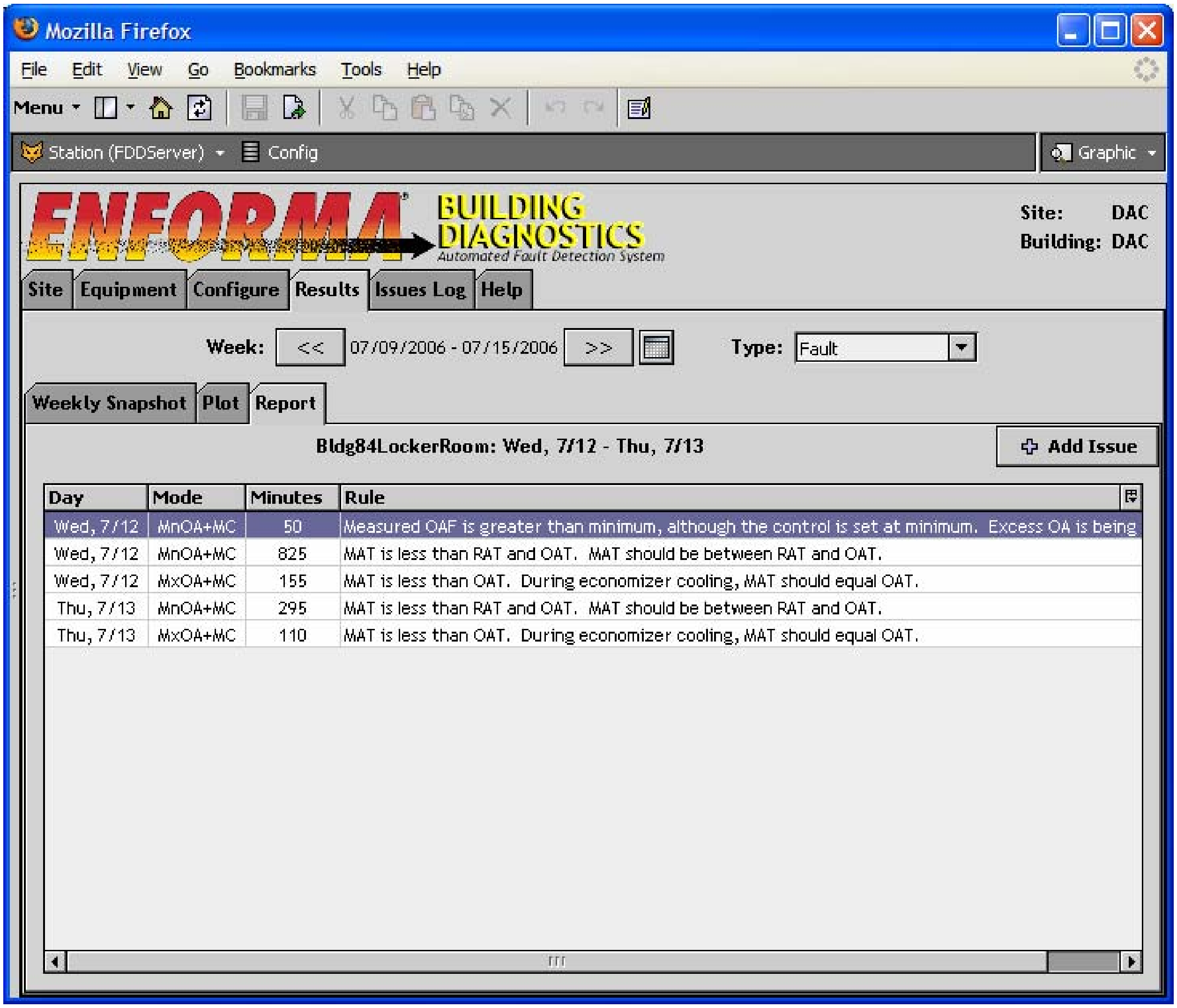


Figure 7. Report tab - Daily view

4.2.3 Plot tab

The plot tab (Figure 8) provides a method of viewing the data to confirm the results provided in the snapshot and report tabs.

One or more points can be selected in the list on the right-hand side of the screen. To select multiple data points, hold the "control" key down while clicking on the desired points. Once the points have been selected, click on "Update…" to refresh the plot. If a point has not been associated with a history, there is no data to plot. Asterisks indicate which points have not been associated with histories.

