Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program

Final Production Readiness Plan

CONSULTANT REPORT

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1.0 Executive Summary

This plan outlines the steps involved in moving from the prototype development stage to full production for the Sentinel, FDSI's FDD monitoring system for rooftop HVAC units. The plan identifies three stages in the process (prototype stage, initial limited production, and full production) and the characteristics of each. For quality control testing, it is also necessary to design and produce test fixtures and test software to be used during production. Potential constraints and critical issues that might affect development and production are identified, although no critical problems are foreseen at this time. Based on the information available to date, the estimated manufacturing costs can vary considerably depending upon volume and on setup costs, with an average manufacturing cost of $890 per rooftop unit (RTU), assuming nine RTUs per rooftop and an average of 1.6 circuits per RTU, and assuming production volume for 500 RTUs. Reductions in cost of 10%-15%, or more, can be expected for larger production volumes.

2.0 Production Stages and Key Elements

The following subsections describe the contemplated production stages and the key elements of the production process, with the final subsection highlighting the elements that are considered to be critical for successful production.

2.1. Production Stages

There are three production stages: (1) the prototype stage, (2) the initial small volume or limited production stage, and (3) full production. Issues that are associated with a particular production stage will be identified as such where applicable.

2.1.1. Prototype Stage

The prototype stage is characterized by the in-house production of a small quantity of units, probably fewer than a half-dozen. Prototyping is done to verify design assumptions, check for design flaws and resolve any problems.

During this stage, the circuit boards are designed and the designs are sent out for the bare boards to be produced. When the bare boards are received, components are soldered to the boards, and modules are assembled, by in-house personnel. This version of the Sentinel is based upon an earlier version, and some of the modules changed more than others. Therefore, it is possible to start the prototype process with the modules that involved fewer design changes, while continuing to work on the design of the other modules. The first module to be prototyped in the latest version is the airside module, followed by the compressor module, the communications module, the outdoor air module and finally the processor module. (The latter two modules are based, or could be based, on the use of off-the-shelf components requiring no hardware design.)

Based on experience, it is quite likely that the board designs will need to be revised at least once, and more likely twice, before they will be ready for the next stage of production. The actual production of the bare boards is a relatively quick process (2-3 day turnaround) but then it takes time to populate the boards, and even longer to determine if further changes are advisable.

Also during the prototype stage, the lists of materials and the CAD drawings for the modules need to be developed and verified.

See Section 2.3, Testing and Quality Control, for comments regarding testing during the prototype stage.

2.1.2. Initial Limited Production

An initial run of up to 100 Sentinel systems will be produced for the pilot phase of the FDD project. Given a target of 12 sites with a total of 60 HVAC units for the FDD pilot, this would require approximately 100 compressor modules (one per stage), 60 airside modules (one per HVAC unit), 60 communications modules (one per HVAC unit), 12 outdoor air modules (one per site), and 12 processor modules (one per site). Because some modules are currently more finished than others (in terms of all open issues being resolved), it is likely that the production process will not start with all modules at the same time. For example, production of the airside module could be started first, followed by the compressor module, and then the communications module. As noted above, the outdoor air module and the processor module can be primarily assembled from off-the-shelf products.

We anticipate working closely with the production facility during this initial production run. The production facility might offer suggestions (e.g., to alter the sequence of an assembly process, or to substitute one material for another) that may need to be incorporated into the designs and plans. It is possible that for the small initial production run, some parts of the production process might be done in-house, depending upon the availability of in-house staff, the time requirements of the production facility, and the relative costs.

Quality control will require all modules to be tested at the board and module levels (see Section 2.3, Testing and Quality Control).

2.1.3. Full Production

Full production will be handled by an outside production facility, and ideally will not begin until after the end of the pilot phase, so that any design changes resulting from the pilot test results can be accomplished before full production.

No decision has been made yet regarding whether or not the production facility for full production will be the same as for the small initial production.

2.2. Production Facilities

For this FDD project, we have approached three outside production facilities and are soliciting estimates. The final decision will be based not only on estimated cost but also on estimated production time, the capabilities of the production facility for handling the tasks, and the ability of the production facility to work closely with us to achieve our overall production goals.

2.3. Testing and Quality Control

Three types of tests are applicable: design verification, quality control, and product reliability. The design verification and product reliability testing is addressed in a separate document, "FDD Test Plan Report D5.8a" (in progress).

