

**Advanced Automated HVAC Fault  
Detection and Diagnostics  
Commercialization Program**

**Final Product Implementation Report**

**CONSULTANT REPORT**

*Prepared For:*

**California Energy Commission**  
Public Interest Energy Research Program

*Prepared By:*

**Field Diagnostic Services, Inc.**



Arnold Schwarzenegger, *Governor*

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## 1.0 Executive Summary

This “Final Product Implementation Report D5.8c” (Task 5.8) documents the final design for the rooftop HVAC Fault Detection and Diagnostics (FDD) monitoring system now referred to as the Sentinel system. The test plans for this product implementation will be covered in separate documents, “FDD Test Plan Report, D5.8a,” and “FDD Final Production Readiness Plan, D5.11b.”

The Sentinel is an embedded diagnostic system for HVAC units that can detect, diagnose and report a defined list of abrupt failures, refrigeration cycle degradation faults, and control faults. In addition, the Sentinel can report on the health of the monitoring system itself, and can provide real-time or near real-time sensor data (the latter feature depends upon the communications option selected by the customer). The system is composed of on-site components (e.g., on the rooftop), communications, and a centralized database/Web site component. Customers or monitoring facility personnel can access the Web site to view summary statistics and charts depicting site and unit performance. In addition, a technician on the rooftop with a PDA can view real-time data using a standard browser, or can run diagnostic tests as well, using software designed for the Palm PDA.

This implementation of the Sentinel is based on the results of the prototype phase, including feedback from customers and potential customers. In contrast to the prototype version, the major differences in this implementation are: a local on-site processor module is included (which has a number of advantages); the modules are physically smaller; fewer sensors are involved; the communication between the modules at each unit and the local on-site processor utilizes a different wireless technology; the diagnostic alarms are presented somewhat differently on the Web site; and on-site technicians can use a PDA to read real-time data.

## 2.0 Introduction

This document describes the final product implementation of the Rooftop Unit Fault Detection and Diagnostics (FDD) System, as defined by Task 5.8. The scope of Task 5.8 was defined as:

Finalize the product specification, and implement the product on Honeywell's preferred platform for light commercial customers. (For the purposes of this project, "Honeywell's preferred platform" has been defined to be FDSI's FDD monitoring system.)

When this task was originally written, the assumption was that the final product specification would define the replacement for the modified version of FDSI's Virtual Mechanic (VM) FDD monitoring system that would be in use during most of this project's lifespan. However, the VM system was replaced early in the project by a monitoring system based on the use of Point Six wireless data collection/communications modules. The Point Six-based system was a temporary stage (although it lasted two years) between the old VM system and the final product implementation now known as the Sentinel. In addition, the Sentinel itself has gone through an initial prototype stage prior to this final product specification.

Also, when this task was originally written, the assumption was that the field-testing of the final product implementation would take place at two groups of then-existing customer sites (McDonalds and Walgreens). However, for several reasons, these sites became increasingly less suitable for project participation, and were replaced by other sites (including three universities in California, a Honeywell location in Georgia, and a retail location near FDSI's offices in Pennsylvania).

A major goal of the final product design is to respond to problems and concerns that surfaced during this project. Specific objectives of the new design are:

- Reduced physical size of the modules
- Reduced installation complexity and cost
- Overall reduced cost of the Sentinel hardware
- Improved communications between the sensors and the data collection module
- Reduced data transmissions to the server (e.g., using on-site processing)
- Options for viewing real-time data on-site, and running diagnostics, using a PDA.
- Better presentation of the diagnostic information on the Web site.

### 3.0 Product Overview

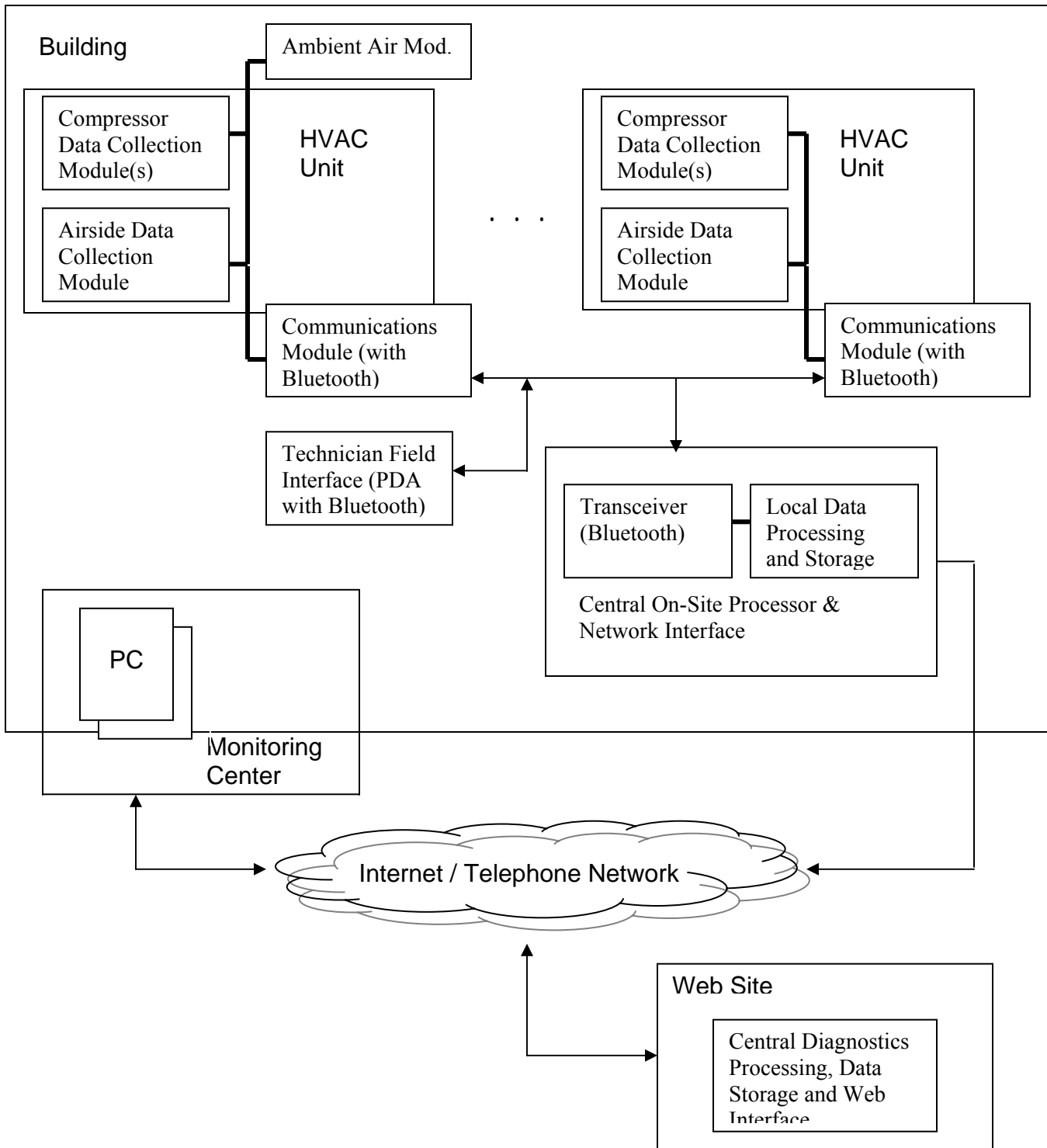
The final product implementation, the Sentinel, is an embedded diagnostic system for HVAC units that can detect, diagnose and report a defined list of abrupt failures, refrigeration cycle degradation faults, and control faults. The system is composed of on-site components (e.g., on the rooftop), communications, and a centralized database/Web site component.