Each system type has a set of default points that will be plotted when initially viewing the plot tab. This set of points can be modified, as described above. When the plot tab is exited, the selection of points is saved so that the next time the plot tab is selected, the new set of points is plotted. This allows custom plots for each system. For example, if one air handler is having problems with interaction between the control valves and dampers, the engineer might plot HW and CHW valve position, damper position, and fan status. Similarly, another air handler might be having sensor calibration issues. On this system it would be appropriate to plot the fan status and the suspect sensors. In both cases, the fan status was selected so that it was clear when the system was actually operating.

The plotting tool included within the Niagara framework allows zooming and panning through mouse clicks. The plot can be zoomed by clicking and dragging the mouse cursor. Once the plot has been zoomed, a control is displayed that allows panning in the zoomed axis, or returning to the original scale.

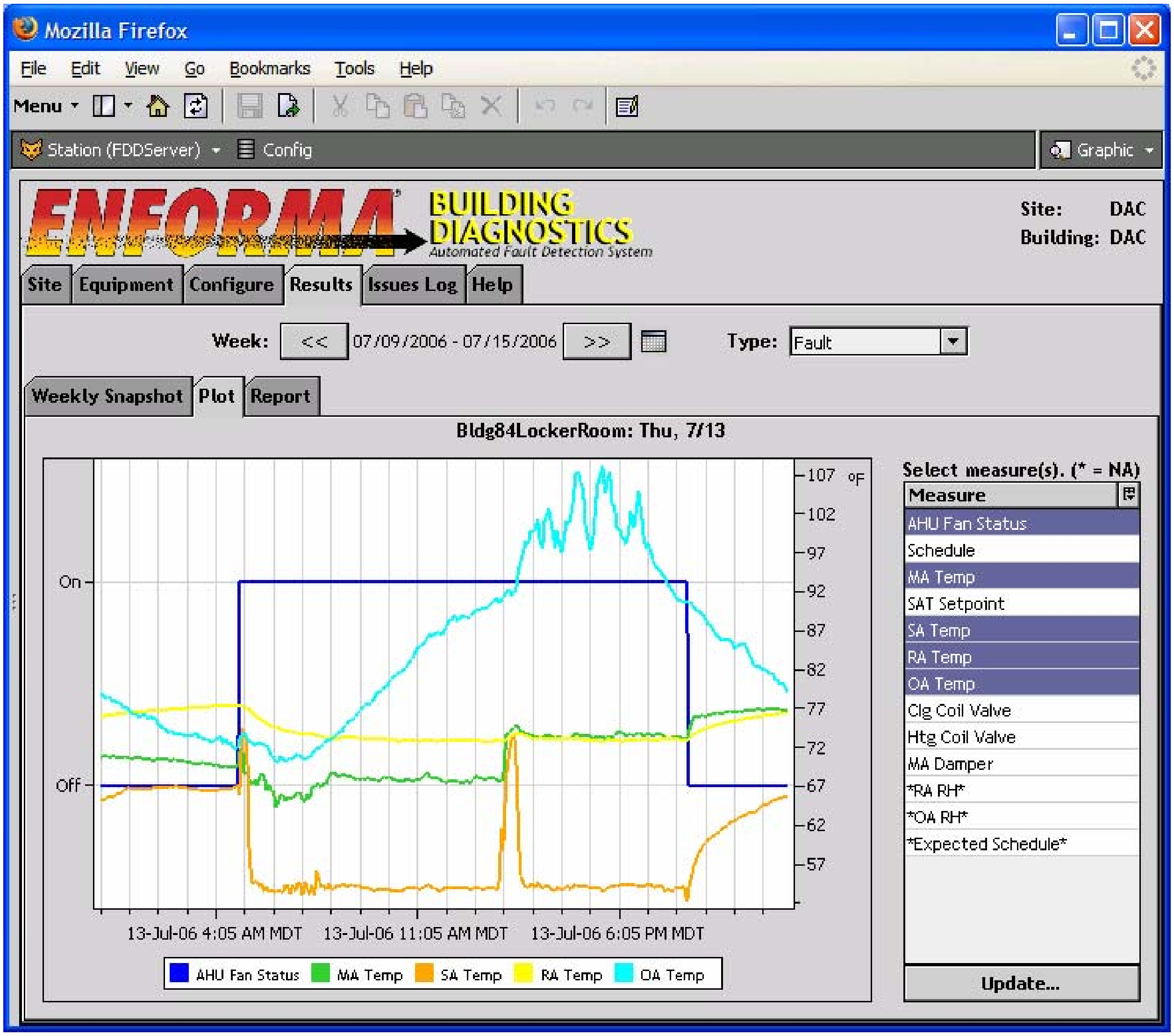


Figure 8. Plot tab

4.2.4 Issues log

Actions taken to resolve problems within the HVAC systems identified by the FDD tool should be recorded. The Issues Log is where these actions can be recorded within the FDD environment. Figure 9 shows the Issues Log view. This view consists of a list of the systems with the number of issues entered for each unit, and a list of the issues displayed for the highlighted unit.

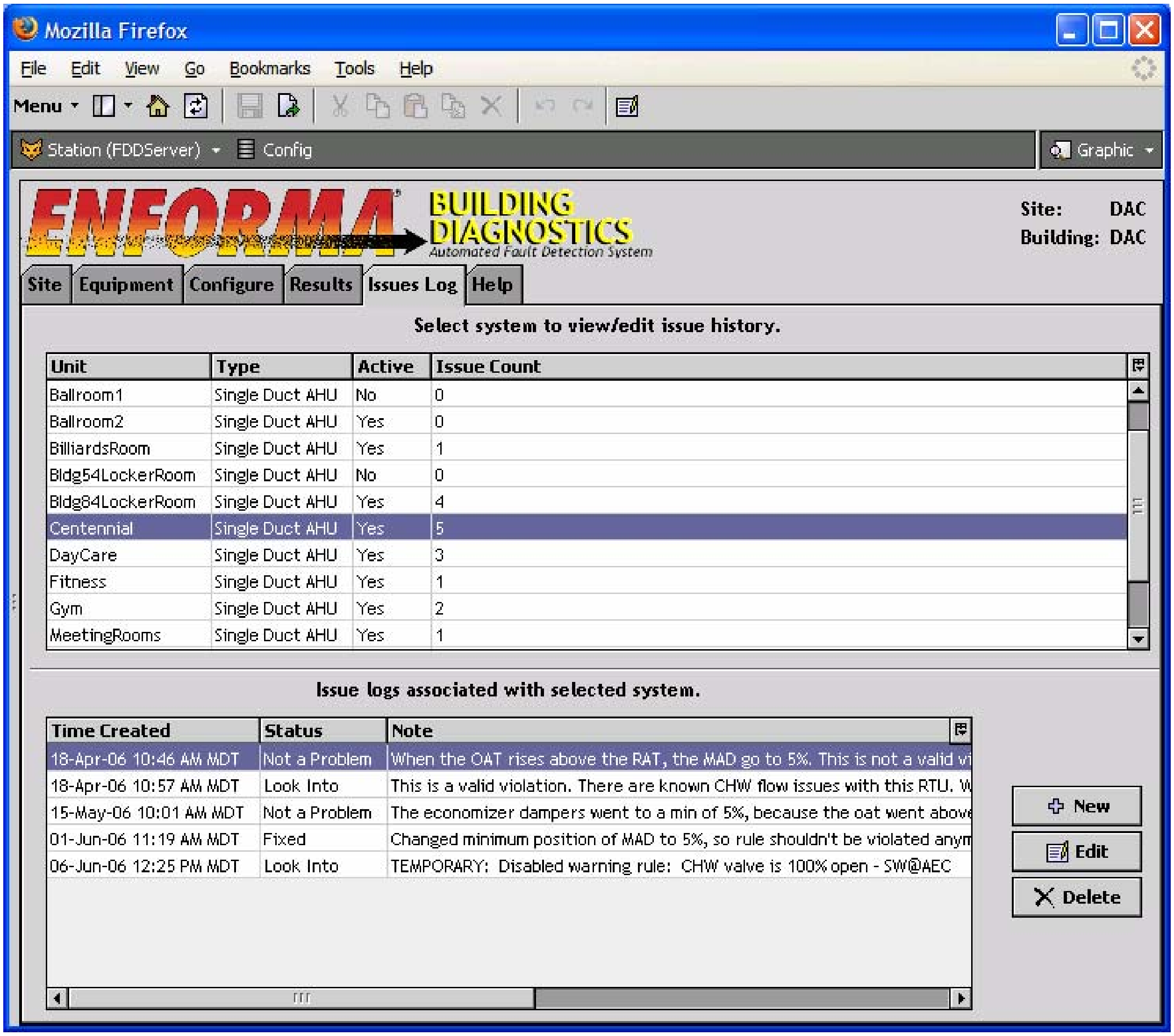


Figure 9. Issues Log tab

Figure 10 shows the Add Issue dialog. This is displayed when the “Add Issue” button is clicked in the report displays, as discussed earlier, or when “New” or “Edit” is clicked in the Issues Log view.