For quality control (QC) during production, test hardware and test software is required. During the prototype stage, in-house versions of the test hardware and software will be used to verify that the boards and modules have been correctly assembled. For any production by an outside facility, the final version of the test hardware and software will be provided to the production facility, and the production facility will test each board individually and each assembled module individually.

The basic test configuration will consist of a PC, one or more test fixtures, and a test program to run on the PC.

2.3.1. Test Fixtures

The base text fixture is a device that sits between the board or module being tested and the PC used for testing. The connection between the PC and base test fixture is a serial cable. The connection between the base test fixture and the item being tested depends upon the item being tested. For example, for the airside and compressor modules, the connection is via wire; for the communications module, the connection is a wireless Bluetooth connection.

In addition to the base test fixture, other test 'jigs' are also needed to produce an expected value for a given sensor. For the airside module, a 'bed-of-nails' test jig is required because there are no connectors on the board. For the compressor module, the test jigs can be small components plugged into a given connector, or alternatively a bed-of-nails test jig can be used. For the communications module, the base test fixture itself provides the test-jig capability.

2.3.2. Test Software

A screenshot of the test program is shown in Figure 1. As the screenshot indicates, there are a number of functions available beyond the testing indicated by the Run Test button. The additional functions include the options to update the firmware on the board being tested, and to initialize the Bluetooth component in the communications module (a necessary step during production) as well as to use Bluetooth to discover and connect to the communications module to test it individually or to use it to communicate with, and test, airside and compressor modules. The current list of tests is shown in Table 1.