Figure 1 presents an overview of a basic Sentinel system configuration.

Beyond the basic configuration, the system has been designed to accommodate more complex arrangements. For example, depending upon the physical layout of a site and the location and number of HVAC units, there can be data collection modules from more than one HVAC unit wired to a single communications module, or the data collection modules for a single HVAC system can be connected to two communications modules (e.g., for a split system). Also, depending upon the site, the on-site processor can be located on the rooftop, where it may or may not be wired directly to a communications module. Alternatively, the on-site processor can be located within the building, using Bluetooth to communicate with the rooftop modules, or if that is not possible it could be connected by wire to the rooftop. In other words, a variety of custom configurations are possible.

The Sentinel is suitable for:

- Packaged unitary HVAC units – any make or model
- Cooling-only or heat pump
- Air-cooled condensers
- Direct expansion (DX) evaporator coils
- Fixed orifice or TxV metering devices
- HVAC units with one to four refrigeration cycle circuits per unit



**Figure 1. Basic Sentinel System Configuration**

Notes:

1. The indoor airside module is contained within a cylindrical temperature probe, with a supply air sensor probe external to the indoor airside probe.
2. The communications module is mounted on the exterior of the HVAC unit.
3. The ambient air module is outside the HVAC unit and there is only one ambient air module per site.

The following is a summary of the conditions covered by the Sentinel diagnostics processing:

Refrigeration cycle cooling abrupt faults:

(These are detected by diagnostic processing on the on-site processor.)

- Failed indoor fan (motor or belt problem)
- Failed outdoor fan (motor or belt problem)

Refrigeration cycle cooling degradation faults:

(These are detected by diagnostic processing on the Web server.)

- Indoor coil heat transfer problem
- Outdoor coil heat transfer problem
- Low or high refrigerant charge
- Liquid line restriction
- Inefficient compressor
- Non-condensable gas in refrigerant
- Extreme readings associated with premature equipment failure  
(This latter category covers extremely high superheat, or extremely low superheat, or extremely high condenser over ambient, or extremely low evaporating temperature, where none of the other abrupt or degradation faults has been triggered.)

Control faults:

(These are detected by diagnostic processing on the Web server.)

- Compressor short cycling
- Mechanical cooling when unit should be economizing

Other Measurements:

(These are evaluated by diagnostic processing on the Web server.)

- Refrigeration cycle cooling efficiency and capacity assessed on an on-going basis
- Identification of conditions when cooling capacity cannot meet load
- Monitoring system self-diagnostics to detect inconsistent measurements and sensor failures

This is a reduced set of features resulting from the effort to reduce costs in order to produce a more marketable product. Additional features associated with economizer and control

diagnostics (as discussed in an earlier project document, "FDD Final Report 5.4d," September 2005) will be included in future module development.

## 4.0 On-Site Components

The basic Sentinel configuration consists of three individual types of modules for each HVAC unit (connected via a communications bus wire), one ambient air module per site, and one central on-site processor, as follows:

- One or more compressor modules per HVAC unit (one for each circuit).
- One indoor airside module (housed within a cylindrical probe) per HVAC unit. A second probe, the supply air temperature sensor, is wired to the indoor airside module.
- One communications module per HVAC unit. This module communicates wirelessly to an on-site Linux-based processor.
- One ambient air module per site.
- One central on-site Linux processor per site, with local storage. The processor includes the network interface, which in turn supports the connection to a Web-based server via the Internet, either directly or via the telephone network.

### 4.1. Compressor Modules

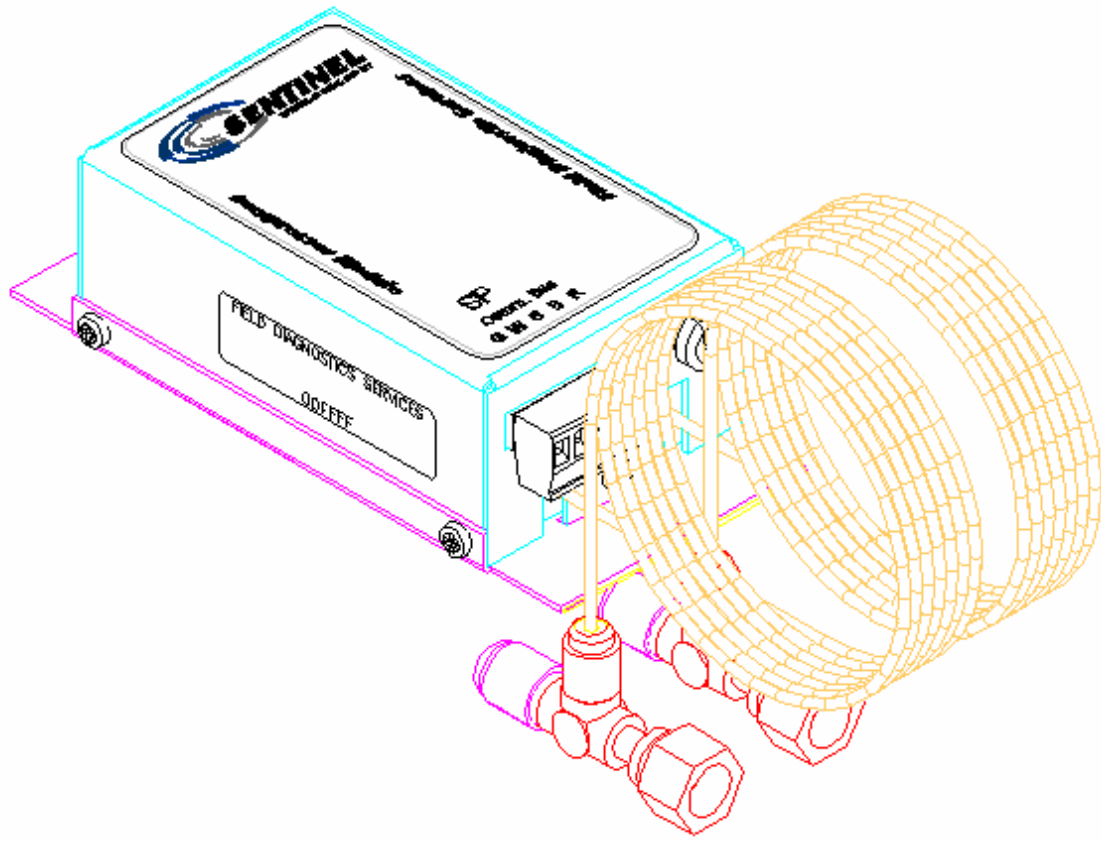
The compressor module (Figure 2) measures the refrigeration system temperatures and pressures (liquid temperature, suction temperature, suction pressure, and liquid pressure/discharge pressure). These measurements provide the core data to assess refrigeration cycle performance. The module has a small amount of memory available for sensor data to store 20 to 30 sets of data; if the data is collected at 15 second intervals, this will allow up to 7 minutes worth of data to be buffered between 'read' requests from the on-site processor.