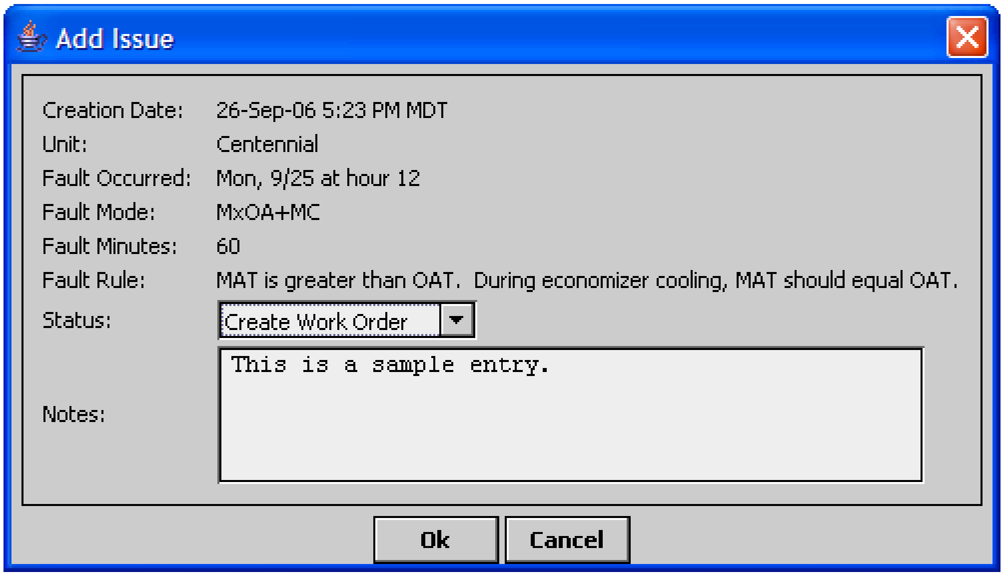


Figure 10. Add Issue dialog

When the Add Issue dialog is opened from one of the report views, the time that the fault occurred, the mode, and the duration of the fault are displayed. If the Add Issue dialog is opened when viewing hourly results, it will list the time of the fault on an hourly basis, as shown in Figure 10. If viewing daily results, it will list the date of the fault, but not list the hour of the fault.

If an issue is added from the Issues Log view, the fields associated with identifying the fault time, type, and duration will be blank.

5.0 Deployment options

The FDD can be deployed in new or existing buildings, in either as a single or multi-building/site implementation. This section discusses these variations.

In a single-building implementation, the FDD software runs on-site. All data are archived on a server running Niagara AX. This Niagara server will generally also be responsible for building control. The FDD user interface can be accessed through a browser that has access to this machine, either through a LAN or the internet.

In a multi-building implementation, a Niagara server with the FDD tool will be installed at a central location. Both performance and results data from each building will be archived on this central server. Generally, a JACE[1] running Niagara AX will be installed in each building and will be used to collect building performance data before archiving it to the centralized FDD server.

Implementation in existing buildings requires that data be accessed from the existing controller. The difficulty of this step varies, depending on the capabilities of the controller. If FDD is being implemented in new buildings, the required hardware and software should already be present.

Table 1 summarizes the various deployment options.