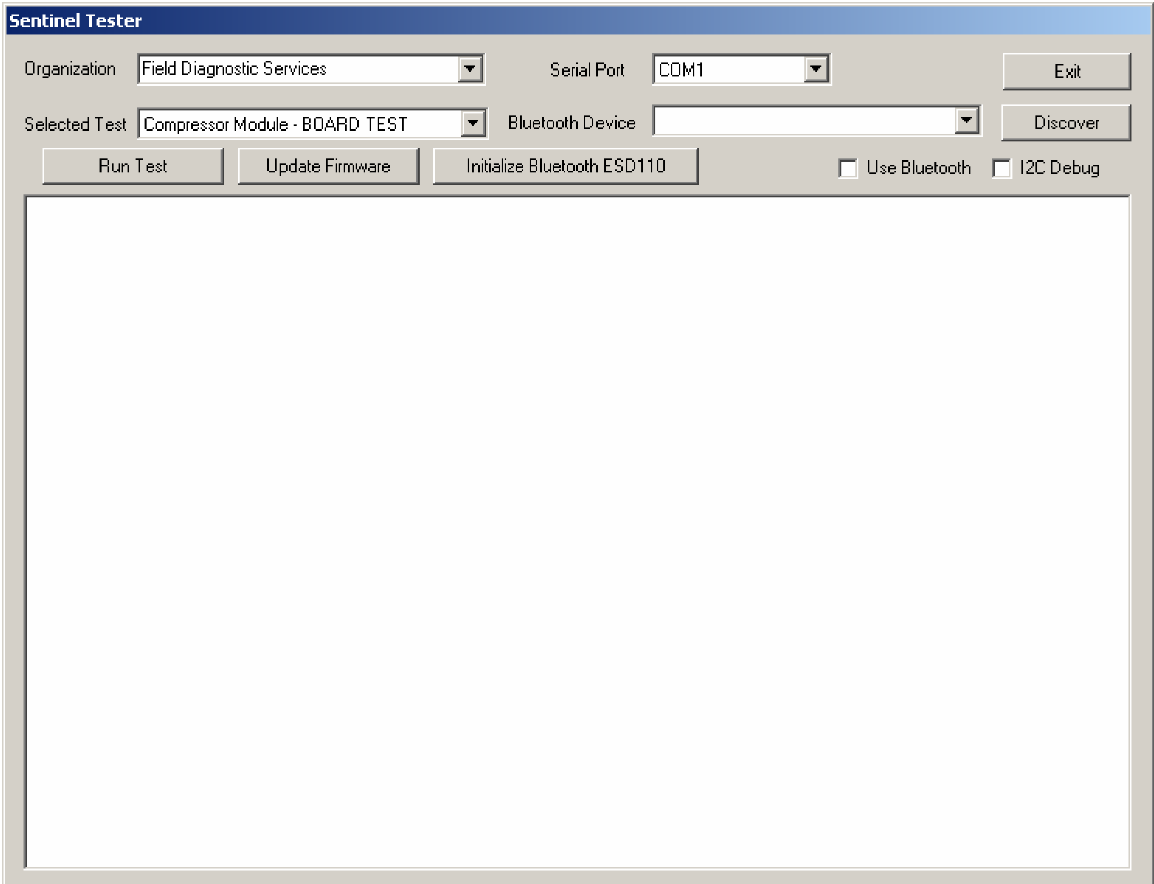


Figure 1. Test Program Screen

Board-Level Tests	Airside board
	Compressor board
	Communications LED board
	Communications Base board
	Processor board
Module-Level Tests	Airside module
	Compressor module
	Communications module
	Processor module

Table 1. Quality Control Tests

The test process requires test personnel to connect the board or module to the FDSI test fixture (which in turn is connected to the PC), select the desired test, attach a test jig if applicable, and click the Run Test button. The result will be a Pass or Fail, along with some relevant information about the board or module (e.g., the serial number, and the values read from the sensors where applicable). In cases of failures, additional information is provided about the probable cause.

For the airside module, the board-level test includes the following:

- The humidity sensor channel will be checked for mid-scale, which in this case should be 56% (with 0.1% precision resistors).
- The thermistor channels will be checked for 25 C (with 0.1% precision resistors). A 'Pass' will require a reading within a quarter percent of full scale.
- The serial number on the chip will be displayed and will cause a small label printer to print out a serial number label that must be adhered to the PCB. Alternatively, if the PCB already has the serial number label, the read-out on the PC screen should be visually compared with the tag on the board.

For the module-level test, the purpose is basically to ensure that nothing got damaged between the time the board was tested and the assembly of the module, and that the assembly was done correctly. Therefore, the module-level test for the airside module will be a series of Pass/Fail sanity checks (e.g., the output of the temperature sensor is the room temperature, and the output of the humidity sensor is the room humidity). A decision has not yet been made regarding which device(s) will be used to determine the room temperature and humidity, and whether or not a direct connection is needed between the device(s) and the test program.

For the compressor module, the board-level test includes the following:

- For the suction pressure sensor (200 psig), the sensor channel will be checked for mid-scale (0.1% precision resistors). A 'Pass' will require a reading within a few tenths of a psig.
- For the liquid/discharge pressure sensor (500 psig), the sensor channel will be checked for mid-scale (0.1% precision resistors). A 'Pass' will require a reading within a few tenths of a psig.
- The suction temperature thermistor channel will be checked for 25 C (with 0.1% precision resistors). A 'Pass' will require a reading within a quarter percent of full scale.
- The liquid temperature thermistor channel will be checked for 25 C (with 0.1% precision resistors). A 'Pass' will require a reading within a quarter percent of full scale.
- The serial number on the chip will be displayed and will cause a small label printer to print out a serial number label that must be adhered to the PCB. Alternatively, if the PCB already has the serial number label, the read-out on the PC screen should be visually compared with the tag on the board.

For the module-level testing, the same comments apply as for the airside module. The module-level test for the compressor module will be a series of Pass/Fail sanity checks (e.g., the output of the temperature sensor is the room temperature, and the output of the pressure sensors is 0 psig). These tests will be at a looser tolerance than the board-level tests.

For the communications module, the board-level test includes the following:

- The power supply voltage will be checked to see that it is 5 volts.
- With a load resistor, the SDA and SCL pull-up current will be checked to see that it is 10 mA, and without a load the open circuit voltage will be checked to see that it is 5 volts.
- The EEPROM will be tested to ensure that it was soldered correctly. (This might be done by a small number of program-generated read/write operations.)
- The serial number on the chip will be displayed and will cause a small label printer to print out a serial number label that must be adhered to the baseboard PCB. Alternatively, if the PCB already has the serial number label, the read-out on the PC screen should be visually compared with the tag on the board.

The module-level test for the communications module will consist of general sanity checks to ensure that everything is still working as expected after full assembly.