There is one compressor module per circuit (for up to a maximum of 4 circuits per HVAC unit). The module will be mounted in the compressor compartment, and is compatible with common refrigerants.

### 4.2. Airside Module

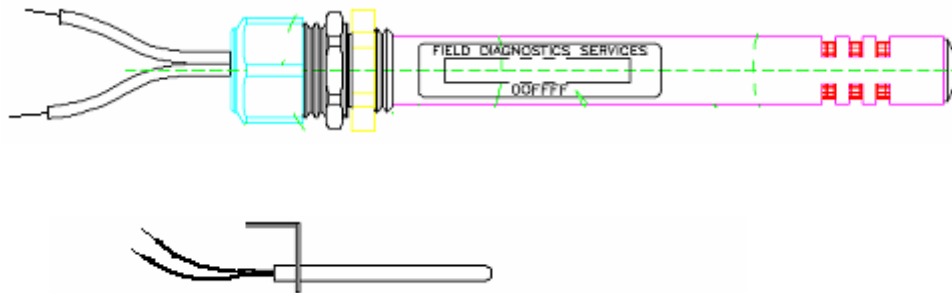
The indoor airside module measures return air temperature, return air relative humidity, and supply air temperature. There is one module per HVAC unit. The electronic components are contained within a cylindrical sensor device (Figure 3) except for the supply air sensor, which is remotely mounted and connected by wire to the indoor airside module.

There is no memory within the airside module for sensor data storage, which means no data buffering. Sensor data is acquired dynamically at the time the on-site processor requests it, and the timing could be affected by the total number of modules to be polled.



**Figure 2. Compressor Module.**

Size is approximately 1.5 in. x 2.5 in. x 4 in. (excluding tubing and refrigerant line fittings).



**Figure 3. Airside Module with Supply Air Probe.**

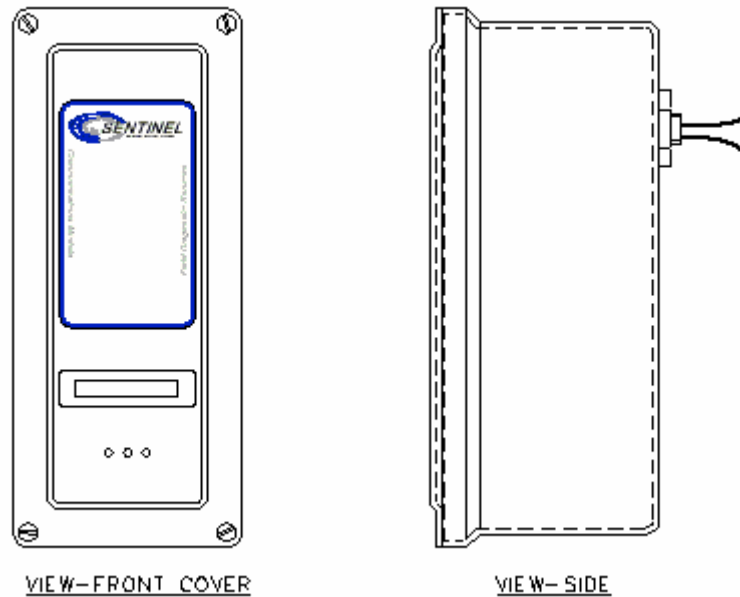
Airside probe length is approximately 6.5 in.; supply air probe length is 2 in.

### 4.3. Communications Module

The communications module (Figure 4) is a bi-directional wireless communication bridge between each individual HVAC unit and the central on-site processor. A 24VAC power supply is also incorporated within this module to supply 5VDC to the compressor and airside modules.

The communications link between this module and the modules inside the HVAC unit (the compressor module(s) and the airside module) is the communications bus wire.

For the communications link between this module and the central on-site processor, the module contains one Class 1 Bluetooth transceiver capable of transmitting and receiving data up to 100 meters. The module is mounted on the outside of the HVAC unit to maximize the range of the Bluetooth signal, and wiring from the module will pass into the HVAC unit via a conduit connector.



**Figure 4. Communications Module.**

Size is approximately 4 in. x 4 in. x 9 in.

The module housing is fiberglass-reinforced polyester, and the Bluetooth antenna (for communication with the on-site processor) is located within the module.

## 4.4. Ambient Air Module

There is normally one ambient air module per site, to measure outdoor ambient air temperature and humidity. This module contains an off-the-shelf housing (Figure 5), and the same temperature and humidity sensors as in the airside module.



**Figure 5. Ambient Air Module**

Size is approximately 5 in. wide by 10 in. high.

In the previous version of the Sentinel, the ambient air sensor was located under the economizer hood, but this led to problems, especially given the desire to limit the number of ambient air sensors per site. For example, an unshaded economizer hood facing south tended to produce warmer temperatures (by 10 degrees or so) than economizer hoods not in direct sunlight; furthermore, the economizer hood acts like an oven when the indoor fan is off or the economizer is closed or barely open. If there is only one ambient air sensor per site, and it is under the economizer hood of a unit that is off, the ambient temperature and humidity readings may not be correct for the other units at the site. For these and related reasons, some additional experimentation may be done during the pilot phase to gather more data with respect to the location and number of ambient air sensors.

In a normal installation, the ambient air module will be installed on the outside of an HVAC unit (or close to it), and wired to the communications bus for that HVAC unit. In some situations, though, it might be advisable to install the ambient module elsewhere, and if necessary provide it with its own communications module.

There is no memory within the ambient module for sensor data storage, which means that there is no data buffering. Sensor data is acquired dynamically at the time the on-site processor requests it via the communications module.