Table 1. FDD Deployment Options

Installation Type	Single Building	Multiple Buildings
New Building	Plug into Niagara AX server used for building control.	JACE (or server) on site used to archive data to central location.
Existing Building with Niagara AX	Plug into Niagara AX server used for building control.	JACE (or server) on site used to archive data to central location.
Existing Building with Niagara R2	Expose BACnet points on existing Niagara R2 system. Niagara AX server installed on-site to run FDD tool.	Expose BACnet points on existing Niagara R2 system. Niagara AX JACE (or server) on site used to archive data to central location.
Existing Building with BACnet or Lonworks-compatible controller	Expose BACnet points on existing controller. Niagara AX server installed on-site to run FDD tool.	Expose BACnet points on existing controller. Niagara AX JACE (or server) on site used to archive data to central location.
Existing Building with legacy controller	Legacy driver (developed by Tridium) and server running Niagara AX installed on site to communicate with legacy control and to run FDD tool.	Legacy driver and JACE running Niagara AX installed on-site to communicate with legacy controller and to archive data to central location.

5.1 Implementing FDD in new buildings

In both new and existing buildings, an instance of Niagara AX is required to incorporate the FDD tool. In new installations, if the use of FDD is anticipated, then the use of Niagara AX should be considered to integrate the multiple systems within the building. If Niagara AX is used, the FDD tool can be plugged in directly into a server running Niagara AX. In smaller buildings, however, a server is not generally necessary to control the building: a JACE is often all that is necessary. Although the FDD tool can run on a JACE, the resources for archiving data are minimal and so if the on-site hardware must be limited to a JACE, a centralized deployment of FDD is more appropriate. Centralized (multi-building) deployment of FDD is discussed in a later section.

[1] A JACE (Java Application Control Engine) is a small industrial computer that runs an instance of the Niagara software. It provides connectivity to systems within a building using standard and proprietary communications protocols.

5.2 Implementing FDD in existing buildings

Implementing FDD in existing buildings requires some level of integration between the existing EMS and an installation of Niagara AX. The extent of the Niagara AX installation depends on the controller currently installed in the building, and whether a single or multi-building installation of FDD is desired. The issues associated with single versus multi-building installations are discussed in a later section.

5.2.1 Existing buildings with Niagara

Implementing FDD in existing buildings that already have Niagara AX installed is identical to implementation in new buildings with AX.

Existing buildings with Niagara installed prior to mid-2005 will most certainly use an earlier version of Niagara called R2. In these cases, FDD cannot run directly within the R2 environment. It is necessary to install a JACE or a server that runs an instance of Niagara AX. Once the AX JACE is installed, the R2 system can be integrated with the AX JACE by mapping required data points using BACnet from the R2 system to the AX system. Once the data are in the Niagara AX environment, installation of the FDD tool depends on whether this is a single or multi-site implementation of FDD.

5.2.2 Existing buildings with BACnet or LonWorks compatible controller

FDD implementation in buildings that currently have a BACnet or LonWorks-compatible controller is somewhat similar to the implementation within buildings with Niagara AX. The required points are exposed, and are then mapped to a JACE or server running Niagara AX. Once the data are in the Niagara AX environment, installation of the FDD tool depends on whether this is a single or multi-site implementation of FDD.

5.2.3 Existing buildings with legacy controllers

One of the advantages of Tridium is that drivers have been developed that allow communication with a wide variety of legacy controllers. This feature was developed so that a building owner could expand and modify the control of an existing building by utilizing the existing controllers and add new devices that use a more open communications protocol. Niagara provides a single framework and UI that can be used to interact with both the old and new systems.

Implementing FDD in a building with legacy controllers will require installing hardware capable of running the legacy drivers. In some cases, a JACE will suffice, although there are cases where a server will be required. In either case, once Niagara is running with the legacy driver, it can communicate with the legacy controllers and read the required points. As before, once the data are in the Niagara AX environment, installation of the FDD tool depends on whether this is a single or multi-site implementation of FDD.

5.3 Single building implementation

In a single-building implementation, a server running Niagara AX and the FDD tool is located at the building. Ideally, the Niagara AX server running the FDD tool is also being used for all building control. This implementation is probably best suited for large buildings with a full-time building engineer responsible for all phases of building operation and maintenance. It is unlikely that small buildings will be able to justify both a server and a building engineer, so single-building implementations in small buildings will be less practical than in large buildings. However, if reduced data archival is acceptable, then implementing FDD on a JACE in a single building is possible. The amount of data that can be archived depends on the number of systems in the building, the model of JACE that's installed, and the control requirements that the JACE would also be performing.