The manufacturer will be responsible for meeting the standards set by Field Diagnostic Services, Inc., for each part. If feasible, some of the finished products will be subsequently tested in-house at Field Diagnostic Services, Inc., based on a representative sample determined by the number of units shipped at a time.

2.4. Critical Production Processes and Constraints

The most critical elements are the time required to complete the designs, the availability of materials, the lead-time required for certain steps, the production time itself, and relations with the production facility. In addition, there are a few issues specific to this product that still need to be resolved. The following issues have been identified:

- The final design, from circuit boards to a complete Sentinel system, has been an iterative process, in that decisions made later in the process sometimes require earlier designs to be revised. For example, decisions about how testing will be conducted may cause a change to a board design in order to accommodate that particular test process. Our goal is to minimize these iterations, but the fact remains that it has been hard to force a strict chronological process where earlier designs do not have to be revisited.
- Availability of materials from suppliers can be a factor (e.g., the timeline is impacted when parts are on back-order). There may also be cases where the preferred part is only available in quantities that are too large, or the part's availability time frame is too long. In those cases, a suitable substitute must be used.
- Lead-times for manufacturing the printed circuit boards (and similar components) need to be accommodated. Typically four to six weeks is required for circuit boards.
- Serialization of the chips and serial-number label application is an issue that still needs to be resolved with the production facility. Our design calls for each chip to have a unique serial number, and that the serial number be on a label affixed to the circuit board as well as on a label affixed to the outside of the module housing (for the airside

and compressor modules). For the communications module, the serial number on the outside of the box is to be the number that appears on the Bluetooth board. Considerations include whether or not the chips themselves will have visible serial numbers, and the trade-off in production time between arranging chips and pre-printed labels in serial number order, or printing labels on demand as each module is tested.

- Time required for machining of raw materials must be included (e.g., the metal housings). This is not considered to be a critical factor as long as enough time is allocated in the production cycle.
- Time required for the assembly of sub-assemblies into the finished product, and the relative timing of these steps, needs to be managed so that delays do not occur when dependent sub-assemblies are not completed on time.
- Time and effort may be needed to resolve any problems that arise after production has begun, whether originating on our side or at the production facility. This might include mistakes in the original specifications, or mistakes in the assembly process, or the use of parts that are not up to the desired quality.
- Availability of in-house personnel can be a factor. For all tasks involving in-house personnel (especially during the prototype stage), delays may occur when personnel are not available due to other commitments. This can easily occur when staff size is small and all personnel have other responsibilities competing for time.

Generally speaking, we are expecting finished products to be ready three months after the order is given to the production facility to begin. There are no critical problems foreseen at this time as long as adequate time is available for each production stage.

3.0 Economic Considerations

3.1. Target Manufacturing Cost Per RTU

The overall cost per site depends upon the number of RTU units per site, the number of compressor stages, and the volume of production. A site that has one RTU, with a one-stage compressor, will have one of each Sentinel module. However, beyond that, there is one compressor module per stage, one airside module per RTU, one communications module per RTU, one ambient air module per site, and one processor module per site.

The following table (Table 2) looks at estimated costs based on producing 100 Sentinel systems, with the per-module manufacturing costs based on 500 airside and communications modules and 1000 compressor modules. Different average costs per RTU are then shown depending upon the number of RTUs per site and the number of stages per RTU (for general calculations, we assume that the average number of stages is 1.6, although in reality the larger group is expected to be 1-stage units, with a smaller group of 2-4 stage units).