## 4.5. Central On-Site Processor and Network Interface

The on-site processor collects data from all the communications modules (which transmit data from the other modules) and analyzes the data in near-real time to detect any abrupt faults, as well as processing raw data for efficient data transfer. A certain amount of data is temporarily stored locally. The processor module also runs a local Web server to support the technician's field interface (see Section 4.7). The design of the processor module includes the ability to remotely manage and upgrade software. For Internet connectivity, the module incorporates a network interface providing a network connection between the site and the Web-based server, via the Internet, through one of these means:

- Serial modem or Bluetooth modem connected to analog phone line
- Wired Ethernet
- WiFi
- Bluetooth access point
- Cellular Internet connection

The central on-site processor incorporates a PC-104 single board PC with an AMD Elan 520 (133 MHz) processor running the Linux operating system, and a 1 Gigabyte compact flash card. It is also possible that for installations where the processor is indoors, the processor could be a low-cost off-the-shelf computer rather than a custom-built computer in a weather-tight box. The amount of local sensor data storage that will be possible is still being determined, but 1 Gigabyte should provide substantial storage.

## 4.6. Sensors

The sensors are listed in the following table.

**Table 1. Sentinel Sensors**

Sensor	Module	Notes
Liquid Temperature (LT)	Compressor Module	One per circuit (stage)
Suction Temperature (ST)		
Suction Pressure (SP)		
Liquid Pressure/Discharge Pressure (LP/DP)		
Return Air Temperature (RAT)	Airside Module	One per HVAC unit
Return Air Relative Humidity (RAH)		
Supply Air Temperature (SAT)		
Outdoor Air Temperature (OAT)	Ambient Air Module	One per site (under some conditions, more than one per site might be necessary)
Outdoor Air Relative Humidity (OAH)		

In Table 2, the nominal operating ranges and accuracies are listed for each sensor. These are the manufacturer’s ratings, based on the sensors currently specified in the design documents. In practice, lookup tables that are defined in the software governing a given sensor may tighten or expand the stated operating ranges. In the current design, to simplify production, the outdoor air temperature sensor is the same model as the one used for the return air temperature, and the stated low end is 32 °F. However, the actual low end is substantially below -20 °F.

**Table 2. Nominal Operating Ranges and Accuracies**

<b>Sensor</b>	<b>Nominal Operating Range</b>	<b>Nominal Accuracy</b>
Liquid Temperature (LT)	-58 °F to 257 °F	+/- 1% of 10k ohms at 77 °F
Suction Temperature (ST)	-58 °F to 257 °F	+/- 1% of 10k ohms at 77 °F
Suction Pressure (SP)	0 to 200 psi; -40 °F to 257 °F	+/- 0.25% FS BFSL
Liquid Pressure (LP) / Discharge Pressure (DP)	0 to 500 psi; -40 °F to 257 °F	+/- 0.25% FS BFSL
Return Air Temperature (RAT)	32 °F to 122 °F	+/- 0.4 °F
Return Air Relative Humidity (RAH)	0% to 100% RH; -40 °F to 185 °F	+/- 3.5% RH (BFSL)
Supply Air Temperature (SAT)	-40 °F to 221 °F	+/- 0.4 °F
Outdoor Air Temperature (OAT)	32 °F to 122 °F	+/- 0.4 °F
Outdoor Air Relative Humidity (OAH)	0% to 100% RH; -40 °F to 185 °F	+/- 3.5% RH (BFSL)

## **4.7. Technician’s Field Interface**

Two separate methods are being prepared for on-site technicians to view real-time data from individual HVAC units. The first method is based on the Service Assistant software—the Service Assistant is FDSI’s portable hand-held device, including software on a Palm platform, to provide fault detection and real-time diagnostics for technicians servicing HVAC units. The second method allows the use of a standard PDA browser to view real-time data but does not include any diagnostic capability.

### **4.7.1. Service Assistant PDA Software**

A version of the Service Assistant software, which runs on a Palm PDA, is being developed to serve two purposes with respect to the Sentinel. The Palm PDA will connect via Bluetooth to the communications module of an individual HVAC unit, and will be used to:

- install and commission a Sentinel site
- view sensor values and run diagnostics during, and at any time after, installation.

When the Sentinel modules are first physically installed on an HVAC unit, the Palm PDA will be used to commission the unit. At this time, it is necessary to capture the Bluetooth addresses and module serial numbers for all modules, and to associate each module with the HVAC unit that it is attached to. For compressors with more than one circuit, the compressor module has to be further identified as to the circuit that it is attached to. In addition, other information about each HVAC unit (e.g., its name, type, manufacturer, refrigerant type, and the like) can be captured as well. Alternatively, some of the static information might already be available on the central Web server and can be downloaded from there prior to beginning installation.

After all the static information about the HVAC unit (as well as the site information) is collected on the Palm, then the Service Assistant software can be run to collect sensor data (via Bluetooth) and run diagnostics (assuming the Sentinel hardware is already installed), just as if the Palm were connected to the Service Assistant tool itself and the hoses and sensors from the tool were physically connected to the HVAC unit. This will help the installer to detect if anything has been installed incorrectly, e.g., when inconsistent or unreasonable sensor values are reported.

After the Sentinel modules are installed, the Palm PDA with the modified Service Assistant software will be used to connect to the Internet and upload all the configuration information to the central Web server, using the same connection options as currently available in the Service Assistant. This is a necessary step prior to getting the on-site processor up and running, because the processor will get the site and unit configuration information from the Web server.

The Palm PDA will also be used by the installer to configure the on-site processor such that it will be able to make its initial connection to the central Web server.

As noted above, at any subsequent time, a technician with a Palm PDA and the modified Service Assistant software will be able to visit the rooftop, connect to an individual HVAC unit (via Bluetooth), collect Sentinel sensor data, and run all the diagnostics supported by the Service Assistant without any of the hoses and sensors associated with the Service Assistant tool.

#### **4.7.2. Browser**

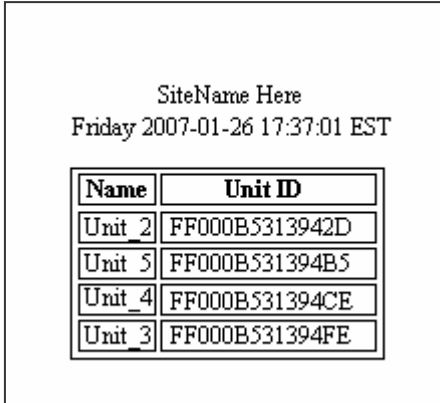
A technician with a PDA (or a laptop or PC)—with a Web browser—can view the raw data coming from the sensors attached to the HVAC units at that site, as well as viewing calculated values derived from the raw data, given an appropriate communications link. If the on-site processor is connected to a LAN, then any PC or PDA that can connect to the LAN can use a browser to view sensor data and calculated values for any of the HVAC units. This capability is based on the fact that a local Apache Web server is running on the on-site processor.