5.4 Multi-building/site implementation

A multi-building implementation is appropriate when multiple buildings are being managed at a central location. Examples of this include a campus, an HVAC service support center, a real estate management company, or multi-site retail. The requirements for a multi-building implementation include the following:

- JACE at each building running Niagara AX. Each JACE must be set up to archive the required points as histories. This requirement has been discussed in sections 5.1 and 5.2.
- Centrally located server running Niagara AX and the FDD tool. (FDD Server)
- Connectivity for all JACEs and the central FDD server. Internet connectivity is recommended, but dialup is supported by Niagara AX.

One of the advantages of a multi site implementation is that the hardware requirements on each site are minimal. Furthermore, from a management perspective, the results from multiple buildings can be viewed from a single interface. However, communications between the distributed JACEs and the central computer is necessary so that the archives on the central computer are updated on a regular basis.

This is the implementation that is being used for the field testing activities.

6.0 References

[1] 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

[2] 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.

[3] Architectural Energy Corporation, 2005, Deliverable D2.2b – APAR Rules Implementation & Testing

[4] Architectural Energy Corporation, 2005, Deliverable D2.2d – Plant Diagnostics Implementation & Testing

[5] Architectural Energy Corporation, 2005, "Deliverable D2.3b – Final Evaluation of Criteria for Selection Web-enabled FDD System"

7.0 Appendix A AHU diagnostic constants

This appendix provides definitions for the diagnostic constants used for single-duct air handlers, as well as selection guidance.

Name	Description
EconFlagTempOrEnthalpy	Flag to indicate Temperature (1), or Enthalpy (2) economizer.
Units_IP1_SI2	Units flag. Inch-pound (1), or SI (2).
TimeStepInMinutes	Time step in minutes. Default is 5.
Altitude	Elevation of site, in feet.
Uccmin	Minimum (fully closed) position of chilled water coil valve.
Uccmax	Maximum (fully open) position of chilled water coil valve.
Uhcmin	Minimum (fully closed) position of hot water coil valve.
Uhcmax	Maximum (fully open) position of hot water coil valve.
Udmin	Minimum position of outside air damper. Note that "minimum" may be greater than fully closed.
Udmax	Maximum (fully open) position of outside air damper.
epsilon_t	Threshold for temperature calculations. Larger values reduce sensitivity.
epsilon_f	Threshold for outside air calculations. Larger values reduce sensitivity.
epsilon_hc	Threshold for heating coil valve calculations. Larger values reduce sensitivity.
epsilon_cc	Threshold for cooling coil valve calculations. Larger values reduce sensitivity.
epsilon_d	Threshold for outside air damper calculations. Larger values reduce sensitivity.
epsilon_h	Threshold for enthalpy calculations. Larger values reduce sensitivity.
DelTmin	Minimum difference between return and outside air temperatures to allow outside air fraction calculations.
DelTsf	Temperature rise across supply fan.
DelTrf	Temperature rise across return fan.
FanOnThreshold	Used to determine when air handling unit is active. Compare fan status/current/power/fan speed.
ScheduleRuleDelay	Minimum amount of time that a schedule rule must be violated before it is reported.
RuleDelay	Minimum amount of time that a rule must be violated before it is reported.
EvalRulesDelay	Minimum amount of time that system must operate before rules will be evaluated.
Qoa_frac_min	Minimum outside air fraction.

Default values are provided for all of the diagnostic constants. However, the following list of constants will probably need to be altered from the default, depending on the max-min positions of the valves and dampers, and the type of datastream being used to indicate when the system is operating.

- Altitude
- Uccmin
- Uccmax
- Uhcmin
- Uhcmax
- Udmin
- Udmax
- FanOnThreshold
- Qoa_frac_min

The default values for the following constants should not be changed without a good understanding of their effect. Changing these values could significantly alter the performance of the FDD engine.

- epsilon_t
- epsilon_f
- epsilon_hc
- epsilon_cc
- epsilon_d
- epsilon_h
- DelTmin

Decreasing the time delays will increase the number of reported faults, and may result in false positives – incorrect results. Use the default values for the following constants unless there is good reason to change them.

- ScheduleRuleDelay
- RuleDelay
- EvalRulesDelay

The temperature rise across the supply and return fans may be different than the default. If the mixed, supply, and return temperature measurements are accurate, then the following constants may be changed to reflect the actual temperature rise across the fans. However, since the FDD tool will indicate potential sensor calibration problems, it is important to verify the accuracy of these sensors.

- DelTsf
- DelTrf