Table 2. Comparative Manufacturing Costs Per RTU

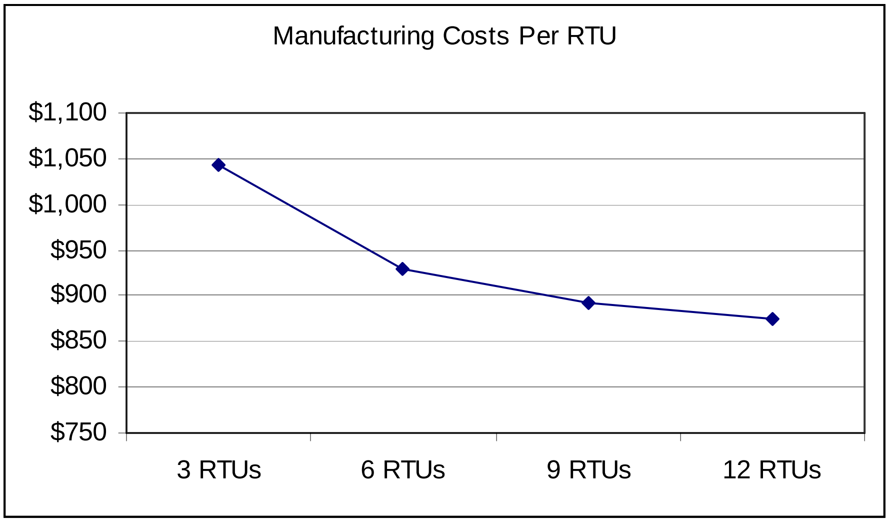
Item	Mfg. Cost	*Cost Basis	3 RTUs per Site			6 RTUs per Site		
			1 stage	1.6 stages	2 stages	1 stage	1.6 stages	2 stages
Compressor Module	$272	1,000	$816	$1,306	$1,632	$1,632	$2,611	$3,264
Airside Module	$112	500	$336	$336	$336	$672	$672	$672
Communications Mod	$270	500	$810	$810	$810	$1,620	$1,620	$1,620
Ambient Air Module	$252	100	$252	$252	$252	$252	$252	$252
On-Site Processor	$425	100	$425	$425	$425	$425	$425	$425
Sub-Total	$1,331		$2,639	$3,129	$3,455	$4,601	$5,580	$6,233
Cost Per RTU			$880	$1,043	$1,152	$767	$930	$1,039
Add manufacturing setup costs **	$5,800		$58	$58	$58	$58	$58	$58
Cost Per RTU			$899	$1,062	$1,171	$777	$940	$1,049

* The compressor cost is based on 1000 modules; the airside and communications manufacturing costs are based on 500 modules each, and the ambient and processor module costs are based on 100 modules each.

** Manufacturing setup costs shown here are based on the lowest estimate that we received, and are allocated across 100 sites, i.e., the setup costs shown are per site assuming 100 sites. The impact of the setup charges goes down as production volume increases.

One of the variable costs per site is related to the number of stages per compressor, since each stage needs a compressor module. Figure 2 takes the working average of 1.6 stages per compressor and plots the per-RTU manufacturing costs for 3 to 12 RTUs per site.

Figure 2. Per-RTU Costs for 3-12 RTUs per site



Note: The above chart is based on 1.6 stages per compressor, and does not include manufacturing setup charges, which would be negligible for large volume production.

At the other end of the scale are the fixed costs for one ambient air module and one central processor module per site. The per-RTU impact of the ambient air module and the processor module obviously decreases as the number of RTUs per site increases.

The impact of the manufacturing setup costs is hard to represent because these are one-time fixed costs unrelated to production volume. For the purposes of the above comparison, the total cost is allocated across the 100 sites. However, as the production of modules continues, the impact of the setup costs becomes less and less. Another aspect of the setup costs is that estimates from different production facilities varied widely, with the highest estimates being roughly five times that of the lowest estimates. To date it has been difficult to compare the estimates in detail because the production facilities have not yet provided full breakdowns of the component factors into categories that are equivalent across production facilities.

The manufacturing costs presented here are for rather low volume production (500 units), and reductions in cost of 10%-15%, or more, can be expected for larger production volumes.

3.2. Other Cost Considerations

Other costs to be considered include software development (for the central website as well as for the technician using a PDA to install a system and later to check real-time readings), inventory costs (for warehousing completed Sentinel systems), installation costs (including labor, incidental materials, possibly transportation and travel expenses), documentation (e.g., installation guides, user guides for the Sentinel website, user guides for technicians visiting installed sites), training (e.g., to train installers, and to train personnel in using the website to monitor installed systems), on-going costs to maintain the monitoring database and website, and any costs associated with re-visiting an installed site to address monitoring system problems.

For the customer, costs beyond the price of the product may include communications charges (e.g., for phone lines or for Internet service), installation fees (if not bundled in with the price of the product), and ongoing fees for the monitoring service.

From a business point of view, the manufacturing, installation and monitoring costs might be all bundled into a single "enhanced service" contract. From the customer's point of view, the return on investment could come from a combination of direct and indirect savings, ranging from reduced energy costs, fewer service calls and lower maintenance costs in the long run, to fewer complaints from tenants requesting adjustments to the air conditioning.