In order to use a PDA to read the sensor data, a communications link must be established between the PDA and the Web server in the on-site processor. Options under consideration include Bluetooth, WiFi, serial cable, and LAN. Each of the options has disadvantages. For the Bluetooth connection, the disadvantage is the fact that the technician must be within Bluetooth range of the on-site processor. (A side issue is that the Bluetooth component in the on-site processor will have to be one that permits multiple connections and will accept the PDA's connection request; a suitable Bluetooth component has not yet been selected.) The disadvantage for a WiFi connection is the fact that the PDA will have to be set up to make the WiFi connection, i.e., the technician will have to know the setup parameters, and how to enter them into the PDA, in order to establish the connection. The disadvantage of the serial connection is the fact that the technician would be physically tethered to the on-site processor while getting the data. The disadvantage of a LAN connection, assuming the site allows the on-site processor to be connected to the LAN, is setting up the PDA so that it can connect to the LAN to see the Web server running on the on-site processor.

In any event, as part of the process of establishing the connection, there will be a level of security to prevent unauthorized access to the Web server running on the on-site processor.

To use this interface, given the establishment of the communications link, the technician opens a Web browser and enters the IP address of the local server running on the on-site processor. A CGI program on the on-site processor reads and interprets the sensor data file containing the sensor data and displays the most recent readings. The interpretation and display is based on editable configuration files to provide the maximum flexibility in accommodating different configurations.

The first PDA screen lists all the units at the site, as shown in Figure 6.



The screenshot shows a text-based interface. At the top, it displays "SiteName Here" and "Friday 2007-01-26 17:37:01 EST". Below this is a table with two columns: "Name" and "Unit ID". The table lists four units: Unit\_2, Unit\_5, Unit\_4, and Unit\_3, each with a corresponding hexadecimal Unit ID.

Name	Unit ID
Unit_2	FF000B5313942D
Unit_5	FF000B531394B5
Unit_4	FF000B531394CE
Unit_3	FF000B531394FE

**Figure 6. Technician's Interface, Screen A**

To see more detail for each unit, the technician taps on an HVAC unit name or unit ID (the final four characters of the unit ID number are printed on a label on the outside of the communications module attached to each HVAC unit).

The second screen is a vertically scrollable page containing at least three tables. The number of tables depends upon the number of circuits, and up to four circuits can be accommodated. The tables are shown in Figure 7. The “Circuit 1” data corresponds to the first compressor module.

SiteName Here – Unit 2				
Friday 2007-01-26 17:38:25 EST				
Circuit 1				
Sensor	Value	Age	Calc	Value
SP	0.8 psig	57	ET	-- F
DP	2.1 psig	57	CT	-- F
ST	75.2 F	57	SH	-- F
LT	74.9 F	57	SC	-- F
Air Side				
Sensor	Value	Age	Calc	Value
RAT	75.0 F	57		-- F
RAH	11.4 %	57	RAWB	50.2 F
SAT	78.4 F	57		-- F
OAT	-- F	--		-- F
OAH	-- %	--	OAWB	-- F
Configuration				
<b>Type</b>	Package Cool			
<b>Stages</b>	1			
<b>Refrigerant</b>	R22			
<b>Altitude</b>	400			

**Figure 7. Technician’s Interface, Screen B**

The ‘Value’ column to the right of the ‘Sensor’ column shows the data from the sensors. The ‘Value’ column to the right of the ‘Calc’ column shows calculated values. The ‘Age’ column shows the time since the last reading, in seconds. The calculated values

are determined dynamically as the CGI program reading the sensor data file calls a routine to calculate a given value.

In the example shown, there are some cases where the display for either the sensor reading or the calculated result contains two dashes instead of a number. For sensor data, it indicates that either the sensor is not present, or could not supply data. The above example was taken from a lab prototype that did not have the sensors for outdoor air temperature and outdoor air humidity. For calculated values, two dashes can mean the software was unable to calculate a value, or the software routine for that calculated value was not present. Again, the above example was based on a lab prototype in which most of the add-on modules had not been implemented yet.

## **5.0 Data Processing and Diagnostics**

The data processing approach was developed in conjunction with the system hardware design. The system hardware configuration includes local and central data processing and storage locations. Multiple data collection modules (with associated sensors) are located at each HVAC unit at a building. The modules for a given unit are wired to a communications module. The communications module at each HVAC unit wirelessly transmits time-based data to the on-site processor, where the data are processed, stored locally as necessary, and then periodically transmitted to a central server for further diagnostic processing.

### **5.1. Hybrid Data Processing Approach**

A hybrid data processing and storage approach has been developed that customizes the data processing for the FDD application. The approach provides an efficient method for collecting, processing, and storing data that allows identification of faults as well as evaluation of system performance.

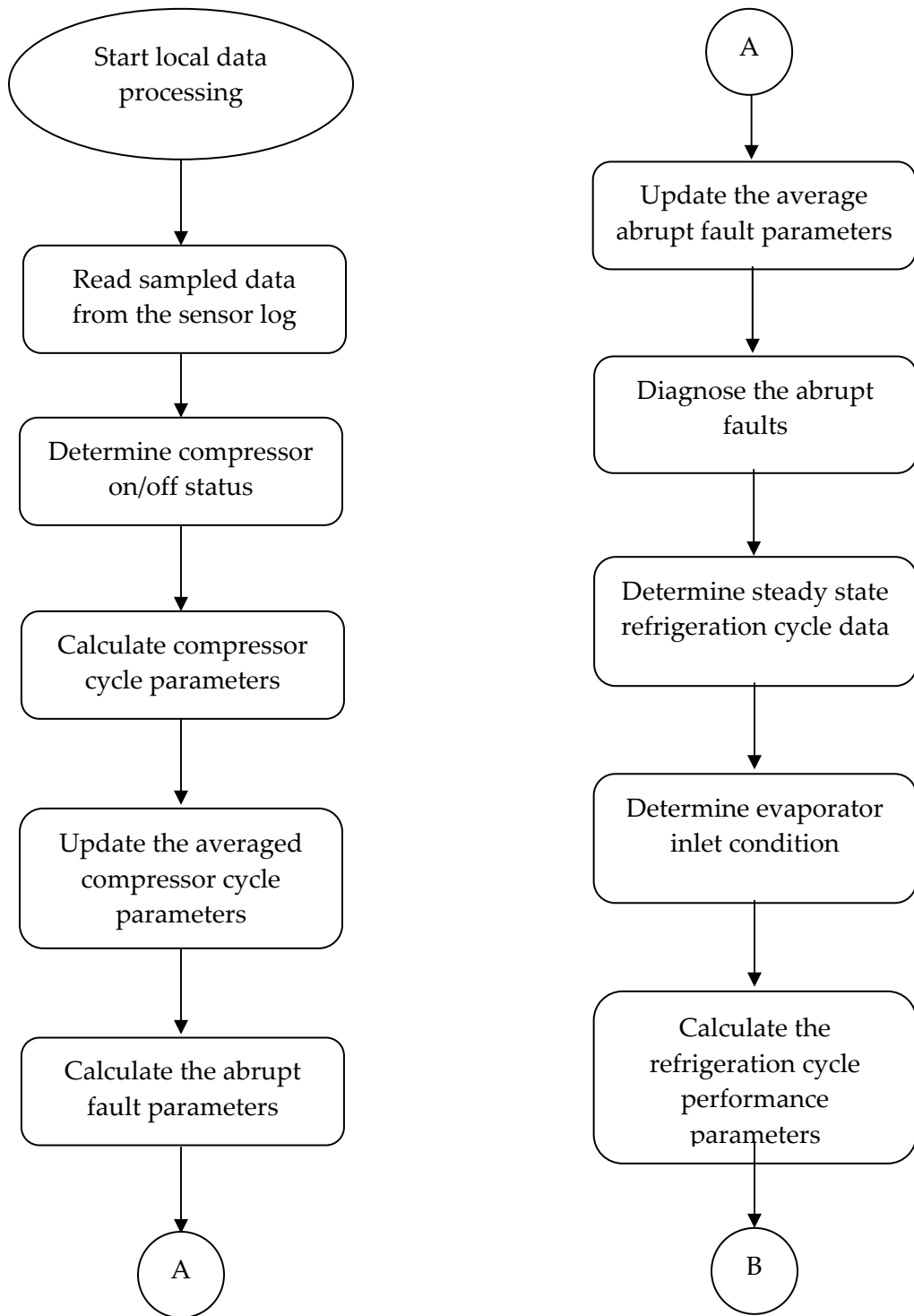
This method of employing both local and centralized processing was developed to limit the memory requirements for the data collection hardware at the monitoring site while at the same time retaining the required information to identify faults and evaluate system performance. The approach also limits the requirements for data transmission from the local site to the central data storage location for installations where there is no constant Internet connection between the sites and the central Web-based server.

#### **5.1.1. Local Data Processing**

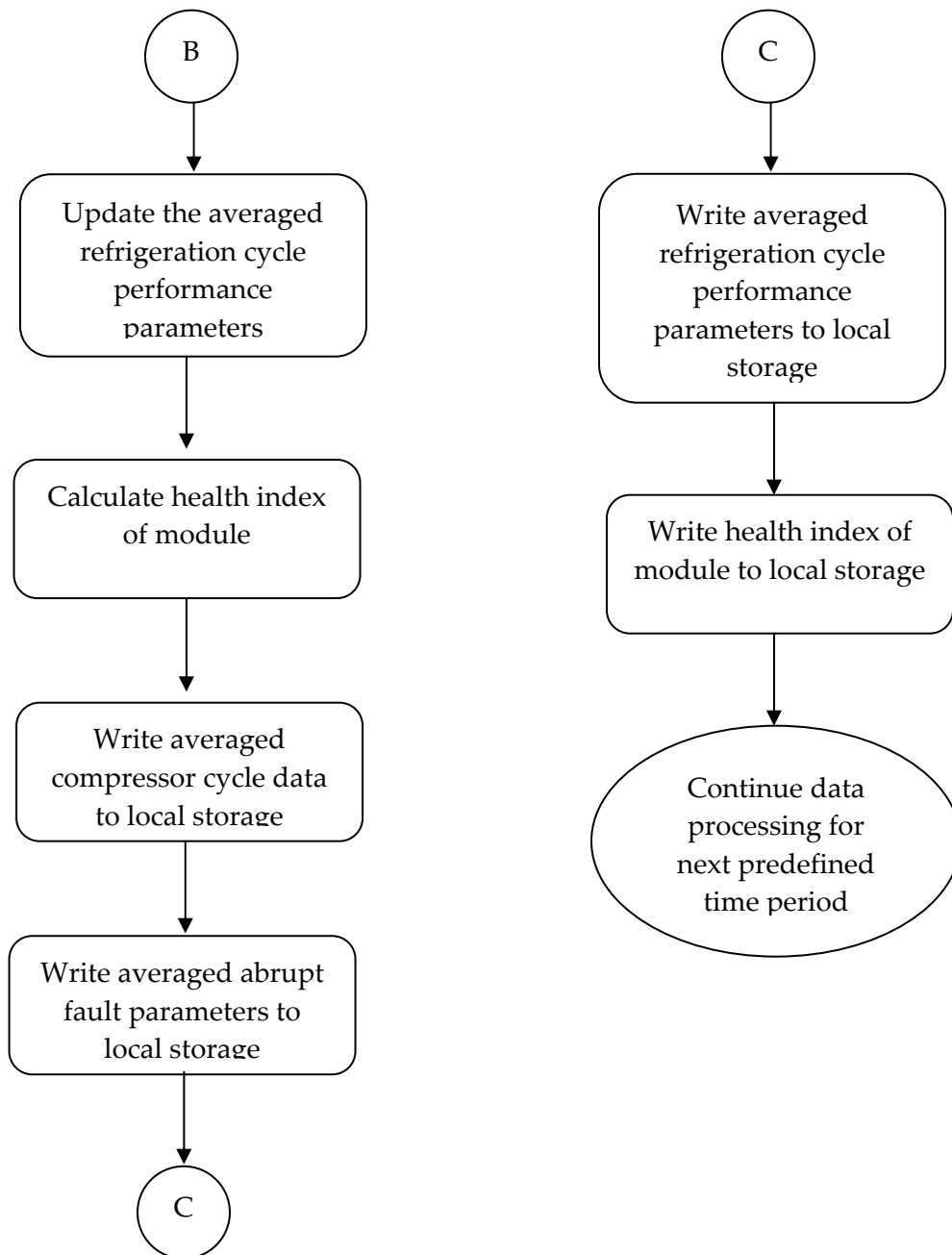
The flowcharts presented on the following pages (Figure 8 and Figure 9) outline the distributed (local) data processing that will be implemented in the hardware located at the monitored site. Local processing is done to detect abrupt failures and to condense all raw data in order to reduce memory and data transmission requirements while retaining important relationships between parameters.

#### **5.1.2. Central Data Processing**

Central data processing includes calculation of additional performance indices, implementation of FDD algorithms, calculation of economic parameters for identified faults, and data processing associated with generating plots. Further discussion of the data processing is provided in previous project documents (“FDD Final Report D5.4d”, September 2005; “FDD Final Report D5.6a”, September 2006; “FDD Final Report D5.6b”, January 2007).



**Figure 8. Local Data Processing Flowchart A**



**Figure 9. Local Data Processing Flowchart B**

### **5.1.3. Raw Sensor Data**

In response to customer requests during the course of this project to see the raw sensor data, the new design will provide a certain amount of raw data for display via the Web site, as long as the customer has selected an appropriate communications option. For example, a near-real-time display of raw data every 15 seconds can be provided if there is a constant communications link of sufficient bandwidth (e.g., a live high-speed Internet connection, or a dedicated phone line). At a less detailed level, the raw data for the previous 24 to 72 hours (from the present time) could be displayed based on 10- or 15-minute intervals.

In addition, as described in Section 4.7, a technician with a Palm PDA will be able to see raw data for a given unit either by connecting to the local Web server running on the on-site processor (and using a browser to view the Web pages), or by connecting (wirelessly via Bluetooth) to a given HVAC unit (and using a version of the Service Assistant software). If the on-site processor is connected to a LAN, any PC or PDA that can connect to the LAN can use a browser to view sensor data and calculated values.

## **5.2. Diagnostics**

The Sentinel fault diagnostics algorithms have the ability to diagnose abrupt equipment failures, refrigeration cycle degradation faults, and control related faults. In addition, the algorithms can track the monitoring system self-diagnostics.

### **5.2.1. Refrigeration Cycle Cooling Abrupt Faults**

The detection and diagnosis of abrupt equipment failures is conducted at the local site based on real-time sensor data. The abrupt equipment failures occur in a short period of time with significant variations in the performance parameters. The diagnostic algorithms can detect the following abrupt equipment failures during cooling operation:

- Failed indoor fan (motor or belt)
- Failed outdoor fan (motor or belt)

When an abrupt equipment failure occurs and is detected by the monitoring system, a notification will be sent out immediately (if the customer has selected a communications option that supports an immediate transmission) to the central Web site, where the notification will then be sent out to the customer or to a designated maintenance facility.

### **5.2.2. Refrigeration Cycle Cooling Degradation Faults**

The detection and diagnosis of refrigeration cycle degradation faults is conducted at the central server. The diagnostics algorithm runs once per day on the central server to update the alarm information and the performance information of each HVAC unit.

To detect and diagnose the cooling degradation faults, the diagnostics algorithm uses the following unit performance data: evaporating temperature (ET), suction line superheat (SH), condensing temperature over ambient (COA), and liquid line subcooling (SC). The daily steady state unit performance data are analyzed and the actual performance data and the expected performance data are compared. The residuals of the performance data are fed into a fault detector to determine whether the unit operates within the normal operating region. If the unit does not operate in the normal operating region, the residuals of the performance data are fed into a fault classifier to diagnose the fault.

The diagnostics algorithm can identify the following refrigeration cycle degradation faults during cooling operation:

- Indoor coil heat transfer problem
- Outdoor coil heat transfer problem
- Low or high refrigerant charge
- Liquid line restriction
- Inefficient compressor
- Non-condensable gas in refrigerant

When a refrigeration cycle fault is identified, the fault is categorized into the following categories based on the impact of the fault on the system operation:

- Comfort
- Equipment safety
- Economics

### **5.2.3. Control Faults**

The algorithms can diagnose the following control related faults:

- Compressor short cycling
- Mechanical cooling when unit should be economizing

The diagnostics rules for the above control faults are shown in Table 3.

**Table 3. Control Fault Diagnostics**

<b>Fault Name</b>	<b>Basic Fault Criteria</b>	<b>Occurrence Criteria</b>	<b>Possible Causes</b>
Mechanical cooling at low outdoor air temperature	Mechanical cooling =on and OAT < 50°F	10 minutes in 24h period	Controls setup or economizer problem
Short off-time for compressor	Off-time < 5 minutes and (mechanical cooling or HP heating)	10 occurrences in 24h period	Controls problem
Short on-time for compressor	On-time < 5 minutes and (mechanical cooling or HP heating)	10 occurrences in 24h period	Controls problem

#### **5.2.4. Monitoring System Self-Diagnostics**

The Sentinel fault diagnostics algorithms can track the health of the monitoring system itself and diagnose sensor faults. The algorithm tracks the following monitoring system health information:

- Time stamp of the last data record received
- Health index of the data acquisition module
- The total daily records received from the module

The health index of the module (HIM) is defined as:

$$HIM = \frac{1}{N} \sum^N HIS$$

Where,

$$HIS \text{ (Health Index of Sensor)} = \frac{Rec_{val}}{Rec_{tot}}$$

N: number of sensors for the module

Rec<sub>val</sub> : number of valid sensor data records

Rec<sub>tot</sub> : number of total sensor data records

Based on the health information of the monitoring system, the status of the monitoring system health can be defined as:

- OK
- Alert
- Alarm

The health index threshold levels associated with each of the above status categories are still being discussed.

The algorithm also diagnoses the following out-of-range sensor faults and inconsistent data faults:

#### Out of Range Faults

- $RAT < 65\text{ F}$  or  $RAT > 85\text{ F}$
- $OAT > 125\text{ F}$  or  $OAT < -15\text{ F}$
- $MAT > OAT$  and  $MAT > RAT$ , or  $MAT < OAT$  and  $MAT < RAT$
- $SAT > 130\text{ F}$  or  $SAT < 40\text{ F}$
- $OAH > 100\%$  or  $OAH < 15\%$
- $RAH > 70\%$  or  $RAH < 15\%$

#### Inconsistent Data Faults

- RAT Sensor or SP Sensor Problem ( $ET > RAT$  and cooling operation)
- RAT Sensor or LP Sensor Problem ( $CT < RAT$  and heating operation)
- OAT Sensor or LP Sensor Problem ( $CT < OAT$  and cooling operation)
- OAT Sensor or SP Sensor Problem ( $ET > OAT$  and heating operation)
- LT Sensor or LP Sensor Problem ( $LT < CT$ )
- ST Sensor or SP Sensor Problem ( $ST < ET$ )

### **5.2.5. Performance Indices**

In addition to the fault diagnostics, the algorithms can evaluate the mechanical cooling runtime statistics and mechanical cooling efficiency index and capacity index. Based on the mechanical cooling efficiency index and capacity index, the annual energy saving potential associated with refrigeration cycle faults is estimated (see "FDD Final Report D5.4d", September 2005).

## 6.0 Web User Interface

The Sentinel Web site provides summary graphics, charts, email alerts and Web-based reports to help customers better manage HVAC equipment service and maintenance, with the goals of improving HVAC performance and reducing energy consumption. On the Web site, customers can view charts supporting the diagnostics based on daily averages, up to midnight of the previous day. Depending upon the communications option chosen, abrupt faults and current sensor data may also be displayed.

The Sentinel Web site is being reviewed for possible revisions, so the final details are not available yet. Nevertheless, the basics of the Web site will remain the same as, or very similar to, the descriptions provided below.

### 6.1. Summary Display and Performance Categories

A graphic 'dashboard' approach is used to provide a visual overview of the status at a given site or collection of sites. The final graphic method to be used for the dashboard is still under discussion. Currently, a pie chart is used but this may be changed.

In order to give customers a quick way to assess the situation, color-coding is used to convey the status of each unit. There are six color categories, in decreasing order of importance, as listed in the following table. (At present, the use of black for loss of communication, and green for 'all okay,' are still under consideration and they have not yet been implemented.)

**Table 4. Status Color Codes**

Priority	Condition	Color Code
1	Loss of communication with unit	Black
2	Comfort Affected	Red
3	Equipment Maintenance Needed	Orange
4	Energy Savings Opportunity	Yellow
5	Monitoring System Inconsistency	Blue
6	All Okay	Green

The categories are calculated dynamically based upon the impact on comfort, equipment condition, and potential energy savings. For each triggered refrigeration cycle alarm, the following values are calculated:

- Capacity Index (CI),
- Superheat (SH) and SH residual,
- Condensing temperature over ambient (COA) and COA residual,

- Evaporating temperature (ET), and
- Efficiency index (EI).

If CI is less than 50%, then the alarm is categorized as a comfort problem. Otherwise, if SH residual  $< 0$  °F or SH residual  $> 15$  °F or COA residual  $> 15$  °F, the alarm is categorized as an equipment safety or maintenance issue. If none of the preceding apply and EI  $< 90\%$ , then the alarm is categorized as an energy savings opportunity.

A monitoring system 'health' status indicator is also planned, indicating whether the communications link is working or not between the Web site and the HVAC units, and whether the data values seem reasonable.

## **6.2. Fault Explanation and Trend Charts**

For each monitored HVAC unit, in addition to static unit information, the Web site provides summary and detailed information in the form of tables and charts. The summary information includes the following performance charts:

- Mechanical Cooling Efficiency Index Trend Graph
- Mechanical Cooling Runtime Fraction Trend Graph
- Refrigeration Cycle Performance Indices Graph

Detailed information is provided for each fault detected, showing the trigger date, the most recent date the same fault was observed, an explanation of the fault, and suggestions for possible causes and possible impacts. In addition, customers can view a trend plot for the fault and dynamically change the time period for the chart.

## **6.3. Notification Options and Response Tracking**

An email option is available so that when a fault is detected and an alarm triggered, an email can be automatically sent to a customer's email address. Optionally, the category of the alarm can be used to determine to whom the email is sent, and an embedded link can be provided in the email to give the customer a quick link to the pertinent data on the Web site.

The alarm notification and response feature includes four states, or status levels. The possible status values are shown in the following table.

**Table 5. Alarm Status Values**

<b>Alarm Status</b>	<b>Time Period</b>	<b>Action</b>
New	Alarm triggered	None
Delay	Delay period active	Customer acknowledged alarm and established a delay period
Active	Delay period expired	Customer acknowledged alarm, but alarm is not resolved and no delay period is in effect.
Resolved		Customer indicated alarm has been resolved. Customer can also indicate what service was done or what action, if any, was taken to resolve the alarm condition.

The operation of this feature is as follows:

1. Initial identification of an alarm condition will create an alarm with the status of "New" and trigger an e-mail notification to Person-A for the site. ("Person A" is the person who has been identified as the first-level HVAC maintenance responder for the site.)
2. Acknowledgment of an alarm can be accomplished through the user interface by clicking on the alarm status for an individual alarm. This will display the Alarm Response page with the alarm status information. The user can then select "Delay Alarm" or "Resolve Alarm".
3. When the user selects "Delay Alarm" he or she will be prompted to enter the current action taken and a delay time period. The status of the alarm will be changed to "Delay".
4. If an alarm remains in delay status for more than the defined period of time, then a reminder message will be sent to Person-A and the status will be changed to "Active".
5. If the alarm is delayed again, the procedure is the same. An alarm can be delayed a maximum of 3 times.
6. If the delay expires and it has already been delayed three times, in addition to the above notifications, an e-mail notification can be sent to Person-B.
7. Resolution (clearing) of an alarm can be accomplished through the user interface by selecting "Resolve Alarm" on the alarm response page. The user then enters a description of the service completed. The alarm status will be changed to "Resolved" and the alarm will no longer appear on the alarm page.
8. Alarms with a status of "New", "Delay", and "Active" will be displayed on the alarm pages (All Alarms, Unit Alarms) along with their status.
9. The Alarm History page (link from Unit Status page) can be used to display all alarms for a given unit including alarms that are "Resolved".

10. For a given unit, an individual alarm will not be triggered as a new alarm if the current status is “New”, “Delay”, or “Active”.

There is currently no difference in alarm notification based on category of alarm (equipment safety, energy savings, comfort, or monitoring system) but the plan is to implement an option for associating different email addresses with different alarm categories.

## 6.4. Hierarchical Access

The Web site organizes information, and access to the information, in a hierarchical fashion. The lowest level is the site with one or more HVAC units. The highest level is the customer organization. The customer organization can be divided into regions, each region can be divided into areas, each area can be divided into offices, and each office can be divided into sites, as follows.

Organization

- └ Region 1
  - └ Area 1
    - └ Office 1
      - └ Site 1
        - └ HVAC Unit 1
        - └ HVAC Unit 2+
      - └ Site 2+
    - └ Office 2+
  - └ Area 2+
- └ Region 2+

Access to the Web site can be controlled such that one person (user) in an organization may see the information for only one site, while another person may see all sites within an office, a third person may see all sites within the area, and so on, up to the broadest level of all sites for the entire organization.

## 7.0 References

1. FDD Final Report D5.4d, Final Report Describing Economizer, DCV, and Controls Diagnostic Algorithms. Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program. Contract #500-03-030. Prepared for the California Energy Commission, September 2005.
2. FDD Final Report D5.6a, Final Report Describing VM Implementation, Emulation / Bench Testing and Laboratory Testing, and Field Installation. Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program. Contract #500-03-030. Prepared for the California Energy Commission, September 2006.
3. FDD Final Report D5.6b, Final Report Describing the Field Evaluation of the Initial Prototype FDD System. Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program. Contract #500-03-030. Prepared for the California Energy Commission, January 2007.
4. FDD Test Plan Report, D5.8a, Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program. Contract #500-03-030. Prepared for the California Energy Commission, in progress.
5. FDD Final Production Readiness Plan, D5.11b, Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program. Contract #500-03-030. Prepared for the California Energy Commission, in progress.